Understanding the use of automation in helicopters

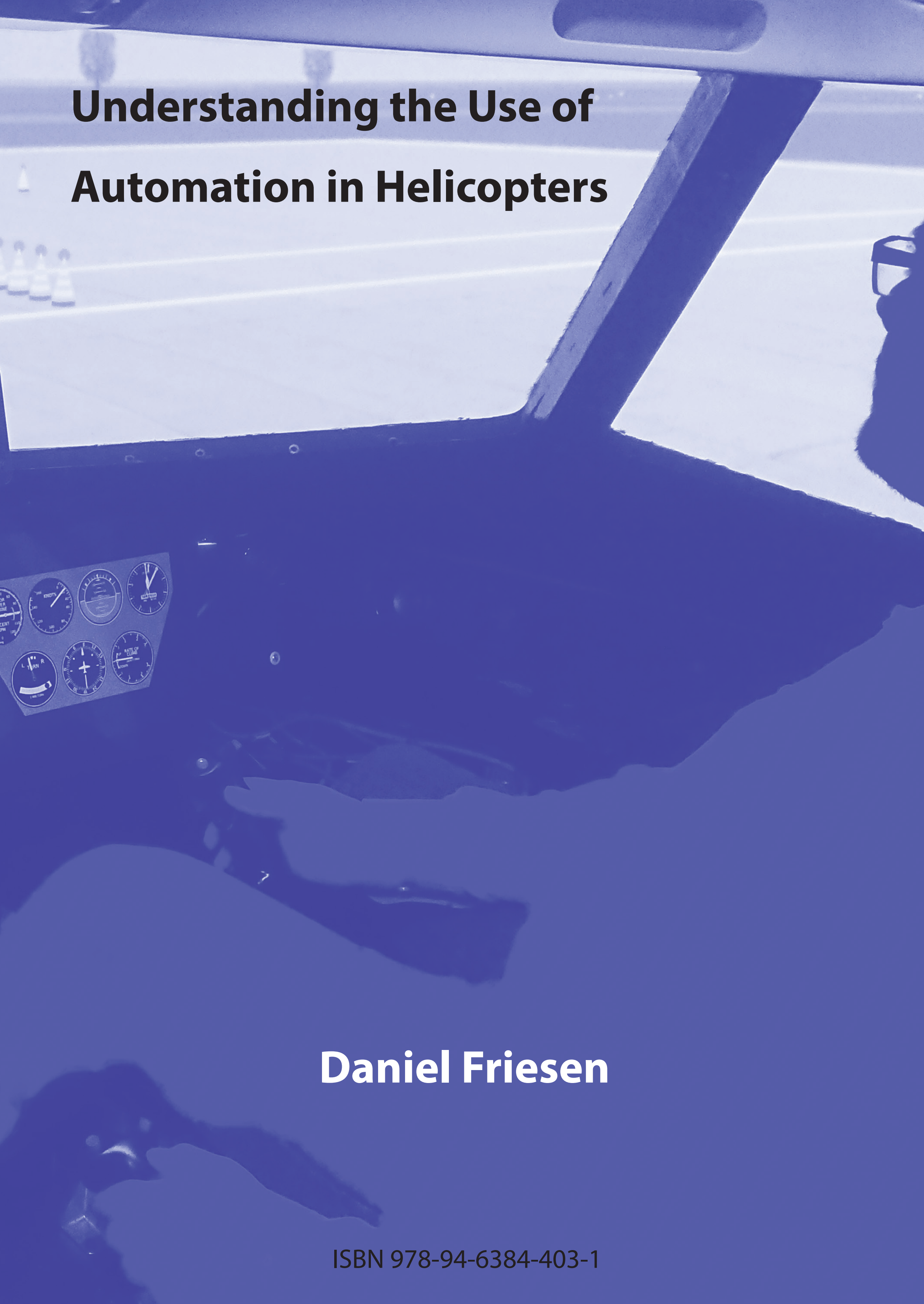
Friesen, D.

DOI
10.4233/uuid:9bd2f753-1944-411d-b29c-95316f008564

Publication date
2023

Document Version
Final published version

Citation (APA)
Friesen, D. (2023). *Understanding the use of automation in helicopters*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:9bd2f753-1944-411d-b29c-95316f008564



Understanding the Use of Automation in Helicopters

Daniel Friesen

ISBN 978-94-6384-403-1

Propositions

accompanying the dissertation

Understanding the Use of Automation in Helicopters

by

Daniel Friesen

1. When compared to commercial fixed-wing operations, the peculiarities of helicopter control, including the requirement to often fly hands-on, exacerbates inadvertent negative automation effects. (This thesis)
2. Providing support predominantly through information automation and not decision automation increases both pilot workload and the pilot-vehicle system's resilience towards unexpected events. (This thesis)
3. Advisory automation provides the illusion of improved decision-making support, regardless of the quality of the provided advice. (This thesis)
4. Gaps in decision automation coverage across timescales have significant negative effects on safety and pilot decision-making. (This thesis)
5. The optimisation problem to maximise the research output of a human-in-the-loop experiment has an ever-changing reward function and an unreachable global optimum.
6. The researcher's body language, tone of voice, and personal chemistry with an experiment participant have a larger influence on the results than any part of the official briefing document.
7. A significant or insignificant test statistic is the beginning, not the end, of the analysis of experimental results.
8. Allocating a time-slot to think about creative solutions to a problem is the worst possible way to devise creative solutions to a problem.
9. A four year old's unrelenting chain of "But why?"-questions serves as a great tool to question your scientific arguments.
10. Comparing helicopter and fixed-wing cockpits is akin to comparing German and Dutch culture: at first, they appear largely similar, with only a small number of obvious variations. Long-term studies and multiple experiments, however, reveal an increasing number of significant differences.

These propositions are regarded as opposable and defendable, and have been approved as such by the promotors dr. M.D. Pavel, prof. P. Masarati, and dr.ir. C. Borst.

Understanding the Use of Automation in Helicopters

Understanding the Use of Automation in Helicopters

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, prof.dr.ir. T.H.J.J. van der Hagen,
Chair of the Board of Doctorates
to be defended publicly on
Thursday 19 January 2023 at 15:00 o'clock

by

Daniel FRIESEN

Master of Science in Maschinenbau — Mechanical and Process Engineering,
Technische Universität Darmstadt, Germany
born in Wuppertal, Germany

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus	chairman
Dr. M. D. Pavel	Delft University of Technology, promotor
Prof. dr. P. Masarati	Politecnico di Milano, Italy, promotor
Dr. ir. C. Borst	Delft University of Technology, copromotor
Independent members:	
Prof. dr. M. P. Hagenzieker	Delft University of Technology
Prof. dr. M. Tanelli	Politecnico di Milano, Italy
Prof. dr. J. Lundberg	Linköping University, Sweden
Prof. dr. K. M. Feigh	Georgia Tech, United States of America
Prof. dr. ir. G. C. H. E. de Croon	Delft University of Technology, reserve member

Prof. dr. ir. M. Mulder has contributed greatly to the preparation of this dissertation. The doctoral research has been carried out in the context of an agreement on joint doctoral supervision between Politecnico di Milano, Italy, and Delft University of Technology, the Netherlands. Delft University of Technology and Politecnico di Milano made important contributions to the work described in this dissertation. This research has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement N° 721920.

Keywords: Helicopter, Automation, Human-Machine Interface

Printed by: Ipskamp

Front & Back: Daniel Friesen, SIMONA Research Simulator

ISBN 978-94-6384-403-1

An electronic version of this dissertation is available at
http://repository.tudelft.nl/.

Contents

Summary

Helicopters possess the unique capability of hovering stationary in the air and landing with relative ease in a variety of terrain, which sets them apart from fixed-wing aircraft. However, due to operations close to terrain and obstacles, piloting a helicopter can be a challenging task that involves risk of incidents and accidents. One avenue to increase helicopter safety is providing improved cockpit automation functions which optimally support the pilots, such that they can react to every safety-critical situation to the best of their ability.

Throughout history, automation has brought tremendous improvements to human productivity. However, the effects of automation are not always beneficial. Automation can have a detrimental influence on manual control capabilities, the reaction time to safety-critical events, and workload, in particular in situations that have not been anticipated by the automation designer. It is therefore paramount that helicopter automation development takes the whole operational envelope into account, including off-nominal and unforeseen events.

There already exist many approaches for developing automation in aviation, in particular in the commercial fixed-wing domain. However, due to different operational environments and pilot responsibilities, the results of fixed-wing automation development cannot be used to guide helicopter automation development. Also, some systems that have been evaluated in the helicopter domain seem to focus only on very specific operational envelope and timescales, neglecting the wider operational context. This dissertation aims to close this gap between isolated task-support systems, providing insight into the effects of employing different automation design principles both within and outside of their operational envelope.

Two distinct automation design philosophies are investigated in this dissertation: ecology-centred and task-centred automation. Both approaches were investigated and compared in the commercial fixed-wing domain before and showed profound differences based on the operational environment. This dissertation investigates whether these differences are identical in commercial fixed-wing and helicopter operations.

The ecology-centred or constraint-based design approach focuses on the ecology or work domain of the helicopter. It is based on ecological interface design, a methodology that, up until now, has not been widely applied in the helicopter domain. It aims to provide information about the underlying work domain structure and constraints, while leaving the final decision in the hands of the pilot. This design approach encourages robust control by providing a wide range of feasible solutions, with the pilots as the final decision-makers.

The task-centred or advisory design approach focuses on technology-centred automation capabilities. It aims to provide task-related information and optimal

suggestions without disclosing the underlying reasoning. The given advice encourages optimal control by providing one specific suggested solution to the pilots.

How can advisory and constraint-based automation design philosophies improve helicopter safety at different timescales of operation? To answer this question, three subquestions are investigated: What are the peculiarities of helicopter automation; how do different automation design philosophies influence safety (and other parameters) in helicopters during short-, medium-, and long-term scenarios; and how can the experimental results be incorporated into guidelines for helicopter automation design? These questions are first answered on separate timescales, utilising the results of four human-in-the-loop experiments performed in the SIMONA Research Simulator at Delft University of Technology. Afterwards, the results are discussed in the context of the whole operational envelope of helicopters.

To structure the work of this dissertation, two established automation classification methods are utilised: the level of automation and the stage of automation. These methods are extended with the level of control sophistication, which correlates with the timescale, complexity, and uncertainty of supported task environments. Classifying automation systems in such a way enables the discovery of automation coverage clusters and gaps in the helicopter domain.

This analysis motivates the four human-in-the-loop experiments of this dissertation. The first experiment focused on the short timescale task of hovering, a task that is included in practically every helicopter mission. During hovering and low-speed manoeuvring, head-down hover displays and instrument panels theoretically provide all necessary flight data information to control the helicopter. However, past experiments have shown that head-down displays can incur high workload and control instability. This result has been replicated in the first experiment: pilots were unable to perform the hover task with a task-centred head-down hover display, while the ecology-centred outside visuals enabled task completion. This highlights the positive impact of a natural representation of the work domain (i.e., good outside visuals) during short-term tasks, and how a focus on only task-related state representation in displays can make the control task impossible.

The following experiment focused on head-up, conformal symbology to support helicopter low-speed manoeuvring and hovering. Within the frame of conformal head-up displays, the same design approaches as in the previous experiment were investigated. The first, ecology-centred display contained a grid ground texture and a box indicating the hover target position. The second, task-centred display bore close resemblance to a standardised hover course. Both displays were compared with a baseline condition with good outside visibility. The ecology-centred display produced similar, good performance as the baseline condition, although workload and situation awareness deteriorated. This time, the task-centred display at least afforded task completion, but performance was worse. It appears that distinctive ground textures and far-field references play a much larger roles in hover performance than task-specific cues.

The following experiment expanded the timescale to investigate an obstacle avoidance task. This task is located in the medium timescale of operation, separated from the immediate, short-term stabilisation control task. It is similar to

a task chosen in past research in the fixed-wing domain to investigate ecological interface design. Pilot preference remained identical between both domains: pilots preferred advisory automation in nominal, and constraint-based automation in off-nominal situations, highlighting the increased resilience of the constraint-based system towards unexpected events. However, this experiment in the helicopter domain also showed a trend of improved pilot workload and situation awareness while using the ecology-centred display, even in nominal situations. Besides pilot opinion, constraint-based automation led to better results.

The analysed task was still connected to manual helicopter control, albeit on a higher level than the stabilisation task. The next experiment investigated whether results differ when performing cognitive decision-making tasks, as opposed to skill-based manual control tasks. The focus lied on pilot trajectory decision-making in the long timescale. This setup aimed to emulate the requirements of real-world helicopter operations, where pilots are required to exert control on all timescales at the same time, from short-term stabilisation to long-term navigation.

The results show a significant negative impact of the advisory display on pilot trajectory decision-making during unexpected events. As the temporal gap between the short-term manual control task and the performed decision-making task increases, the inadvertent negative effects of automation appear more pronounced. The constraint-based display did not negatively impact the pilots' decision-making, but also failed to improve any of the other dependent metrics. This showcases the potential of constraint-based displays to avoid inadvertent automation effects, but also highlights their training and familiarisation issues. If constraint-based automation should be a contender for real-world helicopter automation, these issues need to be addressed in future research.

Combining the results of all experiments, it appears that the peculiarities of helicopter control and the broader operational envelope influence the effect of the employed automation. Ecology-centred and constraint-based automation generally enables the pilots to successfully complete the task with acceptable performance, albeit there is room for improvement with respect to the systems' ease-of-use. Advisory automation is preferred by the pilots, but it produces significant negative effects on navigational decision-making when confronted with off-nominal situations.

It is hypothesised that a "cognitive gap" in automation coverage across timescales, between the requirements of manually controlling the helicopter on the short timescale and supervising advisory automation on the long timescale, exacerbates negative automation effects. These effects seem to be particularly strong when the "gap" occurs in the action selection stage. Helicopter automation should focus on supporting the pilots' information acquisition and analysis tasks across all timescales, while leaving the final action selection and implementation to the pilots. Advisory automation should only be employed when this does not cause an "action selection gap", i.e., the same process should be supported at least as strong on lower timescales. Supporting pilots in the suggested way should enable them to employ their control and decision-making skills to the best of their extensive capabilities, and therefore increase helicopter operational safety.

Samenvatting

Helikopters bezitten de unieke eigenschap dat ze op hun plaats kunnen blijven hangen in de lucht, en makkelijk kunnen landen in verschillende vormen van terrein, wat hen onderscheidt van vliegtuigen met vaste vleugels. De nabijheid van de grond en obstakels tijdens de operatie maakt het besturen van een helikopter echter een uitdaging met risico op een incident of ongeluk. Een mogelijkheid om helikoptervluchten veiliger te maken is het aanbieden van verbeterde automatisering in de stuurcabine welke de piloot optimaal ondersteunt zodat die zo goed mogelijk kan reageren op een situatie waar de veiligheid in het gedrang is.

In de loop der jaren heeft automatisering tot grote verbeteringen in de menselijke productiviteit geleid. De neveneffecten van die automatisering zijn echter niet altijd wenselijk: het kan een negatieve invloed hebben op de stuurcapaciteiten, de reactietijd voor situaties waar de veiligheid in het gedrang is, en de werklast, in het bijzonder in situaties die niet door de ontwerper van de automatisering zijn voorzien. Het is daarom uiterst belangrijk dat automatisering bij helikopters wordt ontwikkeld met de gehele operationele enveloppe in gedachten, inclusief uitzonderlijke en onvoorziene situaties.

Er bestaan al verschillende benaderingen om automatisering voor de luchtvaart te ontwikkelen, voornamelijk voor commerciële vliegtuigen met vaste vleugels. Omdat zowel de operationele situaties als de verantwoordelijkheden voor de piloot anders zijn, kunnen de resultaten voor vliegtuigen met vaste vleugels niet gebruikt worden om de ontwikkeling van helikopterautomatisering te helpen. Daarnaast zijn sommige systemen die geëvalueerd zijn voor helikopters gefocust op heel specifieke operationele enveloppes en een enkel tijdsbestek, waardoor ze dus de bredere operationele context negeren. Dit proefschrift wil de verschillende alleenstaande systemen voor taakondersteuning dichter bij elkaar brengen. Dit wordt gedaan door inzicht te geven in de gevolgen van het gebruik van een bepaalde manier om automatisering te ontwikkelen, zowel binnen als buiten de bedoelde operationele enveloppe.

In dit proefschrift zijn twee verschillende strekkingen om automatisering te ontwikkelen onderzocht: de ecologische en de taakgerichte benadering van de automatisering. Beide strekkingen zijn reeds onderzocht en vergeleken in de wereld voor commerciële vliegtuigen met vaste vleugels, waarbij duidelijke verschillen te zien waren in hun gebruik bij een bepaalde operationele context. Dit proefschrift onderzoekt of deze verschillen hetzelfde zijn voor de toepassing bij helikopters.

De ecologische, of limiet gebaseerde benadering gaat voornamelijk in op de ecologie of het werkdomein van de helikopter. Het is gebaseerd op het ecologisch ontwerp van interfaces, een manier die tot nu toe niet wijd is toegepast bij helikopters. Deze benadering probeert informatie te geven over de grenzen van het onderliggende werkdomein en laat de uiteindelijke beslissing over aan de piloot.

Door een heel scala aan mogelijke oplossingen te presenteren benadrukt deze benadering robuuste controle waar de piloot de uiteindelijke beslissing maakt.

De taakgerichte of advies gebaseerde benadering benadrukt de technische capaciteiten van de automatisering. Zijn doel is om informatie te geven bij de taak en een optimale oplossing voor te stellen zonder de onderliggende redenering. Het advies legt de focus op optimale controle door één oplossing voor te stellen aan de piloot.

Hoe kunnen advies en limiet gerichte automatiseringsbenaderingen de veiligheid tijdens het besturen van een helikopter verbeteren bij verschillende tijdsbestekken? Om deze vraag te beantwoorden zijn drie deelvragen onderzocht: Wat zijn de speciale aspecten voor de automatisering van helikopters; hoe beïnvloeden verschillende benaderingen voor het ontwerp van automatisering de veiligheid (en andere parameters) in scenario's met zowel korte, middellange, als lange tijdsbestekken; en hoe kunnen de experimentele resultaten gebruikt worden om richtlijnen op te stellen voor de verdere automatisering van helikopters? Deze vragen worden eerst voor ieder tijdsbestek apart beantwoord, gebruikmakend van de resultaten van vier mens-machine experimenten in de SIMONA onderzoeksimulator van de Technische Universiteit Delft. Daarna worden de resultaten besproken in de context van de gehele operationele enveloppe van helikopters.

Om structuur te geven aan dit proefschrift is gebruik gemaakt van twee bestaande classificaties van automatisering: het niveau en het moment van de automatisering. De controle complexiteit is toegevoegd aan deze methoden, welke het tijdsbestek, de complexiteit en de onzekerheid van de taakomgeving combineert. Door automatiseringssystemen op deze manier te classificeren kunnen automatiseringsgebreken gevonden worden binnen het helikopterdomein.

Deze analyse motiveert de vier mens-machine experimenten beschreven in dit proefschrift. Het eerste experiment richtte zich op de korte-tijdsbestek taak van het in de lucht stil blijven hangen, een taak die in vrijwel alle helikoptermissies voorkomt. Tijdens het stilhangen en het manoeuvreren op lage snelheid, bieden instrumentpanelen binnen de bestuurscabine in theorie alle benodigde vluchtgegevens om de helikopter te kunnen besturen. Eerdere experimenten hebben echter aangetoond dat zulke instrumentpanelen kunnen leiden tot hoge werkdruk en instabiliteit van de besturing. Dit resultaat is gerepliceerd in het eerste experiment: piloten waren niet in staat om accuraat in de lucht stil te blijven hangen met een taakgericht instrumentpaneel binnen de bestuurscabine, terwijl het ecologisch-benaderde zicht naar buiten het mogelijk maakte om de taak te voltooien. Dit benadrukt het positieve effect van een natuurlijke weergave van het werkdomein (d.w.z., goed zicht naar buiten) tijdens korte-termijn taken, en hoe een focus op alleen taakgerelateerde informatie in displays de controletaak onmogelijk zou kunnen maken om uit te voeren.

Het volgende experiment richtte zich op symbolen geprojecteerd op het buitenzicht om helikoptermanoeuvres op lage snelheid en het stilhangen in de lucht te ondersteunen. Binnen dit kader van het projecteren van informatie op het buitenzicht werden dezelfde ontwerpbenaderingen als in het vorige experiment onderzocht. Het eerste, ecologisch-benaderde display bevatte een rastergrondtextuur en een kader dat de gewenste positie voor het stilhangen aangaf. Het tweede, taakgerichte display leek sterk op een standaardomgeving die gebruikt wordt om het stilhangen van helikopters te beoordelen. Beide displays werden vergeleken met een basisconditie met goed zicht naar buiten. Het ecologisch-benaderde display resulteerde in vergelijkbare goede prestaties als de basisconditie, hoewel de werkdruk en het situatiebewustzijn verslechterden. Ditmaal zorgde het taakgerichte display in ieder geval voor het kunnen voltooien van de taak, hoewel de prestaties slechter waren. Het lijkt er dan ook op dat onderscheidende grondtexturen en op afstand gelegen referentiepunten een veel grotere rol spelen bij het in de lucht stil blijven hangen dan taakspecifieke signalen.

Het volgende experiment breidde de tijdschaal uit om een obstakel-vermijdende taak te onderzoeken. Deze taak behoort tot de middellange operationele tijdschaal, losstaand van de directe, korte-termijn stabilisatie controletaak en is vergelijkbaar met een taak die in eerder onderzoek voor vliegtuigen met vaste vleugels is gekozen om een ecologisch interface-ontwerp te onderzoeken. De voorkeur van de piloten bleek identiek tussen beide domeinen: adviserende automatisering in standaard situaties en limiet gebaseerde automatisering in uitzonderlijke situaties. Dit benadrukt de veerkracht van het limiet gebaseerde systeem bij onverwachte gebeurtenissen. Dit experiment in het helikopterdomein liet echter ook een trend van verbeterde werkdruk en situatiebewustzijn bij piloten zien met het gebruik van het ecologisch-benaderde display, zelfs in standaardsituaties. De mening van piloten daargelaten, leidde limiet gebaseerde automatisering tot betere resultaten.

De geanalyseerde taak was nog steeds gerelateerd aan handmatige helikopterbesturing, zij het op een hoger niveau dan de stabilisatietaak. Het volgende experiment onderzocht of resultaten verschillen bij het uitvoeren van cognitieve besluitvormingstaken, in tegenstelling tot vaardigheidsgebaseerde handmatige besturingstaken. De focus lag op de lange-termijnbesluitvorming van piloten betreffende het te vliegen traject. Het doel van deze opstelling was om de vereisten van helikoptermissies in de echte wereld na te bootsen, waarbij de piloot tegelijkertijd actief is op alle tijdschalen, van stabilisatie op de korte termijn tot navigatie op de lange termijn.

De resultaten laten een significant negatief effect zien van het adviserende display op de besluitvorming van piloten betreffende het traject tijdens onverwachte gebeurtenissen. Naarmate het tijdsinterval tussen de korte-termijn handmatige besturingstaak en de besluitvormingstaak toeneemt, lijken de onbedoelde negatieve effecten van automatisering meer uitgesproken. De limiet gebaseerde display had geen negatieve invloed op de besluitvorming van piloten, maar slaagde er ook niet in om een van de andere afhankelijke parameters te verbeteren. Dit toont de potentie van limiet gebaseerde displays om onbedoelde effecten van automatisering te voorkomen, maar benadrukt ook hun trainings- en gewenningsproblemen. Als limiet gebaseerde automatisering zou moeten meedingen voor helikopterautomatisering in de echte wereld, zullen deze problemen verholpen moeten worden in toekomstig onderzoek.

Wanneer de resultaten van alle experimenten worden gecombineerd, blijken de speciale aspecten van helikopterbesturing en de bredere operationele enveloppe het effect van de toegepaste automatisering te beïnvloeden. Over het algemeen stellen ecologisch benaderde en limiet gebaseerde automatisering de piloot in staat om de taak succesvol uit te voeren met acceptabele prestaties, al is er ruimte voor verbetering met betrekking tot het gebruiksgemak van de systemen. Adviserende automatisering heeft de voorkeur van piloten, maar leidt tot significant negatieve effecten bij de besluitvorming omtrent navigatie wanneer ze worden geconfronteerd met uitzonderlijke situaties.

Er wordt verondersteld dat een "cognitieve kloof" in automatiseringsdekking over verschillende tijdschalen, tussen de vereisten van handmatige helikopterbesturing op de korte-termijn tijdschaal en het toezicht houden op adviserende automatisering op de lange-termijn tijdschaal, de negatieve effecten van automatisering verergert. Deze effecten lijken in het bijzonder sterk te zijn wanneer de "kloof" optreedt tijdens het selecteren van een actie. Helikopterautomatisering zou zich moeten richten op het ondersteunen van de taken van de piloot op het gebied van informatievergaring en - verwerking op alle tijdschalen, terwijl het de uiteindelijke selectie en implementatie van een actie aan de piloot overlaat. Adviserende automatisering zou alleen moeten worden gebruikt wanneer dit geen "actieselectiekloof" veroorzaakt, d.w.z., hetzelfde proces zou op zijn minst even sterk op de lagere tijdschalen moeten worden ondersteund. Het op de voorgestelde manier ondersteunen van piloten zou hen in staat moeten stellen om hun vaardigheden op het gebied van besturing en besluitvorming zo goed mogelijk in te zetten, en daarmee de operationele veiligheid van helikopters verhogen.

Riassunto

Gli elicotteri possiedono le capacità uniche di librarsi fermi in aria e atterrare con relativa facilità su una varietà di terreni, cosa che li distingue dagli aerei ad ala fissa. Queste capacità consentono loro di svolgere molti ruoli critici nella società moderna. Ad esempio servizi di ordine pubblico, medici, la ricerca e il salvataggio e operazioni di lavoro aereo.

Per effetto di questa elevata varietà di missioni e della conseguente necessità di volare vicino al suolo e a ostacoli, pilotare un elicottero può essere un compito impegnativo, che comporta il rischio di incidenti. Un modo per aumentare la sicurezza degli elicotteri è fornire migliori funzionalità di automazione del pilotaggio. Per aumentare la sicurezza operativa, il miglioramento dell'automazione del pilotaggio mira a fornire un supporto ottimale al pilota, affinché possa reagire al meglio delle proprie capacità a ogni situazione critica per la sicurezza.

Nel corso della storia, l'automazione ha apportato enormi miglioramenti alla produttività umana. Tuttavia, gli effetti dell'automazione non sono sempre vantaggiosi. L'introduzione dell'automazione può avere un'influenza negativa sulle capacità di controllo manuale del pilota, sul tempo di reazione agli eventi critici per la sicurezza e sul carico di lavoro, in particolare in situazioni che non sono state previste in fase di progetto dell'automazione. È quindi fondamentale sviluppare ulteriormente l'automazione degli elicotteri tenendo conto dell'intera dotazione operativa, compresi eventi fuori dalle condizioni nominali e l'eventualità di imprevisti.

Esistono già molti approcci per lo sviluppo di display e funzioni di automazione nell'aviazione, in particolare nel settore commerciale dell'ala fissa. Tuttavia, a causa di ambienti operativi molto diversi e di diversi compiti e responsabilità tipici dei piloti, i risultati dello sviluppo dell'automazione ad ala fissa non possono essere utilizzati così come sono come riferimento per lo sviluppo dell'automazione nel settore degli elicotteri. Inoltre, alcuni sistemi che sono stati valutati in ambito elicotteristico sembrano concentrarsi solo sul loro specifico inviluppo operativo o sulla sua specifica scala temporale, trascurando il più ampio contesto operativo. Questa tesi mira a colmare questo divario tra supporto per attività a breve e lungo termine, fornendo informazioni sugli effetti dell'utilizzo di diversi principi di progettazione dell'automazione sia all'interno che all'esterno della loro struttura operativa.

Al fine di ottenere una panoramica dei fattori che influenzano i diversi aspetti di progettazione dell'automazione, in questa tesi vengono studiate empiricamente due distinte filosofie di progettazione dell'automazione: l'automazione centrata sull'ecologia e l'automazione centrata sul compito. Entrambi gli approcci sono stati studiati e confrontati nel dominio commerciale dell'ala fissa e hanno mostrato profonde differenze in base all'ambiente operativo. Questa tesi indaga se l'effetto di entrambe le filosofie di progettazione dà nell'ambito delle operazioni elicotteristiche

commerciali risultati differenti da quelli ottenuti nell'ambito delle operazioni commerciali ad ala fissa.

L'approccio alla progettazione centrato sull'ecologia, o sui vincoli, si concentra sull'ecologia o sul contesto di lavoro dell'elicottero. Si basa sulla progettazione di interfacce ecologiche, una metodologia che, fino ad ora, non è stata ampiamente applicata e valutata nel settore elicotteristico. Essa mira a fornire informazioni sulla struttura e sui vincoli del contesto di lavoro corrente, lasciando nelle mani del pilota la decisione finale su quali azioni intraprendere. Questo approccio progettuale mira ad aumentare la comprensione delle situazioni da parte dei piloti e a incoraggiare un controllo robusto, ovvero fornendo un'ampia gamma di soluzioni fattibili, con i piloti come decisori finali.

L'approccio progettuale centrato sulle attività, o consultivo, è orientato verso capacità di automazione incentrate sulla tecnologia. Mira a fornire informazioni strettamente correlate alle attività e suggerimenti/consigli ottimali, senza esporre il processo logico sottostante. Questo approccio progettuale mira a fornire scorciatoie che riducono al minimo lo sforzo cognitivo richiesto. Il compito dei piloti si riduce all'esecuzione delle azioni suggerite o alla reazione agli allarmi. I consigli forniti incoraggiano il controllo ottimale fornendo ai piloti una specifica soluzione suggerita.

In che modo le filosofie di progettazione dell'automazione basate sulla consulenza e sui vincoli possono migliorare la sicurezza degli elicotteri in diverse scale temporali di funzionamento? Per rispondere a questa domanda, questa tesi indaga consecutivamente tre sottodomande: Quali sono le peculiarità dell'automazione degli elicotteri; in che modo le diverse filosofie di progettazione dell'automazione influenzano la sicurezza (e altri parametri) negli elicotteri durante scenari con condizioni di attività a breve, medio e lungo termine; e come si possono incorporati i risultati sperimentali raccolti in linee guida per la progettazione dell'automazione degli elicotteri? A queste domande viene prima data risposta su scale temporali separate, utilizzando i risultati di quattro esperimenti "human-in-the-loop" eseguiti nel SIMONA Research Simulator presso la Delft University of Technology. Successivamente, i risultati vengono discussi nel contesto dell'intero spettro di operazioni degli elicotteri.

Al fine di costruire una solida base per gli esperimenti di questa dissertazione, precedenti ricerche nell'ambito dell'automazione degli elicotteri vengono esaminate e organizzate. Vengono utilizzati due metodi consolidati di classificazione dell'automazione: il livello di automazione (Level of Automation, LoA) e lo stadio di automazione (Stage of Automation). Questi metodi sono estesi con l'aggiunta del livello di sofisticazione del controllo (Level of Control Sophistication, LoCS), che è correlato alla scala temporale, alla complessità e all'incertezza degli ambiti di attività supportati.

Classificare i sistemi di automazione in questo modo consente di individuare agglomerati di copertura dell'automazione e lacune in ambito elicotteristico. Sia i sistemi di automazione a breve termine, come i regolatori di velocità del rotore o i sistemi antighiaccio, sia i sistemi di automazione della gestione della missione a lungo termine, forniscono funzioni uniche per la loro scala temporale di funzionamento. Su scale temporali intermedie, a prima vista, le funzioni fornite dall'automazione sembrano abbastanza simili, ad esempio, determinazione, visualizzazione e implementazione della traiettoria futura. Tuttavia, i sistemi su scale temporali diverse prendono in considerazione diversi tipi di informazioni e basano la loro funzione su una diversa scala temporale di informazioni e previsioni. Soprattutto per questi sistemi è importante definire chiaramente i confini e le capacità operative, o definire un sistema che incorpori queste funzioni simili in un quadro di supporto unificato per il pilota, che tenga traccia delle capacità e dei limiti dei suoi moduli di automazione.

I risultati di questa analisi guidano la progettazione dell'automazione dei quattro esperimenti con soggetti umani eseguiti in questa tesi. Il primo esperimento si è concentrato sul compito a breve termine di volo a punto fisso (hover), un compito che fa parte praticamente di ogni missione di un elicottero. Durante il volo a punto fisso e le manovre a bassa velocità, i display e i quadri strumenti "a testa bassa" (Head-Down) forniscono teoricamente tutte le informazioni sui dati di volo che occorrono per pilotare l'elicottero. Tuttavia, esperimenti precedenti hanno dimostrato che i display "head-down" possono comportare un elevato carico di lavoro, instabilità del controllo e persino perdita di controllo se utilizzati dal pilota come unica fonte di dati di volo.

Per capire meglio perché possono verificarsi tali problemi, una buona visuale esterna (approccio centrato sull'ecologia) è stata confrontata con un display per hover "head-down" e un pannello strumenti (approccio centrato sul compito). Sebbene entrambi gli approcci forniscano teoricamente tutte le informazioni di stato necessarie per eseguire l'attività di volo a punto fisso, i piloti non sono stati in grado di eseguire l'attività con il display per l'hover relativo all'approccio centrato sul compito. Questi risultati evidenziano l'impatto positivo di una rappresentazione naturale del dominio di lavoro (cioè una buona visuale esterna) durante le attività a breve termine e come concentrarsi solo sulla rappresentazione dello stato correlato alle attività nei display potrebbe rendere impossibile il completamento dell'attività di controllo.

Nel tentativo di utilizzare questi risultati, l'esperimento seguente si è concentrato sull'uso di simbologia conforme "a testa alta" (head-up) per supportare le manovre a bassa velocità e il volo stazionario dell'elicottero. All'interno di questo schema di display head-up conformi, sono stati considerati gli stessi approcci di progettazione dell'esperimento precedente. Il primo display incentrato sull'ecologia contiene una trama del terreno a griglia e un riquadro che indica la posizione del riferimento per il volo a punto fisso. Il secondo display incentrato sull'attività ha una stretta somiglianza con un percorso di transizione verso il volo a punto fisso standardizzato, definito dalla Aeronautical Design Standard (ADS) 33E-PRF. Riproduce la rappresentazione visiva di tutti gli elementi del percorso come il display head-up. Entrambi i display sono stati confrontati con una condizione di riferimento con buona visibilità esterna. Il display incentrato sull'ecologia ha prodotto prestazioni simili e buone rispetto alla condizione di riferimento, sebbene il carico di lavoro e la consapevolezza situazionale fossero peggiorati. Questa volta, per lo meno, la visualizzazione incentrata sull'attività ha consentito il completamento dell'attività, ma le prestazioni sono state peggiori rispetto alle altre due condizioni. Sulla base di questi risultati, sembra che le strutture caratteristiche del terreno e i riferimenti in lontananza, ovvero elementi del dominio del lavoro dell'elicottero o dell'ecologia in buona visibilità, svolgano un ruolo molto più importante nelle prestazioni di volo rispetto ai segnali specifici del compito associato al percorso di volo standardizzato.

Mentre i due esperimenti precedenti hanno studiato l'attività a breve termine di volo a punto fisso, l'esperimento seguente ha ampliato la scala temporale operativa per indagare su un'attività di evitamento di ostacoli. Questo compito si trova nella scala temporale intermedia di operazione, separata dall'attività di controllo di stabilizzazione a breve termine su una scala temporale breve. È simile a un compito scelto in ricerche precedenti nell'ambito dell'ala fissa per studiare la progettazione di interfacce ecologiche. Tuttavia, le differenze tra le operazioni di aeromobili commerciali ad ala fissa e quelle con elicotteri portano a un risultato diverso. La preferenza del pilota è rimasta identica tra i due domini: i piloti preferivano l'automazione consultiva in situazioni nominali e quella basata su vincoli in situazioni non nominali. Il carico di lavoro e la consapevolezza situazionale sono stati maggiormente migliorati dall'approccio basato sui vincoli, così come la resilienza agli eventi imprevisti. Questi risultati suggeriscono che nel compito su scala temporale media considerato, l'automazione basata su vincoli abbia portato a risultati migliori.

L'attività analizzata era ancora direttamente collegata al controllo manuale dell'elicottero, sebbene a un livello superiore rispetto all'attività di stabilizzazione di basso livello. L'esperimento successivo ha studiato se i risultati durante l'esecuzione di compiti decisionali cognitivi differissero rispetto ai compiti di controllo manuale basati sulle abilità. Ci si è focalizzati sul processo decisionale del pilota sulla traiettoria nella scala temporale lunga, l'attività di controllo manuale dell'elicottero sulle scale temporali inferiori ha agito solo come attività secondaria ad alta intensità di carico di lavoro. Questa configurazione mirava a emulare i requisiti delle operazioni con elicotteri del mondo reale, in cui ai piloti è richiesto di esercitare il controllo su tutte le scale temporali contemporaneamente, dalla stabilizzazione a breve termine alle decisioni di navigazione a lungo termine.

I risultati mostrano un significativo impatto negativo della visualizzazione di avviso sul processo decisionale della traiettoria del pilota durante eventi imprevisti. Con l'aumentare del divario temporale tra l'attività di controllo manuale a breve termine e l'attività decisionale svolta, gli effetti negativi involontari dell'automazione sembrano essere più pronunciati. La visualizzazione basata sui vincoli non ha un impatto negativo sul processo decisionale dei piloti, ma non migliora nemmeno le altre metriche collegate. Quest'ultimo esperimento mostra il potenziale dei display basati su vincoli per evitare effetti involontari dell'automazione, ma evidenzia anche i problemi di formazione, familiarizzazione e facilità d'uso. Perché l'automazione basata sui vincoli possa essere un valido candidato per l'automazione di elicotteri operativi, questi problemi devono essere risolti dalla ricerca futura.

Combinando i risultati di tutti gli esperimenti, sembra che le peculiarità del controllo dell'elicottero (la necessità di azioni di controllo continuative "con le mani sempre sui comandi" in parallelo all'uso di qualsiasi sistema di automazione a bordo) e il più ampio inviluppo operativo influenzino l'effetto dell'impiego dell'automazione. L'automazione incentrata sull'ecologia e basata sui vincoli generalmente consente ai piloti di completare con successo l'attività con prestazioni accettabili, sebbene vi siano margini di miglioramento per quanto concerne la facilità d'uso dei sistemi. L'automazione consultiva è generalmente preferita dai piloti, ma produce significativi effetti negativi sul processo decisionale di navigazione quando si trovano alle prese con situazioni impreviste e fuori dalle condizioni nominali.

Si ipotizza che un "divario cognitivo" nella copertura dell'automazione su scale temporali, tra la necessità di controllare manualmente l'elicottero sui tempi brevi e quella di supervisionare l'automazione consultiva su scale temporali lunghe, tenda a esacerbare gli effetti negativi dell'automazione. Questo effetto sembra essere particolarmente forte quando il "divario" si verifica nella fase di automazione della selezione dell'azione. Per aumentare la sicurezza delle operazioni, l'automazione futura degli elicotteri dovrebbe concentrarsi sul supporto alle attività di acquisizione e analisi delle informazioni da parte dei piloti su tutte le scale temporali, lasciando ai piloti la selezione e l'attuazione dell'azione finale. L'automazione consultiva dovrebbe essere impiegata solo quando ciò non causi un "divario nella selezione delle azioni", ovvero lo stesso processo è supportato in modo almeno altrettanto forte anche su scale temporali più brevi. Ciò evita la necessità di eseguire un'attività di controllo manuale su una scala temporale di funzionamento breve e, in parallelo, un'attività di controllo di supervisione su una scala temporale di funzionamento più lunga. Supportare i piloti nel modo suggerito dovrebbe consentire loro di utilizzare le proprie capacità di controllo e decisionali al meglio delle loro (ampie) capacità, e quindi aumentare la sicurezza operativa dell'elicottero.

List of Abbreviations

ADS-33 Aeronautical Design Standard 33E-PRF
AI Action Implementation
ANOVA Analysis of Variance
AS Action Selection
AW Aerial Work

BOSS Brown-Out Symbology System

CAA Civil Aviation Authority of the United Kingdom
CAT Commercial Air Transportation
CPL Commercial Pilot Licence
CSE Cognitive Systems Engineering
CWA Cognitive Work Analysis

DL Decision Ladder
DLR German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt)
DVE Degraded Visual Environment

EASA European Aviation Safety Agency
EHEST European Helicopter Safety Team
EID Ecological Interface Design
ESPN-R European Safety Promotion Network — Rotorcraft
EU European Union

FAA Federal Aviation Administration
FIPS Full Ice Protection System

GA General Aviation

HABA–MABA Humans are better at — Machines are better at
HDD Head-Down Display
HEMS Helicopter Emergency Medical Services
HFACS Human Factors Analysis and Classification System
HMD Helmet-Mounted Display
HUD Head-Up Display

IAc Information Acquisition
IAn Information Analysis
IHSF International Helicopter Safety Foundation
IHST International Helicopter Safety Team
IMC Instrument Meteorological Conditions

JHSAT Joint Helicopter Safety Analysis Team

KBB Knowledge-Based Behaviour

LiDAR Light Detection and Ranging
LIPS Limited Ice Protection System
LoA Level of Automation
LoCS Level of Control Sophistication

MBB Bo 105 Messerschmitt-Bölkow-Blohm Bo 105 Helicopter
MTE Mission Task Element

NASA TLX NASA Task Load Index
ND Navigation Display
NITROS Network for Innovative Training on Rotorcraft Safety
NLR Netherlands Aerospace Centre

PFD Primary Flight Display
PPL Private Pilot Licence

RBB Rule-Based Behaviour
RMS Root Mean Square
RMSE Root Mean Square Error
rpm Revolutions per Minute
RSME Rating Scale Mental Effort

SAE Society of Automotive Engineers
SAR Search and Rescue
SART Situation Awareness Rating Scale
SAS Stability Augmentation System
SBB Skill-Based Behaviour
SCAS Stability and Control Augmentation System
SoA Stage of Automation
SPS Standard Problem Statement
STD Standard Deviation

TU Delft Delft University of Technology

UCE Usable Cue Environment

UH-60 RASCAL JUH-60A Black Hawk

US United States of America

USHST United States Helicopter Safety Team

USJHSAT United States Joint Helicopter Safety Analysis Team

WDA Work Domain Analysis

List of Symbols

$1-\beta$ [-]	Power of statistical tests
α [-]	Significance level or type 1-error of statistical tests
β [-]	Type 2-error of statistical tests
χ^2 [-]	Chi-squared distribution, utilised in two-way Friedman test statistics
δ [rad]	Depression angle
δ_a [rad]	Absolute visual displacement
δ_v [rad]	Observed visual displacement
$\dot{\gamma}$ [rad/s]	Flight path angle rate of change
$\dot{\gamma}_{max}$ [rad/s]	Maximum flight path quickness
γ [rad]	Flight path angle
γ_{end} [rad]	τ-manoeuvre flight path angle end value (zero, per definition)
γ_{gap} [rad]	τ-manoeuvre flight path angle gap
γ_{limit} [rad]	Maximum effective climb angle
$\gamma_{manoeuvre}$ [rad]	τ-manoeuvre flight path angle
γ_{max} [rad]	Maximum climb angle
$\gamma_{obstacle}$ [rad]	Visual angle between the top of an obstacle's safety zone and the horizon
γ_{start} [rad]	τ-manoeuvre flight path angle start value (negative, per definition)
$\hat{t}$ [-]	τ-manoeuvre normalised time
$\mathbf{a}_{hor}$ [m/s^2]	Helicopter horizontal acceleration vector
$\mathbf{c}_{acc}$ [m]	Hover display horizontal acceleration cue vector
$\mathbf{c}_{vel}$ [m]	Hover display horizontal velocity cue vector
$\mathbf{u}$	Vector of state space control inputs
$\mathbf{v}_{hor}$ [m/s]	Helicopter horizontal velocity vector
$\mathbf{x}$	Vector of state space system states
Ω [rad/s]	Main rotor speed
ω [rad/s]	Frequency
ω_c [rad/s]	Crossover frequency

ω_i [rad/s]	Forcing function bandwidth
ϕ [rad]	Euler role angle
ψ [rad]	Euler yaw angle
$\square_e$	Error value
$\square_{geo}$	Geodetic parameter
$\square_{inner}$	Inner loop parameter
$\square_{middle}$	Middle loop parameter
$\square_{outer}$	Outer loop parameter
$\square_t$	Target value
τ_e [s]	Effective time-delay
τ_p [s]	Pilot reaction onset delay
τ_{guide} [s]	τ-manoeuvre intrinsic constant acceleration guide
$\tau_{manoeuvre}$ [s]	τ-manoeuvre momentary time-to-contact
θ [rad]	Euler pitch angle
θ_0 [rad]	Collective input
θ_{1c} [rad]	Lateral cyclic input
θ_{1s} [rad]	Longitudinal cyclic input
θ_{TR} [rad]	Pedal/tail rotor collective input
φ_m [rad]	Phase margin
A	State space model matrix
A_{SAS}	State space model matrix with SAS
B	State space control matrix
d [m]	Observer displacement
d_0 [m]	Display design variable; minimum distance for which the manoeuvre constraints are valid
e_r [1/m]	Edge rate
F	Matrix of SAS parameters
F [-]	F distribution, utilised in ANOVA test statistics
g [m/s^2]	Gravitational constant
h [m]	Altitude
h_{limit} [m]	Maximum altitude difference achievable within d_0 at the given forward speed V
k [-]	τ-manoeuvre coupling constant

K_m [-]	Gain margin
K_p [-]	Pilot gain
l_1 [m]	Distance between observer and object
l_2 [m]	Distance between object and visual backdrop
m [kg]	Mass of the helicopter
p [-]	Probability value of employed statistical tests
p [rad/s]	Body roll rate
$P_{available}$ [W]	Available manoeuvring power available at the given forward speed V
P_{max} [W]	Maximum engine power
P_{req} [W]	Steady state power required at the given forward speed V
$p_{reserve}$ [-]	Power reserve ratio for manoeuvring, tail rotor and aerodynamic power consumption
q [rad/s]	Body pitch rate
r [rad/s]	Body yaw rate
R^2 [-]	Coefficient of determination of a prediction
S [rad]	Splay angle
T [s]	τ-manoeuvre time
t [s]	Time
T_I [s]	Lag time constant
T_L [s]	Lead time constant
T_x [m]	Edge separation
T_{acc} [s]	Hover display acceleration scaling factor
t_{end} [s]	τ-manoeuvre end time
t_{start} [s]	τ-manoeuvre start time
T_{vel} [s]	Hover display velocity scaling factor
u [m/s]	Body surge velocity
V [m/s]	Forward speed of the helicopter
v [m/s]	Body sway velocity
w [m/s]	Body heave velocity
x [m]	Body longitudinal position
x_τ [m]	Pilot reaction distance
$x_{manoeuvre}$ [m]	Distance between manoeuvre onset and point of origin of resulting flight path γ_{max}

y [m]	Body lateral position
Y_c	Controlled element transfer function
Y_p	Pilot model transfer function
Y_{CL}	Closed-loop transfer function
Y_{OL}	Open-loop transfer function
z [m]	Body vertical position

1

Introduction

1

1.1. Background

Helicopters possess the unique capabilities of hovering stationary in the air and landing with relative ease in a variety of terrain, which sets them apart from fixed-wing aircraft. These capabilities, combined with their mobility, enable helicopters to fulfil many critical roles in modern society. Examples include law enforcement, medical services, search and rescue, and aerial work operations.

Due to this high mission variety, and the accompanying increase of flights close to the ground and obstacles, piloting a helicopter can be a challenging task that involves risk of incidents and accidents. According to estimations from April 2020 by the International Helicopter Safety Team (IHST), there were on average 3.8 accidents per 100,000 flight hours of US-registered helicopters in the span from 2014 up until 2018 (Anonymous, 2020). This accident rate is more than 20 times higher than the accident rate of commercial fixed-wing aircraft, estimated by the Federal Aviation Administration at 0.17 for the year 2017 (Anonymous, 2019b).

Safety initiatives like the IHST strive to reduce this comparatively high helicopter accident rate. For example, in 2006, the IHST set the ambitious goal of reducing the United States helicopter accident rate by 80 % between 2006 and 2016, which would mean at most 1.8 accidents per 100,000 flight hours (Tristrant and Greiller, 2016). Unfortunately, this goal has not been reached yet, and helicopter safety remains a focus of attention for industry, operators, and research projects alike.

One such research project is NITROS[1] (Network for Innovative Training on Rotorcraft Safety), a Marie Skłodowska-Curie European Action Joint Doctorate, funded by the European Union (Quaranta et al., 2018). The goal of NITROS is "to train a new generation of talented young engineers (up to doctoral level) to become future specialists in developing innovative approaches to address rotorcraft safety issues" (Quaranta et al., 2018, p. 1). NITROS defines three research objectives for its members:

1. "Develop a detailed framework for rotorcraft modelling integrating rigid-body and aero-servo-elastic modelling features capable of dealing with structural or propulsion / mechanical system failure in rotorcraft.

2. Understand how humans can safely and efficiently use and be interfaced with rotorcraft technology.

3. Enhance the understanding of the unique and complex aerodynamic environment in which rotorcraft are working, often in hostile conditions of wake encounter threats, undesirable interactions with obstacles, icing and, brownout conditions." (Quaranta et al., 2018, p. 1)

The research presented in this dissertation pertains to research objective two. In particular, the research objective of this dissertation has been defined early on in NITROS as "understanding the use of automation in helicopters". Throughout the project, the research objective has been refined into the goals later presented in this chapter.

[1] More information can be found at `https://www.nitros-ejd.org/`.

In this introductory chapter, the rationale for choosing this automation-centred research trajectory is elaborated upon. First, the topic of automation is covered. Definitions employed in this dissertation, as well as a brief background on fixed-wing and helicopter automation systems, is given. Automation is then connected to safety, the overarching goal of NITROS and this dissertation.

Afterwards, a brief summary of ecological interface design (EID) is provided. EID is a design methodology whose aspects are utilised throughout this dissertation to design novel helicopter automation systems. EID principles have not been broadly applied in the helicopter domain and could offer new insights into the helicopter human-machine interface. This represents the major novelty of the research presented in this dissertation. In the following section, the main research question and the accompanying subquestions are elaborated upon. Lastly, the structure of this dissertation is explained.

1.2. What is automation?

Throughout history, automation has brought tremendous improvements to human productivity. From the rise of mechanised manufacturing systems in the first industrial revolution (Hitomi, 1994) to the automation of digital processes in the information age (Parasuraman et al., 2000), humans were able to delegate more and more labour to automated machines. Automation has increased productivity and safety across many work domains, from industrial process management (Naito et al., 1995) to aircraft control (Inagaki, 2006).

However, the effects of automation are not always beneficial. Already in 1983, Bainbridge (1983) outlined several "ironies of automation", i.e., how the implementation of automation can cause additional potential for failures, even if it is able to improve system performance in nominal conditions. For example, the introduction of automation can have a detrimental effect on the manual control capabilities of human controllers, as they have fewer and fewer opportunities to maintain their skills by controlling the system manually.

1.2.1. Definitions

The term automation can be (and is) applied to a multitude of systems. It is therefore useful to briefly investigate how automation has been defined, and afterwards elaborate on the definition used in this dissertation. According to the definition of the Oxford English Dictionary (1989), as cited by Parasuraman et al. (2000), automation is:

1. "automatic control of the manufacture of a product through a number of successive stages;
2. the application of automatic control to any branch of industry or science;
3. by extension, the use of electronic or mechanical devices to replace human labour" (Parasuraman et al., 2000, p. 287).

The first definition seems closely tied to the kind of automation that impacted manufacturing processes during the industrial revolution. The second definition seems to correspond most to the field of control theory and its many applications in industry and science, while the third definition is a very broad definition which focuses on the automation "taking over" specific aspects of human labour. Following this definition, an electric drill, a house thermostat, automated processes in a factory, e-mail filters, cruise-control functions in a car, and the multitude of systems that make up a modern-day cockpit autopilot can all be called automation, as they all replace aspects of human labour to fulfil the respective tasks.

Other definitions are more restrictive. The Cambridge Dictionary, for example, defines automation as "the use of machines and computers that can operate without needing human control"[2]. Following this definition, an electric drill would not qualify as automation, as a drill can certainly not operate by itself, without the human input of aiming it at a to-be-drilled surface and exerting a sufficient amount of force to push the rotating head through the surface. The cruise control system of a car might present an ambiguity: it does not require human control to hold the selected speed, but in most cases, the driver is still required to monitor its function and to react to situations on the road that are not anticipated by the system. In this case, it is not immediately clear whether a cruise control system can be defined as an automated system or not.

In this dissertation, a broader definition by Parasuraman and Riley (1997) of automation is adopted. According to them,

> automation is "the execution by a machine agent (usually a computer) of a function that was previously carried out by a human" (Parasuraman and Riley, 1997, p.230).

This definition includes all systems that acquire and analyse information on behalf of the pilot (i.e., sensors, algorithms, and displays), as well as systems that support the human controller's task of action selection and implementation. Adopting this broad definition of automation enables the analysis of the wide array of support systems that is being utilised and developed in the aviation domain in general, and in helicopter cockpits in particular.

1.2.2. Automation in fixed-wing aircraft

The continued implementation of automation can be clearly observed in the aviation domain. The most prominent and popularly known automation development took place in large passenger aircraft cockpits. Control of an aircraft, which historically required the constant manual control of at least the thrust and pitch, roll, and yaw deflectors, has transformed to a largely supervisory control task. Instead of manually closing the control loop, the pilots are supervising and monitoring an automated system that closes the control loop. Only occasionally, manual control actions are necessary. This trend had already been identified by Wiener and Curry (1980), and automation capabilities only increased between then and now.

[2]AUTOMATION | meaning in the Cambridge English Dictionary, `https://dictionary.cambridge.org/dictionary/english/automation`, retrieved 25-11-2020

Figure 1.1 depicts the cockpits of two Airbus fixed-wing aircraft: the Airbus A300 on the left, which entered operation in the year 1983, and the Airbus A350 on the right, which began commercial operation in 2015. The evolution from analogue indicators and gauges on the left to a "glass cockpit", which predominantly consists of digital screens, is clearly visible. The development of automated control complemented this evolution, providing more and more functions and capabilities to take over tasks from the pilots (Dorneich et al., 2017).

As previously stated, the introduction of additional automation can have inadvertent effects. Examples of automation contributing to system failures contain, for example, Air France flight 447, which crashed into the Atlantic Ocean on June 1st 2009 during a flight from Rio de Janeiro to Paris (Anonymous, 2012). In this case, a sensor failure during cruise led to the automation system transferring control to the pilots. The flight data shown on the cockpit displays was ambiguous, and the pilots did not immediately choose the correct control strategy, resulting in a continuous stall and the subsequent crash of the aircraft.

Turkish Airlines flight 1951 can serve as another example, which crashed into a field near Schiphol Airport, Amsterdam (Anonymous, 2010a). In this flight, a faulty radio altimeter sensor caused the automation system to incorrectly reduce thrust during approach. This error was not immediately apparent to the pilots, which caused the aircraft to crash-land short of the runway on a field. While both systems clearly improve performance and safety in nominal situations, in case of off-nominal situations, the added complexity of automation can make it harder for pilots to understand the systems' reactions and correct them timely and accordingly.

Figure 1.1: Cockpit of an Airbus A300 (left) and an Airbus A350 (right).[3]

1.2.3. Automation in helicopters

Helicopter cockpits, just like fixed-wing aircraft cockpits, underwent a drastic evolution, from their early beginnings to modern-day implementations. As an example, Figure 1.2 shows the cockpit of an Messerschmitt-Bölkow-Blohm Bo 105 Helicopter (MBB Bo 105) on the left, which was introduced in the year 1970, versus the cock-

[3]Left image: "Airbus 300B Flight Deck", by Clemens Vasters from Viersen, Germany, CC BY 2.0, via Wikimedia Commons. Right image: "Cockpit view of Airbus A-350 XWB F-WWYB", by Joao Carlos Medau (`https://secure.flickr.com/photos/medau/`), CC BY 2.0, via Wikimedia Commons.

pit of the recent NH Industries NH90, which entered operation in 2007. Again, the evolution from analogue knobs and dials to a digitised cockpit is obvious.

However, helicopter automation integration lags somewhat behind fixed-wing aircraft developments (Lim et al., 2018). Helicopters can fulfil a broad variety of missions, which can include a high number of different manoeuvres and situations. While this is a major selling point of helicopters, it can also make the typically large investment into the development of mission-specific automation systems less "worth it" (Lim et al., 2018). However, there are many research initiatives investigating the future of helicopter automation, as can be seen by the growing number of publications pertaining to it.[4]

Given all these possible development avenues, one question becomes more and more important: what should the future helicopter-pilot interface look like, and how can it be assured that the effect of the developed systems is positive? The impact of automation systems can be measured in a myriad of ways, e.g., from a performance and efficiency standpoint, from the standpoint of pilot workload, situation awareness, and ease-of-use, or through trying to determine the increase or decrease of "safety". In this dissertation, all of the mentioned measures will be considered. The largest focus, however, will be placed on safety, as described in the following section.

Figure 1.2: Cockpit of an MBB Bo 105 (left) and an NH Industries NH-90 (right).[5]

1.2.4. Increasing safety through automation

How can we ensure that the implementation of automation system reliably increases safety? In order to answer this question, the contributing factors of past helicopter accidents should be analysed. In an effort coordinated by the IHST, the European Helicopter Safety Team (EHEST) (Anonymous, 2010b, 2015) and the United States Helicopter Safety Team (USHST) (Anonymous, 2011a,b) compiled helicopter accident analysis reports. According to the reports, both *pilot judgements and actions*, as well as *pilot situation awareness* contributed to a large percentage of analysed

[4]Please refer to chapter 2 for a review of helicopter automation publications.

[5]Left image: "Cockpit of a PAH BO 105 P-1A1 of the German Kampfhubschrauberregiments 26 "Franken".", by High Contrast, CC BY 2.0 DE, via Wikimedia Commons. Right image: "NHI NH90 helicopter cockpit", by C.bronson, public domain, via Wikimedia Commons.

accidents (between 65 % and 84 % for *pilot judgements and actions*, between 29 % and 46 % for *pilot situation awareness*). These high numbers signify that at times, pilots would benefit from increased support from the systems at their disposal to safely operate the helicopter.

Van der Meer et al. (2011) summarise the findings of these and other reports to formulate recommendations to increase helicopter safety, including the installation of "state-of-the-art technologic developments into helicopter cockpit/system with a more mandatory and flight scenario dependent aspect" (van der Meer et al., 2011, p.1). Based on the results of the accident analysis reports, the Netherlands Aerospace Centre (Stevens and Vreeken, 2014) conducted a study to identify potential technologies to mitigate helicopter accident factors. According to the study, the five most promising technologies to increase safety, and which address multiple accident contributors, are:

1. "enhanced ground proximity warning system / terrain awareness and warning system,
2. digital range image algorithms for flight guidance aids for helicopter low-level flight,
3. laser radar obstacle and terrain avoidance system,
4. digital map, and
5. deployable voice and flight data recorder." (Stevens and Vreeken, 2014, pp. 32-34)

Improved helicopter automation, and its mandatory installation in helicopters, could potentially address the first four identified categories.

It is important to note that the high percentage of *pilot judgement and actions* and *pilot situation awareness* do not imply that the blame lies solely with the pilots. The pilots' control strategy and response is inadvertently shaped by the system they control (and its automation), their training regimes, operational procedures, and airline- or culture-dependent common practices. Placing the blame of an accident solely on the mistake of a pilot can hinder discovering how this mistake was enabled by the situation and system.

Dekker (2003) elaborates on this, arguing that human errors do not exist in isolation, and that failures of systems are caused by the architecture of the whole system and many of its actors. The pilot "misjudgement" could be attributed to wrong pilot behaviour, but also to other causes, e.g., a lack of training, insufficient warnings, improper reliance on cockpit systems (through procedure or emergent behaviour), or insufficient redundancy in the automation system. Therefore, the goal of improving helicopter safety will not be achieved by "removing the human from control through automation". This approach has a large number of drawbacks, as described before. Rather, this goal should focus on improving the support pilots receive while they are judging situations, performing actions, and maintaining situation awareness.

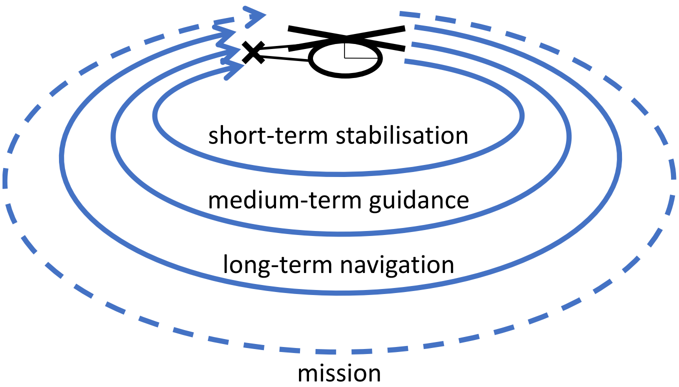


Figure 1.3: Short-term (stabilisation), medium-term (guidance), and long-term (navigation) control loops, necessary to complete a helicopter mission, adapted from Padfield (2007).

This touches upon the many other impacts of employing automation. Automation can improve helicopter mission productivity and efficiency, as well as reduce the pilots' workload and increase their situation awareness. It can also change the way pilots operate the helicopter, and how they achieve the mission objective — i.e., it can impact the employed control strategy. Lastly, even the "best" automated system will not find support among pilots if it is cumbersome to use or otherwise negatively impacts the pilots' experience. The quest of designing a "good" automation system has multiple goals, and these goals might conflict with each other in specific operational contexts or scenarios. Automation design is a multidimensional optimisation problem along axes like safety, workload, situation, performance, pilot acceptance, and many more.

1.3. Scope

Helicopter flight in all but the most advanced, often military helicopters still requires continuous "hands-on" control from the pilots Lim et al. (2018). Support systems that are supposed to be used by a single pilot therefore often focus on providing control augmentations, warnings, or displays that can be used either in tandem or as a total replacement of the outside visuals (Lim et al., 2018). Most of these systems focus on the short- and medium-term control of the helicopter, as described by Padfield (2007), shown in Figure 1.3. For longer-term navigation tasks, pilots need to rely on pre-mission planning, navigation or map displays (which can be distracting to use when not in cruise at a safe altitude), or their co-pilot. This can require significant cognitive resources, in addition to the manual control requirements placed on the pilots at all times.

This dissertation aims to close the gap between short-term stabilisation and long-term navigation automation support. Bridging this gap is associated with both scientific and engineering challenges. The pilots' decision-making processes in navigation or trajectory evaluation tasks require the acquisition and analysis of many different information sources, from real-time sensor-data to mission goals and vehicle performance limitations. This process of information integration can be laborious and error-prone, in particular when the pilots need to perform this task in addition to a demanding multi-axis manual control task. The challenge lies in supporting the pilots with this long-term task, while still enabling them to manually control the vehicle, as is required in most current helicopters. Under these constraints, what are the properties of automation systems that enable the pilots to more easily engage in creative decision-making processes to solve safety-critical situations without compromising mission performance?

The following simplifications and assumptions are set as the basis for this dissertation's research:

1. Only single pilot operations are considered, all automated systems need to be controlled and managed by the pilot flying. This is a deliberate research design decision based on the fact that many current-day helicopter operations depend on a single pilot. Investigating the effect of automation on multi-pilot helicopter operations is a worthwhile goal, but not the intent of this dissertation.

2. No advanced control augmentations (like position hold or translational rate command) are employed, the helicopter dynamics broadly behave like attitude rate control systems. Again, this is a deliberate research decision to make the results applicable to a large part of the current-day helicopter fleet.

3. The pilots are always required to manually control the helicopter. This requirement is based on the two previous points: with no advanced augmentation functions or copilot available, the pilot flying needs to manually control the helicopter at all times.

4. Unless otherwise specified, helicopter systems work 100 % reliably. This assumption is consciously violated in the later experiments, which introduce automation failures.

5. Flight instruments and sensors are 100 % accurate, unless otherwise specified (e.g., to simulate malfunctions).

6. Wind and its effects are not considered.

7. Aerodynamic interactions with the environment (ground, structures, foliage) are not considered.

8. Engine or drive train dynamics are not considered, the rotor rpm is assumed to be constant and nominal.

9. The utilised helicopter model is either an in-house generic six degrees-of-freedom helicopter flight dynamics model, run with a MBB Bo 105 parameter set (Miletović et al., 2018), or a linear MBB Bo 105 model presented by Padfield (1981, 2007), based on Helisim.

Developing automation systems that provide meaningful support while enabling the continuous manual control of the helicopter by the pilot represents the engineering challenge of this dissertation. How can the pilots interact with, supervise, and utilise automation systems in parallel to controlling the helicopter manually? One promising design paradigm that could present a solution to this problem is ecological interface design. EID has not been applied extensively in the helicopter domain before, and might provide new insights into the interaction between helicopter pilots and their vehicle.

1.4. Ecological interface design

There have already been substantial developments and investigations in the helicopter automation domain, as Chapter 2 shows. In this project, however, some of the automation is designed utilising aspects of ecological interface design and compared to automation that is designed with a more "classical", advisory design approach. EID is a design methodology based on cognitive work analysis (CWA), from the field of cognitive systems engineering (CSE) (Vicente, 1999). It has been employed in the fixed wing-domain, and originates in process control, but might prove beneficial for the highly varying mission structure of helicopters, in particular in off-nominal or unexpected situations.

EID is a framework for human-machine system design that focuses on the ecology of the work domain of a system. It originated in the domain of process control, and was eventually used to develop novel interfaces for power plant control (Itoh et al., 1995), health care (McEwen et al., 2014), fixed-wing aircraft control (Borst et al., 2010b), and air traffic control (Klomp et al., 2016), to name a few examples. It is extensively described by Vicente and Rasmussen (1992). While EID may face misconceptions based on the meaning of the term "ecological" and what it means in the display design context (Borst et al., 2015), it shows particular potential in its application to vehicle locomotion control, as described by Van Paassen et al. (2018). Up until now, it has been only sparsely employed in the helicopter domain, for example for shipboard landing (Jenkins et al., 2015) or precision landing manoeuvres (Smith et al., 2006)[6]. Ecological interfaces are expert displays that make the capabilities and limitations of the controlled system tangible to the controller. They focus on the ecology of the work domain and aim to visualise the work domain-inherent constraints and action possibilities. Research in the fixed wing domain showed that pilots preferred ecological displays to classic, suggestion-based automation systems in unexpected situations (Borst et al., 2010b).

Even without employing the full EID design methodology, automation systems can take inspiration from EID. For example, they can focus less on completely taking over a specific task, but rather on visualising system capabilities and constraints, leaving full decision authority with the human pilot. As such, employing aspects of EID can alter and potentially improve the effects of helicopter automation systems.

[6] Smith et al. (2006) actually describe a lunar landing display. The display, with minor alterations, was also evaluated with respect to helicopter precision landing in a master thesis of the same author (Smith, 2006).

1.5. Transferring results from fixed-wing aircraft to helicopters

As mentioned, EID has been investigated in the civil fixed-wing domain before[7]. However, the results of civil fixed-wing investigations may not be directly transferable to the helicopter domain. Helicopter operations, and the task of helicopter pilots, differ significantly between civil fixed-wing and civil helicopter operations. The most prominent differences discussed in this dissertation include:

1. **Vehicle dynamics**: civil fixed-wing aircraft are typically stable while following a straight trajectory. In contrast, helicopters are inherently unstable, in particular during low-speed manoeuvring and hovering.

2. **Extent of required manual control inputs**: as civil fixed-wing aircraft are typically stable, pilots are free to remove their hands from the control inceptors for some periods of time. In contrast, helicopters without advanced control augmentations (as investigated in this dissertation) require constant control input in all four degrees of freedom to maintain stability. This may reduce the spare mental capacity of helicopter pilots to recognise and react to unexpected events or to ponder on long-term strategic decisions. This characteristic may fit particularly well with the goal of EID to support pilots in their decision-making without completely taking actions over from them.

3. **Possible trajectories**: for a steady system state, civil fixed-wing aircraft require a minimum forward velocity to generate sufficient lift. Accordingly, the trajectory pitch and turn angles are limited. Conventional fixed-wing aircraft always have to move forward, which can limit the time pilots have to make trajectory decisions (unless they enter a holding pattern). In contrast, helicopters possess a much larger space of possible steady system states, in particular in the low-speed regime. They can reduce their forward velocity to zero and hover in place, enabling the pilots to “pause” to make decisions about future trajectories. During hover, they can then modify their longitudinal position, lateral position, altitude, and heading independently from each other.

4. **Distance/time-to-contact to obstacles**: civil fixed-wing operations usually consist of a combination of standard flight phases like take-off, cruise, and landing. These phases are often planned in advance and their procedures are clearly defined. Distance to other aircraft, the terrain, or obstacles is usually (required to be) large. In contrast, helicopter missions often include flight close to terrain, buildings, and other obstacles. This reduces the time-to-contact when inadvertently following an unsafe trajectory towards an obstacle and requires the pilots to react quickly.

[7] For an overview of past EID applications, please refer to the references presented by Borst et al. (2015) and Van Paassen et al. (2018).

5. **Mission variability**: As previously mentioned, civil fixed-wing operations usually consist of a combination of standard flight phases. In contrast, many helicopter mission profiles like helicopter emergency medical services (HEMS) or search and rescue (SAR) require the pilots to frequently make safety-critical decisions while facing unexpected or off-nominal situations like a change of mission requirements, adverse weather conditions, or obstacles to mission success that were unaccounted for during mission planning.

Given these differences, the effects of employing different automation designs in the helicopter domain might be exacerbated or attenuated, compared to the fixed-wing domain. Different effects might be observed, and they might manifest in different measurable outcomes.

1.6. Approach

In order to gain an insight into the influencing factors of this problem field, two distinct automation design approaches are empirically investigated. The aforementioned constraint-based design approach, which is based on principles of EID, is compared to a more classical, advisory-based or task-centred approach. The main differences can be summarised as follows:

1. The constraint-based design approach focuses on the ecology or work domain of the helicopter. It aims to provide information about the physical and intentional boundaries of operations that limit the envelope of all possible actions to solve a problem (i.e., the underlying work domain structure and constraints), while leaving the final decision in the hands of the pilot. The goal of these systems is to increase the pilots' understanding of situations and to encourage robust control, i.e., providing a wide range of feasible (but not necessarily optimal) solutions, with the pilots as the final decision-makers.

2. The advisory design approach is oriented towards technology-centred automation capabilities. It aims to provide optimal decisions/advisories without disclosing the underlying reasoning. The aim of such systems is to provide shortcuts that minimise the required cognitive effort. The task of the pilots is reduced to executing suggested actions or reacting to alerts. The given advice encourages optimal control by providing one specific suggested solution to the pilots.

Results will be gathered by a series of two theory-based, exploratory studies and two human-in-the-loop experiments in the SIMONA Research Simulator at Delft University of Technology. Each investigation will cover a specific timescale of operations, ranging from short-term manoeuvre-samples to long-term navigation tasks. The exploratory studies investigating short-term tasks focus on understanding the requirements and parameters of human manual control of helicopters, and how this basic function can be supported (or hindered) by different automation systems. The later, longer-term experiments draw on the results of the previous studies to design scenarios in which automation support can be unreliable, either caused by faults or by encountering situations outside the operational envelope of the employed support systems. These off-nominal situations will require increased cognitive resources of the pilots and might offset the positive automation effects in nominal situations. In particular during these later experiments, the constraint-based approach is expected to yield more robust results, as these systems enable the flexibility to react to unforeseen events. In contrast, advisory systems focus on one specific solution — if this solution is unfeasible, for whatever reason, the provided support is reduced dramatically.

This effect can be explained by the lumberjack analogy, as described by Trapsilawati et al. (2017) in the context of air traffic control: "the higher the tree, the harder it falls." In terms of automation support, this analogy represents the fact that a higher degree of automation (a term coined by Onnasch et al. (2014)) leads to higher performance in nominal situations, but subsequently to more problematic consequences in off-nominal situations. Onnasch et al. (2014) found that there is a cut-off degree of automation where this effect gains strength rapidly: between information acquisition/analysis and action selection/implementation. They discuss that the best automation support in the face of uncertainty and expected failures should be focused on increasing operator situation awareness, and not action selection/implementation. This forces the operator to "stay in the loop", make decisions, and better "implant the state of the system in the operator's memory" (Trapsilawati et al., 2017).

The analysis of Trapsilawati et al. (2017) focuses on air traffic control, but the effects of the lumberjack analogy can be observed in the commercial fixed-wing domain, too (recall the catastrophic effects of automation malfunctions in the two accident examples described above). However, in the commercial fixed-wing domain, operations are planned very well in advance and ideally do not include a large amount of variability of unexpected situations. Therefore, the trade-off between increased performance in nominal situations and the increased workload in off-nominal situations appears to skew towards focusing on nominal operations. This is exemplified by the large number of automation support systems in the commercial fixed-wing domain that focus in action selection and implementation (e.g., autopilots, flight directors, automatic throttle systems). The pilots' responsibility shifts from manually controlling the aircraft to system management and automation supervision.

The question this dissertation aims to answer is: how do these effects manifest in the helicopter domain? Will the differences between commercial fixed-wing and helicopter operations cause a shift towards generally better results with the constraint-based approach, or will the positive aspects of advisory automation in nominal situations outweigh their weaknesses in off-nominal situations? As explained, helicopter missions often possess a greater variability than commercial fixed-wing missions, and the typical helicopter pilot task differs in many critical aspects from its commercial fixed-wing counterpart. In order to further develop automation integration in helicopters, it is of great importance which results from the commercial fixed-wing domain can be "transferred" to the helicopter domain, and which results will differ based on the domain differences observed.

1.7. Research question and subquestions

The main research question of this dissertation can be formulated as:

> **Main research question**
>
> How can advisory and constraint-based automation design philosophies improve helicopter safety at different timescales of operation?

To answer the main research question, three subquestions are defined. The first subquestion investigates helicopter operations as a whole. Helicopter operations span a wide range of functions that can conceivably be supported by improved automation systems. In order to identify worthwhile scenarios and functions that can be supported through automation, it is necessary to analyse helicopter operations, currently employed helicopter automation, and existing research initiatives that aim to improve these systems. This analysis of the "lay of the land" might reveal clusters and gaps in current automation coverage. Both of these could potentially warrant exploration through the application of EID principles — either to support a widely investigated task in a different way, or to support a function that, currently, is lacking automation support. This helicopter operation and automation analysis will also be the first step towards identifying differences in safety-critical tasks, typical automation support, and automation evaluation methods between commercial fixed-wing and helicopter operations.

The first subquestion is stated by:

> **Subquestion 1**
>
> What are the peculiarities of helicopter automation?

The answer to subquestion one will provide operational candidate scenarios for further investigation. For a given scenario, it has to be determined how the constraint-based design approach could be used to design novel automation systems, which can subsequently be compared experimentally with advisory automation systems.

After defining and designing novel automation systems for specific scenarios, these systems have to be evaluated with respect to their effect on safety, mission performance, and other relevant parameters. Initial investigations are performed based on theory, utilising the SIMONA research simulator for proof-of-concept, exploratory data collection. The evaluation of the automation will take place through two human-in-the-loop experiments. It is of particular interest to compare the novel, EID-inspired automation with existing, "classical" automation systems, as well as with "baseline" cockpit configurations without automation. This will not only reveal the effect of employing automation systems versus no automation support, but will also enable the analysis of differences between classical automation systems and EID-inspired systems. This goal is formulated in the second subquestion:

Subquestion 2

How do different automation design philosophies influence safety (and other parameters) in helicopters during short-, medium-, and long-term scenarios?

The results of subquestion two will reveal the influence of different automation designs on mission productivity, efficiency, and safety in different scenarios. However, these results themselves are not sufficient to support future automation design for helicopters, which is the main research question of this dissertation. The results of each study and experiment need to be analysed with respect to how they can inform the automation design process, and which parts of the employed automation proved particularly useful in which scenario.

Lastly, the results of all studies and experiments need to be combined and analysed, with the goal of identifying underlying trends and working principles across all investigated scenarios and timescales of operation. Design guidelines and suggestions based on these underlying trends can then be utilised to improve upon helicopter automation design. This results in the last subquestion:

Subquestion 3

How can the gathered experimental results be incorporated into guidelines for helicopter automation design?

In addition to providing design guidelines for specific scenarios and general helicopter automation integration, the developed guidelines can also provide a methodology for evaluating helicopter automation systems. The gained insights into general helicopter operation and automation support can support future evaluations of helicopter automation systems. By detailing how different automation approaches effect different helicopter missions, the developed design guidelines will contain the answer to the main research question of this dissertation, and they will support the reader to better "understand the use of automation in helicopters".

1.8. Structure of this dissertation

Chapters 2 through 6 represent the body of this dissertation. Each of the chapters two to six represents an independent study, with a set problem definition and goal. As such, they can be read independently. Each chapter contains a preamble which connects the content of the chapter with the overall topic of the dissertation, as well as a reference to the original publication pertaining to this chapter. The contents of each chapter largely resemble the contents of a corresponding conference or journal publication. The chapters have been modified to unify the nomenclature across the chapters, improve the visibility of the overarching story, and to increase readability.

Figure 1.4 depicts the structure of this dissertation, and how its chapters pertain to the main research question and subquestions. Chapter 2 answers subquestion one. A methodology to compare and classify helicopter automation systems based on manoeuvre timescale is presented. This methodology is applied to scientific publications pertaining to helicopter automation systems, summarising their functions and working principles.

After surveying this "lay of the land" of helicopter automation, chapters three to six present the methodology and results of investigating helicopter automation systems on three different operational timescales and accompanying pilot tasks:

1. short-term, manual control,

2. medium-term, tactical decision-making, and

3. long-term, strategic decision-making.

The pilots are always required to close the innermost stabilisation loop. Depending on the operational scenario, they are also required to make decisions and manually control the other control loops.

Chapters 3 and 4 are theory-based, exploratory studies that focus on the short-term hovering task. No longer-term control actions like guidance or navigation are required, the control task is very close to the short-term stabilisation task. Hovering is a basic helicopter manoeuvre that is regularly performed, for example during take-off, landing, or while surveying a specific area. At the same time, controlling a helicopter during hover is challenging because of the pronounced cross-coupling between the flight control axes. This can lead to a high workload to maintain acceptable hover performance, which accentuates the tension that can arise between performance and safety (Padfield, 2013). The information gained and discussed during the exploratory studies in Chapters 3 and 4 are used to inform the design of the human-in-the-loop experiments in Chapters 5 and 6.

Chapter 5 presents the first scientific human-in-the-loop experiment of this dissertation and focuses on the task of obstacle avoidance during forward flight. Most of the time, a collision with obstacles or inadvertent flight into terrain causes catastrophic damage to the helicopter and its inhabitants. Therefore, this task has been identified as a worthwhile object of analysis for medium-term, tactical decision-making support, even though there already exist many approaches to support the pilot with obstacle detection and collision avoidance. Pilots are required to perform both the short-term stabilisation/course holding task, and the medium-term guidance task of obstacle avoidance. This division of attention across timescales might accentuate the differences caused by the employed automated systems.

Chapter 6 presents the second human-in-the-loop experiment of this dissertation. It pertains to the task of long-term mission path-planning, in the presence of stationary obstacles and fuel constraints. In this experiment, pilots are required to close all control loops at once: the task requires short-term stabilisation control while hovering and cruising; it requires medium-term guidance control inputs to perform the chosen trajectory; and it requires long-term navigational decision-making. The pilots' attention is spread across all timescales at once, which could create a cognitive gap between the short-term manual control task and long-term cognitive/supervisory control task.

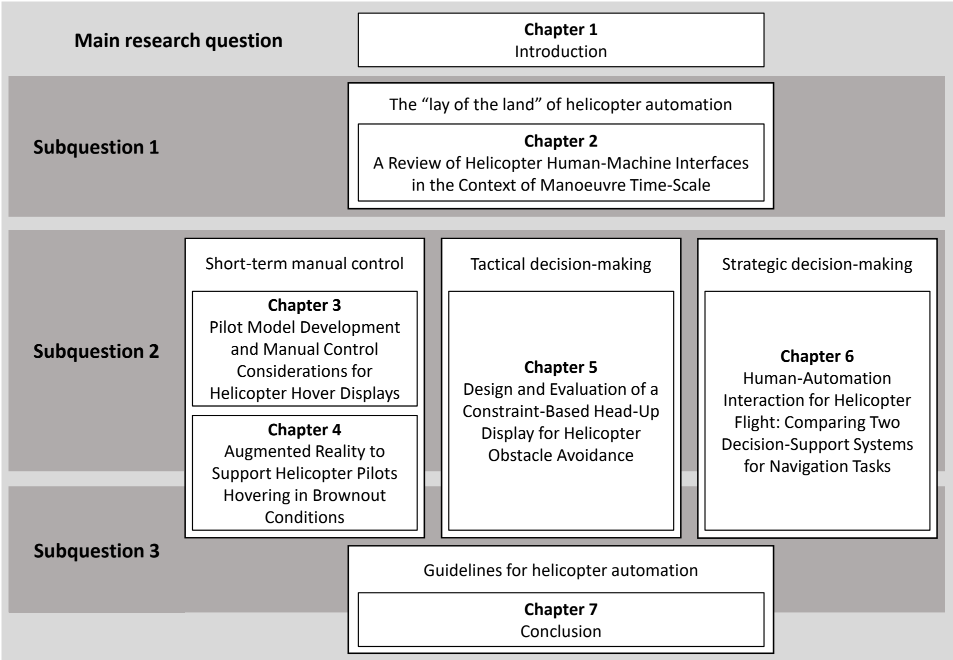


Figure 1.4: Structure of this dissertation.

Therefore, the introduction of constraint-based automation is of particular interest in this timescale. Existing automation systems in this timescale often focus on providing information through digital maps, or only provide one specific flight path to follow. Constraint-based automation might be able to extend the theoretical capabilities of automation systems, by focusing on supporting the decision-making of the pilots.

Subquestion two is first answered separately for short-term, tactical, and strategic decision-making. Afterwards, in Chapter 7, the results of each timescale are combined to answer subquestion three across operational boundaries and timescales.

2

A Review of Automation in Helicopters

To support helicopter pilots, many different automated systems and displays have been developed, analysed, and employed. However, introducing advanced automation may introduce cognitive challenges like transient workload peaks and out-of-the-loop situation awareness for pilots, and may cause inadvertent, negative effects. In order to build a solid foundation for the experiments of this dissertation, this chapter reviews and organises past efforts in helicopter automation research. It utilises two established automation classification methods, the level of automation and stage of automation. These methods are extended with the level of control sophistication, which enables the analysis of helicopter operations and automated systems in different levels of complexity and operational timescales. The results of this chapter motivate the automation design principles employed in the next chapters: task-centred and ecology-centred automation in the short timescale experiments, and advisory and constraint-based automation in the medium and long timescale experiments.

2.1. Introduction

Helicopter operations span a wide range of missions, from commercial transport and law enforcement to business, firefighting, and offshore transportation (Anonymous, 2011a,b). High-risk missions like helicopter emergency medical services (HEMS) or search and rescue (SAR) place intense and specific requirements on the pilots. High mission variability and generally more dangerous mission phases (e.g., flight close to obstacles) contribute to this high workload. Many different research efforts have been undertaken to develop avionic systems, displays, and automation to support helicopter pilots in high workload scenarios and unexpected events. This chapter aims to provide a concise overview of existing helicopter automation system types, as well as an overview of prototype helicopter automation systems that have been described analytically, and/or evaluated experimentally.

The term automation covers a wide range of systems, including revolutions per minute (rpm) governors, stability and control augmentation systems (SCAS), primary flight displays (PFD), navigation displays (ND), autopilots, flight directors, and any other systems that support the pilots in controlling the helicopter throughout the whole operational envelope. This includes short-term stabilisation, medium-term guidance, and long-term navigation tasks, as well as mission-level path planning and safety-critical tasks like obstacle and collision avoidance.

Automation can substantially improve aviation safety and performance (Inagaki, 2006). However, there are many possible drawbacks of implementing more automation to support the controller of a system, as already described by Bainbridge (1983). Examples of possible negative consequences of introducing automation are a loss of manual control skills, a disconnect between the controller and the internal state of the system, or over-reliance on the capabilities of automation (Bainbridge, 1983). It is therefore paramount to investigate how automation in helicopters can support the pilots in varying scenarios and events, while minimising possible automation drawbacks.

While there has been a substantial amount of research into automation in aviation for example by Billings (1991), in particular in the commercial fixed-wing domain, helicopter missions like HEMS or SAR often possess an inherently larger variability compared to commercial fixed-wing missions, e.g., through an unclear mission duration or location, which may necessitate different approaches to automation design. Past investigations in offshore helicopter automation usage[1] have shown that, while additional automation can be beneficial, it can also introduce new problems and drawbacks through novel and potentially unexpected interactions in the human-machine system.

Many helicopter automation systems have been developed, evaluated, and tested, and many of these systems proved to be extremely useful in supporting helicopter pilots in a variety of tasks, be it hovering, manoeuvring, and landing in degraded visual environments (Pavel et al., 2020; Szoboszlay et al., 2010), avoiding obstacles (Zimmermann et al., 2018), identifying off-nominal landing spots (Takahashi et al., 2018), or responding to unexpected situations like engine fail-

[1] HeliOffshore: Training Videos to Enhance Use of Automation (http://helioffshore.org/automationvideos/, retrieved October 14th 2020)

ures (Aponso et al., 2007). While certain tasks like hovering, landing, obstacle avoidance, or autorotation have received a lot of attention, it might prove useful to analyse a more complete set of tasks that can arise during typical helicopter missions. Historically, some tasks have been heavily investigated and supported, but other tasks might have gone largely unsupported and left to the pilots to solve by themselves.

At the moment, there is a lack of a unifying framework to compare and analyse helicopter automation systems across different tasks and mission profiles. Therefore, before performing the literature review, this chapter first develops a framework that encompasses the whole helicopter operational envelope. The framework utilises the well-established automation categorisation methodologies level of automation (LoA) and stage of automation (SoA). It then extends these two methods with the level of control sophistication (LoCS) (Amelink, 2010). This combination of established classification scales creates a framework that encompasses both automation-specific descriptors and the timescale of operation. The framework is able to describe helicopter operation on all timescales and the role of automation within it.

Afterwards, research into current and future helicopter automation systems is systematically reviewed and sorted based on this framework. This analysis of the parameters of automation systems across mission domains, tasks, and manoeuvre timescales is the first step towards developing novel helicopter automation systems that can address current gaps in automation system coverage in the operational envelope. This chapter lays the groundwork for Chapters 3 to 6, as it identifies parameters of automation systems that have proven useful as well as clusters and gaps in the design space of helicopter automation. The analysis of this chapter, and the subsequent investigation into the chosen scenarios and automation systems in the following chapters, enables the systematic analysis and improvement of helicopter automation systems across timescales.

This chapter is structured as follows: Section 2.2 covers background information about helicopter missions and safety. Section 2.3 briefly covers past efforts to conceptually model human interaction with systems on different timescales and introduces the level of control sophistication. Afterwards, Section 2.4 covers established helicopter automation classification methods and other factors of automation systems and displays that can influence the helicopter human-machine interface. In Section 2.5, the core of this chapter, existing helicopter automation systems are described, and the range of covered functions of these systems are defined. These are then classified and categorised according to their Level of Automation, Stage of Automation, and Level of Control Sophistication. Section 2.6 investigates some clusters and gaps in the coverage of the analysed automation systems, and explores the implication of future modes of transportation and vehicle configurations on automation requirements: personal aerial vehicles, tilt-rotor aircraft, and compound helicopters. Section 2.7 concludes this chapter.

2.2. Background

This Section summarises information about helicopter missions and helicopter safety, briefly covering the results of past helicopter accident analysis efforts. This analysis yields information about common accident causes and identifies operational timescales and tasks that have potential to be better supported by automation systems. The last subsection is dedicated to degraded visual environments (DVE), a factor that contributes to many helicopter accidents and, as such, motivates a large portion of helicopter automation development efforts.

2.2.1. Helicopter missions

The latest annual safety review (Anonymous, 2019a) of the European Aviation Safety Agency (EASA) broadly categorises helicopter operations into four areas, namely: commercial offshore transportation, commercial on-shore transportation, specialised operations (e.g., HEMS, advertisement, photography), and non-commercial operations. The European Helicopter Safety Team (EHEST) (Anonymous, 2010b, 2015) uses four categories: commercial air transport (CAT), aerial work (AW), general aviation (GA), and non-military state flights. The US-based Joint Helicopter Safety Analysis Team (JHSAT) (Anonymous, 2011a,b) utilises a more granular categorisation in their reports:

1. personal/private,
2. instructional/training,
3. aerial application,
4. emergency medical services,
5. commercial,
6. law enforcement,
7. air tour/sightseeing,
8. business,
9. aerial observation,
10. offshore,
11. firefighting,
12. logging,
13. external load,
14. utilities patrol/construction, and
15. electronic news gathering.

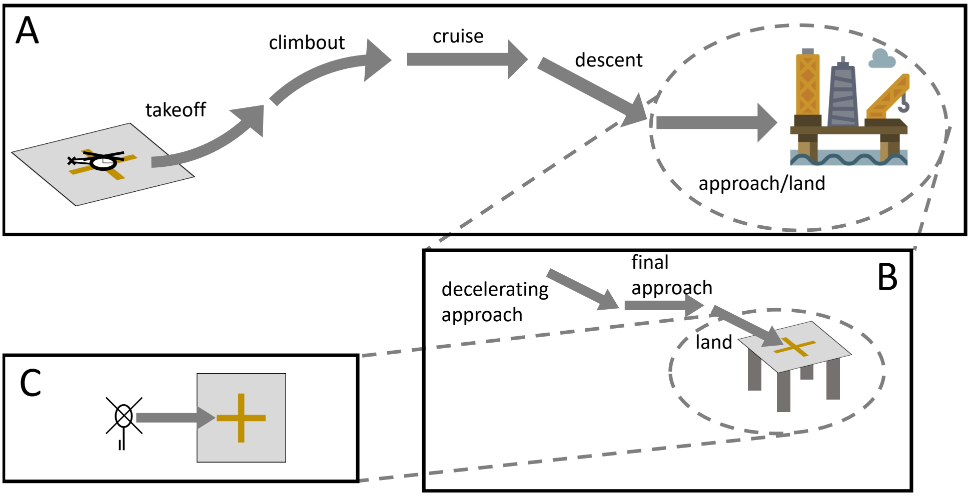


Figure 2.1: Graphical representation of the decomposition of an offshore helicopter transportation mission, based on an example provided by Padfield (2007). A: offshore transportation mission; B: approach/land mission-phase; C: land mission task element.[2]

Helicopter missions can vary greatly in possible accident causes and contributing factors (Anonymous, 2010b, 2015). Safety-critical mission parameters include flying close to obstacles (like aerial work/logging), landing and taking off in unknown terrain (HEMS), or interfacing with heavy external equipment (aerial work/logging, external load). Every helicopter mission type possesses different risks and sets different requirements and expectations for the pilots to mitigate these risks. As an example in the HEMS domain, Kessler (2015) provides a history of HEMS systems in different countries, and discusses the high number of accidents that still occurs in this operational domain.

Risks not only depend on the type of operation, but on the mission phase, too, as Nascimento et al. (2014) show. They identify mission-phase dependent risk levels for offshore transportation missions, highlighting visual segments of nighttime operations as the riskiest phases of flight. In terms of HEMS missions, Fillias et al. (2011) discuss additional altitude limits that can be imposed on some HEMS mission phases, based on patient requirements. Based on these findings, it is clear that helicopter automation design must depend on the specific requirements of the targeted helicopter mission and cater to their specific requirements and safety-critical parameters.

In order to analyse helicopter operations, it is useful to first have a structured approach towards treating helicopter missions and their parts. According to Padfield (2007), helicopter operations can be divided into many different possible missions. A typical mission, offshore supply, is shown in Figure 2.1, adapted from Padfield (2007). A diagram showing the decomposition of this mission into some of its phases, mission task elements (MTE), and manoeuvre samples is depicted in

[2]Oil rig symbol by Puppie PP, `https://www.iconfinder.com/Puppai`, used with permission.

Figure 2.2. A mission can be divided into multiple mission phases, each of which consists of multiple MTEs. An MTE is made up of several manoeuvre samples. Manoeuvre samples represent the smallest flying element. They are often related to a change in only one particular flying axis. Typical manoeuvre samples include a lateral side-step or hovering in place (Padfield, 2007).

The goal of the example mission shown in Figures 2.1 and 2.2 is to transport goods and/or people from a land-based heliport to an offshore platform. This mission is divided into the mission phases takeoff, climbout, cruise, descent, and approach/land. In the aforementioned figures, the mission phase of approach/land is depicted in greater detail, revealing the necessary MTEs (decelerating approach, final approach, and land). Finally, the MTE land is depicted in even greater detail. To perform a landing, several manoeuvre samples like sidestep and hover are required.

The time horizon of these mission parts continuously decreases from the top-level mission (multiple hours) to single manoeuvre samples, whose duration can be closer to tens of seconds. Each of these timescales can put different requirements and pressures on the pilots and may necessitate different kinds of automation support. Section 2.3 will provide a more detailed description of previous efforts of describing and analysing vehicle locomotion control and nested control loop across multiple timescales.

2.2.2. Safety

This subsection provides a brief history of helicopter accidents in the last decades. This overview examines past helicopter accidents with respect to the potential of mitigating them through improved automation systems. Through the provided summary, the potential of improved helicopter automation to improve helicopter safety becomes apparent.

Helicopter safety has been the focus of many initiatives in the last decades. The goal of zero helicopter accidents has been re-affirmed by Harris (2007) in the 20th Alexander A. Nikolsky Lecture. The International Helicopter Safety Team (IHST), formed in 2006, set the goal of reducing worldwide helicopter accidents by 80 % in ten years (until 2016)[3], which corresponds to 1.8 accidents per 100.000 flight hours (Tristrant and Greiller, 2016). The United States Helicopter Safety Team (USHST) estimates the 2016-2020 helicopter accident rate at 3.45 accidents per 100.000 flight hours (Anonymous, 2010a) — as of now, IHSTs goal has unfortunately not been reached.

Helicopter operations still face a higher accident rate per flight hour, when compared to fixed-wing operations. The annual safety review 2019 of the European Aviation Safety Agency determines the European fixed-wing commercial air transport accident rate at 0.19 accidents per 100,000 flight hours (Anonymous, 2019a). While this metric is not directly comparable to its helicopter equivalent, given the very different mission structure and risks associated with helicopter versus commercial fixed-wing aircraft operations, these numbers nonetheless act as a motivation

[3]International Helicopter Safety Foundation (former IHST), "About Us". URL: `http://ihsf.aero/index.php/about/`, retrieved October 14th 2020

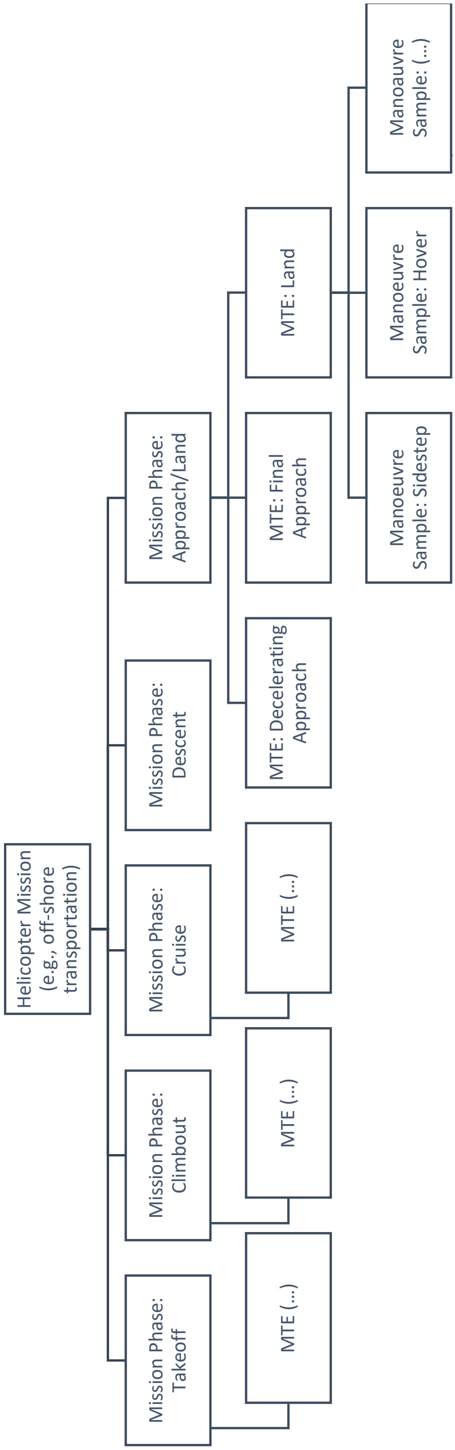


Figure 2.2: Decomposition of an offshore helicopter transportation mission, based on the offshore transportation example provided by Padfield (2007).

to aim for higher safety and lower accident rates in the helicopter domain.

Van der Meer et al. (2011) provide an overview of helicopter safety initiatives and improvements at the beginning of the last decade, including the International Helicopter Safety Team, the European Helicopter Safety Team, and the US-based Joint Helicopter Safety Analysis Team and Joint Helicopter Safety Implementation Team. Currently, helicopter safety is pursued further through the European Safety Promotion Network — Rotorcraft (ESPN-R) (Anonymous, 2019c) and the International Helicopter Safety Foundation (IHSF), including the US-based Joint Helicopter Implementation Measurement and Data Analysis Team, which analyses the implementation of the results of the previous teams[4].

In the 32nd Alexander A. Nikolsky Lecture, Padfield (2013) discussed the tension between safety and performance in helicopter operations, and how good helicopter handling qualities can act as a "safety net". Accident analysis reports (discussed in the following Section 2.2.2) identify "pilot error" as the major contributor to helicopter accidents. However, Padfield argues that these accident-causing "wrong" pilot actions and judgements are often made while being exposed to very challenging handling characteristics. Better handling qualities can relieve this stress on the pilots, which frees up cognitive resources to improve control actions and judgements. Better handling qualities, therefore, improve safety by enabling pilots to make better decisions. Accordingly, impaired handling qualities or challenging factors like degraded visual environments can decrease handling qualities and therefore safety.

The view that human error and misjudgements are enabled by the underlying system characteristics and parameters at the time of operation is reminiscent of Dekker's discussion of industrial mishaps and their causes (Dekker, 2003). According to the "new view in ergonomics", human error is an effect of trouble "deeper within the system". According to Padfield (2013), in case of helicopter operation, this trouble can come in the form of insufficient handling qualities. This chapter extends this argument from handling qualities to the whole helicopter human-machine interface. A "good" human-machine interface, comprised of transparent and reliable automation systems, supports pilots in the control of the helicopter, in their decision-making, and in avoiding behavioural traps and biases (as described in an EHEST information leaflet (European Helicopter Safety Team, 2010)). It enables them to spend a large part of their available cognitive resources on safety-critical off-nominal or unexpected events, if necessary. Accordingly, a convoluted, non-transparent automation set-up that requires regular high-workload pilot supervision and intervention can limit the pilots' capability to exert optimal control actions and to make good decisions in the face of high-risk mission phases (Kaletka et al., 2005).

Accident analysis

Both in the United States and Europe, accident investigation teams have been set up to analyse past accidents and investigate common accident causes. While the

[4] International Helicopter Safety Foundation (former IHST), "Organization". URL: `http://ihsf.aero/index.php/2339-2/`, retrieved November 12th 2020

Table 2.1: Level 1 standard problem statements per operation type (commercial air transportation (CAT), aerial work (AW), or general aviation (GA)). (Anonymous, 2010b, 2015, 2011a,b)

	EU CAT	EU AW	EU GA	US
Pilot judgements and actions	71 %	65 %	71 %	84 %
Safety management	52 %	54 %	48 %	43 %
Ground duties	36 %	42 %	40 %	37 %
Pilot situation awareness	46 %	32 %	29 %	31 %
Data issues	22 %	36 %	45 %	not used
Mission risk	28 %	55 %	9 %	19 %
System component failure	28 %	25 %	20 %	28 %
Maintenance	13 %	14 %	11 %	20 %

operational categorisation differs between the teams, the same standard problem statements (SPS) are used to identify accident causes. The European Helicopter Safety Team analysed 487 helicopter accidents which took place between 2000 and 2010 in the European Union (Anonymous, 2010b, 2015). As anticipated, the results are divided by operation type: commercial air transportation (CAT), aerial work (AW), general aviation (GA), and non-military state flights. The United States Joint Helicopter Safety Analysis Team (USJHSAT) analysed 523 US-registered helicopter accidents that occurred in 2000, 2001, and 2006 (Anonymous, 2011a,b). These accident analyses serve as a reference to identify areas where novel helicopter automation systems could have a positive impact on safety.

In the accident reports, a list of standard problem statements was developed. These statements were subsequently assigned to each accident if they played a role in it. The six most prominent level 1 standard problem statements of both European Union (EU) and United States of America (US) data are shown in Table 2.1. In the context of this chapter, the categories “pilot judgement and actions” and “pilot situation awareness” are of particular importance, as both can be impacted by helicopter automation systems.

Pilot judgement and actions is the most influential parameter, consistently across all operational types. Table 2.2 shows the contribution of the level 2 SPS within the pilot judgement and actions category. In commercial air transportation and general aviation operations, human factors–pilot’s decision is the dominant contributor and human factors–pilot/aircraft interface plays a smaller role, whereas in aerial work both factors contribute more evenly to accidents. These categories are particularly relevant when investigating helicopter automation systems. Obviously, a human-machine interface with improved automation will impact the influence of the pilot/aircraft interface. In addition, automation systems can also impact and support pilot decision-making, by offering suggestions or improved information.

In terms of level 1 SPS, pilot situation awareness is especially relevant for commercial air transport operations, where it has been assigned to 46 % of accidents. Within this category, in data from the EHEST reports, 50 % of accidents are influenced by the level 2 SPS external environment awareness, 7 % by internal aircraft awareness, and the remaining 43 % by visibility/weather. The US data show similar values, with 59 % of accidents influenced by external environment awareness,

Table 2.2: Top six level 2 standard problem statements within "pilot judgement and actions" category per operation type (commercial air transportation (CAT), aerial work (AW), or general aviation (GA)). (Anonymous, 2010b, 2015, 2011a,b)

	EU CAT	EU AW	EU GA	US
Human factors–pilot's decision	43 %	27 %	41 %	36 %
Human factors–pilot/aircraft interface	9 %	21 %	8 %	13 %
Flight profile	17 %	23 %	16 %	24 %
Landing procedures	12 %	16 %	13 %	40 %
Crew resource management	7 %	3 %	6 %	10 %
Procedure implementation	12 %	10 %	16 %	35 %

26 % by visibility/weather, 12 % by internal aircraft awareness, and 3 % by crew impairment. Helicopter displays and automation currently in development or evaluation often aim to improve pilot situation awareness, in order to improve awareness of obstacles in the external environment, or in order to counteract the effects of degraded visual environments caused by, e.g., flat light or brown-/white-outs.

Mission risk is particularly important in EU aerial work operations, with the level 2 SPS terrain/obstacles contributing to 58 % of accidents, and pilot intensive (large requirements placed on the pilot) contributing to 33 % of accidents. AW operations are often characterised by obstacles in close proximity, for example during power line tree cutting. These tasks are typically associated with a consistently high workload as well. Possible automation systems have to take into account the specific AW mission profile, to be able to support the pilots with the peculiarities of the respective task.

In addition to the SPS analysis, a human factors analysis and classification system (HFACS) was employed by EHEST. The top three level 1 contributions are shown in Table 2.3. In general aviation accidents, unsafe acts — errors played a larger role than in aerial work or commercial air transportation accidents. This might be due to the often limited experience of general aviation pilots, whereas commercial air transportation and aerial work pilots are required to possess more advanced pilot licences and usually are more experienced. For commercial air transportation operations, unsafe acts — errors are made up of 49 % of judgement & decision-making errors, 40 % skill-based errors, and 11 % perceptual errors.

Table 2.3: Top three human factors analysis and classification system categories per operation type (commercial air transportation (CAT), aerial work (AW), or general aviation (GA)). (Anonymous, 2010b, 2015)

	EU CAT	EU AW	EU GA
Preconditions — condition of individuals	40 %	41 %	45 %
Unsafe acts — errors	35 %	41 %	59 %
Preconditions — personnel factors	21 %	24 %	20 %

A study by Bazargan and Guzhva (2011) provides an insight into the effect of age, gender, and experience on the risk of general aviation pilot error and fatal accidents. Although they investigate both fixed-wing and helicopter general aviation operations, their results can inform and contribute to helicopter safety analyses, as well. They find a significant effect of pilot experience (measured in flight hours) on the risk of making an error, where pilots with more experience make fewer errors. Interestingly, pilots over the age of 60 with extensive flying experience are more prone to be involved in fatal accidents. However, it is not clear whether this result is caused by age-related skill degradation, experience-induced overconfidence, or because highly experienced pilots are more likely to fly higher-risk manoeuvres.

The USJHSAT ranks all SPS level 3 occurrences based on their contribution to the analysed accidents. Out of the top 10 SPS level 3, seven are part of the pilot judgement and actions category, while one SPS level 3 is part of pilot situation awareness, as shown in Table 2.4. Automation systems can support pilots in the effort of avoiding these errors, by providing decision-support, improving the control response of the helicopter, or by providing the pilot with flight data information to counteract perceptual problems.

Table 2.4: Top ten standard problem statements (SPS) level 3 (US data). (Anonymous, 2011a,b)

SPS level 1	SPS level 3	percentage
Pilot judgement and actions	Autorotation – forced	18.9 %
Pilot judgement and actions	Disregarded cues that should have led to termination of current course of action or manoeuvre	17.6 %
Pilot judgement and actions	Pilot control/handling deficiencies	15.3 %
Maintenance	Failure to perform proper maintenance procedure	10.5 %
Pilot judgement and actions	Autorotation – Practice	10.3 %
Pilot Situational Awareness	Aircraft position and hazards	9.8 %
Pilot judgement and actions	Inappropriate energy/power management	9.8 %
Pilot judgement and actions	Pilot's flight profile unsafe – Altitude	9.0 %
Pilot judgement and actions	Pilot decision-making	8.6 %
Ground duties	Inadequate consideration of weather/wind	8.4 %

An EHEST follow-up study to identify potential technologies to mitigate helicopter accident factors has been conducted at the Netherlands Aerospace Centre (NLR) by Stevens and Vreeken (2014). They present a ranking of promising technologies that address three or more SPS level 1 safety issues. The five most promising technologies are:

1. enhanced ground proximity warning system / terrain awareness and warning system,
2. digital range image algorithms for flight guidance aids for helicopter low-level flight,
3. laser radar obstacle and terrain avoidance system,
4. digital map, and
5. deployable voice and flight data recorder. (Stevens and Vreeken, 2014)

Improved helicopter automation can address the first four categories. In each of these categories, acquiring and analysing the necessary data is the first step that can potentially be automated — afterwards, a human-machine interface has to be defined and developed that communicates the newly acquired data to the pilot or that automatically acts on it.

Degraded visual environments

According to a study by the Civil Aviation Authority of the United Kingdom (CAA) (Safety Regulation Group, 2007), degraded visual environments contributed to a significant amount of helicopter accidents between the years 1975 and 2004 in the CAA's accident database. DVEs can be caused by night-time operation, an inadvertent entry into instrument meteorological conditions (IMC), or by flying low-altitude and low-speed over dusty or snowy terrain (brown-out/white-out) (Safety Regulation Group, 2007; Minor et al., 2017). Historically, DVE contributed to a particularly high number of accidents for military operations in sandy/dusty terrain (Task Group HFM-162, 2012) and for the operation of single-engine, piston-powered rotorcraft with inexperienced pilots (Vreeken et al., 2013). An inexperienced pilot can be assumed to have more difficulty flying in DVE, and at the same time, they might be more prone to inadvertently entering IMC.

Automation systems and displays can support pilots during DVE operation, as is shown by existing automation research in this area. This research is discussed later in Sections 2.5.2 and 2.5.3. Conformal head-up displays (HUD) in particular seem to be a promising technology (Minor et al., 2017). HUD systems have been tested and evaluated during the DVE-M flight trials in Arizona, United States (Szoboszlay et al., 2017), as well as in Germany and Switzerland (Münsterer et al., 2018). This chapter focuses on the implications of these head-up displays for the human-machine interaction in helicopters. Hardware and software development, system integration, and data fusion requirements are substantial, as has been shown by, e.g., Waanders et al. (2019) and Zimmermann et al. (2019). However, these efforts lie outside of the scope of this chapter.

2.3. Connecting short- and long-term control

The previous sections discussed many different operational scenarios in which accidents can be caused or exacerbated by insufficient or improper automation support to pilots. The operational scenarios vary greatly, and the proposed technologies to mitigate helicopter accidents by Stevens and Vreeken (2014) cover a wide range of supported tasks, from long-term navigation to short-term obstacle avoidance. The importance of operational timescale when controlling a vehicle has already been described by Van Paassen et al. (2018). This section introduces manoeuvre timescale as a parameter to jointly classify a wide range of automation systems, from short-term stabilisation systems to long-term mission support systems.

Manoeuvre timescale corresponds with previous efforts of analysing different automation goals and complexity. Amelink (2010), in his efforts to extend the abstraction hierarchy to describe systems in a work domain analysis (WDA), classifies goals (and all less abstract system features) according to the level of control sophistication. The level of control sophistication (LoCS) corresponds with the complexity of the goal, as well as with the manoeuvre timescale: goals in short timescales tend to be less complex, while goals in long timescales tend to be more complex. As previously mentioned, manoeuvre timescale also corresponds with the level within the helicopter mission hierarchy. On the lowest level, it corresponds with the helicopter pilot tasks of stabilisation, guidance, and navigation, which have been described by Padfield (2007). As such, manoeuvre timescale is a critical parameter that can bring together the results of general automation research and the specific properties of automation in helicopters.

This section first contains a brief, non-exhaustive description of previous efforts of modelling nested control loops with respect to controlling a vehicle. Afterwards, it presents background information about cognitive work analysis. Then, the level of control sophistication, which is used in this chapter to differentiate between different manoeuvre timescales, is described in more detail.

2.3.1. Modelling nested control-loops for vehicle control

According to Kong and Mettler (2013), historic efforts to model human spatial behaviour are either model-based or non-representational. Model-based approaches assume internal representations of systems, e.g., the muscular and skeletal system in a manual control task. Non-representational approaches do not require internal representations. They treat information as situation-specific stimulus patterns, which are perceived by humans, e.g., optic flow field information or the time-to-contact τ. Kong and Mettler point out shortcomings of each approach: model-based approaches often focus on either perception or action, not on a unified description, while non-representational approaches often focus on low-dimensional dynamics without physiological or psychological significance, and without the capability to explain complex behaviours.

Kong and Mettler then present a unified, agent-based model to capture short-term and long-term human guidance behaviour. They hypothesise that "interaction patterns" emerge from the closed-loop agent-environment interaction, which are subsequently utilised as "building blocks" by the human controller to reach higher-level goals. Qualitatively, this approach is similar to the nested control loop approach utilised in this chapter: lower timescale manoeuvre-samples are used as building blocks to form longer timescale and more complex manoeuvres, which finally serve the purpose of reaching a mission-specific goal.

Padfield (2007) and Padfield et al. (2007) define three distinct timescales of helicopter operation: stabilisation (1 s, maintain attitude), guidance (10 s, where to go in the short-term), navigation (100 s, where to go in the long-term). In terms of mission decomposition, they define a hierarchy of parts of a mission:

1. mission,
2. mission phase,
3. mission task element, and
4. manoeuvre sample.

These levels of the mission structure hierarchy coincide with a change of timescale, from long-time mission to short-time manoeuvre samples. They also correspond with the multi-loop control problem defined by Van Paassen et al. (2018), which differentiates between

1. short-term control (seconds), including
   (a) vehicle dynamics and
   (b) state control;
2. medium-term control (minutes), including
   (a) path control; and
3. long-term control (hours), including
   (a) trajectory control.

Windridge et al. (2013) developed the extended control model, a hierarchical perception-action model to describe human control behaviour when controlling a car. The extended control model is characterised by four distinct layers:

1. targeting,
2. monitoring,
3. regulating, and
4. tracking.

Actions on the lowest level (tracking) are typically rapid, short timescale tasks and feedback loops, while higher-level actions encompass long-term planning and abstract goals. On each level, the available information is first acquired and afterwards analysed, in order to create a desired goal (which is handed down to "subsumptive" levels, or translated into a control action on the lowest, tracking level).

All described models have in common that they use the timescale of control actions as a dividing factor between different levels of control. Short-term control loops receive target values from higher-level, longer-term control loops, in order to reach the overall system goal. It seems that an understanding of the timescale of operation and control is a necessary step in the process of understanding and, finally, of supporting human control actions through automation.

2.3.2. Cognitive work analysis for helicopter operations

Cognitive work analysis (CWA) represents the start of the cognitive systems engineering-based process to design human-machine interfaces and displays. It can be used as a tool to design and improve cockpit automation, as discussed by Borst et al. (2010a). The five steps of CWA have been described by Vicente (1999):

1. "Work domain analysis — *What are we working with?*,
2. control task analysis — *What must be done?*,
3. strategies analysis — *How can it be done?*,
4. social organisation and cooperation analysis — *Who can best perform each (sub)task?*, and
5. worker competencies analysis — *How can human actors be supported in their task?*" ((Vicente, 1999) as cited by Borst et al. (2010a, p. 1))

Finally, the result of these analyses can result in the design of an ecological interface (Burns and Hajdukiewicz, 2004). Even without designing a specific interface, the five steps of CWA can be utilised to describe and analyse system operations and work domains.

Van Paassen et al. (2018) provide a review of how ecological interface design can be employed in the domain of vehicle locomotion control. Among other points, they elaborate on the importance of considering the operational timescale and the pursued goal in the nested control loop analysis of vehicles. In his work on ecological automation design, which is based on ecological interface design, Amelink (2010) expands the abstraction hierarchy through the addition of a perpendicular axis called level of control sophistication. According to Amelink (2010), the LoCS increases when "higher order, more sophisticated control" goals are pursued.

With a growing manoeuvre timescale, the operational possibilities and the amount of required information increase. The level of uncertainty rises, which results in a less clearly defined objective and a requirement for more adaptive control and creative solutions. A growing timescale typically requires more interaction with external actors, like air traffic control or mission control. Therefore, the LoCS, i.e., the order and sophistication of pursued goals, increases with an increasing manoeuvre timescale.

This connection between timescale of operation and LoCS provides the critical link between helicopter operations analysis, the timescale of operation, and task-specific automation support. By using timescale as the primary classifier, all operations from short-term stabilisation to long-term mission planning can be holistically analysed, and their interaction can be described. Automation systems can be located in this framework to determine what specific goal on what timescale is supported by the system, and what function the system performs.

On first glance, the increase in possible creative solutions and uncertainties on longer timescales might lead to the conclusion that automated systems should focus on taking over the low-complexity, monotonous tasks of lower LoCS, while the human operators' resources should be focused on the higher-level LoCS. It is important to note, though, that this approach is dangerously close to the "humans are better at — machines are better at" (HABA–MABA) philosophy of task allocation described by Fitt's list (de Winter and Dodou, 2014), which can cause a new set of problems in the context of the previously discussed ironies of automation

(Bainbridge, 1983). While automation development should enable and support human decision-making, in particular in high complexity tasks, it should not do so by completely removing the human from certain control loops (Bainbridge, 1983; de Winter and Dodou, 2014).

In a complex system, at any given time, multiple dependent and possibly competing goals are pursued at the same time. For example, the high-level goal of "transport passengers" requires the successful completion of multiple subgoals (e.g., the completion of mission phases like take-off, climb, cruise, ...). These subgoals, in turn, require the successful completion of many different mission task elements. As the analysis moves towards more granular tasks, the dependence on the more sophisticated functions diminishes. While the location of the target airport, for example, is obviously relevant for the high-level goal of passenger transport, it is irrelevant for performing the take-off mission phase, or even more so, for performing single mission task elements during take-off. Higher-level goals and functions depend on the completion of lower-level goals and functions, while lower-level goals and functions depend on a specific handed-down target (e.g., cruise in eastward direction), without requiring explicit knowledge of *why* the specific goal is desirable at this moment. Although the determination of the goal takes place on a higher LoCS, only the goal itself is handed down.

2.3.3. Level of control sophistication

The goal of this section is to develop a framework for general helicopter operations, including the LoCS as an axis representing the timescale of operation. Figure 2.3 shows this framework. It is important to note that the LoCS is a conceptual model — it can just as likely be defined with a different number of stages, and different separations between levels. In this dissertation, five levels have been chosen to accommodate the three typical pilot tasks stabilisation (LoCS 2), guidance (LoCS 3), navigation (LoCS 4) in the middle, while providing one layer on top for mission objectives (LoCS 5), and one layer below for all functions that enable controlled flying of the helicopter in the first place (system readiness, LoCS 1). This definition aligns with helicopter mission decomposition categories mission (LoCS 5), mission phases (LoCS 4), mission task elements (LoCS 3), and manoeuvre samples (LoCS 2). On each LoCS, different goals are pursued, for example:

- LoCS 5, mission: perform search-and-rescue mission, transport passengers, perform helicopter emergency medical services mission;
- LoCS 4, navigation/mission phases: take-off, approach/land, cruise, search-and-rescue pattern, looking for landing spot in unknown terrain;
- LoCS 3, flying/mission task elements: landing, autorotation, decelerating approach, obstacle evasion;
- LoCS 2, controlled locomotion/manoeuvre samples: pull-up, hold velocity, hover in place, sidestep;
- LoCS 1, system readiness: steady engine rpm, steady rotor rpm, electrical power.

Level of Control Sophistication	1 System Readiness	2 Controlled Locomotion	3 Flying	4 Navigation	5 Mission
Time-scale		Short-term control: stabilisation	Medium-term control: guidance	Long-term control: navigation	
Goals	Aircraft controllability	Perform manoeuvre samples, maintain safe attitude, stay in safe flight envelope, avoid impending collision with obstacles/terrain	Perform mission task elements, avoid obstacles and terrain, maintain safe trajectory	Perform mission phases, fulfill mission navigation requirements effectively and efficiently	Produce mission deliverables; Production, Efficiency, Safety
Typical functions, tasks, or manoeuvres	Fuel store & injection, combustion, rpm control, vibration control, ice accretion management, power generation, …	Pitch, Roll, Yaw, Heave, Surge, Sway, collision avoidance, manoeuvre samples (hover, sidestep, rotation, translation, ...)	Autorotation, obstacle avoidance, combine manoeuvre samples to form MTEs (decelerating approach, final approach, land, …)	Combine MTEs to form mission phases (take-off, climb-out, cruise, descent, approach/land, search pattern, ...)	Combine mission phases to form mission (SAR, HEMS, passenger transport, ...)
To-be-considered elements of the task environment	Gas, gas tank, combustion chamber, compressor, turbine, transmission, rpm sensor and injection controller, structure, hard- and software, …	Air, pressure, temperature, wind, immediate surroundings, helicopter stability, …	landing platforms, obstacles, ground, other vehicles, manoeuvre and performance limitations, …	Cleared or blocked airspace, ATC, navigation targets (locations), search area, waypoints, fuel consumption, noise, …	Hospital, helipad, hangar, HEMS patient, lost person, airport, …

Figure 2.3: Goals, typical functions, and relevant elements of the environment of generalised helicopter operations across all levels of control sophistication.

LoCS 2 could conceivably be split into the goal of pure stabilisation tasks at the lower end, and the goal of performing simple manoeuvre samples on the higher end. Here, these two goals are handled together in LoCS 2, to be able to examine all stability and control augmentation systems (SCAS) within the same category. If the category would be split, stability augmentation systems would be treated in the stabilisation category, while control augmentation systems move more towards supporting and implementing manoeuvre samples (e.g., position hold when no control is exerted).

Within LoCS 2, vehicle parameters like position, velocity, attitude, or attitude rate are controlled. In reality, these system states are strongly coupled and interdependent. After linearising, decoupling and simplifying the underlying dynamics, they can be decomposed further into outer, middle, and inner control loops of vehicle parameters, containing the pilot transfer functions Y_p and vehicle system transfer functions Y_c, as depicted in Figure 2.4. Through the definition of LoCS and its connection to system parameter control loops (and the underlying, "enabling" LoCS 1), it is now possible to locate any display and automation system within this scheme, and to analyse the specific system functions and goals it supports, as well as the system functions and goals it depends on.

On each LoCS, the functional purpose represents the goals pursued on this level. On the abstract function level, priority measures and information/mass/energy/money flows that pertain to the targeted goal are described. The separate missions/mission-phases/mission task elements/manoeuvre samples, and the combination of lower-level elements, make up the generalised functions level. On the next level, the required physical functions and work processes are shown. The last level describes the physical form, appearance, and location of the material objects. For the purpose of the abstract description in this dissertation, no specific descriptions are given for this last level.

It is important to note that at the transition between LoCS 2 and 1, the functional purpose shifts from aircraft dynamics and position to "enabling" aircraft systems which are not directly coupled to one or more aircraft degrees of freedom. Rather, the systems on this level sustain helicopter controllability, maintain nominal engine processes, and aim to minimise the effects of adverse factors like ice accretion and vibration.

2.4. Helicopter automation

This section briefly motivates the requirement for holistic automation design and analysis methodologies and provides background information about two selected existing automation classification methods. It is important to note that the described automation classification methods are by no means the only possible method to classify automation or human-machine interface systems. An extensive review of all existing automation classification themes lies outside of the scope of this chapter. This section concludes with a brief description of additional display characteristics than can influence the effectiveness of display and automation systems. For an extensive review on human-machine systems for manned and unmanned aircraft, readers are referred to Lim et al. (2018).

2.4.1. Automation definition in this dissertation

The term automation is used in a broad variety of ways, and many definitions exist. As has been mentioned in Chapter 1, this dissertation adopts a definition by Parasuraman and Riley (1997). To recall,

> automation is "the execution by a machine agent (usually a computer) of a function that was previously carried out by a human" (Parasuraman and Riley, 1997, p. 230).

This definition includes all systems that acquire and analyse information on behalf of the pilot (i.e., sensors, algorithms, and displays), as well as systems that

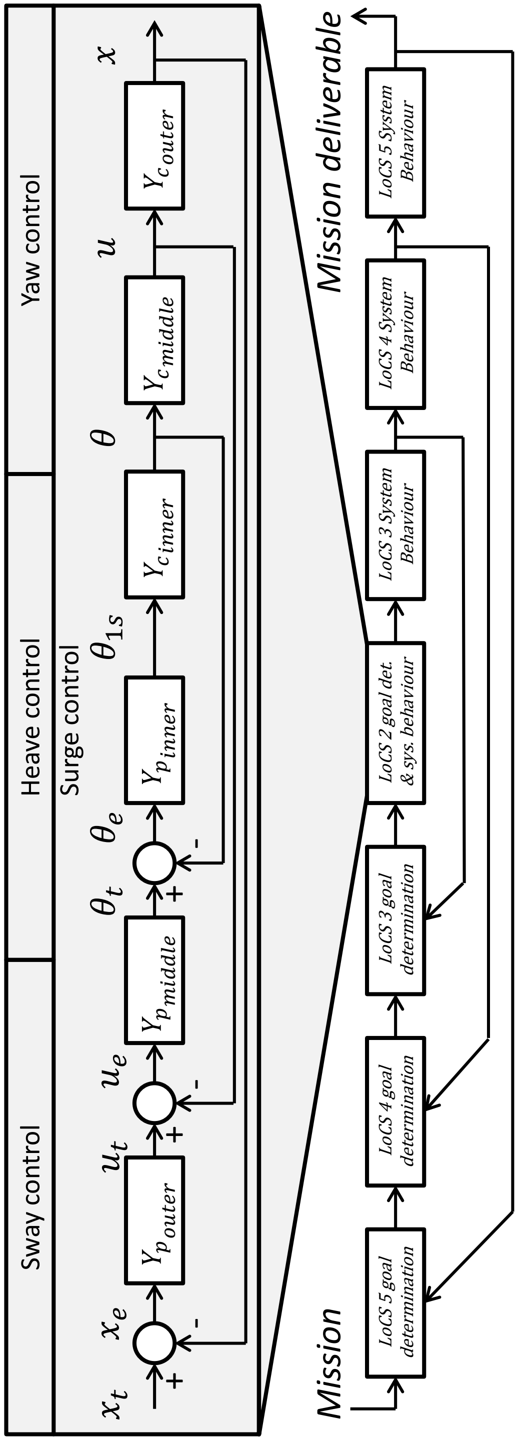


Figure 2.4: Levels of Control Sophistication depicted as nested control loops in helicopter control with longitudinal cyclic input θ_{1s}, helicopter pitch angle θ, longitudinal velocity u and position x. Subscript t denotes a target value, subscript e an error value.

support the human controller's task of action selection and implementation. Adopting this broad definition of automation enables the analysis of the wide array of support systems that is being utilised in helicopter cockpits, while remaining open to those that are currently foreseeable.

The focus of this definition lies on the *function* that is being taken over by the automation. An important differentiation has to be made between activities of the vehicle that are supported (e.g., hover), the mode of operation of particular support systems (e.g. "visualise desired flight path"), and the human control actions of the pilots that are supported (e.g., information acquisition, decision-making, action implementation). With respect to the definition of automation, the relevant function is the human control action that is being taken over or supported by the automation, not the resulting vehicle behaviour.

A useful tool of visualising the impact of automation on human control behaviour is the decision ladder described by Rasmussen (1983), depicted in Figure 2.5. In the decision ladder, three different kinds of operator behaviour are shown: skill-based behaviour (SBB), rule-based behaviour (RBB), and knowledge-based behaviour (KBB) (Rasmussen, 1983).

On the lowest level, SBB describes the subconscious, often highly integrated and feed-forward sensory-motor control performance of the human operator (Rasmussen, 1983). The manual, stabilising control of helicopter attitude and, to an extent, position, falls into this category. Automation systems on this level, denoted by the number **1** in Figure 2.5, can provide support or can completely take over the translation of perceived activation and alerts into desired procedures, and can potentially execute them.

On the intermediate level, RBB describes operator control actions that are based on "stored rules or procedures" for that particular familiar situation (Rasmussen, 1983). In terms of helicopter operations, this kind of behaviour can be observed in in medium-term manoeuvres like the approach to a prospective landing spot. The deceleration and altitude profile during such an approach is based on operator experience, as well as on relevant operational information (e.g., mission planning), and procedural requirements (e.g., maintain a minimum altitude at specified forward speeds). In these situations, automation systems denoted with a **2** in Figure 2.5 can provide or amplify existing rule-based "shortcuts" between certain observations or current system states (on the left side in the decision ladder), and the resulting desired tasks or procedures (on the right side of the decision ladder).

Lastly, KBB emerges during unfamiliar situations, when no pre-stored rules or procedures are known. In these situations, the human operators need to develop useful plans for action, based on their understanding of the system and its environment, and evaluate them with respect to the desired goal-state (Rasmussen, 1983). Automation systems on this level, denoted by **3** in Figure 2.5, can support this task, e.g., through the analysis and integrated representation of available data, or by providing means to evaluate action plans.

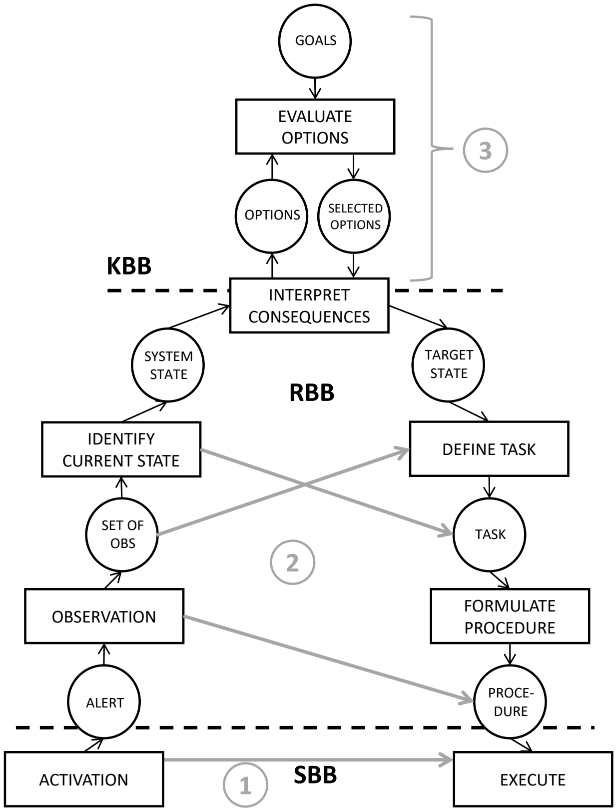


Figure 2.5: Generalised representation of a decision ladder with possible "automation–enabled shortcuts".

2.4.2. The effects of automation

Introducing automated systems in a control task is not straightforward and can cause benefits as well as inadvertent effects. Hoh et al. (1987) investigated how display and autopilot functions impact single-pilot workload during instrument flight rules in fixed-wing aircraft. Most errors were caused by incorrect data input into the autopilot and navigation systems by the pilots, even in low workload conditions. Most errors were discovered during cross-checks against other instruments and the expected behaviour. However, in certain cases, the display did not show significant differences. For example, when a wrong waypoint was selected, but the wrong waypoint was directly behind the desired waypoint, the pilots only realised the mistake after overshooting the target waypoint by multiple miles.

Pilot comments reported by Hoh et al. (1987) hinted at the benefits of implementing a basic autopilot to reduce workload, and at the preference for simplicity in display design. With an increase in automation sophistication, workload ratings generally decreased. However, in some cases, the ability to "avoid blunders", i.e., the proneness to make a mistake, grew, and stayed at a similar level across other conditions. The type of blunder shifted from flying-related mistakes to automation operation errors.

A pertinent example of automation-induced errors is the accident of Air Inter 118, F-GGED (Anonymous, 1993). The pilots erroneously selected a vertical speed of 3300 ft/min instead of a flight path angle of 3.3 deg, which corresponds to the actually desired vertical speed of approximately 800 ft/min. As both conditions were indicated as "33" on the display, with the only difference being very small dot that was easily overlooked, the pilots did not detect their mistake in time. The aircraft subsequently crashed into a forest.

This coincides with the theory posited by Hoh et al. increasing automation and display sophistication has two different, non-linear effects on workload: while it reduces the workload required to perform the task, it increases the workload to interpret and monitor the automated systems. This sentiment is elaborated upon by Bainbridge's "ironies of automation" (Bainbridge, 1983), as well, and reinforces the requirement for helicopter automation design to take the whole human-machine system into account, and not just "takes over" certain tasks from the pilots.

2.4.3. Level of automation

Parasuraman et al. (2000) provide a model for levels and stages of automation. This chapter utilises their approach of defining two distinct models for human interaction with automation: the level of automation (LoA), and the stage of automation (SoA). Parasuraman et al. base their definition in concepts of human-centred automation, focusing on the interaction between automation and the human operator. They define automation with respect to which function it supports or accomplishes that has been carried out by a human operator before. This Subsection elaborates on the first model, LoA.

Level of automation is a common classification tool for automation systems. Parasuraman et al. define LoA as a continuum between the two extremes of "the human does everything, without automation interference" and "the machine does everything, without human interference", for a specific task or function. This range can be separated into multiple levels, or treated as an actual continuum without discrete borders. One example of ten possible LoA within the function of "action selection and implementation" is reproduced here, based on work by Sheridan and Verplank (1978), with increasing levels of automation from 1 (low) to 10 (high):

1. The computer offers no assistance; human must take all decisions and actions.
2. The computer offers a complete set of decision/action alternatives.
3. The computer narrows the selection down to a few.
4. The computer suggests one alternative.
5. The computer executes the suggestions if the human approves.
6. The computer allows the human a restricted time to veto before automatic execution.

7. The computer executes automatically, then necessarily informs the human.
8. The computer informs the human only if asked.
9. The computer informs the human only if it, the computer, decides to.
10. The computer decides everything, acts autonomously, ignoring the human.

It is important to note that the number of levels and their description are not the same for every function or system. Depending on the task and system specifications, a different amount and definition of levels can be appropriate. For example, the Society of Automotive Engineers (SAE) has recently defined six levels of driving automation, with increasing levels of automation from 0 (low) to 5 (high) (Anonymous, 2018):

0. no driving automation,
1. driver assistance,
2. partial driving automation,
3. conditional driving automation,
4. high driving automation, and
5. full driving automation.

A publication by SAE (Anonymous, 2018) provides a detailed description of each level of driving automation. These levels are being constantly improved upon and refined, as is evident by the regular revisions available from SAE, and critiques regarding its specifics, for example by Inagaki and Sheridan (2019). These levels are defined with the operational environment of (consumer) cars and the accompanying typical operational envelopes, situations, and driver competencies in mind. As these factors change depending on the investigated operational environment (fixed-wing aircraft, helicopters, cars, civil/military, private/commercial, etc.), the most useful description of levels of automation very much depend on the investigated system.

In this dissertation, a generic, simplified three-level definition of level of automation is utilised. This generic definition of LoA allows the classification of all automation systems across different time/scales, without the requirement of changing LoA definitions to fit the investigated function or system. The employed levels of automation are:

1. low (requires constant human control actions and interaction with the automation system),
2. medium (occasional or regular human interaction necessary), and
3. high (little or no human interaction necessary).

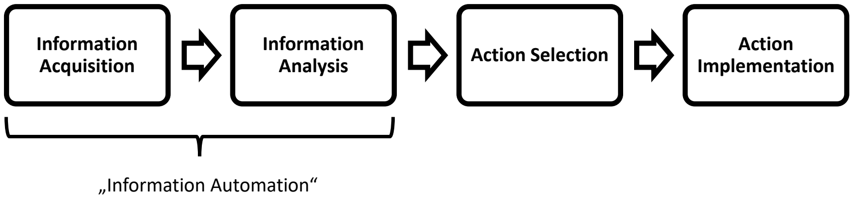


Figure 2.6: The four stages of automation as defined by Parasuraman et al. (2000).

2.4.4. Stage of automation

The stage of automation corresponds with the specific class of functions the automation system supports or performs. Parasuraman et al. (2000) define four generic classes of functions that can be supported by automation:

1. information acquisition (IAc),
2. information analysis (IAn),
3. action selection (AS), and
4. action implementation (AI).

For one singular action, they are assumed to be performed sequentially, as shown in Figure 2.6. When a system in continuously controlled, and multiple tasks have to be performed at once, they are not necessarily performed sequentially, but in parallel. The model does not capture these interdependent processes or multiple, parallel processes. Nonetheless, it can serve as a tool for automation analysis, provided these shortcomings are considered (Parasuraman et al., 2000).

Automation can support any number of these stages, and to a different extent: each SoA can possess a different LoA. Parasuraman et al. (2000) provide a detailed description of each of these stages, and typical tasks on each stage, while Onnasch (2015) perform a meta-analysis of the effect of different levels and stages of automation and human-automation system performance.

Automation in the first two stages is referred to as information automation, as it does not directly support action selection or implementation, but rather, the preprocessing of information necessary to perform these tasks (Parasuraman et al., 2000). In this dissertation, the term automation refers to automation on each of the described stages, it is not restricted to systems that support or perform action implementation only, see also Chapter 1. For example, a full-authority autopilot, haptic envelope protection systems, and navigation displays are all called automation; they only differ in the supported stage of automation, and in the extent (LoA) they support it.

2.4.5. Display characteristics

There are more factors determining the success of a display or an automation system. The data representation plays an important role: do pilots perceive the system

Table 2.5: Categories of display systems to support helicopter control, reproduced from Minor et al. (2017).

	Displayed image primary pilotage	Guidance algorithm primary pilotage
Helmet mounted display	**Category I**: reliable option with 1:1 magnification	**Category IV**: focusing on 2-D cues through 3-D picture can be difficult; permits coupling flight controls
Panel mounted display	**Category II**: unusable	**Category III**: excellent option for following guidance, permits coupling flight controls

inputs via a head-down display, or a head-up representation? What kind of information is presented? Table 2.5 contains a display classification scheme developed by Minor et al. (2017). They have shown that head-down representations of primary pilotage information are not feasible for high-gain tasks like hovering, while conformal head-up displays excel at providing this kind of information in a usable manner. Conversely, head-down displays function well when providing pilots with strictly to follow manoeuvre guidance, while head-up displays may suffer from a visual overload, and an ambiguity arising from overlaying a two-dimensional manoeuvre cue onto a three-dimensional representation of the outside world.

There are many more parameters when designing a display, for example its colour, the size, shape, and movement of the used symbols, or the arrangement of the display elements. All of these factors play a role in the effectiveness of the employed display and automation. They are, however, outside the scope of this chapter and dissertation.

2.5. Automation classification

This section presents current developments and research in helicopter automation system applications. Each subsection focuses on one level of control sophistication. First, common goals in the respective timescale are presented. Afterwards, existing systems are surveyed. Systems are categorised based on their function, and these categories of systems are then classified according to their level of automation on each stage of automation. This creates a "lay of the land" of current helicopter automation research efforts and provides the basis for the selection of experiment scenarios of this dissertation.

2.5.1. LoCS 5: mission

On LoCS 5, the high-level mission requirement is broken down into mission-phase goals, which are to be handed down to LoCS 4 for implementation. Typical mission goals include:

- productivity (transport passengers, provide helicopter emergency medical service, perform search-and-rescue mission, ...),

- efficiency (fulfil mission with the minimum required resource investment, e.g., time, fuel, equipment usage), and
- safety (guarantee safety of personnel, equipment, and external actors).

2

Multiple methods address the risk assessment of missions and mission phases. Nascimento (2014); Nascimento et al. (2014) assess the individual risk of night-time offshore transportation mission phases based on pilot questionnaires. Kerler and Erhard (2014) analyses the risk implications of operating in single-engine mode during certain mission phases, even on twin-engine helicopters, to increase mission efficiency, at the cost of redundancy and an increased effect of unexpected mission changes or emergencies like engine failures.

Based on risk factors or other impacts, navigation routes can be calculated or evaluated automatically, as described by, e.g., Ebel (2019), Murrieta-Mendoza and Botez (2015), Greenwood and Rau (2020), Rolando et al. (2016), or Bakker and van der Geest (2018).

Heinemann et al. (2018) describe a smart autoflight control system, which is intended to utilise data to compute and continuously evaluate flight trajectories. The tasks of this autonomic system correspond with the stages of automation described earlier: (1) monitor, (2) analyse, (3) plan, (4) execute. They envision a system where the pilot has the task of supervisory control, acknowledging and correcting the decisions made by the automatic system. They note that, on the mission planning level, communication with other actors, as well as air traffic control, has to be incorporated into the decision-making process.

Byrne (2001) describes a number of requirements for technologies to enhance rotorcraft capabilities in day/night all weather situations, as well as automated tools for military mission planning. All weather tools include head-up conformal symbologies to support helicopter pilots in nap of the earth-flying and obstacle avoidance, e.g., through tunnel-in-the-sky displays and orientation aides. The discussed mission planning and execution requirements reflect the stages of automation:

1. data capture (corresponds to IAc and IAn),
2. plan development (corresponds to AS),
3. mission execution (corresponds to AI), and
4. post mission debriefing.

Rataj et al. (2000) describe a human-centred design effort by the German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt, DLR) to develop an integrated helicopter Human-Machine Interface. They aim to avoid the high cognitive pilot workload of monitoring, managing, and integrating a high number of task-specific automation systems and displays. They employ the “act recognise” cycle, which corresponds to the stages of automation, only dividing the Information Acquisition and Information Analysis steps into three steps: (1) recognise world state and disparity to target world state; (2) analyse this deviation; (3) generate actions to influence world state. Their system incorporates support systems for take-off and landing (trajectory generation, LoCS 3), obstacle evasion (for unknown obstacles, LoCS 2) and avoidance (known obstacle, e.g., infrastructure or closed airspace, LoCS 3). It can automatically coordinate with air traffic control, command and control, or Air Traffic Information Services (LoCS 4), relieving the pilot of this data management task. Automatic mission phase planning (based on, e.g., waypoints, weather data, to-be-inspected infrastructures like pipelines or country borders) on a navigation display is supported, too (LoCS 4). The navigation display also shows important geographic information like obstacles or additional landing sites. The information can be mission-specific, e.g., when a hospital is ready to receive a patient. It also includes internal awareness modules to discover control system failures and causes (LoCS 1).

Takahashi et al. (2017) describe a flight control system with different levels of pilot interaction: (i) fully coupled autonomy, (ii) additive control, and (iii) piloted decoupled attitude command. It is embedded in an automatic mission-manager control architecture, which enables the pilot to define waypoints that are to be approached by the automated system, automatically avoiding obstacles. The system also includes landing site evaluation algorithms based on light detection and ranging (LiDAR) data. Trajectories to waypoints or to landing spots can be calculated automatically, and autonomously followed by the flight control system. Alternatively, the pilots can use visualisations of the generated trajectories on panel-mounted displays.

Okuno et al. (2016) describe D-NET, a helicopter operations management system for disaster relief missions. A system like this could operate on LoCS 6: which mission should be assigned to which vehicle, in which order, and at what priority.

Charlesworth et al. (2005) describe a decision-support system for the evaluation of crew capability for different HEMS scenarios. This could be employed in a system developed by Sinha et al. (2002), detailing a framework to automatically evaluate the predicted success of HEMS missions, based on operational, human, and machine factors. Based on work by Sinha et al. (2002), Nguyen et al. (2003) define a system which is, like D-NET, physically implemented at flight control, at HEMS bases, and on-board of helicopters. Its functions are projected to be (1) the determination whether a mission should be accepted or declined, and (2) the determination of the most appropriate response team (i.e., resource assignment). Atyeo et al. (2004, 2005) aim to develop a pre-mission decision support system to counteract the biggest elements of crew error, which has been identified as a relevant contributor to HEMS flight accidents in Australia (Blumen and UCAN Safety Committee, 2002; Veillette, 2001). The framework defines two distinct pre-mission decisions: during "resource assignment" (LoCS 6), missions are prioritised, and assigned the most suitable HEMS vehicle/team. During "route planning", LoCS 5, the actual flight plan for the assigned mission is generated.

Table 2.6 shows the performed functions of the investigated automated systems. The described systems in this LoCS can be broadly separated into the following categories of performed functions:

1. mission phase risk and requirement assessment,

2. mission path-planning algorithms (and supporting functions like cost/noise calculation),
3. integrated human-machine interfaces (including multiple functions), and
4. HEMS communication and pre-mission planning systems.

Relevant references	Mission phase risk and requirement assessment	Mission path-planning algorithms	Integrated human-machine interfaces	HEMS communication and pre-mission planning
Nascimento 2014; Nascimento et al. 2014	X			
Kerler and Erhard 2014	X			
Ebel 2019		X		
Vadlamani and De Haag 2009		X		
Murrieta-Mendoza and Botez 2015		X		
Greenwood and Rau 2020		X		
Rolando et al. 2016		X		
Bakker and van der Geest 2018		X		
Heinemann et al. 2018			X	
Byrne 2001			X	
Rataj et al. 2000			X	
Takahashi et al. 2017			X	
Okuno et al. 2016				X
Celi 2010				X
Sinha et al. 2002				X
Nguyen et al. 2003				X
Atyeo et al. 2004, 2005				X

Table 2.6: Allocation of automation systems on LoCS 5 to performed functions (horizontal lines added for improved readability).

Mission phase risk assessment

The described mission planning support systems either determine the risk of specific mission phases or describe them in terms of requirements. The LoA–SoA-matrix of mission phase risk assessment techniques is shown in Figure 2.7. The described methods provide medium support during IAc and IAn: based on a defined set of information pertaining to the analysed mission phase, its associated risk is computed. The system does not directly support the AS phase, mission planners use the provided information to improve their decision-making.

Mission path-planning algorithms

The described path-planning algorithms are predominantly employed off-line, in the mission-planning phase, while some systems are also available to the pilots during

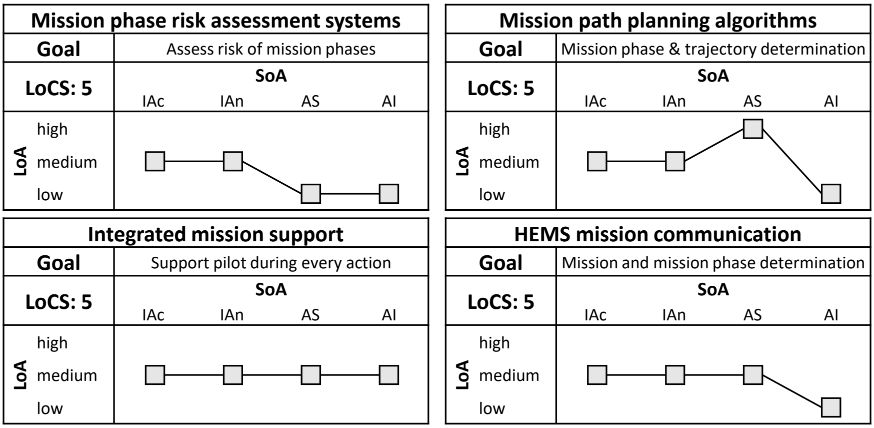


Figure 2.7: Level of automation (LoA)– stage of automation (SoA)-matrices of automation systems on the 5th level of control sophistication (LoCS), with the stages information acquisition (IAc), information analysis (IAn), action selection (AS), and action implementation (AI).

flight. These systems support the mission-planning phase by generating navigational requirements, based on a variety of factors like risk, noise, cost, or terrain restrictions. The goal of these systems is termed "mission phase determination", located on LoCS 5. The corresponding LoA – SoA - matrix is shown in Figure 2.7. The LoA in the first two stages is medium: on this LoCS, the path-planning algorithms take a certain set of information into account, based on their design. It might be possible, however, that other information is not utilised, e.g., weather information or airspace restrictions. This depends on the specific system design and operator choice. The LoA during action selection is high, as one particular or just a few alternative options are suggested to the mission planner. These need to be checked against any non-incorporated data, as described before. Lastly, as the described systems do not directly support action implementation, their LoA on this stage is low. The generated trajectories or waypoints need to be handed down to other automated systems like flight directors or any of the integrated human machine interfaces mentioned below, if action implementation support is wanted.

Integrated human-machine interfaces

Approaches to holistically re-design the helicopter human-machine interface aim to utilise a common problem analysis and cockpit representation to combine and moderate the functionalities of the separate employed support systems. These systems are hard to categorise as a single "automation system", as they incorporate a multitude of functions on this LoCS and other, lower LoCS like path planning, obstacle avoidance, and different autopilot functions. In broad strokes, they can be categorised as shown in Figure 2.7: Every SoA is categorised with a medium, "catch-all" LoA. While these systems aim to support the pilot in many tasks, they also explicitly require the involvement of the pilot in every flight state, be it through manual or supervisory control actions. Each of these approaches contain multiple lower-level automation systems for tasks like obstacle avoidance. These lower-level separate functions are further discussed in the respective LoCS sections.

HEMS mission communication

There is extensive literature covering HEMS communication and (pre-) mission planning support. These systems optimise the mission assignment phase, which could be called LoCS level 6, and the subsequent alignment of lower-level LoCS actions with HEMS mission-specific requirements. For the pilot flying, these systems seem to present an additional way of receiving and transmitting mission-critical information with helicopter-external mission partners like operation control, other helicopters, ground-based rescue teams or hospitals. Figure 2.7 shows an attempt to categorise these systems with respect to their impact in in-helicopter automation behaviour. The LoA on the first two stages is medium — additional information is being acquired and analysed, but the systems require active participation from the flight crew (i.e., requesting and receiving information, determining the impact on their current mission). Action selection, too, is supported with a medium LoA, as extra tasks and requirements can be communicated or derived from transmitted information. Lastly, action implementation is left to the pilot flying and the remaining automation systems on-board; the LoA is categorised as low.

2.5.2. LoCS 4: mission phase

On this LoCS, a set of mission-specific requirements is received from LoCS 5, such as mission target locations, temporal goals and constraints, or high-level trajectory requirements. Goals to be reached/tasks to be completed on LoCS 4 are mission phases like:

- take-off,
- climb-out,
- cruise,
- descent, and
- approach/land.

The task timescale typically ranges between multiple minutes or even hours. Flight directors, which generate desired trajectories based on pre-mission planning or waypoint data and show the desired trajectories to the pilots via a navigation display or as cues on the primary flight display, fall under this category.

De Bernardi and Ferroni (2018) describe Leonardo's electronic flight bag system Skyflight Mobile. The pilot can be made made aware of possible terrain collisions, restricted airspace, and warnings prior to the mission. Roos and de Reus (2015) analyse the use of tablet-based electronic flight bag in the helicopter cockpit, especially investigating effects on flight- and mission-safety induced by an additional, feature-rich tool in the cockpit. Based on available task load restrictions, the tablet could only be used in low-workload mission phases like cruise or holding.

Zimmermann and Peinecke (2015) describe a LiDAR-based landing site evaluation algorithm to support the pilot during emergency situations. Takahashi et al. (2013, 2018) describe a LiDAR-based automatic landing site determination system, which has been experimentally evaluated on a RASCAL JUH-60A Black Hawk (UH-60). The pilot can manipulate the parameters of the system during flight and can select one of the proposed landing spots. The system also generates manoeuvre cues for an approach to the selected landing spot, which are shown on a head-down display utilising the cueing-symbology employed by Szoboszlay et al. (2014).

Zoppitelli et al. (2018) describe an image processing algorithm to identify the helicopter landing pad on offshore platforms. The algorithm utilises data from an on-board camera to pinpoint the location and orientation of the marked area in real-time. As such, the described system is a step towards developing vision-based autopilot systems.

Multiple publications address the generation of optimal flight trajectories. Greiser et al. (2011) develop a method to plan take-off trajectories based on pilot requirements. Gursky et al. (2014) develop a head-down tunnel-in-the-sky display to enable helicopter pilots to follow noise abatement procedures. Hartjes et al. (2009) describe a method to calculate multiple non-interfering rotorcraft approach trajectories that reduce the noise impact on communities close to airports.

Guillanton and Germanetti (2011) describe the architecture of the 2011 Eurocopter avionics system, including a 4-axis autopilot coupled to a flight management system, a synthetic vision system, and a digital map display with a variety of functions. Germanetti et al. (2002) describe the EC225/725 Cougar avionics system, including vehicle monitoring systems, flight display systems, autopilot systems, health and usage monitoring systems, and digital maps including overlays.

Haisch et al. (2009) describe the results of project PILAS, a Eurocopter project to investigate helicopter pilot assistance systems, including a description of the cognitive model they employed to design systems. The main goal of the developed system was to increase situation awareness comprehensively and unambiguously. Two head-down displays are used to interface with the pilot: a PDF and a navigation management display. Capabilities include:

- tunnel-in-the-sky guidance on a synthetic vision system,
- digital map function with adaptive route planning (e.g., caused by changing weather) and map overlays, and
- terrain, weather, airspace, obstacle overlays in both displays (database-based obstacles, synthetic vision boxes around obstacles).

Lüken et al. (2019) describe a system to support helicopter pilots follow arrival and departure procedures when flying with in instrument flying rules. A synthetic vision system, flight management system and helmet mounted display support manual flight when following defined flight corridors. Halbe et al. (2018) describe the Helionix external situation awareness system. Among other functions, this system incorporates a fuel consumption estimation function for flights between waypoints.

Many of the systems described on this LoCS fulfil multiple functions at once, see Table 2.7. The separate functions can be categorised according to the following generalisation:

- primary flight displays, navigation displays, and electronic flight bags with information overlays;
- landing site determination and evaluation;
- trajectory generation for specific mission phases, e.g., land, cruise, take-off;
- trajectory visualisation through tunnel-in-the-sky, manoeuvre cues; and
- trajectory implementation through a coupled flight director or autopilot.

Reference	Displays with information overlays	Landing site determination and evaluation	Trajectory generation	Trajectory visualisation	Trajectory implementation
De Bernardi and Ferroni 2018	X				
Zimmermann and Peinecke 2015		X			
Takahashi et al. 2013, 2018	X	X	X		
Zoppitelli et al. 2018		X			
Greiser et al. 2011			X		
Gursky et al. 2014			X	X	
Hartjes et al. 2009			X		
Guillanton and Germanetti 2011	X		X	X	X
Germanetti et al. 2002	X		X	X	X
Haisch et al. 2009	X		X	X	X
Lüken et al. 2019	X	X	X	X	X
Halbe et al. 2018	X		X		

Table 2.7: Allocation of automation systems on LoCS 4 to performed functions (horizontal lines added for improved readability).

Navigation/primary flight display with information overlay

Primary flight displays, navigation displays, and electronic flight bags that provide information overlays, but no further manoeuvre cues or functions, are discussed first. Information that can be displayed include weather, prohibited air space, terrain elevation, and mission navigation points/waypoints. These systems provide information to the pilot, they do not generate manoeuvre suggestions based on this information. In the LoA–SoA-matrix for digital maps with overlays, Figure 2.8, they possess a high LoA in the IAc stage, and a medium LoA in the IAn stage: They acquire data from a multitude of sources, and analyse it to generate the aforementioned data overlays. However, the resulting AS and AI are left to the pilot.

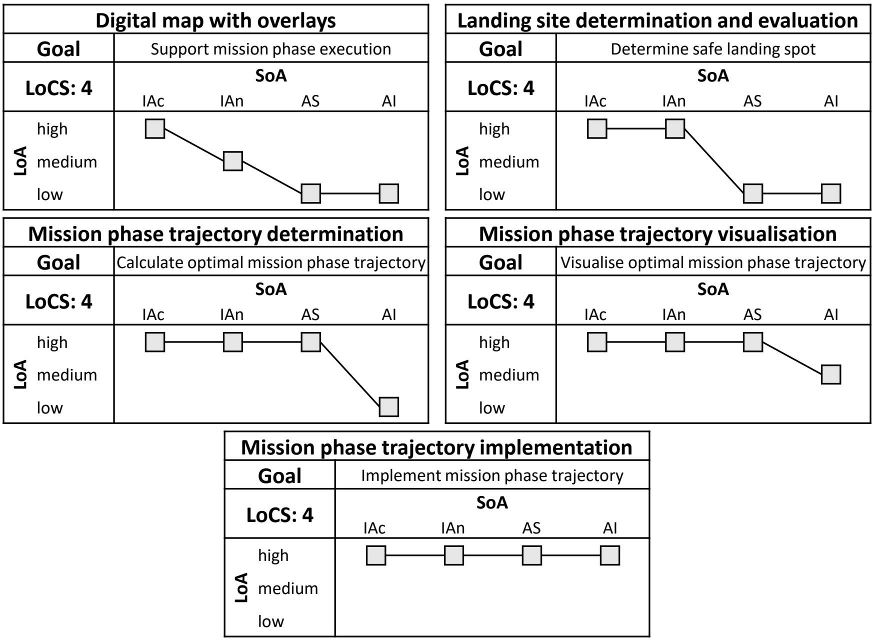


Figure 2.8: Level of automation (LoA)– stage of automation (SoA)-matrices of automation systems on the 4th level of control sophistication (LoCS), with the stages information acquisition (IAc), information analysis (IAn), action selection (AS), and action implementation (AI).

Landing site determination and evaluation

Specific for the goal of determining a safe landing spot in unknown terrain, support systems in this category generally employ on-board sensor suites to scan the ground for elevation, inclination, and obstacles. All investigated systems provide landing site evaluation data to the pilot. More advanced functions, including manoeuvre trajectory generation and execution, are discussed at a later point. Only investigating landing point identification and evaluation, the LoA–SoA-matrix can be defined as shown in Figure 2.8. IAc and IAn are heavily supported, the LoA is high. The decision on how to act according to this information is left to the pilot.

Trajectory generation

For mission-phase implementation planning, the pilot can be supported in estimating the fuel costs of selected flight legs between waypoints. Such a system, that provides fuel cost estimations based on waypoint location and meteorological conditions, can be classified like the fuel cost estimation system shown in Figure 2.8. The described systems only take limited information into account to estimate trajectory fuel costs — the LoA during IAc and IAn is medium. AS and AI are not supported, the pilots need to use the predicted fuel costs of different evaluated trajectories to plan the mission phase themselves.

Based on an identified landing spot and the surrounding obstacles, or based on weather-, elevation-, waypoint, or fuel cost data, systems are described that can generate a target trajectory for a specific mission phase like take-off, cruise, or landing. These can be integrated in the landing spot evaluation methods or in integrated navigation displays. These systems expand the previously described systems by increasing the LoA in the AS stage, as shown in Figure 2.8: Now, the LoA is high in the IAc, IAn, and AS stage. Only the implementation of the action (i.e., implementing the suggested trajectory) is left to the pilot.

Trajectory visualisation and implementation
To support the pilot with implementing the suggested trajectories, these trajectories can be shown to the pilot through additional means. For example, they can be shown as a path to follow on a navigation display, as a tunnel-in-the-sky visualisation on a HUD or a head-down synthetic vision system, or through manoeuvre-cues on the primary flight display. In this case, the AI stage is supported through a medium LoA. Lastly, when a full-authority autopilot is coupled to the generated trajectories, specific mission phases can be executed fully automatically (provided no unaccounted-for situations arise). Figure 2.8 shows the LoA–SoA-matrix for both systems.

2.5.3. LoCS 3: mission task element

On this level, the following tasks are supported:

- obstacle avoidance & nap-of-the-earth flying,
- landing support (virtual landing pad, trajectory determination, manoeuvre cues, based on questionnaire, ...),
- take-off support (oil-rig take-off, ...), and
- autorotation.

Some existing systems address more than one of the mentioned tasks. These **multi-purpose systems** systems are elaborated upon first.

Fillias et al. (2011) describe Eurocopter's state-of-the-art advances (as of 2011) in efficient flight path computation algorithms for civilian missions, which incorporate medium-term trajectory planning, obstacle avoidance, and manoeuvring support for hover. Based on operator waypoint input on a digital map, a smooth, medium, or hard (with increasing vertical speeds and shorter legs) trajectory is automatically generated, based on aircraft performance characteristics. They also present a short-term obstacle avoidance support HUD, based on obstacle contour lines painted on radial segments originating from the helicopter. Based on a pilot-set safety-margin and aircraft load factor limits, suggestions to "pull up" or "pull down" can be displayed to the pilot, in order to stay as close to the ground as safely possible.

Waanders et al. (2019) describe a DVE mitigation system installed on a Airbus H145 helicopter in the form of a helmet mounted display, supporting obstacle avoidance and landing support functions. They integrate both systems in the Airbus H145 and demonstrate their operation. Terrain and obstacles are highlighted in the displays. Virtual landing pads can be shown, including landing site evaluation and approach support.

Walko and Schuchardt (2019) describe an augmented reality HoloLens helmet mounted display for offshore flight to increase safety. It incorporates obstacle symbology, navigation markers, flight-path marker, horizon, primary pilotage information, and tunnel-in-the-sky support.

The tasks of **obstacle avoidance and nap of the earth-flying** are addressed by many publications. Viertler and Hajek (2017) evaluate a multi-coloured head-up display to support pilots in DVE. They evaluated two display systems: a basic flight guidance HUD, and the same flight guidance HUD augmented with terrain awareness and obstacle avoidance support. The flight guidance system provided flight data, artificial horizon, and ground track markings to follow. The augmented display additionally included a terrain grid, contour lines, obstacle outlines, and obstacle highlighting (red).

Mämpel et al. (2011) develop a terrain awareness and warning system that does not solely depend on off-line databases of terrain, but incorporate real-time laser-sensor data. Off-line and on-line obstacle data is combined in a perspective head-down display, overlaid on a camera image of the outside visuals. Real-time detected obstacles are highlighted more intensely than database-based obstacles. Visual warnings to avoid controlled flight into terrain are incorporated, as well, and are based on the current helicopter speed and direction.

As previously mentioned, Halbe et al. (2018) describe the Helionix external situation awareness system, whose functions are now elaborated upon in more detail. It contains (1) a synthetic vision system based on terrain and obstacle database, overlaid with primary pilotage information; (2) a visual and auditory terrain warning system, taking into account vertical distance/descent rate towards terrain, as well as forward-looking terrain avoidance; and (3) a digital map, showing a top-down map including terrain awareness warnings, elevation data, obstacle locations, rough fuel range estimations, and track lines.

Godfroy-Cooper et al. (2018, 2019) and Miller et al. (2019) describe an isomorphic spatial audio-visual display for obstacle avoidance in DVE, later incorporating tactile cueing, as well. The risk area considered by the system is dependent on helicopter forward speed, morphing from a circle to an elongated oval with increasing speed. Auditory warnings are encoded to contain obstacle type (e.g., wire), direction, and severity/danger.

Kahana (2015) describes an arrow-shaped display that supports pilots in recognising approaching obstacles, and in identifying the optimal time to initiate a climb-over manoeuvre. Chapter 5 of this dissertation compares a comparable display with a constraint-based display that aims to fulfil a similar task.

Lantzsch et al. (2012) comprehensively describe the capabilities of the DLR ALLFlight system. It encompasses on-line sensor fusion and path planning. It adapts the chosen trajectory based on a terrain database and helicopter performance limitations. The flight path is shown to the pilot on a head-down display. Lüken et al. (2010) evaluate the employed sensor suite. Döhler et al. (2013) investigate on-line obstacle detection algorithms through image recognition and data fusion.

Riberon (2016) describes the Clearvision system. It integrates real-time sensor-data with flight data information, conformal symbology for terrain/landing spots, and terrain warning systems (ground proximity and forward-looking).

Rakotomamonjy et al. (2016) describe the DLR/ONERA joint research efforts in tactile cueing for obstacle avoidance during low-speed manoeuvring. For the ONERA system, based on time-to-contact (or distance, at zero speed), haptic cues are generated on the cyclic stick. The DLR system is based on the ALLFlight sensor suite, utilising an obstacle database which is updated on-line through sensor data. A risk vector based on work by Lam (2009) is generated and mapped onto each control axis, where, based on risk intensity, different tactile warning cues are activated.

Zhou et al. (2019) evaluate a forward-looking obstacle warning method based on image matching, in particular for low-altitude flight where typical terrain warning system limits are exceeded frequently. They increase the reliability of the warning data by incorporating real-time imaging sensors. Labun et al. (2011) describe a terrain anti-collision system based on altimeter altitude and altitude rate data.

Gaffal and Gollnick (2003) compare different early guidance symbologies for obstacle highlighting and trajectory cues through a tunnel-in-the-sky, utilising a human-in-the-loop experiment in a simulator. The participating pilots preferred the tunnel-in-the-sky, which also produced the best performance and safety results. Obstacle highlighting methods were appreciated, but these lacked flight guidance information.

Padfield et al. (2005, 2007) investigate τ-theory as a first step to develop perspective visual guidance based on τ-theory in terrain-hugging flight. Experiment data suggests that the participating pilot tried to maintain a 6–8 s look-ahead time. Future guidance symbologies should incorporate this information to support pilots in exercising their "natural" flight control behaviour.

Next, automation support for the task of **landing** are discussed. Zimmermann and König (2016) describe an automatic, on-line path-planning algorithm to a landing area from an unknown entry point, based on the ALLFlight system. The computed trajectory is shown to the pilot via a tunnel-in-the-sky on a head-down display.

Zimmermann et al. (2019) describe preliminary results of LiDAR-aided approaches during the NATO DVE-mitigation trials. The employed system combines eyes-out tunnel-in-the-sky symbology with dynamic path planning algorithms. The system works as follows: (i) the pilot sets a hover target point; (ii) a flight path to the selected point is calculated; (iii) the path is communicated to the pilot via a tunnel-in-the-sky. Real-time obstacle scanning results can cause the desired flight path to be deemed unsafe, in which case a new trajectory can be computed.

In a pilot-in-the-loop simulation experiment, Stanton et al. (2018) investigate a virtual landing pad shown to pilots via a HUD. The HUD also incorporated two-dimensional flight data information. While this virtual landing pad did not improve dependent measures in good visibility, it significantly reduced pilot workload in DVE conditions.

Strohmaier et al. (2010) develop an automatic approach planner for landing in confined areas. It is based on questionnaire answers of 80 air rescue pilots. Alfred et al. (2017) describe a method to calculate approach and landing trajectories during brown-out. They aim to minimise pilots' exposure to reduced visibility conditions caused by the brown-out. Haverdings et al. (2006) evaluate novel, steep landing procedures for operation in instrument flight rules. To support the pilots in implementing the new trajectories, some of which cause a high workload, they implement cue symbology on the primary flight display. The employed cues communicate actual and desired aircraft state (e.g., lateral deviation and altitude deviation for current and next waypoint) to the pilots.

2

Szoboszlay et al. (2010, 2014) evaluate 3D landing zone LiDAR systems and the Brown-Out Symbology System (BOSS) through flight tests. The employed hover displays and BOSS symbology utilise a top-down approach, visualising the prospective landing point and horizontal velocity and acceleration cues. In some display variants, a combined altimeter and vertical speed symbology is included. A speed-dependent flight path marker is included, but generally not preferred by the participating pilots. All displays were head-down and showed different synthetic vision representations of the outside scenery behind the employed two-dimensional symbology. Later experiments included colour enhancement of obstacles during approach and manoeuvring, and a conformal, head-down virtual landing pad representation.

To support helicopter pilots during **take-off**, Thomas and Voinchet (2019) describe the "Performance Class 2 Defined Limited Exposure"–method to plan take-off procedures for offshore transportation to maximise safety, based on helicopter performance and weight. They are computed before take-off.

Autorotation is a safety-critical helicopter manoeuvre which is required after an engine failure or after running out of fuel. This manoeuvre is addressed by Aponso et al. (2007), who describe an autorotation flight training device that communicates desired pitch and collective commands to the pilot. The necessary command inputs are calculated by solving an optimal control problem. Sunberg et al. (2015) describe another methodology to compute desired control inputs during autorotation, and implement it in an automatic controller which is demonstrated in simulation on a Bell AH-1G helicopter and a small remote controlled helicopter.

Jump et al. (2018) describe the autorotation manoeuvre in terms of time-to-contact, and present results that indicate that pitch angle and range distance are coupled to intrinsic tau motion guides. They present a tau-based methodology to generate deceleration trajectories which, in future systems, could be shown to the pilot as a guidance cue.

All systems located on LoCS 3 can be categorised according to the function they perform:

- conformal visualisation (obstacles, landing zones, terrain),
- danger warnings (auditory and haptic, obstacle and terrain warning),
- MTE trajectory determination (off-line, to confined landing areas, on-line to avoid obstacles),

- MTE trajectory cues (tunnel-in-the-sky to confined area landing point, based on tau-theory, around obstacles),
- MTE control cues (autorotation, approach-to-hover, obstacle avoidance during hover), and
- Automatic MTE control (autorotation).

Table 2.8 shows an overview of the analysed systems. In the following subsections, the provided functions are discussed and categorised.

Conformal visualisation

Many systems in LoCS 3 provide a conformal information overlay on the outside visuals. A baseline HUD with flight data information is almost always included. Other information that is being shown or highlighted include obstacles, landing zone visualisations ("virtual landing pad"), and terrain information. These systems can be classified as shown in Figure 2.9. In most cases, the HUD systems show all necessary information to the pilot in order to control the helicopter. Therefore, the LoA in the IAc stage is high. To an extent, the shown information is analysed, for example by highlighting the most dangerous obstacles in the flight path or by generating a virtual landing pad at a desired landing zone. However, some IAn activities still fall to the pilot. For example, the pilots need to judge what kind of restrictions are placed on future trajectories by highlighted obstacles. The pilots are also required to select an appropriate control action in light of these data and implement these changes themselves. The LoA during AS and AI is low.

Danger warnings

Systems that warn pilots of impending danger (e.g., coming close to an obstacle or the ground) can be classified as shown in Figure 2.9. It is important to note that the goal of these systems is not to support performing a specific MTE, but to avoid dangerous situations in a range of different MTEs. All information regarding avoiding specific dangerous situations is acquired and analysed, the LoA in the first two stages is high. The warnings given to the pilot can be considered as an implicit manoeuvre cue: the warning might not tell the pilots what exact action should be performed, but it is a clear advice to recognise the danger and react accordingly. The AS stage is supported to a medium extent. Only the implementation of the control input is left completely to the pilots, the LoA during AI is low.

MTE Trajectory determination

In the category of trajectory determination, two distinct possibilities exist: the trajectories can be determined off-line, before the mission, or on-line, during the mission, incorporating up-to-date information and the current flight trajectory. Off-line trajectory calculation systems can be classified according to Figure 2.9. Information has to be provided to the system by the pilots or mission planners. The system analyses all information provided to it. However, it does not incorporate on-line up-to-date information. This results in a low LoA in IAc, and a medium LoA in IAn.

Relevant references	Conformal visualisation	Danger warnings	MTE trajectory determination	MTE trajectory cues	MTE control cues	Automatic MTE control
Multi-purpose systems						
Fillias et al. 2011	X	X	X	X		
Waanders et al. 2019	X		X	X		
Walko and Schuchardt 2019	X		X	X		
Obstacle avoidance and nap-of-the-earth flying						
Viertler and Hajek 2017	X	X		X		
Mämpel et al. 2011	X	X				
Halbe et al. 2018	X	X		X		
Godfroy-Cooper et al. 2018, 2019; Miller et al. 2019	X	X				
Kahana 2015					X	
Lantzsch et al. 2012	X		X	X		
Döhler et al. 2013		X				
Riberon 2016	X	X				
Rakotomamonjy et al. 2016		X				
Zhou et al. 2019		X				
Labun et al. 2011		X				
Gaffal and Gollnick 2003	X	X	X	X		
Padfield et al. 2005, 2007				X	X	
Landing						
Zimmermann and König 2016	X		X	X		
Zimmermann et al. 2019	X	X	X	X		
Stanton et al. 2018	X					
Strohmaier et al. 2010			X			
Szoboszlay et al. 2010, 2014	X					
Alfred et al. 2017			X			
Haverdings et al. 2006			X	X		
Take-off						
Thomas and Voinchet 2019			X			
Autorotation						
Aponso et al. 2007			X	X	X	
Sunberg et al. 2015			X			X
Jump et al. 2018			X			

Table 2.8: Allocation of automation systems on LoCS 3 to performed functions (horizontal lines added for improved readability).

The generated trajectory is a concrete suggestion, the LoA during AS is high. The implementation of the suggested trajectory is left to the pilots.

If the trajectory is generated on-line during the mission, the systems can be categorised as shown in Figure 2.9. Given a sensor suite that collects data on

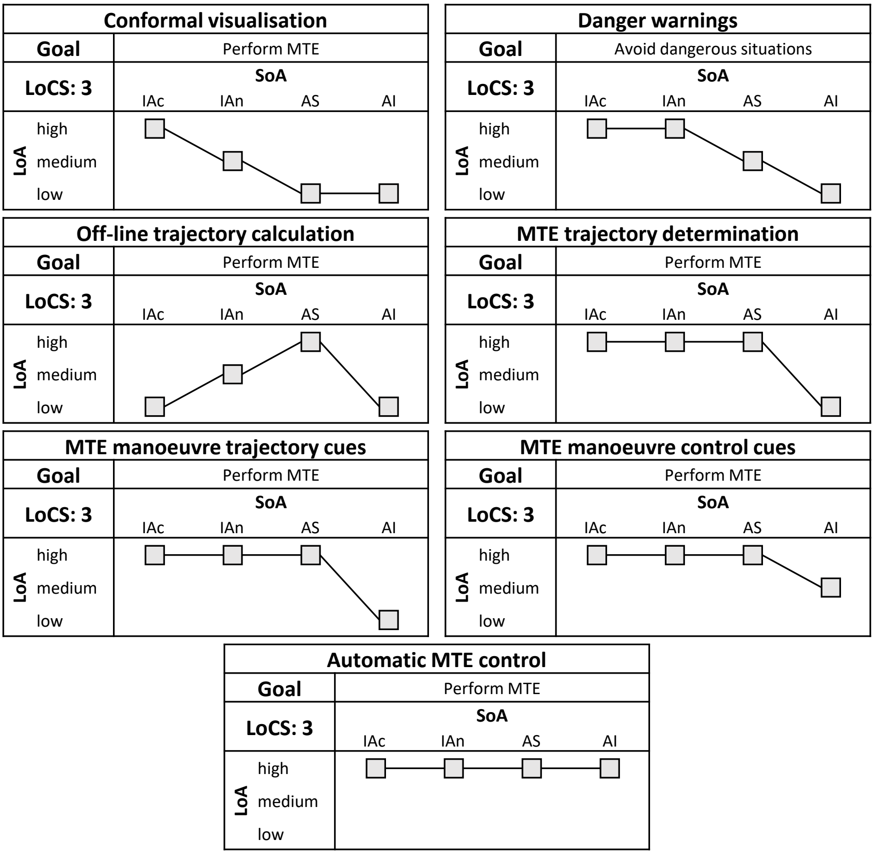


Figure 2.9: Level of automation (LoA)– stage of automation (SoA)-matrices of automation systems on the 3rd level of control sophistication (LoCS), with the stages information acquisition (IAc), information analysis (IAn), action selection (AS), and action implementation (AI).

surrounding terrain and obstacles, all necessary information to generate the future save trajectory is acquired and analysed, corresponding to a high LoA. Likewise, the system generates a specific future trajectory to follow, LoA during AS is high, as well. The implementation is left to pilots, and the LoA during AI is low.

MTE trajectory cues

As an extension of trajectory determination systems, the calculated trajectory can be shown to the pilots, including specific cues on how the current aircraft trajectory differs from it. This can be through conformal visualisations of the calculated trajectories, e.g., through a tunnel in the sky, or by placing “desired state” markers on aircraft instruments like airspeed tapes or altitude tapes or on navigation displays through navigation target points. The implementation is still left completely to the pilots, the trajectories are only communicated more clearly and deliberately to the pilot. Figure 2.9 depicts the according classification: up until and including the selection of the desired trajectory, the LoA is high. During AI, the LoA is low.

It could be argued that any determined trajectory is communicated *somehow* to the pilots, otherwise the systems would be obsolete. Therefore, the *trajectory determination* and *trajectory cue* categories could be merged into one. In this classification, both system classes are treated as separate systems, in order to highlight the difference between (i) generating the trajectory, (ii) using different methods to communicate it to the pilots, and (iii) helping the pilot implement these trajectories.

MTE control cues

Systems that not only communicate a desired trajectory to the pilot, but also communicate corresponding control suggestions, can be classified as shown in Figure 2.9. Instead of a low LoA in the AI phase, these systems possess a medium LoA: the pilots are supported in implementing the suggested trajectory. This support can be in the form of tactile cues on the inceptors that support the pilots in following a specific required control input to perform a manoeuvre, or it can be in the form of "desired" control input markings on a display.

Automatic MTE control

Lastly, if the control cues provided by the previous systems are implemented automatically, the LoA during AI rises to a high level, as well, as shown in Figure 2.9. The automatic system can perform MTEs autonomously. The pilots are still required to supervise the system and react to any information or situation that the system is not designed to incorporate into its decision-making.

2.5.4. LoCS 2: manoeuvre sample

Tasks on this level are:

- hover,
- translation, and
- rotation.

Many of the investigated automation systems support multiple or all of these tasks. Therefore, the investigated automation system are immediately sorted based on the function they provide (see also Table 2.9):

- helicopter control response type (SAS, SCAS, ...),
- primary flight data representation (HUD, conformal displays),
- flight envelope protection,
- hover/low-speed manoeuvring support,
- short-term manoeuvre support (obstacle avoidance), and
- full authority autopilots.

Relevant reference	Response type	Primary pilotage data	Envelope protection (cue-based & automatic)	Hover (with and without manoeuvre cues)	Short-term obstacle avoidance	Full authority autopilots
Cooper et al. 2014	X					
Soneson et al. 2016	X					
von Grünhagen et al. 2014	X				X	
Schuchardt 2019	X					
Whalley and Howitt 2002	X					
Lantzsch et al. 2014	X					
Miller et al. 2010	X					
Lüken et al. 2015		X				
Thorndycraft and Craig 2004		X		X	X	
Viertler et al. 2015		X				
Funabiki et al. 2018		X				
Craig et al. 2011		X				
Gatter 2015		X		X		
Gatter 2019		X		X		
Schmerwitz et al. 2015a,b		X		X		
Vreeken and Haverdings 2013		X				
Abildgaard and Binet 2009			X			
Varnes et al. 2000			X			
Jeram and Prasad 2005			X		X	
Sahasrabudhe et al. 2006			X			
Lopez et al. 2019			X			
Bottasso and Montinari 2015			X			
De Reus and Van Witzenburg 2007				X		
Craig et al. 2007				X		X
D'Intino et al. 2020				X		
Waanders et al. 2012, 2013, 2015				X	X	
Müllhäuser 2018					X	
Truong et al. 2016				X		X
Ruffier and Franceschini 2004; Ruffier 2005				X		X

Table 2.9: Allocation of automation systems on LoCS 2 to performed functions (horizontal lines added for improved readability).

Control response type modification

Systems that modify the dynamic response type of the helicopter are described here. Targeted response types typically depend on the control axis. Possible response types are (Padfield, 2007; Soneson et al., 2016):

- rate command,
- turn coordination,
- attitude command/attitude hold,
- attitude command/velocity hold, and
- translational rate command/position hold.

Besides modifying the dynamic control response type, systems in this category can also aim to reduce the effect of environmental factors on the vehicle, e.g., air-wake effects and gusts.

Cooper et al. (2014) evaluate a gust compensating control law for rotorcraft during ship-board operations. The investigated system reduced pilot input activity and increased handling quality ratings while operating in an air-wake. Soneson et al. (2016) develop a full authority non-linear dynamic inversion control law in order to change the control response type of a UH-60 to attitude command/ attitude hold, attitude command/velocity hold, and translational rate command/position hold, with respect to the ship deck's motion[5]. They evaluate different combinations of control response types during approach and landing.

von Grünhagen et al. (2014) investigate different haptic characteristics for centre-stick and side-stick helicopter control during turns and slalom tasks. They predict and analyse how to maximise handling quality ratings by changing these characteristics.

Schuchardt (2019) investigates a helicopter control concept based on a steering wheel for highly augmented rotorcraft through a human-in-the-loop experiment. Especially for car-driving experiment participants, workload could be reduced, compared to the regular control set-up.

Whalley and Howitt (2002) evaluate a UH-60 hover/low-speed partial authority control support system in DVE, whose aim is to provide an attitude command/attitude hold control type response. Lantzsch et al. (2014) develop and evaluate an air-resonance controller that suppresses the air resonance roll mode of the DLR EC135 research helicopter. Miller et al. (2010) describe the roll-on-deck control law design to improve the handling of V-22 aircraft close to ship decks. Functions include increased lateral control power, enhanced response bandwidth and predictability, and disturbance rejection.

Systems in this category can be classified according to Figure 2.10. Generally, their goal is to support any and all manoeuvre samples, even if their focus may lie on one or two specific aircraft movements. The systems do not support the pilot in acquiring or analysing information, nor do they help pilots choose an appropriate action. However, they support the pilots in implementing whichever control action they choose to enact. The LoA in the first three stages is low, whereas during AI it is medium.

[5]Please refer to Padfield (2007) for a detailed description of control response types and their impact on handling quality.

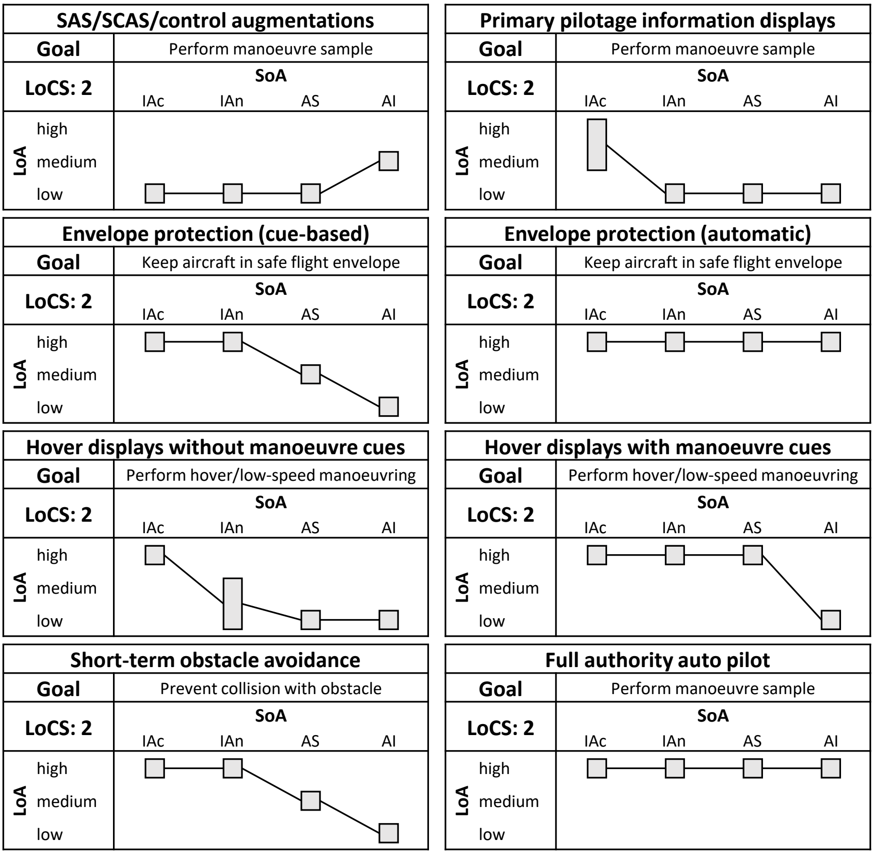


Figure 2.10: Level of automation (LoA)– stage of automation (SoA)-matrices of automation systems on the 2nd level of control sophistication (LoCS), with the stages information acquisition (IAc), information analysis (IAn), action selection (AS), and action implementation (AI).

It might seem counter-intuitive to classify these often highly advanced systems at such low LoA across most stages. It is important to remember that this classification depends on the chosen automation goal. In this classification, the goal was defined as performing manoeuvre samples on LoCS 2. As explained, the systems only support the implementation of manoeuvres. Determining which manoeuvres to perform, and how to perform them, is the sole responsibility of the pilot. However, these systems could also be located on LoCS 1, where their goal would change to *modify the vehicle control response type*. If they would be categorised according to this goal on LoCS 1, the LoA on every stage would be high: the systems autonomously acquire and analyse all necessary data to generate and implement correcting control actions which modify the dynamic control behaviour of the helicopter.

Primary pilotage information displays

Systems with this function aim to provide pilots with new or improved means to perceive primary pilotage information like altitude, attitude, position, and velocity.

Lüken et al. (2015) describe a helmet-mounted virtual cockpit design based on see-through helmet-mounted displays. Primary flight displays, navigation displays, and other typical cockpit instruments can be shown and re-arranged individually by pilots. Thorndycraft and Craig (2004) evaluate different types of symbologies used in night vision goggles, including tunnel-in-the-sky and hover symbology. The evaluated systems consisted of:

- An overlaid, two-dimensional, horizontal hover display including position, velocity, and acceleration cues;
- Two "hover arrow" symbology sets, de-cluttering and improving the previous design;
- A perspective display, showing conformal symbols to give longitudinal, lateral, and height cues;
- Conformal representations of hazards, landing, and hover positions, as well as waypoint, ground, pathway, flight path marker, and alignment symbols;
- A combined, advanced concepts display symbology, combining elements of the previous systems.

It can be argued that the last two systems can also be classified as a LoCS 3 system, given their focus on longer-term information highlighting. The hover-specific displays enabled improved performance in high-hover tasks. Perspective displays increased pilot situation awareness with respect to hazards and obstacles.

Viertler et al. (2015) discuss two issues of visual clutter in see-through, conformal, head-mounted displays: (i) showing too much information at the same time, and (ii) obstructing the outside view by bright display pixels. Multiple methodologies to reduce display clutter and improve the usability of these displays are discussed.

Funabiki et al. (2018) describe advances of the Japan Aerospace Exploration Agency on research on a vision system for DVE, based on real-time sensor data and off-line maps and elevation data. The system incorporates a visible light camera, long-range and short-range infrared cameras, and a night-vision sensor. Different fused images of theses sensors can be shown on a helmet-mounted display. The system has been evaluated experimentally on a BK117C-2 research helicopter.

Craig et al. (2011) investigate the difference in task performance and pilot preference with high- and low-gain night time goggles. Pilots preferred the high-gain goggles. However, performance was only significantly negatively impacted during the tail-turn task, the other tasks showed similar performance.

Gatter (2015) describes an edge-based drift estimation system, based on camera images. Gatter (2019) also describes a method which utilises optical navigation methods to assess helicopter motion during DVE before landing. Schmerwitz et al. (2015a,b) present an ego motion drift indication system for landing. The system utilises helmet-mounted, conformal ground texture symbology to amplify the pilots' perception of lateral drift movement close to the ground.

Vreeken and Haverdings (2013) develop and evaluate four different helicopter pilot aids for flying in DVE: a head-up visualisation of the current horizon line ("Malcolm Horizon"), an "Orange Peel" visualisation of the helicopter attitude and altitude, a horizon-visualisation through cockpit LEDs, and an auditory terrain avoidance and warning system. Pilots most appreciated the auditory system, and the "Orange Peel" visualisation improved the Usable Cue Environment (UCE) level the most. They also highlight the confidence-building aspect of all investigated systems, and how that could lead to overconfidence when encountering DVE situations.

Systems in this category support the pilot in perceiving the external environment (without MTE-specific highlighting like obstacles or waypoints), and/or the aircraft flight state. They can be categorised as shown in Figure 2.10. In most cases, they provide a certain selection of primary flight data, like drift or attitude. Only a few systems provide the full set of primary flight data and reference information that is sufficient to control the helicopter. Information acquisition is therefore supported through a medium or high LoA, depending on the system. IAn, and the following AS and AI, are left to the pilots; therefore, the LoA is low.

There can be a trade-off between improving the control response type of the helicopter and improving the way primary pilotage information can be perceived. Gmelin and Pausder (1985) postulate that pilot workload can be maintained constant when increasing the intensity of display augmentation on the one hand, and decreasing intensity of control augmentation on the other hand. The relationship is not linear: at very low levels of display support, the required control augmentation increases rapidly. Likewise, very low control augmentation requires exceptionally good visibility and display support.

This relationship between the helicopter response type and visibility (measured through the usable cue environment level) is also discussed by Padfield (2007). In order to maintain a high handling qualities rating, certain combinations of usable cue environment and helicopter response type are required. If the helicopter response type is a basic rate command, retaining the highest handling qualities rating requires a level 1 usable cue environment. Accordingly, when the usable cue environment degrades to level 3, an advanced translational rate command/position hold control response type is required to maintain the highest handling qualities rating. It is important to note that the required visibility and control response type levels can differ depending on the evaluated task. Different tasks have different requirements and might incur different levels of pilot workload to complete within desired or adequate performance.

Flight envelope protection

Abildgaard and Binet (2009) develop and test a tactile cueing system for vortex ring state avoidance. When coming close to entering a vortex ring state, the tactile cue is realised through a soft-stop on the collective lever.

Varnes et al. (2000) develop an on-board vortex ring state warning system. When approaching the vortex ring state, visual and audio warnings make the pilots aware of the impending danger.

Jeram and Prasad (2005) present an open architecture for helicopter tactile cueing systems. Functions include manoeuvre envelope limit cues, emergency procedure cues, routine task support, instrument cues, and pilot customisation of haptic stick characteristics.

2

Sahasrabudhe et al. (2006) develop a collective axis cueing system to communicate system thresholds such as torque limits, rotor rpm limits, and optimal rpm after an engine failure to the pilots. Soft-stops and stick-shaker behaviour is implemented and tested.

Lopez et al. (2019) develop a full envelope flight and vibration controller. This controller combines the vibration controller and the flight controller, which results in increased performance of the vibration controller. Bottasso and Montinari (2015) present a flight envelope protection system utilising model predictive control. Control input limits are calculated on-line and communicated to the (in this study: virtual) pilots to avoid leaving the safe flight envelope.

Some systems provide the pilots with cues as to when they might leave the safe flight envelope. They can be categorised according to Figure 2.10. Their goal is to keep the aircraft in the safe flight envelope, regardless of manoeuvre sample. They acquire and analyse all necessary information to fulfil this task, the corresponding LoA are high. AS is only supported through a medium LoA: while limits are communicated to the pilots, they need to decide on how to avoid these limits. The implementation of the selected control is left to the pilots, as well.

In contrast to the previous systems, there are other envelope protection systems that automatically keep the aircraft in the safe envelope. Systems like these expand the support of the previous envelope protection systems to also include a high LoA on the AS and AI stage, as shown in Figure 2.10. The LoA in every stage is high: the system prohibits the aircraft from leaving the safe flight envelope.

Hover support

Chapter 3 of this dissertation highlights the added complications of head-down, top-down hover displays, compared to the perspective out-of-window view and conformal data representations.

De Reus and Van Witzenburg (2007) evaluate an earth-referenced, top-down acceleration symbol during landing and hovering. Unlike other hover displays, the velocity vector is not directly shown, but only indirectly presented as the origination point of the acceleration-line (which is ended by a dot). The symbol was shown on a helmet-mounted HUD, either with or without night vision capabilities.

Craig et al. (2007) describe a video-based automatic station-keeping system, which has the goal of enabling a helicopter to automatically follow a moving target, recorded by a video camera mounted on the Canadian NRC Bell 412 helicopter. The system also included an approach function, which enabled the helicopter to assume the hoist position above a target selected by the pilots.

D'Intino et al. (2020) present a pilot intent estimation system that generates desired flight trajectories on-line, for a 2D horizontal re-positioning task. These target trajectories are then communicated to the pilot as desired control inputs via haptic feedback.

Hover support systems focus on the tasks of hovering in place or on low-speed horizontal manoeuvring. Systems without guidance cues can be categorised as shown in Figure 2.10. For the given task, they acquire all necessary information. Depending on the specific display implementation, they provide a low (no data analysis) or medium (provision of additional, derived data, e.g., horizontal acceleration information) LoA in the IAn stage. The selection of an appropriate response, and its implementation, is left to the pilots.

Displays with manoeuvre cues, e.g., velocity and position profiles during an approach to hover, can be categorised according to Figure 2.10. Through the calculation of a desired manoeuvre-trajectory, and its communication to the pilot, the systems now possess a high LoA in the IAn and AS stage. Only the implementation is left to the pilots, corresponding to a low LoA.

Short-term obstacle avoidance

Waanders et al. (2012, 2013, 2015) describe an obstacle avoidance support display (head-down, top-down) for low-speed manoeuvring close to the ground, e.g., during take-off and landing in uncharted terrain. The initial goal was to cover the complete lower hemisphere of the helicopter within a 250m radius. Complexity restrictions lead to the re-focus on areas critical to the main-rotor and tail-rotor and the so-called rotorstrike alerting system. This system provides a visual warning when an obstacle comes close to the helicopter. Its direction is indicated on a pie-like display, the colour (ranging from green, through yellow, to red) indicates how close the obstacle is.

Müllhäuser (2018) describes a tactile cueing system for 360 degree obstacle avoidance during landing. Similar to Godfroy-Cooper et al. (2018, 2019), they define a geometric speed-dependent “risk field” around the moving helicopter. When an obstacle enters this field, the pilot is warned of it via haptic forces and stiffness changes on the cyclic stick. The obstacle detection and data fusion algorithms are based on the ALLFlight project.

Short-term obstacle avoidance systems provide obstacle avoidance support during low-speed manoeuvring and hovering close to the ground. They can be categorised according to Figure 2.10. For the goal of avoiding a collision with an obstacle, they acquire and analyse all necessary information. AS is supported with a medium LoA: the warnings given to the pilots typically come with a suggested direction of control, in order to avoid collision. The implementation of this suggestion is left completely to the pilots, signified by a low LoA at the AI stage.

Full authority autopilots

Full authority autopilots translate a desired trajectory (given by the pilot or handed down from higher LoCS) into required control actions to perform the manoeuvre. Some examples of autopilot development include Truong et al. (2016), who describe a vision-based translational rate command controller to land on a moving ship deck, and Ruffier and Franceschini (2004); Ruffier (2005), who describe an optic-flow based autopilot that enables automatic landing on sloped landing spots. These systems can be categorised according to Figure 2.10. The LoA in every stage is high: the system acquires and analyses all necessary information, calculates the desired response, and implements the required actions.

2.5.5. LoCS 1: System-level automation

Systems on this LoCS typically do not require pilot intervention. For the most part, the pilot intervention is limited to engaging and disengaging the automation. Tasks on this level are:

- provide "systemreadiness" and
- hard- and software that enables flight control functions.

Functions that are supported on this level are:

- keep rpm nominal,
- minimise vibration, and
- rotor de-icing.

The human-machine interaction with these systems is minimal. Therefore, only general descriptions of possible systems is given, without a detailed review of existing system architectures and developments.

rpm governors

Automated rpm governors are systems that keep the main and tail rotor rpm at a nominal value. They modify engine parameters like fuel injection rate in order to increase or decrease the power that is transmitted to the rotor. In early helicopters, this task was done manually by the pilots via a knob at the collective lever. Nowadays, however, most helicopters possess an automatic rpm governor. Pilots do not need to monitor rpm during regular manoeuvres, but only when encountering unexpected situations like engine or governor failures, or during manoeuvres whose power consumption exceed the maximum power of the engine. In this case, the rpm governor will not be able to maintain steady, nominal rpm (Padfield, 2007).

An rpm governor can be classified as shown in Figure 2.11. The LoA in every stage is high, the system does not require pilot intervention as long as the engine provides enough power to maintain nominal rpm.

Anti-vibration systems

Anti-vibration systems aim to minimise vibratory loads and their effect on the passengers and/or freight (Lopez et al., 2019). These systems can be categorised according to Figure 2.11. In every stage, the system possesses a high LoA: the system acquires and analyses all necessary information that is necessary to select and implement the required control actions to minimise vibrations. The pilots are not involved in this process.

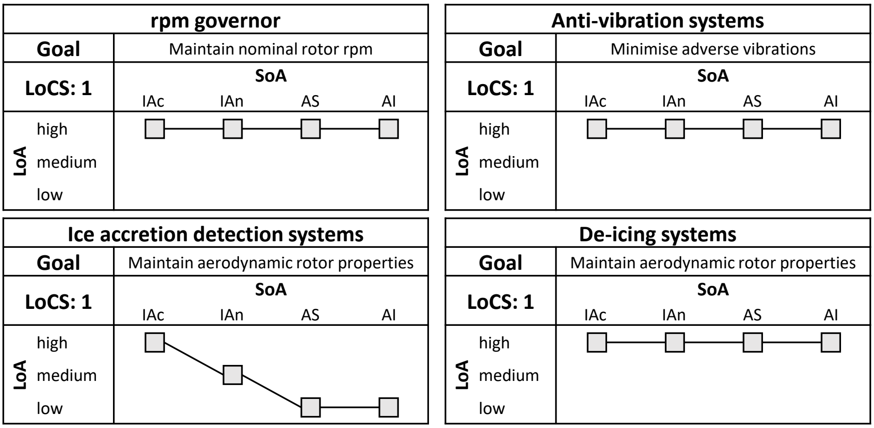


Figure 2.11: Level of automation (LoA)– stage of automation (SoA)-matrices of automation systems on the 1st level of control sophistication (LoCS), with the stages information acquisition (IAc), information analysis (IAn), action selection (AS), and action implementation (AI).

Ice accretion detection systems

Ice accretion detection systems aim to assess the amount of ice that has gathered on the helicopter rotor. They can be classified according to Figure 2.11: a high LoA in the IAc stage signifies the systems' capability to acquire all necessary information regarding ice accretion. Information analysis is supported through a medium LoA: there might be organisational or aircraft-related limits or regulations, but the pilots need to connect these limitations with the information provided by the ice accretion detection system. How to react to this information is left to the pilots.

De-icing systems

De-icing systems actively or passively try to regulate or minimise ice formation on the helicopter rotor, or other exposed parts. Electrothermal or electro-expulsive de-icing systems can shed ice from rotor-blades, as described by Flemming (2003), and have been operational on a number of aircraft, e.g., the UH-60A. Recent advances investigate piezo-electric de-icing systems (Villeneuve et al., 2020a,b,c). Figure 2.11 shows the classification of such de-icing systems. As soon as the pilots turn this system on, they are not involved in any of the processing stages. The systems provide their capabilities without pilot intervention. However, these systems are probably more often engaged and disengaged, based on the challenges posed by the external environment. Current operational de-icing systems include the full ice protection systems (FIPS) and limited ice protection systems (LIPS) certified for the Leonardo-Finmeccanica AW189. According to Leonardo, FIPS enables operation in full icing conditions, whereas LIPS enables operation in limited icing conditions and requires the possibility to descent into non-icing conditions at all times.[6]

[6]"Leonardo-Finmeccanica AW189 Full Ice Protection System Certification Clears Way for All-Weather Operations" (`https://www.leonardocompany.com/en/press-release-detail/-/`

2.6. Discussion

This section discusses the findings of the performed analysis. First, the intended operational envelope of automation systems is discussed. Afterwards, clusters and gaps in the surveyed automation systems are identified and discussed, in particular with respect the operational timescale. In the last subsection, the implication of the performed analysis on the performed exploratory studies and experiments of this dissertation are described.

2.6.1. Operational envelope

One critical question for every automation system is its operational envelope, and its capability to incorporate changing parameters within and outside of its defined operational bounds. How much human supervision and monitoring is required during operation? The levels of automation defined by the society of automotive engineers (Anonymous, 2018) offer one possible way of looking at this problem, by defining certain "take-over" cues and protocols on different levels of automation. It might be problematic, however, to combine the requirement of supervision and manual take-over in off-nominal situations with the level of automation — a system might fully autonomously operate within its well defined operational boundaries, but it might cause catastrophic failure if operational parameters leave the pre-defined range. A critical component of automation systems is therefore this resilience towards unexpected events, both on the same timescale of operations, and towards disruptions on higher and lower timescales.

Many automated driving systems for cars provide anecdotal reference for this problem.[7] The human driver is always required to monitor the automation system, and take over if necessary — even without a cue from the automation. The human must always understand the vehicle's situation and environment, and quickly detect incorrect or dangerous automation behaviour. This set-up is eerily close to some ironies of automation as defined by Bainbridge (1983), more than three decades ago. As some of the discussed automated systems already have done, it is crucial to consider the holistic implications of employing automation systems, especially during already high-risk and complex helicopter missions.

The high-level automation systems envisioned by Heinemann et al. (2018), Byrne (2001), or Rataj et al. (2000) provide approaches to integrated automation support systems, which operate across multiple timescales and LoCS. When employing systems that can re-calibrate mid-mission, based on changing weather conditions or mission-critical requirements, it is crucial to maintain automation transparency and comprehensibility. Only then can the pilot "stay in control", have an overview of all the automation's actions, and intervene or correct if necessary.

For future developments in helicopter automation, this means that a focus should

detail/farnborough-fips-aw189-2016, retrieved January 28th 2021)

[7]For example, the Tesla homepage on "Autopilot and Full Self-Driving Capability" (https://www.tesla.com/support/autopilot, retrieved October 15th 2020) requires the driver to agree to (1) keep their hands on the steering wheel at all times, and to (2) maintain control and responsibility for your vehicle. The homepage asserts that "the currently enabled features require active driver supervision and do not make the vehicle autonomous."

be set on evaluating these systems in *complete operational contexts* and in situations *within and outside of their respective operational envelope*. As will be shown in later chapters of this dissertation, encountering situations outside of the operational envelope of automated support systems with specific characteristics can have inadvertent, undesirable effects. It is important to consider the behavioural changes that are induced by automation systems. These need to be investigated not only in narrowly defined evaluation tasks that are tailored to the automated system's function, but in broad experimental setups that encompass a wide array of scenarios and events.

2.6.2. Clusters and gaps

Table 2.10 summarises the reviewed automation system categories per LoCS. Systems on LoCS 5 are mostly concerned with abstract functions and mission planning. Systems on LoCS 1 cover enabling functions without reference to actual dynamic manoeuvres. These levels are the two "extremes" of the covered automation systems.

Systems on LoCS 2, 3, and 4 are often quite similar in their functionality, the only difference being the timescale of the function operation, see Table 2.11. These similar functions across time domains present the potential of combining similar functions across timescale domains into one integrated automation system. For example, presenting a desired manoeuvre trajectory in a consistent manner across LoCS can increase automation system transparency, whether it is a long-term cruise trajectory, medium-term approach/land trajectory, or short-term obstacle avoidance manoeuvre.

Designing automation systems that span multiple timescales presents unique potential problems: it might be unclear to the pilots how much information the automation system uses at any given moment, and whether any re-considerations of longer timescale manoeuvre decisions are being carried out. Conversely, an automation system on a single timescale might have a more clearly defined scope and capability, with more obvious limits of its functions. This might make it easier for the pilots to correct the automation's actions, or to determine whether it is necessary to intervene.

Both approaches can present challenges. On the one hand, when utilising integrated automation systems that cross multiple LoCS, it might be hard to determine on which LoCS a potential error is located, and on which level it should be addressed. On the other hand, task-specific automation systems can be brittle and susceptible to situations outside of their defined envelope. Whichever design approach is chosen, it is paramount to consider these automation characteristics when analysing system risks and determining operational procedures.

2.6.3. Automation on different timescales

Issues can arise when systems pursue a goal on a "high" LoCS like mission phase or mission, but do not take into account the restrictions of lower LoCS. As a hypothetical example, Figure 2.12 shows the flight director, and its interfaces to other LoCS, in the developed framework. This flight director might follow a certain set of

Table 2.10: Automation system categories.

LoCS 5	LoCS 4
Mission phase risk assessment systems	Digital map with overlays
Mission path planning algorithms	Landing site determination and evaluation
Integrated mission support	Mission phase trajectory determination
HEMS mission communication	Mission phase trajectory visualisation
	Mission phase trajectory implementation
LoCS 3	**LoCS 2**
Conformal visualisation	SAS/SCAS/control augmentations
Danger warnings	Primary pilotage information displays
Off-line trajectory calculation	Envelope protection (cue-based)
MTE trajectory determination	Envelope protection (automatic)
MTE manoeuvre trajectory cues	Hover displays without manoeuvre cues
MTE manoeuvre control cues	Hover displays with manoeuvre cues
Automatic MTE control	Short-term obstacle avoidance
	Full authority auto pilot
LoCS 1	
rpm governor	
Anti-vibration systems	
Ice accretion detection systems	
De-icing systems	

waypoints, but does not react to changing weather, airspace restrictions, or other traffic on the same LoCS. For these potential hazards, other warning systems might or might not exist. It is the pilots' responsibility to react to these emerging threats accordingly and to overrule or deactivate the flight director. This case exemplifies a system on a high LoCS (the flight director) suggesting the implementation of certain lower-level MTEs and manoeuvre samples, but disregarding the specific limitations that can arise in lower LoCS.

Another example can be drawn from the multitude of existing obstacle avoidance systems, usually operating on the lower LoCS 3 (MTE) or 2 (manoeuvre sample), as shown in Figure 2.13. Most importantly, the question arises how reliably the

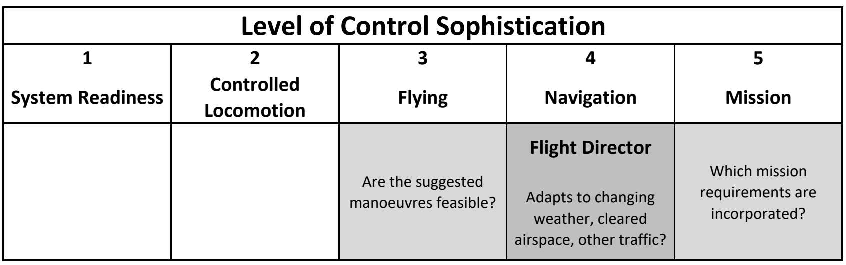


Figure 2.12: The "flight director" automation system and its interfaces with adjacent LoCS, located in the developed framework.

Table 2.11: Parallel functions across LoCS 2-4.

Focus area	LoCS 4	LoCS 3	LoCS 2
Off-line functions		Off-line trajectory calculation	
In-flight information acquisition	Digital map with overlays	Conformal visualisation	Primary pilotage information displays Hover displays without manoeuvre cues
In-flight information analysis	landing site determination and evaluation Fuel cost estimation	Danger warnings	Short-term obstacle avoidance
Trajectory determination	Mission phase trajectory determination	MTE trajectory determination	
Trajectory visualisation & communication	Mission phase trajectory visualisation	MTE manoeuvre trajectory cues MTE manoeuvre control cues	Hover displays with manoeuvre cues
Trajectory implementation	Mission phase trajectory implementation	Automatic MTE control	Full authority auto pilot
Dynamic behaviour/limits			Envelope protection (cue-based) Envelope protection (automatic) SAS/SCAS/control augmentations

Level of Control Sophistication				
1 System Readiness	2 Controlled Locomotion	3 Flying	4 Navigation	5 Mission
	How should collision warnings be reacted to?	**Obstacle Avoidance System** Reliability?	Higher-order constraints and value-functions considered?	

Figure 2.13: The "obstacle avoidance" automation system and its interfaces with adjacent LoCS, located in the developed framework.

automation detects obstacles. Can the pilots trust the system to detect all and every obstacle in their path, or are they regularly required to react to obstacles without a prompt from the system? Are only certain types of obstacles detected, for example houses and trees, but no power lines? Besides these important questions, the effect of obstacle avoidance automation can also impact different LoCS. On higher levels, the question arises whether the suggested evasive manoeuvres take wind or restricted airspace into account. Are certain evasive manoeuvres detrimental to mission performance, or lead to a much larger mission duration, compared to other possible evasive manoeuvres? On lower levels, it might be unclear whether the obstacle avoidance systems take the current helicopter performance, load, or other factors into account. Are the system's recommendations feasible to implement with the current helicopter performance and configuration?

The stated questions and resulting problems are amplified when a partial- or full-authority autopilot system is coupled to the aforementioned systems. In these cases, it becomes all the more important that the pilots are acutely aware of the operational envelope of the autopilot system, of the currently pursued goal, and of every external influence that is and is not incorporated into its operation.

Each of the examples, drawn from the systems described in this study, reinforces the need for automation systems that "enable pilots to function to their full potential" (Borst et al., 2010a, p. 1), while avoiding the many potential complications arising from using automation that have been described by Parasuraman and Riley (1997) or Bainbridge (1983). Recently, the topic of ironies of automation has been re-visited by other authors, including Baxter et al. (2012) and Strauch (2018), reinforcing the actuality of the topic, and that these issues continue to exist and persist.

For future automation developments, it is once again of paramount importance to consciously investigate the impact of automation systems on different timescales of operation, and their interaction with higher and lower timescale operations. Locating automated systems in the proposed framework can be a valuable tool to identify potential hazards, and a first step towards counteracting their occurrence or their negative impact.

2.6.4. Implications for this dissertation's investigations

The results presented in this chapter provide the background for the investigations discussed in the following chapters of this dissertation. First, the accident analysis reports, coupled with common scenarios chosen for automation developments, supported the selection of the scenarios on each timescale:

1. short-term operation, LoCS 2: approach-to-hover and hover (Chapter 3 and Chapter 4),
2. medium-term operation, LoCS 3: obstacle avoidance during forward flight (Chapter 5), and
3. long-term operation, LoCS 4: navigational decision-making (Chapter 6).

It is important to note that each scenario will require different tools and methods to analyse the results, based on the operational timescale (on the chosen scenario). Short-term control tasks enable the control-theoretic analysis of closed-loop system behaviour, whereas medium- and long-term tasks enable and require the analysis of different kinds of task-related and cognitive metrics.

Secondly, the issue of limited and sometimes unclear or nontransparent operational envelopes (Subsection 2.6.1), exacerbated by automation providing very similar functions on different timescales (Subsection 2.6.3, provided the motivation for the design of the experimental automation systems. On LoCS 2, this motivates the theoretic analysis of two different automation design approaches in Chapter 3 and Chapter 4, which focus on analysing how helicopter pilots control helicopters on the short timescale:

1. task-centred automation (displays or conformal visualisation that focus on providing information directly pertinent to the hover task) and
2. ecology-centred automation (good outside visuals or conformal visualisations that focus on supporting the pilots' natural perception of the outside world).

For experiments on LoCS 3 and 4 (in Chapter 5 and Chapter 6, respectively), two slightly different automation design principles are investigated:

1. advisory automation (displays that focus on providing one specific manoeuvre suggestion to the pilots) and
2. constraint-based automation (displays that focus on providing information about the helicopter's capabilities and limitations, without prescribing one specific manoeuvre solution).

Both comparisons have in common that they compare an automation design approach with a high LoA in the action selection stage (task-centred & advisory), and one automation design approach which focuses more on high levels of automation in the earlier stages of information acquisition and analysis, while leaving the later steps to the pilots. It is of particular interest whether "keeping the pilot in the loop" reduces the negative inadvertent effects of automated systems, in particular in the longer-term experiments on LoCS 3 and 4.

2.7. Conclusion

Classifying automation systems according to their timescale of operation and function enables the discovery of automation coverage clusters and gaps in the helicopter domain. Short-term, “enabling” automation systems like rpm governors or anti-ice systems, as well as long-term, mission management automation systems provide functions that are unique to their timescale of operation. On intermediate timescales, at first glance, the provided functions are quite similar. However, systems on different timescales take very different types of information into account, and they base their function on a different timescale of information and prediction. Especially for these systems, it is important to clearly define operational boundaries and capabilities, or to provide an automation “scheduler” function that incorporates these similar functions into a unified support framework for the pilot, which keeps track of the capabilities and limitations of its “modules”.

Integrated automation approaches exist and have been described in this chapter, but much of the covered research into novel automation systems focus on only specific evaluation scenarios and capabilities. This approach makes sense for research, to narrow down the amount of “moving pieces”, and to better investigate the exact properties and effects of the evaluated displays. However, in order to integrate these novel systems into an actual operational context, it also has to be investigated how these systems interact with situations outside their operational envelope and on different timescales. Automation systems’ capability to provide support to pilots even when operational conditions are not as clear and defined as in evaluation trials, is a crucial parameter of their potential to increase helicopter operational safety in the future.

3

Short-Term Manual Control: Head-Down Hover Displays

After providing a framework to analyse helicopter automation systems, this chapter focuses on the short timescale task of hovering, a task that is included in practically every helicopter mission. During hovering and low-speed manoeuvring, head-down hover displays and instrument panels theoretically provide all necessary flight data information to control the helicopter. However, past experiments have shown that head-down displays can incur high workload, control instability, and even loss of control when used as the sole flight data source. To better understand why such problems can occur, this chapter compares good outside visuals (ecology-centred approach) with a head-down hover display and an instrument panel (task-centred approach). The impact of both approaches on state observably and vehicle controllability are analysed and discussed from two angles: from a theoretical point of view using a pilot model based on crossover theory and τ-theory, and from an experimental point of view, utilising proof-of-concept data collected in the SIMONA Research Simulator. While both ecology-centred and task-centred approaches theoretically provide all necessary state information, pilots were unable to perform the task with the task-centred hover display. The results of this chapter highlight the impact of a natural representation of the work domain (i.e., good outside visuals), and how a focus on only task-related state representation in displays can cause additional time-delays and ultimately instability in the closed-loop control system.

Parts of this chapter have been published as "D. Friesen, M. D. Pavel, C. Borst, P. Masarati, M. Mulder, *Pilot Model Development and Human Manual Control Considerations for Helicopter Hover Displays*, in *Proceedings of the 45th European Rotorcraft Forum, Warsaw, Poland (2019)*". The introduction utilises parts of the the paper "N. Meima, C. Borst, D. Friesen, M. Mulder, *Augmented Reality to Support Helicopter Pilots Hovering in Brownout Conditions*", which is part of the MSc graduation report of the same name by Niek Meima, available in the Education Repository of Delft University of Technology.

3.1. Introduction

The safety of helicopter flight remains subpar compared to fixed-wing flight, especially in degraded visual environments (DVE). When a helicopter operates in a DVE, the number of visual cues that is available to the pilot decreases — the usable cue environment (UCE)-level increases from level 1, which represents near perfect visibility, to level 2 or 3. A DVE can be caused by, e.g., a brown-out/white-out, nightfall, or dense fog. In such conditions, the view of the outside world can be obstructed.

This can lead to perilous situations, a finding supported by a study of 375 rotorcraft losses, conducted for the US Department of Defence (Couch and Lindell, 2010), which found that 55% of combat non-hostile losses of rotorcraft during low-speed or hover occurred due to flight in DVE. According to a report by the North Atlantic Treaty Organisation (Task Group HFM-162, 2012), approximately 75% of helicopter mishaps that took place in arid climates such as Afghanistan and Africa can be attributed to brownout conditions.

As Chapter 2 discussed, the hover manoeuvre is a basic helicopter manoeuvre that is part of many, if not all, imaginable helicopter mission profiles. It is frequently performed at low altitudes before touch-down and after lift-off. It also is a flight phase that, in dry climates, can lead to brownout formation. Safely performing a hover in a brownout is particularly difficult because the manoeuvre requires constant pilot attention and control input. Moreover, for good visual environments, pilots are instructed to make use of outside visual references to maintain a stable point above which to hover (Federal Aviation Administration, 2019). Therefore, when the out-the-window information is lost, pilots are forced to adjust their normal control strategy. Providing visual support systems, either head-down or head-up, is a promising means to improve the safety and performance of hovering with degraded visuals (Minor et al., 2017).

In order to maintain good operability of helicopters under worsening visibility conditions, different head-up display (HUD) and head-down display (HDD) systems can be employed. These displays can decrease the UCE-level by providing the pilot with additional flight state data and information about the attitude and position of the helicopter with respect to its environment. While many different display systems are possible[1], this chapter focuses on the theoretic analysis of two-dimensional hover displays.

In this chapter, hover displays are defined as visualisations of the horizontal position of the helicopter with respect to objects or locations in the environment, for example, hover target points or landing zones. In many existing displays, additional information about the horizontal velocity and acceleration is shown. The information is represented in a top-down view, with the helicopter at its centre. Information about the yaw angle is apparent through the rotation of the environmental objects around the centre of the display. Altitude information is not inherently part of a hover display, but often represented in close vicinity in the cockpit through an altimeter or an altitude tape.

[1]see Minor et al. (2017) for an overview and Münsterer et al. (2018) or Stanton et al. (2018) for current HUD examples.

Many concepts of two-dimensional hover displays have been described in literature — either as a separate HDD, or as a two-dimensional projection on top of a (synthetic) three-dimensional outside view (HDD or HUD), for example by Hess and Gorder (1990), Eshow and Schroeder (1993), or Szoboszlay et al. (2010). A comparison of different displays for vertical and/or short take-off and landing procedures, hover displays among them, has already been conducted in the year 1972 (Beyer et al., 1972). However, according to a literature review and flight experiments described by Minor et al., panel-mounted HDD are not suitable as the source of primary flight data for the pilot: "flight using only a scaled panel mounted image, even at 20/20 day visual acuity, is uncontrollable at low airspeeds in most rotorcraft (...) during high-gain tasks such as approach and landing" (Minor et al., 2017).

While hover displays theoretically provide all necessary aircraft attitude and position information that is required to maintain a controlled flight, they seem to incur additional problems that prohibit pilots from using them as the sole flight data information source. This chapter explores and investigates possible reasons for these added complexities by employing a control-theoretic approach: it investigates the replacement of good outside visuals with a head-down hover display and instrument panel during a helicopter hovering task, with and without an activated stability augmentation system (SAS). Simulated pilot model data and experimental pilot-in-the-loop data from an exploratory simulator study are compared and analysed to identify and quantify the reasons why hover displays appear to be unsuited for being the sole source of flight data information for the pilot.

The goal of the exploratory study in this chapter is threefold:

1. analyse the requirements placed on the pilot control models by low speed helicopter flight with and without a SAS, and identify stability margins ("controllability analysis");

2. analyse the requirements placed on the pilot's visual perceptual system by (1) good outside visuals and (2) zero visuals with a hover display and instrument panel, to acquire the necessary system state information and provide the state input for the previously described control loops ("observability analysis");

3. combine these analyses to identify possible causes for closed loop control instability when switching from good outside visibility to a hover display and instrument panel, and formulate design strategies and requirements to minimise these effects.

Section 3.2 highlights background information about the utilised helicopter model, hover display and pilot model. The following sections 3.3 and 3.4 contain the controllability analysis and observability analysis, respectively. The performance of the developed pilot model is compared with data collected during an exploratory simulator study in Section 3.5. Section 3.6 discusses the results of the previous analyses and simulator study, identifying possible causes for instability and formulating display design recommendations. Conclusions are presented in Section 3.7.

3

3.2. Background

In this section, the utilised helicopter model, its modifications, and the employed hover display are introduced. Lastly, this section describes the human control model based on crossover theory and its applicability to this chapter's control task.

3.2.1. Helicopter model

A linear six degree of freedom state-space model (presented by Padfield (1981, 2007), based on Helisim) of a Messerschmitt-Bölkow-Blohm Bo105 Helicopter (MBB Bo 105) trimmed at zero forward flight speed is used as the simulation test bed. The system is described by the state vector

$$\mathbf{x} = (u, w, q, \theta, v, p, \phi, r) \tag{3.1}$$

and the control vector

$$\mathbf{u} = (\theta_0, \theta_{1s}, \theta_{1c}, \theta_{TR}) \tag{3.2}$$

of the dynamic system

$$\dot{\mathbf{x}} = A\mathbf{x} + B\mathbf{u}, \tag{3.3}$$

with

$$A = \begin{pmatrix} -0.0211 & 0.0113 & 0.7086 & -9.8029 & -0.0170 & 0.0183 & 0 & 0 \\ 0.0091 & -0.3220 & -0.0311 & -0.3838 & -0.0008 & -0.0006 & 0.4445 & 0 \\ 0.1045 & -0.0151 & -3.7472 & 0 & 0.0900 & -0.0972 & 0 & 0 \\ 0 & 0 & 0.9990 & 0 & 0 & 0 & 0 & 0.0453 \\ 0.0170 & -0.0010 & 0.0182 & 0.0168 & -0.0405 & -0.7365 & 9.7927 & 0.1010 \\ 0.3402 & 0.0155 & 0.3688 & 0 & -0.4114 & -14.1949 & 0 & 0.1277 \\ 0 & 0 & -0.0017 & 0 & 0 & 1.0000 & 0 & 0.0392 \\ 0.0607 & 0.0088 & 0.0656 & 0 & -0.0173 & -2.4296 & 0 & -0.3185 \end{pmatrix} \tag{3.4}$$

and

$$B = \begin{pmatrix} 3.6533 & -8.4769 & 3.3079 & 0 \\ -92.9573 & -0.0020 & -0.0004 & 0 \\ -5.6815 & 44.9965 & -17.5587 & 0 \\ 0 & 0 & 0 & 0 \\ -0.5527 & -3.3079 & -8.4770 & 5.0433 \\ 4.9933 & -66.3704 & -170.0832 & 6.1969 \\ 0 & 0 & 0 & 0 \\ 19.7319 & -11.8019 & -30.2442 & -15.4596 \end{pmatrix}. \tag{3.5}$$

3.2.2. SAS implementation

A SAS is incorporated directly into system matrix A_{SAS} according to equation 3.6 by assuming zero time-delay, zero noise and unity transfer functions for SAS sensors and actuators. The MBB Bo 105 SAS parameters in matrix F (Equation 3.7) are based on previous tuning experiments conducted at TU Delft as part of the ARISTOTEL project[2].

[2]No published documents pertaining to ARISTOTEL SAS parameters publicly available. General information at http://aristotel-project.eu/welcome/

$$A_{SAS} = A + BF = \begin{pmatrix} -0.0211 & 0.0113 & 1.4355 & -8.3491 & -0.0170 & 0.0337 & 0.0383 & 0 \\ 0.0091 & -0.3220 & -0.0309 & -0.3835 & -0.0008 & -0.0006 & 0.4445 & 0 \\ 0.1045 & -0.0151 & -7.6056 & -7.7167 & 0.0900 & -0.1791 & -0.2033 & 0 \\ 0 & 0 & 0.9990 & 0 & 0 & 0 & 0 & 0.0453 \\ 0.0170 & -0.0010 & 0.3018 & 0.5841 & -0.0405 & -0.7760 & 9.6946 & 0.6062 \\ 0.3402 & 0.0155 & 6.0599 & 11.3823 & -0.4114 & -14.9884 & -1.9690 & 0.7485 \\ 0 & 0 & -0.0017 & 0 & 0 & 1.0000 & 0 & 0.0392 \\ 0.0607 & 0.0088 & 1.0776 & 2.0240 & -0.0173 & -2.5707 & -0.3501 & -1.8673 \end{pmatrix} \quad (3.6)$$

The effect of the SAS can be observed in the complex plane representation of the system's poles in Figure 3.1, as well as in Bode plots of the simplified inner loop controlled element transfer functions $Y_{c,inner}$ in Figure A.1 (Section 3.3 details how the system and control matrices are simplified prior to this analysis and how the transfer functions are determined). Compared with the unaugmented system, the phugoid mode is no longer oscillatory, and the lateral velocity mode[3] is no longer unstable. In the transfer functions, the amplitude peaks of the controlled element in the surge and sway loops are reduced.

$$F = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.0857 & -0.1715 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.0047 & 0.0116 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.1002 \end{pmatrix} \quad (3.7)$$

3.2.3. Hover display

As explained in the introduction, a hover display and instrument panel can supply the pilot with all necessary attitude and altitude information to control the helicopter in case of DVE conditions. When the UCE-level increases, hover displays provide means to perceive the necessary information through an abstracted top-down view.

Figure 3.2 depicts the hover display used and analysed in this chapter. It is based on the "baseline" hover display explained by Hess and Gorder (1990), incorporating a generalisation of the scaling factors to allow separate scaling for the velocity and acceleration cues. The display is scaled such that it shows the ground in a 80 m diameter. The hover target area represents the desired position, and the ground reference markings mark the desired approach path from the starting position to the hover target position. The display rotates such that the heading of the helicopter always points upwards.

The horizontal velocity cue $\mathbf{c}_{vel}$ is a straight line representing the direction and magnitude of the current horizontal velocity, with its origin at the centre of the current helicopter position. It is measured in metres, as it represents a hypothetical distance in the physical world, which is then shown on the display:

$$\mathbf{c}_{vel} = T_{vel}\mathbf{v}_{hor} \quad (3.8)$$

The scaling factor is chosen to be $T_{vel} = 3$ s, which is then multiplied with the horizontal velocity of the helicopter $\mathbf{v}_{hor}$. The velocity cue represents a linear

[3]As this motion is no longer coupled with the yaw angle, the term "Dutch roll" is not used.

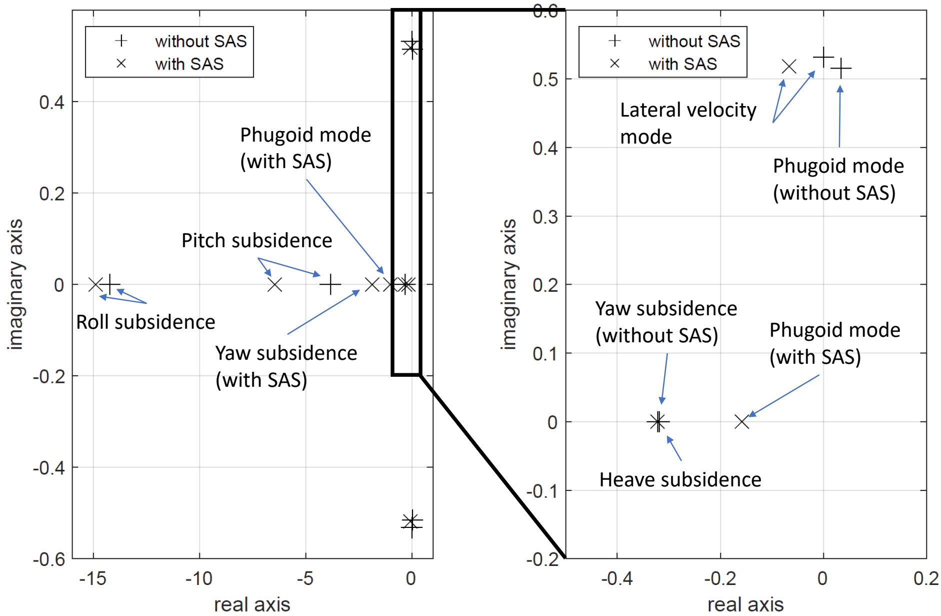


Figure 3.1: Poles of the simplified and decoupled system matrix A with and without SAS.

prediction of horizontal position with a look-ahead time of T_{vel}. As an example, a horizontal velocity of $10\,\frac{\text{m}}{\text{s}}$ creates a cue of 30 m, which is then translated to the display via the display scaling factor of 80 m per diameter. The value of T_{vel} is chosen such that at the beginning of the experimental scenario, the velocity cue fills 75 % of the available display space between the centre and the edge, enabling the use of the majority of the available display space during the deceleration manoeuvre.

The acceleration cue $\mathbf{c}_{acc}$, likewise measured in metres, is calculated via:

$$\begin{aligned} \mathbf{c}_{acc} &= \mathbf{c}_{vel} + T_{acc}\dot{\mathbf{c}}_{vel} \\ &= T_{vel}\mathbf{v}_{hor} + T_{vel}T_{acc}\mathbf{a}_{hor}, \end{aligned} \tag{3.9}$$

with the horizontal acceleration of the helicopter $\mathbf{a}_{hor}$ and the acceleration scaling factor $T_{acc} = 1.5$ s. Selecting $T_{acc} = 0.5 \cdot T_{vel}$ and defining the tip of the velocity cue as origin for the acceleration cue (already incorporated in Equation 3.9) leads to the acceleration cue representing a quadratic prediction of horizontal position, again with a look-ahead time of T_{vel}. These values are chosen in order to generate consistency between the cues: the velocity-cue c_{vel} represents the linear prediction, the acceleration-cue c_{acc} represents the quadratic prediction of horizontal position, both with a look-ahead time of $T_{vel} = 2 \cdot T_{acc} = 3$ s.

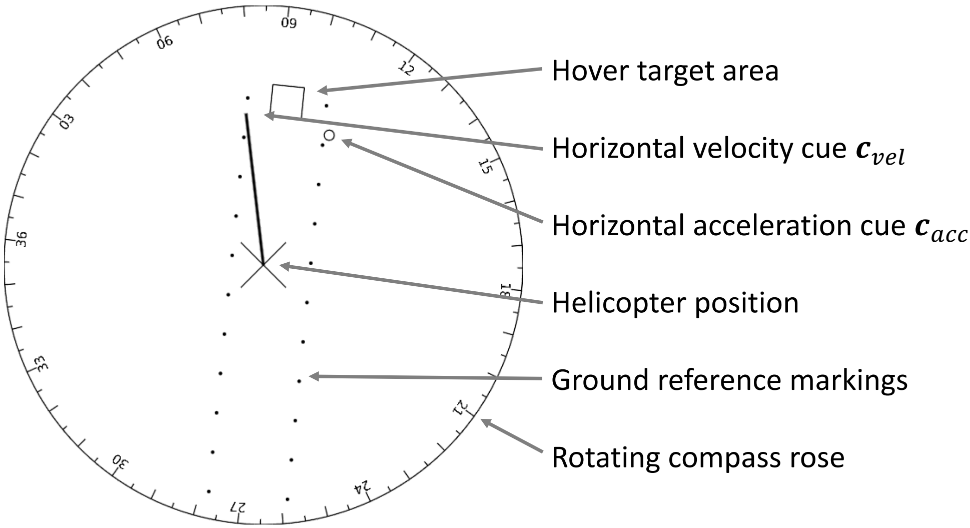


Figure 3.2: Hover display elements.

3.2.4. Crossover model

The crossover model as described by McRuer and Jex (1967) enables the development of models of human control for a variety of dynamic systems. The transfer function of the human controller is given by:

$$Y_p(s) = K_p \frac{1 + T_L s}{1 + T_I s} \cdot e^{-\tau_e s}, \tag{3.10}$$

with gain K_p, lead- and lag-constants T_L and T_I, and the lumped time-delay τ_e. The crossover model postulates how human controllers modify the lead- and lag-constants of their control behaviour to maximise task performance and maintain stability.

Several pilot models of this form are developed in this chapter to control the various degrees of freedom of the described helicopter model. It is important to note that McRuer and Jex only validated this model for single-axis disturbance-rejection tasks with a compensatory display, while the approach-to-hover task described in this chapter is a coupled multi-axis stabilisation task, with a pursuit display that includes some preview display characteristics. Nonetheless, tuning and analysing these model parameters give some insight into the peculiarities of this control task.

3.3. Controllability analysis

In this section, a basic control analysis of six-degree-of-freedom helicopter hovering flight dynamics is conducted. Required control loops and pilot model architectures are discussed. Basic pilot models based on the crossover model (McRuer and Jex, 1967) are developed and tuned for flight with and without a SAS. They are combined with target trajectories based on τ-theory (Padfield, 2011) to generate sample approach-to-hover manoeuvres. Critical control loops and control theoretic bottlenecks to maintain stability are identified and discussed.

3.3.1. System simplification

The system matrices A and A_{SAS} and the control matrix B are simplified to enable the development and tuning of basic pilot models based on the crossover model for each control loop. The system is decoupled into four separate dynamic systems: longitudinal position/surge control, height/heave control, lateral position/sway control, and yaw angle/yaw rate control. any cross-couplings between these parameters are neglected. This results in four completely separate dynamic systems, which disables the typical roll/yaw coupling of the Dutch roll dynamic response. It also disables any couplings of control actions to system states of other degrees of freedom, e.g., the typically strong coupling between collective control and yaw angle. The resulting system control matrices are shown in Equations 3.11 to 3.13.

$$A_{simplified} = \begin{pmatrix} -0.0211 & 0 & 0.7086 & -9.8029 & 0 & 0 & 0 & 0 \\ 0 & -0.3220 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.1045 & 0 & -3.7472 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.9990 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.0405 & -0.7365 & 9.7927 & 0 \\ 0 & 0 & 0 & 0 & -0.4114 & -14.1949 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.0000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -0.3185 \end{pmatrix} \tag{3.11}$$

$$A_{SAS,simplified} = \begin{pmatrix} -0.0211 & 0 & 1.4355 & -8.3491 & 0 & 0 & 0 & 0 \\ 0 & -0.3220 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.1045 & 0 & -7.6056 & -7.7167 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.9990 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0.0405 & -0.7760 & 9.6946 & 0 \\ 0 & 0 & 0 & 0 & -0.4114 & -14.9884 & -1.9690 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.0000 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1.8673 \end{pmatrix} \tag{3.12}$$

$$B_{simplified} = \begin{pmatrix} 0 & -8.4769 & 0 & 0 \\ -92.9573 & 0 & 0 & 0 \\ 0 & 44.9965 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -8.4770 & 0 \\ 0 & 0 & -170.0832 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -15.4596 \end{pmatrix}. \tag{3.13}$$

As an example, the structure of the longitudinal position control loop in hover is depicted in Figure 3.3, with longitudinal position x, longitudinal velocity u, body pitch angle θ and longitudinal cyclic control θ_{1s}. The controlled parameter chain is therefore ($\theta_{1s} \rightarrow \theta \rightarrow u \rightarrow x$). This system includes the phugoid mode of the

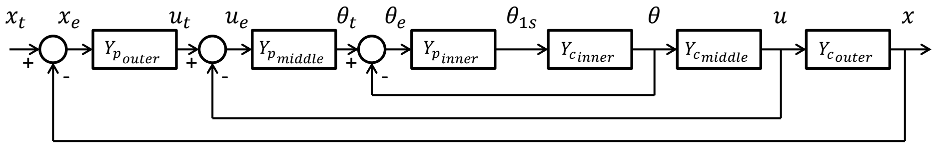


Figure 3.3: Structure of the controlled augmented horizontal longitudinal system.

helicopter. A subscript t denotes control target values, a subscript e denotes control error values, a parameter without subscript denotes the actual system state. System structures to control heave ($\theta_0 \rightarrow w \rightarrow z$), roll/sway ($\theta_{1c} \rightarrow \phi \rightarrow v \rightarrow y$) and yaw ($\theta_{TR} \rightarrow r \rightarrow \psi$) are set up similarly.

The transfer functions from the control input to the first considered inner loop system state (θ for surge, w for heave, ϕ for sway, r for yaw) are calculated with all remaining coupling coefficients within the four decoupled systems. However, the following middle loop states (u for surge, z for heave, v for sway, ψ for yaw) and outer loop states (x for surge, y for sway) are furthermore assumed to only depend on the previous system state in the chain. Cross-control effects and couplings between states in the same chain are neglected to enable the tuning of the pilot models according to the verbal adjustment rules described by McRuer and Jex (1967).

3.3.2. Pilot model development

The verbal adjustment rules of McRuer and Jex (1967) are used to develop models of human controllers for each of the four cascading control loops. Stability and phase margin techniques in the frequency domain are used to tune the pilot model gains, in order to achieve good performance and stability.

The first step in developing the inner loop pilot models is to determine the required lead- and lag-constants T_L and T_I to create an open loop amplitude slope of -20 dB/decade in the area of the crossover frequency. The crossover frequency ω_c is assumed to be around $\omega_c \approx (1-5)\,\frac{\text{rad}}{\text{s}}$. This follows from "rule 3" of McRuer and Jex (1967), $\omega_c \approx \omega_{c0} \approx \frac{\pi}{2\tau_e}$. The effective time-delay is approximated as $\tau_e = 0.295$ s, calculated with a hypothetical forcing function bandwidth of $\omega_i = 1\,\frac{\text{rad}}{\text{s}}$. (This task does not contain a forcing function, ω_i has been chosen as an arbitrary and small value.)

After determining T_I, T_L, and τ_e, the pilot gain K_p is tuned by choosing the maximum value for K_p for which the open loop transfer function Y_{OL} still has a phase margin $\varphi_m \geq 60\,°$ and a gain margin $K_m \geq 3$. These values have been chosen iteratively to create stable system behaviour. to Middle and outer loop controllers consist of only a gain, without lead-,lag- or time-delay-parameters. The crossover frequency is required to be at most half the crossover frequency of the previous loop.

3.3.3. Example: surge pilot model tuning

As an example, the tuning process of the unaugmented surge control loops is described here, starting with the **inner loop**. The inner loop controlled element transfer function $Y_{c,inner}$ is depicted in Appendix A in Figure A.1. It has is an amplitude peak of $42\,dB$ at $\omega = 0.52\,\frac{\text{rad}}{\text{s}}$, caused by two complex poles at $(0.0341 \pm 0.5153i)s^{-1}$, representing the phugoid motion. A third pole is located on the real axis at $-3.8365s^{-1}$, causing a slope decrease from -20 dB/decade to -40 dB/decade at $\omega = 3.8365\,\frac{\text{rad}}{\text{s}}$. To create a slope of -20 dB/decade in the area of the crossover frequency, the pilot model parameter T_L is set to the inverse of the highest frequency pole: $T_L = 0.2607$ s. Afterwards, the gain K_p is tuned such that the phase margin and gain margin criteria are met. The resulting inner loop pilot model transfer function $Y_{p,inner}$ is depicted in Figure A.2, the inner loop open loop transfer function $Y_{OL,inner}$ in Figure A.3.

The **middle loop** equivalent controlled element transfer function $Y_{c,middle,equivalent}$ is computed by multiplying the inner loop closed loop transfer function $Y_{CL,inner}$ with the middle loop controlled element dynamics $Y_{c,middle}$. The middle loop pilot model $Y_{p,middle}$, represented by only a gain, is now tuned such that the middle loop open loop transfer function $Y_{OL,middle}$ satisfies the crossover frequency, phase margin and gain margin criteria.

Similarly, the **outer loop** equivalent controlled element transfer function $Y_{c,outer,equivalent}$ is computed by multiplying the middle loop closed loop transfer function $Y_{CL,middle}$ with the outer loop controlled element dynamics $Y_{c,outer}$. The outer loop pilot model $Y_{p,outer}$ is tuned such that the outer loop open loop transfer function $Y_{OL,outer}$ satisfies the tuning constraints, leading to the outer loop closed loop transfer function $Y_{CL,outer}$.

3.3.4. Tuned pilot model

Table 3.1 shows crossover frequencies, phase-, and gain-margins of every controlled loop, Figures A.4 and A.5 show Bode plots of the closed loop transfer functions without and with SAS. The phase margin criterion is critical in two cases (unaugmented inner loops of surge and sway). In the other cases, the gain-margin is the inner loop's critical tuning parameter, followed by either the frequency criterion or another gain-margin criterion in the next loops.

The tuned pilot model is evaluated while controlling the fully coupled system. Control time-delay stability margins are shown in table 3.2. While the margins are reduced for every degree of freedom when switching the SAS off, the combined tolerable time-delay is slightly higher without a SAS. This might be caused by the generally lower pilot gains in the no-SAS configuration, and a consequential reduction of the intensity of cross-coupling effects.

The development of the pilot models with only the simplified decoupled system represents a limitation on their applicability on the fully coupled system. Couplings between system states will introduce dynamics and feedback loops that are not considered by the developed pilot models. Nevertheless, the pilot models can be applied to the fully coupled state space system, with reasonable performance and

Table 3.1: Crossover frequencies, gain- and phase-margins of every controlled loop. *critical tuning parameter

System	Loop	Target	without SAS ω_c [rad/s]	K_m [-]	φ_m [deg]	with SAS ω_c [rad/s]	K_m [-]	φ_m [deg]
Surge	Inner	θ	1,61	3,62	*60,1	1,74	*3,00	95,9
	Middle	u	*0,80	3,58	70,9	*0,87	3,40	72,2
	Outer	x	0,38	*3,03	66,0	*0,43	4,47	62,4
Heave	Inner	w	1,81	*3,01	69,4	1,81	*3,01	69,4
	Middle	z	*0,90	3,11	63,5	*0,90	3,11	63,5
Sway	Inner	ϕ	1,73	3,35	*60,1	1,91	*3,01	61,4
	Middle	v	*0,86	3,29	70,2	0,93	*3,01	69,4
	Outer	y	0,41	*3,00	64,6	*0,46	3,10	62,9
Yaw	Inner	r	1,81	*3,01	69,3	1,78	*3,02	63,2
	Middle	ψ	*0,91	3,09	63,3	*0,89	3,10	61,8

Table 3.2: Inner loop time-delay stability margins of the coupled system. "Combined" denotes a time-delay introduced in every inner loop at the same time.

time-delay margin [s]	With SAS	Without SAS
Surge	0.34	0.28
Heave	0.42	0.37
Sway	0.26	0.25
Yaw	0.34	0.28
Combined	0.15	0.17

stability close to hover. The coupled controlled system is able to perform low-speed position-following manoeuvres, utilising a three-dimensional target position and a target yaw angle as reference. Figure 3.4 shows the system response to a generic target trajectory. The given target functions (successive longitudinal, lateral, and vertical displacements of 50 m over 10 s, followed by a 90° yaw motion over 10 s) seem to be simple enough to not provoke uncontrollable vehicle motions.

It is important to note that a pilot model based on the crossover model "should not be used, without appropriate modification, to compute the system response to a deterministic input such as a step.", as McRuer and Jex (1967) noted. The developed model only focuses on the domain around the crossover frequency, they are not applicable to lower and higher frequency ranges. In this chapter, the pilot models are not modified in any way before their time response is computed. The presented results can therefore only serve as qualitative comparison data; a rigid, quantitative analysis in the time-domain is not feasible.

3.4. Observability analysis

The previous section assumes perfect information availability for the pilot. In this section, the requirements resulting from the control theoretic analysis are compared with the actual nature of information supply provided by (1) good outside visuals and (2) a hover display. Good outside visuals assume a helicopter position reasonably close to the ground, such that texture and existing objects supply the pilot with all necessary optical cues (UCE-level 1). A basic flight instrument panel and hover display, developed at TU Delft, serves as analysis test bed (Figure 3.5).

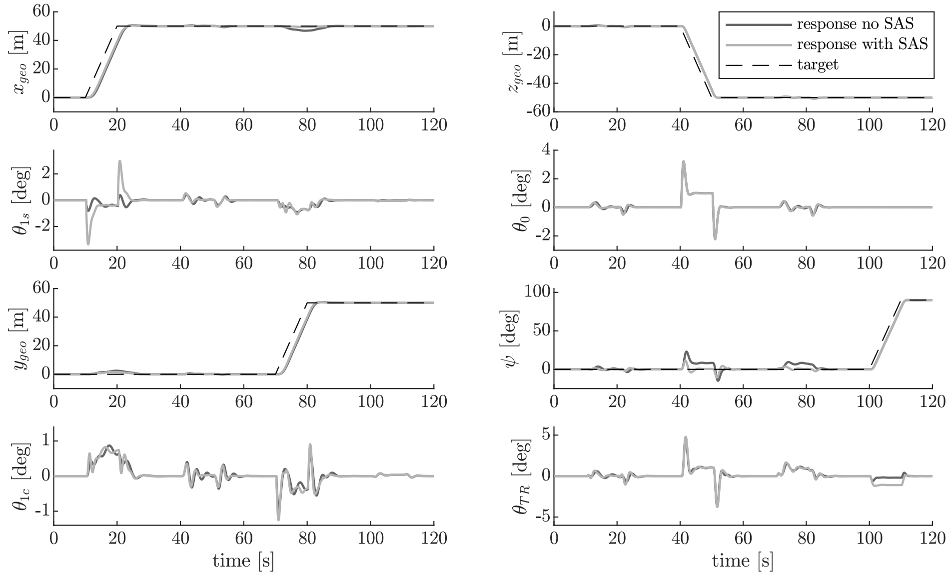


Figure 3.4: Pilot model response with the coupled system to sequential ramp targets in every loop.

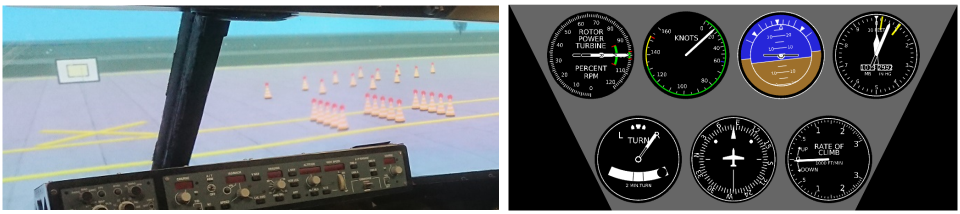


Figure 3.5: Outside scenery while approaching the hover target area of the ADS-33 hover course (left) and primary flight display (right).

The following subsection elaborates on the characteristics of the analysed display system. Then, modes of perception for different system states are shown, and typical perceptual and control time-delays of human controllers are discussed.

3.4.1. Display implementation

The utilised hover display is described in Subsection 3.2.3. For this analysis, the display's size and location in the SIMONA Research Simulator is used. It is shown on a monitor at a distance of 90 cm to the pilot's eyes, its centre approximately 10° inclined downwards from the horizon and approximately 20° to the left. The hover display diameter is 18 cm, which translates to 10.3° in the pilot's visual field. 1 cm of display relates to 0.57° of visual separation.

Table 3.3: Helicopter state perception during ADS-33 hover task.

	Outside View	Instrument Panel	Hover Display
q	Visual flow	Artificial horizon pitch speed	Acceleration cue longitudinal speed
θ	Target board pitch position	Artificial horizon pitch position	Acceleration cue longitudinal position
u	Visual flow, edge rate	Speed metre	Velocity cue longitudinal direction
x	Longitudinal cone position	-	Hover target longitudinal position
w	Visual flow, edge rate	Altitude rate meter	-
z	Board vertical indication	Altimeter	-
p	Visual flow	Artificial horizon bank speed	Acceleration cue lateral speed
ϕ	Horizon bank position	Artificial horizon bank position	Acceleration cue lateral direction
v	Visual flow, edge rate	-	Velocity cue lateral direction
y	Board lateral indicator	-	Hover target lateral Position
r	Visual flow	Compass rose rotational speed	Display edge rotational speed
ψ	Board/cone yaw position	Compass rose rotational position	Display edge rotational position

3.4.2. Human perception

Table 3.3 contains a broad categorisation of pilot perception methods for all necessary system states, based on the hover course described in the Aeronautical Design Standard 33E-PRF (ADS-33), (Anonymous, 2000). While the outside view provides means to perceive every required system state, the instrument panel and the hover display are lacking specific information about x, v, y, or w, z, respectively. Controlling the helicopter without outside visuals requires the integration of information from both displays.

3.4.3. Time-delay

Hosman and Stassen (1998) performed a simulator experiment to determine the necessary visual exposure time that is required for a pilot to generate an adequate control response to a roll attitude stimulus. They also measured the reaction time between the start of exposure and the onset of the control action. The lumped perception-action time-delay of their pilot model controlling a double-integrator system is set to $\tau_I = 0.2$ s. Similarly, Drop (2016) applies a lumped pilot model delay of 0.3 s to control helicopter longitudinal motion.

Time-delays of this magnitude have been identified by McRuer and Jex (1967) for double integrator system dynamics. They were identified based on single input, single output disturbance rejection tasks for double integrator system dynamics. Controlling a helicopter requires the simultaneous control of four system states. Increasing the number of loops controlled in parallel decreases performance and increases the effective time-delay of the controller (Barendswaard et al., 2019). The utilised time-delay of $\tau_e = 0.295$ s in this chapter seems to be reasonably close to comparable values from single- or double-axis control tasks in literature.

3.5. Pilot-in-the-loop study

After Section 3.3 establishes the pilot model parameters, and Section 3.4 confirms the magnitude of time-delay and the theoretic possibility of perceiving all system states in both visibility configurations, this section compares the time response of the developed model with data recorded during an exploratory study in the SIMONA Research Simulator.

The study took place in the SIMONA Research Simulator without motion. An in-house non-linear six-degrees-of-freedom MBB Bo 105 model was used (Miletović et al., 2017). Two helicopter pilots (holding a private helicopter license with 100-120 flight hours, not instrument rated) participated voluntarily and without compensation. The task closely resembles the hover task described in the ADS-33 (Anonymous, 2000). The goal of the task is to approach a predefined hover target point at a height of 2 m and hover in place for 30 s. The full task description given to the pilot is:

> Approach the hover target point with the initial forward speed of the helicopter at the beginning of the run. At a distance you deem appropriate, initiate a deceleration manoeuvre to smoothly and precisely come to a stop at the hover point. After reaching the hover point, maintain a stabilised hover, minimising deviations from the hover target point, for thirty seconds. Please avoid accomplishing most of the deceleration manoeuvre well before the hover point and then creeping up to the final hover position.

The proposed course set-up of ADS-33 is implemented in the outside visuals of the simulator. Both pilots did not have experience performing a standardised hover manoeuvre based on the ADS-33 course. However, because hovering represents a very basic helicopter manoeuvre, it is expected that both pilots have experience performing general hover manoeuvres at least in good outside visibility at varying, non-standardised locations. Desired and adequate hover position areas are denoted by the hover-board directly in front of the hover target, and by cones on the tarmac, placed to the right and in the front of the hover target point. The task was conducted either with good visibility and deactivated hover display, or with zero visibility and activated hover display. Figure 3.5 shows the employed hover display and basic instrument panel, Figure 3.6 depicts the simulator in both conditions at the same time.

The task was modified slightly, compared to ADS-33. Instead of starting in a $45°$ rotated position close to the hover target, the starting point was situated at a distance of approximately 100 m to the hover target, facing it head-on. The starting distances were quasi-randomised by drawing points out of a probability distribution with a mean of 100 m and a standard deviation of 10 m. The drawn starting positions were identical and kept in the same order for every experiment condition. The starting velocity was kept constant at $10\,\frac{\text{m}}{s}$ for every run.

During the study, it became clear that executing the task while only utilising the hover display and instrument panel (without outside visuals) was not possible

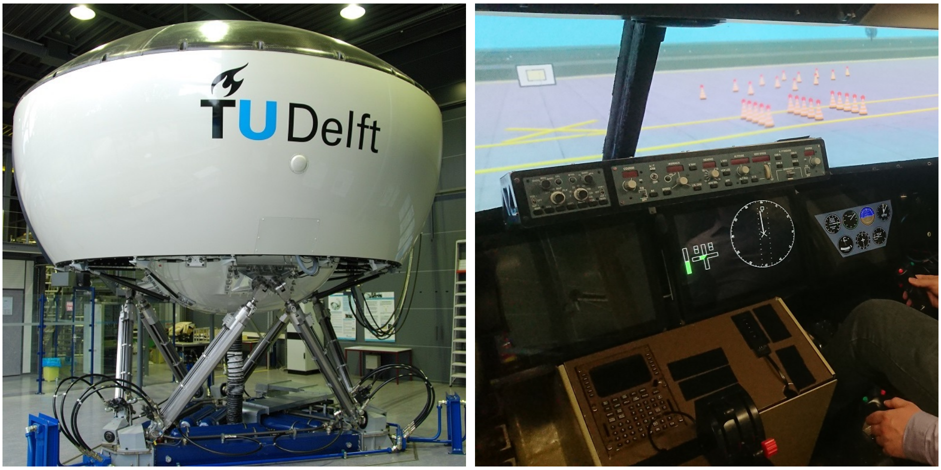


Figure 3.6: SIMONA Research Simulator outside view (left) and inside view (right, with both outside visuals and hover display enabled at the same time).

within the constraints of the setup of the study, which limited the training time to less than ten minutes per condition. In all runs without outside visuals, both participants overshot the target hover point or lost control of the helicopter shortly after decelerating, drifting laterally or longitudinally away from the hover target point and occasionally and unintentionally hitting the ground. It is hypothesised that this behaviour is at least partly caused by the little experience both participants had with piloting a helicopter solely based on display information (both pilots were not instrumented rated). Therefore, only data for the conditions with good outside visuals are used in this chapter. The data serve as a tool to qualitatively compare the developed pilot model with the behaviour of human pilots. Possible reasons for the closed-loop instability while utilising the hover display are discussed in Section 3.6.

Figure 3.7 depicts the geodetic longitudinal position x_{geo}, velocity $\dot{x}_{geo}$ and acceleration $\ddot{x}_{geo}$ of the helicopter in relation to the hover goal ($x_{geo} = 0$ m) during deceleration manoeuvres piloted by the pilot model and by the invited pilots, both with and without a SAS. The target trajectory for the pilot model is a *constant deceleration τ-guide* (Padfield, 2011) with $k = 0.5$. Lockett (2010) found that k-values between 0.45 and 0.55 shows good correlation with deceleration trajectories into hover flown by helicopter pilots.

The pilot model and the invited pilots seem to follow a similar strategy: reduce the velocity almost linearly in time, until smoothly transitioning to a zero-velocity state close to the target. Without a SAS, the invited pilots changed their control behaviour when in close proximity to the hover target point ($x \approx -10$ m), initiating a phase of somewhat constant velocity until reaching the hover point. This behaviour is apparent in the position-plot through the gap between the pilot model and the invited pilot trajectories at around 15 seconds into the manoeuvre.

There seems to be a good qualitative match between the deceleration trajectories of the developed pilot model and of the invited pilots, despite the fact that the

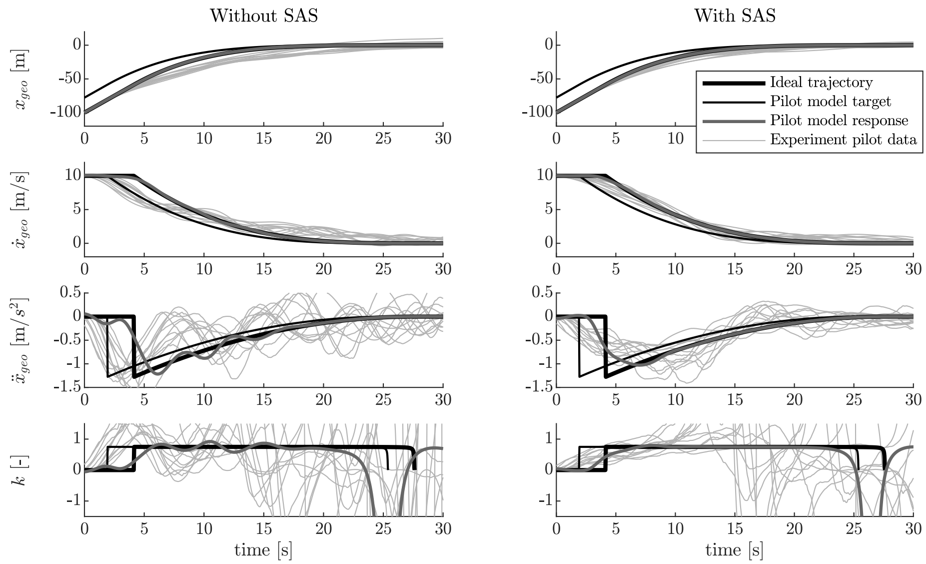


Figure 3.7: Approach-to-hover trajectories: ideal, pilot model target, pilot model response, and experiment pilot data.

invited pilots flew a non-linear model, while the pilot model was applied to a linear model. As previously mentioned, this similarity only holds for good outside visuals. While switching to a hover display does not change the pilot model's behaviour at all — the same input parameters are used — there are clearly additional complications for the invited human pilots. In the next section, possible reasons for the increased task difficulty are discussed.

3.6. Discussion

This section combines the results of the previous three sections to discuss reasons for hover-display-incurred instability (in Subsection 3.6.1) and design recommendations to counteract the negative effects (in Subsection 3.6.2).

3.6.1. Reasons for instability

All invited pilots were able to control the helicopter with good outside visuals. The reason for closed loop instability while using the hover display therefore lies in the effect of the differences between using outside visuals and using the hover display (combined with the primary instrument panel) to control the helicopter. The major differences are:

1. loss of peripheral visual information;

2. loss of flow field information;

3. new requirement to scan multiple displays (altitude only available on altimeter, far from hover display); and

4. new requirement to translate abstract top-down position and attitude information to existing mental model (or: new requirement to adapt mental model to new representation of flight state data).

Difference no. 1, as explained by Hosman and Stassen (1998), leads to an increased perception time-delay. Similarly, as Yamaguchi and Proctor (2010) describe, the perception of an *illusionary motion* helps performing a positioning task. Difference no. 2 eliminates the perception of an *illusionary motion*, only abstract display information remains. This could lead to an increase in required processing time for the pilot to translate the perceived information to his mental model of the vehicle (difference no. 4). This is made harder by the physical distance between the displays the pilot has to integrate data from (difference no. 3), and the fact that both participating pilots were not instrument-rated, limiting their experience with piloting a helicopter solely based on display information. The heave control loop in particular might suffer from an increased time-delay, as the display to perceive altitude is located far away from the hover display. The pilot might be tempted to focus on the hover display and scan the altimeter less frequently, as the altimeter only supplies two of all the necessary flight data parameters.

Yamaguchi and Proctor (2010) elaborate on their idea of a mental model that is used to perform a control task. They imply that changing display arrangements does not immediately make the controller adapt his or her mental model of the system. He or she rather has to adapt the information to fit his or her model. This supports the notion that with sufficient training, pilots would be able to adapt their mental model to fit the more abstract information presented by the hover display, enabling them to utilise the presented information better. In the current study, there was no sufficient time to perform this training step. The pilots immediately needed to interpret the abstract data to fit their internal mental model. This is expected to have incurred an additional time-delay, as explained before.

3.6.2. Hover display recommendations

To best support the pilot, a good hover display design should try to minimise the negative effect of the differences between using good outside visuals and using the hover display. Of the four discussed differences in the previous subsection, only difference no. 3 can be rectified within the constraints of a head-down hover display; placing an altitude tape (or different means of perceiving altitude) close to the hover display in the cockpit would lessen the strain of having to scan multiple displays to acquire all necessary flight data information.

The other differences are inherent to head-down hover displays — they can provide neither peripheral nor flow field information. The information is per definition displayed in an abstract, top-down manner, which requires pilots to change the way they translate the visual inputs to control outputs.

There might be ways of scaling hover displays such that they more closely resemble outside visual information. For example, the velocity and acceleration scaling factors could be tuned such that one degree of pitch- or role-angle relates to a display cue that covers one degree of visual separation on the display, as seen from the pilot. On the other hand, this would imply a direct linear relation between attitude angle and horizontal acceleration, which holds true approximately, but not in all possible cases. It is questionable whether creating these similar scaling factors would help the pilot, or whether it would complicate the information integration even more.

3.7. Conclusion

This chapter reinforced that head-down hover displays have inherent limitations; without guidance cues, they are not well suited to be the only supplier of flight data for the pilot. For good outside visuals, the developed pilot models based on crossover-theory produce similar control strategies than human pilots during a simulator experiment. The models do not capture the added difficulties of using only a hover display and an instrument panel to control the helicopter.

The results of this chapter suggest that the loss of peripheral and flow information and the added requirements on the pilot incurred by hover displays cause an additional time-delay greater than the time-delay stability margin of the pilot model and of the pilots who participated in the study. It is possible to counteract an additional time-delay by tuning the parameters of the control strategy. However, this additional tuning did not take place in this chapter, because the invited pilots only had a very short training time of a few minutes per condition. This limited their options of adjusting their control strategy to the hover display and instrument panel.

Hover displays without guidance cues do not work well as the sole source of flight data information. Therefore, the next chapter of this dissertation will focus on augmented reality visualisations, implemented via HUDs. These systems have shown the capability to replace the pilot's outside view and to introduce additional cues and support systems without severely limiting the pilot's ability to safely and freely[4] fly the aircraft.

[4] *Freely* implies neglecting the provided guidance cues and choosing a different action, caused by, e.g., unexpected events.

4

Short-Term Manual Control: Head-Up Hover Displays

This chapter focuses on head-up, conformal symbology to support helicopter low-speed manoeuvring and hovering. The same display design approaches as in the previous chapter are investigated. The first, ecology-centred display contains a grid ground texture and a box indicating the hover target position. The second, task-centred display bears close resemblance to the ADS-33 course and reproduces the described course elements in the head-up display. Both displays are theoretically analysed and compared with a baseline condition with good outside visibility. In the following exploratory simulator study, the ecology-centred display produced similar, good performance as the baseline condition, although workload and situation awareness deteriorated. The task-centred display at least afforded task completion, but performance was worse than in the other two conditions. Based on these results, it is hypothesised that distinctive ground textures and far-field references, i.e., elements of the helicopter work domain or ecology in good visibility, play a much larger roles in hover performance than task-specific cues of the ADS-33 hover board. The importance of the work ecology is explored and expanded in the following chapter of this thesis, moving this concept into longer timescales of operations and performing experimental analyses.

This chapter is an extension of the paper "N. Meima, C. Borst, D. Friesen, M. Mulder, *Augmented Reality to Support Helicopter Pilots Hovering in Brownout Conditions*", which is part of the MSc graduation report of the same name by Niek Meima, available in the Education Repository of Delft University of Technology. The author of this dissertation filled a supervisory role, including supporting the experimental definition, setup, and analysis. For this dissertation, the paper has been expanded with a control-theoretic visual design analysis and a visual gain analysis. The introduction, discussion, and conclusion have been extended to include these analyses. Parts of the chapter have been re-written and re-arranged.

4.1. Introduction

This chapter continues to investigates the hover manoeuvre. Following the conclusion of Chapter 3, the focus is set on conformal visualisations of the outside world.

Early research on such visual augmentations for hover focused on providing two-dimensional information on a head-down display (HDD) (Hess and Gorder, 1990; Eshow and Schroeder, 1993). However, more recent studies (Minor et al., 2017; Döhler et al., 2012) and the results of Chapter 3 have demonstrated the inherent limitations of both HDDs as well as two-dimensional symbology, and recommended instead to implement three-dimensional conformal imagery, or augmented reality, in head-up displays (HUDs) or helmet-mounted displays (HMDs). Although several groups have developed extensive displays with such scene-linked symbology (Feltman et al., 2018; Stanton et al., 2018; Viertler, 2017; Döhler et al., 2014; Münsterer et al., 2013), those interfaces are not purely conformal because they also contain superimposed two-dimensional elements such as flight instruments. Furthermore, these displays include so many different elements that often parts overlap. This visual clutter can have adverse effects on performance (Curtis et al., 2010), and lead to deteriorated awareness of other displays or external events (Crawford and Neal, 2006). Also, cognitive tunnelling is known to be more substantial for displays with non-conformal elements (Prinzel and Risser, 2004).

Even though experimental evaluation has demonstrated that such displays have a positive effect on hover performance, it remains unclear to what extent each display element is responsible for this. In order to avoid the adverse effects of clutter and tunnelling, a hover display ideally contains a minimum number of exclusively conformal elements. Therefore, only those cues that are crucial for the task at hand should be provided. Research is needed to investigate what kind of conformal cues such a display minimally needs.

In this chapter, two conformal displays are developed and their effectiveness during hover is theoretically analysed. The design of the displays is based on replacing the visual cues that are lost due to degraded visuals, in such a way that pilots can accurately perceive all relevant helicopter states using as few display elements as possible. The results of an exploratory study conducted with two licensed helicopter pilots in the SIMONA Research Simulator are presented.

Both a non-linear and a linearized vehicle model are used during the investigation. The non-linear model is the model including a stability augmentation system (SAS) that is utilised in Chapter 4. The linear vehicle model does not possess any cross-couplings between the controlled degrees of freedom, which should simplify the control task for the participating pilots. Likewise, it is the same SAS-augmented linear model which is utilised in Chapter 3. These simplified vehicle dynamics can be regarded as a model for a helicopter that has stronger, more advanced control augmentation. A simplified control task could lead to increased mental capacity to perceive and understand visual cues, which could counteract positive or negative effects stemming from the utilised display. The influence of the developed displays and helicopter dynamics on hover performance, control activity, workload and situation awareness is investigated.

Basic working principles of visual motion perception are explained in Section 4.2. Based on these principles, the experimental displays are designed and described in Section 4.3. Afterwards, the provided visual cues are discussed in the context of a control-theoretic analysis, utilising results from Chapter 3. This is followed by the design of the exploratory simulator study in Section 4.5. Results of the study and a discussion of the results are presented in Section 4.6 and Section 4.7, respectively. Finally, the chapter ends with a conclusion in Section 4.8.

4.2. Visual motion perception

With degraded visuals, the visual cues that a pilot normally uses during a hover manoeuvre are unavailable. In order to provide adequate replacements on an augmented reality display, understanding how the human visual system allows pilots to perceive and control their motion and orientation is crucial. This section briefly describes the role of the global optical flow rate, splay and depression angles, and optical edge rate.

Successful performance of the hover manoeuvre results in near motionless flight over a target location. In order to remain stationary, pilots have to be aware of, and correct for, any deviation away from the target. These deviations are noticeable as changes in the visual field of the pilot.

Movement of the helicopter causes points at different locations in the pilot's field of view to move at different rates. The relative velocities of these points is known as optical flow (Gibson, 1950). All flow in the optic array radiates outward from a single expansion point, which is a visual cue for the direction of motion of the pilot.

The total rate of optical flow moving past the pilot, known as the global optical flow rate (Larish and Flach, 1990), is defined as $\frac{V}{h}$. If speed V is kept constant, the global optic flow rate is a reliable cue for altitude h, and vice versa.

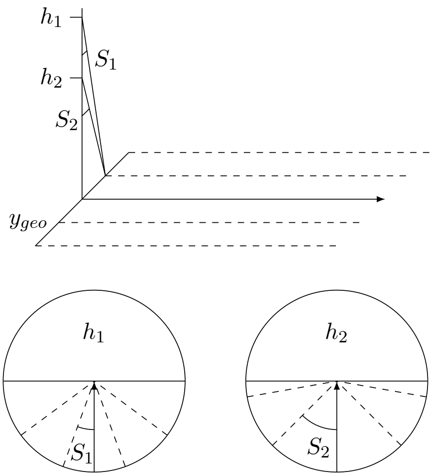
Another visual cue that can encode altitude information is splay angle S. S is the angle between edges parallel to the direction of motion and a line perpendicular to the horizon (Warren, 1982), such as a looming runway. Figure 4.1a conceptually shows the splay angle at two different altitudes. The splay angle S can be calculated with Equation 4.1, where y_{geo} is the lateral displacement of the observer from the line perpendicular to the horizon and h is the altitude.

$$S = \tan^{-1}\left(\frac{y_{geo}}{h}\right) \tag{4.1}$$

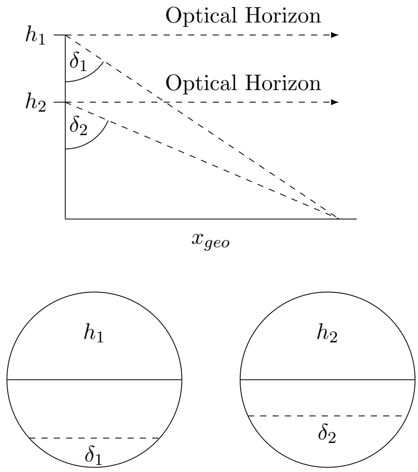
The splay angle changes as the observer moves through the environment. According to Flach et al. (1997), the rate of change of the angle provides a cue for the perception of altitude and lateral speed, and can be calculated with Equation 4.2.

$$\dot{S} = -\left(\frac{\dot{h}}{h}\right)\cos S \sin S + \left(\frac{\dot{y}_{geo}}{h}\right)\cos^2 S \tag{4.2}$$

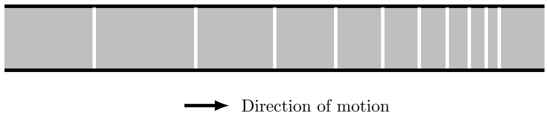
Analogous to splay is the depression angle δ, defined as the angular position of an edge perpendicular to the direction of motion. See Figure 4.1b for a visualisation of δ. In Equation 4.3, x_{geo} is the longitudinal displacement and h is the altitude.



(a) Splay angle S at different altitudes.



(b) Depression angle δ at different altitudes.



(c) Texture with low (left) and high (right) texture density, causing lower and higher edge rates at constant velocity, respectively.

Figure 4.1: Examples of splay angle, depression angle, and texture density/edge rate, adapted from Flach et al. (1997).

$$\delta = \tan^{-1}\left(\frac{x_{geo}}{h}\right) \tag{4.3}$$

The depression rate in case of rectilinear motion over a flat plane can then be defined (Flach et al., 1997), see Equation 4.4. It serves as a cue for altitude if longitudinal position is constant, and vice versa.

$$\dot{\delta} = -\left(\frac{\dot{h}}{h}\right)\cos\delta\sin\delta + \left(\frac{\dot{x}_{geo}}{h}\right)\cos^2\delta \tag{4.4}$$

Finally, edge rate is the rate at which discontinuities pass by a reference point in the observer's visual field. It is dependent on (ground) texture density and speed, but independent of altitude. Defining the separation between edges on the ground surface as T_x, the edge rate can be calculated using Equation 4.5 (Padfield, 2007). If the textures are regularly spaced, the edge rate is directly proportional to speed. Figure 4.1c shows an example visualisation of different texture densities.

$$e_r = \frac{\mathrm{d}x}{\mathrm{d}t}\frac{1}{T_x} \tag{4.5}$$

4.3. Display design

Table 4.1: Available visual cues in each of the displays.

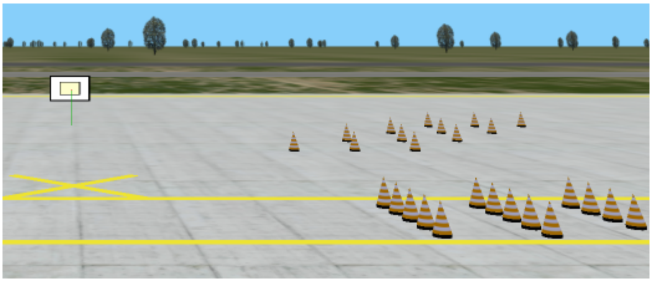
	Outside view (ADS-33)	Display 1	Display 2
x	Longitudinal cone position	Depression lines, hover box and cross	Longitudinal lines (cones), hover cross
u	Optical flow, edge rate	Depression lines	Hover course (depression) lines
θ	Hover board pitch position	Horizon position	Horizon position, hover board pitch position
q	Optical flow	Horizon vertical speed	Horizon vertical speed
y	Hover board lateral indicator	Hover box and cross	Hover board lateral indicator
v	Optical flow, edge rate	Splay lines	Hover course movement, diagonal lines (cones)
ϕ	Horizon bank position	Horizon bank position	Horizon bank position
p	Optical flow	Horizon rotational speed	Horizon rotational speed
$z = -h$	Hover board	Splay and depression lines, hover box and ticks	Hover board and reference marker
w	Optical flow, edge rate	Splay and depression lines	Hover course (depression) lines
ψ	Diagonal cones and hover board yaw position	Hover box position, grid lines	Diagonal lines and hover board yaw position
r	Optical flow	Grid lines	Diagonal lines and hover board rotational speed

With degraded visuals, the outside view is obscured, and the environmental visual cues as explained before are unavailable. Two augmented reality displays are developed to replace those lost visual cues. An often used test course for the hover manoeuvre is described in the ADS-33 (Anonymous, 2000), and will also be applied here as a baseline condition to compare the to-be-designed displays with. The developed display configurations are depicted in Figure 4.2. Table 4.1 shows an overview of the cues available in each of the three display configurations.

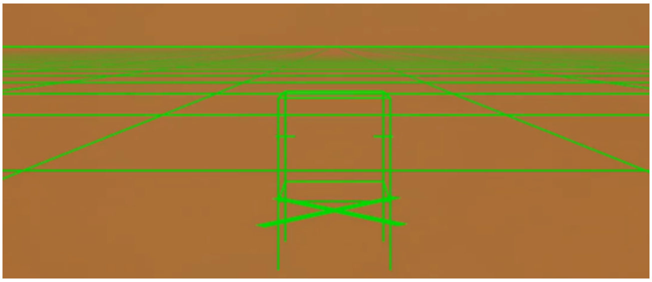
The ADS-33 setup in the baseline condition (Figure 4.2a) contains a hover board with reference marker and two sets of cones. The inner rectangle in the hover board indicates vertical and lateral *desired* performance, whereas the outer rectangle corresponds to the *adequate* performance bounds as specified in the ADS-33 (Anonymous, 2000) (see also Table 4.6).

Longitudinal position is conveyed by means of five rows of cones in between the yellow lines. The middle row corresponds to the target longitudinal position, the second and fourth row are indicative of desired performance and the outer rows of adequate performance. The diagonal set of cones are a cue for the yaw angle.

Regarding the first display (Figure 4.2b, henceforth referred to as Display 1), a straightforward way to implement splay and depression information in a display is by using ground texture (Flach et al., 1997). A grid texture contains both types of cues and thus conveys information about movement in all three axes. Therefore, the first proposed display contains a grid surface. Furthermore, the hover target position on this interface is indicated with a hover box, loosely based on Negrin et al. (1991). Tick marks are added to the rear vertical edges of the box as a cue



(a) Baseline condition with good visibility.



(b) Display 1: grid and hover box.

(c) Display 2: geometric ADS-33.

Figure 4.2: Configuration of proposed displays, as shown in the simulator.

for altitude when inside the box; if these coincide with the horizon, the helicopter is flying at target altitude. Finally, an artificial horizon line is added to convey pitch and roll information.

The second display (Figure 4.2c, hereafter called Display 2), instead, provides similar cues as are available in the ADS-33 hover course. However, the cones are replaced by lines as these are expected to be visible more clearly in a HUD implementation. The cross in front of the box, also present in the other display configurations, must be visible during hover; otherwise, the longitudinal target position is overshot. This display also contains a horizon line for pitch and roll reference.

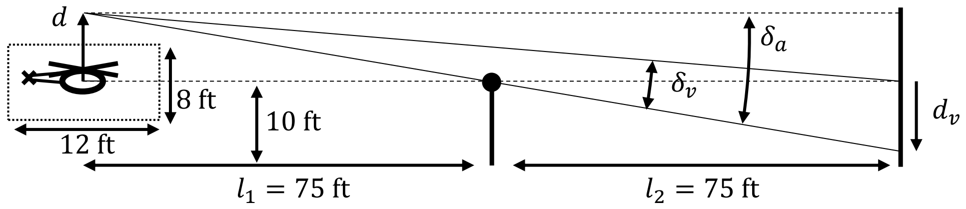


Figure 4.3: Conceptual side-view image of the dimensions of the experiment courses, with the absolute (δ_a) and observed (δ_v) visual displacement of an object at distance l_1 in front of a backdrop at distance $l_1 + l_2$, caused by an observer displacement d.

4.4. Control-theoretic visual design analysis

4

This section will analyse how the three visual setups provide visual cues to the pilot. The analysed degrees of freedom are longitudinal position, lateral position, and altitude, as these are described in the ADS-33 performance standard for this task. The analysis will focus on the hover-specific parts of the course — the hover board and cones for the ADS-33 setup and Display 1, and the hover box for Display 2. The visual cues of the cross-shaped ground marker, which is part of all three setups, are included, as well. The visual cues will be discussed with respect to the change of visual displacement per meter of position, measured in angles per meter. For an analysis of more general visual cues[1] originating from ground texture or flow field information, please refer to Sweet (2013).

To compare the visual cues of the courses, some theoretical considerations concerning the observable visual displacement of an object in front of a visual backdrop need to be discussed. It is assumed that all deviations around the initial position are small, small angle approximations are used. Relative to an observer displacement d, the absolute visual displacement δ_a of an object at distance l_1 to the observer is defined in Equation 4.6. When the visual displacement is not measured in absolute terms, but with respect to a visual "backdrop" at distance l_2, it is called observed visual displacement δ_v, defined in Equation 4.7. When there is no visual backdrop, or the backdrop is at near infinite distance, both visual displacements are identical, $\delta_a = \delta_v$. Figure 4.3 shows the described situation graphically, as well as the dimensions of elements of the ADS-33-based experiment courses.

$$\frac{\delta_a}{d} = \frac{1}{l_1} \tag{4.6}$$

$$\frac{\delta_v}{d} = \frac{1}{l_1} - \frac{1}{l_1 + l_2} = \frac{1}{l_1} \cdot \left(\frac{l_2}{l_1 + l_2}\right) \tag{4.7}$$

The component $\frac{1}{l_1}$ describes the absolute visual displacement, as seen from the observer location. $\frac{l_2}{l_1+l_2}$ represents a modification to account for the distance of the

[1]Visual cues include vertical and horizontal feature displacement, displacement of a feature parallel to lines-of-splay, and horizontal and vertical displacement between two scene features.

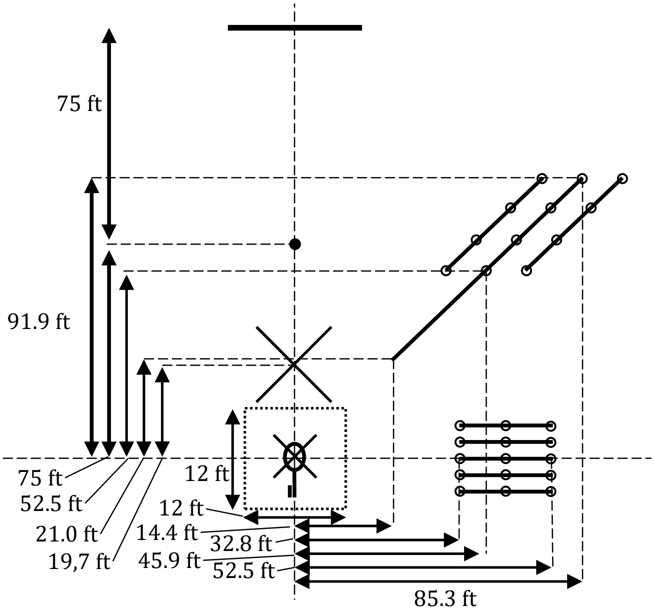


Figure 4.4: Conceptual top-view image of the dimensions of the employed hover courses.

backdrop. This is needed to calculate the relative visual displacement in front of the backdrop. In case of a backdrop at very large distances or near infinity, $l_2 \rightarrow \infty$, the relative displacement and the absolute displacement become (almost) identical.

4.4.1. ADS-33 geometry

First, the ADS-33 course visual cues are discussed, which comprise the hover board and the lateral and diagonal cones/lines. Figure 4.4 shows a top-down view of the course setup, including all necessary distances and dimensions. Figure 4.2a shows how the course setup is visible to the pilots inside the simulator. Altitude and lateral position are determined in the same way, by observing the visual position of the top of the stick in front of the hover board. The relevant visual displacement angle δ_v is therefore not the absolute change of the visual location of the top of the stick, but its relative movement in front of the hover board, taking into account l_2.

As an example, at the optimal hover point, both distances are equal, $l_1 = l_2 = 75\,\text{ft} \approx 22,86\,\text{m}$. This results in a relative visual displacement of the top of the stick in front of the hover board of $\frac{\delta_v}{d} = 1.25°/\text{m}$, for both lateral and vertical observer displacement.

For longitudinal position, the pilots can utilise the cones/lines placed diagonally in the front right position, as well as the lateral cones/lines, which are placed directly to the right. Both cues have inherent flaws: the diagonally placed cones do not provide an isolated longitudinal cue. Rather, they provide a cue pertaining to the diagonal position of the helicopter, perpendicular to the direction of the cones/lines.

The laterally placed cones/lines provide an isolated cue, but they are located at the peripheral vision area of the pilot. This means that the pilots need to either use them only through their peripheral vision, which will reduce the visual accuracy, or they need to briefly move their visual focus to the side, covering the hover board and other frontal cues only with their peripheral vision for that time.

Both cones and lines rely on the "alignment" of the middle row of cones/the middle line with the direction of vision. Therefore, the visual displacement $\frac{\delta_v}{d}$ is defined as the displacement of the closest cone on the "backdrop" of the furthest cone. In case of the diagonally and laterally placed lines, the closest end of the centre line is defined as the visual object, the furthest end of the centre line as the backdrop.

4.4.2. Hover box geometry

Secondly, the cues provided by the hover box are discussed. Figures 4.3 and 4.4 show the dimensions of the hover box and its location, Figure 4.2b shows its appearance to the pilots in the simulator. While inside the adequate hover area, only those four edges of the box that are potentially completely visible from the pilots' point of view are considered. These are the top and bottom edges of the box plane facing forward, and left and right edges of the same plane. The maximum value of l_1 is approximately 6.34 m, which is the longest straight field of view possible inside the hover box. The backdrop for every visual displacement is given by the ground grid. Depending on the specific position, l_2 can therefore vary greatly. However, in most positions (and in particular close to the hover target point), the distance to the ground behind the hover box is much larger than the distance between the observer and the hover box, i.e., $l_2 \gg l_1$. To enable a consistent analysis of cues, it is therefore assumed that the visual displacement of the hover box in front of the grid can be approximated by the absolute visual displacement of the respective part of the box.

One peculiar feature of the hover box setup is the complete disappearance of visual cues at certain locations within the adequate hover area. If the ownship position is too close to the front edge of the hover box, neither the vertical nor the horizontal edges are visible anymore. Another complicating characteristic is the potentially infinitely large visual displacement per position, if the ownship approaches one of the edges very closely, effectively reducing l_1 to values close to zero. In both cases, invisible cues and near infinite visual gains, the pilots need to rely on other cues (grid texture and/or ground cross marker) to return to a better hover position.

For longitudinal and lateral positioning, the pilots need to utilise both vertical edges of the forward-facing plane of the hover box. One edge alone can only provide a visual cue for a displacement *perpendicular to the direction of vision towards it*. For example, when hovering at the very left side of the hover box, the left edge of the forward-facing plane provides a cue to purely lateral movement, while the right edge of the same plane provides a visual cue for movement along a diagonal axis facing to the front and left. This "mixing" of longitudinal and lateral cues of these edges is a function of both longitudinal and lateral position.

To stay at the ideal lateral position, the pilots can try to keep the lateral visual angle of both edges as identical to each other as possible, which corresponds to a lateral position in the centre plane. To maintain the optimal longitudinal position is more complicated, as there is no obvious visual "location" of both edges to signify a longitudinal position in the middle of the box. Rather, the pilots need to remember a specific visual angle of both edges that correspond to an optimal longitudinal position. Instead of memorising a specific visual angle, the pilots could also identify a certain element of the backdrop grid texture that the edges need to align with. While possible, this strategy is complicated by the lack of distinctive ground texture features and the aforementioned mixed influence of both lateral and longitudinal movement.

For vertical positioning, the pilots need to align the horizontal markers on both vertical box edges with the artificial horizon. While the longitudinal position in the hover box can influence the visual displacement per observer displacement, it does not influence the validity of the optimal position of the cue — if the markers align with the artificial horizon (and are visible), the altitude is optimal, regardless of longitudinal position. As a second option, pilots can utilise the top and bottom edge of the forward-facing plane as cues for vertical displacement. In this case, however, there is no clear optimal position, and the cues provided are influenced by both vertical and longitudinal positioning.

4.4.3. Visual gain analysis

Table 4.2 contains visual gain values for all discussed visual cues. All values are also provided for the most extreme observer positions: the closest and furthest possible position within the adequate hover area on the axis that is spanned by the observer position and the cue position. These positions are defined in Table 4.3.

Table 4.2: Visual gains of different elements of the experiment courses.

Visual gain ($\frac{\delta_v}{d}$ [°/m])	optimal	maximum	minimum	Axis the cue can be used for
Hover board	1.25	1.62	1.00	lateral, vertical (independently)
Lateral cones/lines	2.15	2.97	1.63	longitudinal
Diagonal cones	1.19	1.46	1.00	diagonal, fixed mix longitudinal and lateral
Diagonal lines	5.40	9.34	4.16	diagonal, fixed mix longitudinal and lateral
Box vertical edges	22.15	near infinity	11.08	varying mix longitudinal and lateral
Box altitude markers	22.15	near infinity	11.08	vertical
Box horizontal edges	28.02	near infinity	14.01	varying mix vertical and longitudinal
Cross long./vert.	8.51	12.58	6.43	varying mix vertical and longitudinal
Cross lateral	8.51	12.58	6.43	lateral

The visual gains of the hover board, lateral cones, and diagonal cones are all within the range between $1\,^\circ/m$ and $3\,^\circ/m$. The visual gains of the diagonal lines and the cross ground marker are notably larger, from $4.16\,^\circ/m$ to a maximum value of $12.58\,^\circ/m$. Lastly, the visual gains of the hover box are even larger, ranging between $11.08\,^\circ/m$ and near infinite values at certain positions in the adequate hover area. This is caused by the short distances l_1 between the hover box elements and the observer. This also causes the largest gain variations, doubling between the minimum and the optimal condition, and reaching unbound large values when approaching the maximum.

Table 4.3: Optimal, closest, and furthest observer position for every visual cue.

Position	optimal	closest to cue	furthest from cue
Hover board	centre of adequate hover area	Edge of adequate hover area closest to hover board, i.e., on the front edge	Edge of adequate hover area furthest from hover board, i.e., on the back edge
Lateral cones/lines	centre of adequate hover area	Edge of adequate hover area closest to cones, i.e., on the right edge	Edge of adequate hover area furthest from cones, i.e., on the left edge
Diagonal comes	centre of adequate hover area	Edge of adequate hover area closest to cones, i.e., on the front right edge	Edge of adequate hover area furthest from cones, i.e., on the back left edge
Diagonal lines	centre of adequate hover area	Edge of adequate hover area closest to lines, i.e., on the front right edge	Edge of adequate hover area furthest from lines, i.e., on the back left edge
Box vertical edges	centre of adequate hover area	Edge of adequate hover area closest to a vertical edge, i.e., on the front left or front right edge	Edge of adequate hover area furthest from a vertical edge, i.e., on the back left or back right edge
Box altitude markers	centre of adequate hover area	Edge of adequate hover area closest to an altitude marker, i.e., on the front left or front right edge	Edge of adequate hover area furthest from an altitude marker, i.e., on the back left or back right edge
Box horizontal edges	centre of adequate hover area	Edge of adequate hover area closest to a horizontal edge, i.e., on the front top or front bottom edge	Edge of adequate hover area furthest from a horizontal edge, i.e., on the back top or back bottom edge
Cross long/vert	centre of adequate hover area	Edge of adequate hover area closest to the cross, i.e., on the front bottom edge	Edge of adequate hover area furthest from the cross, i.e., on the back top edge
Cross lateral	centre of adequate hover area	Edge of adequate hover area closest to the cross, i.e., on the front bottom edge	Edge of adequate hover area furthest from the cross, i.e., on the back top edge

If the pilot model developed in Chapter 3 is applied to the calculated visual gains and a constant, non-oscillating displacement around the optimal hover position is assumed, the calculated visual gains can be connected to the resulting control input. Table 4.4 shows values for this relationship for each combination of visual cue and control axis. The required control input (cyclic or collective, depending on the direction of displacement) when using the hover board, lateral cones/lines, and diagonal cones is in the range between $0.29\,^\circ/^\circ$ and $0.94\,^\circ/^\circ$. The values shrink down to a range between $0.06\,^\circ/^\circ$ and $0.17\,^\circ/^\circ$ when using the diagonal lines, and to values between $0.02\,^\circ/^\circ$ and $0.04\,^\circ/^\circ$ when using the hover box elements as visual cues. The ground cross marker requires gains between $0.06\,^\circ/^\circ$ (for lateral and vertical displacement) and $0.14\,^\circ/^\circ$ (for longitudinal displacement).

Table 4.4: Control deflection per perceived angular visual deflection at a constant displacement around the optimal hover position, based on the pilot model developed in Chapter 3.

Control deflection per visual displacement ($^\circ/^\circ$)	longitudinal	lateral	vertical
Hover board	not possible	0.39	0.94
Lateral cones/lines	0.62	not possible	not possible
Diagonal cones	0.79	0.29	not possible
Diagonal lines	0.17	0.06	not possible
Box vertical edges	0.04	0.02	not possible
Box altitude markers	not possible	not possible	0.05
Box horizontal edges	0.03	not possible	0.03
Cross long/vert	0.14	not possible	0.06
Cross lateral	not possible	0.06	not possible

Switching from the good visual ADS-33 course setup to the geometric ADS-33 setup, and further to the hover box setup, gradually increases the values of the available visual gains and reduces the required control deflection per perceived visual displacement angle. Large visual gains might be beneficial in a precision manoeuvre like hovering, as deviations from the optimal position become more easily apparent. This could lead to a better hover performance. However, larger gains also have the drawback of a larger variability. Depending on the observer position, the pilots need to account for this change in visual gain to maintain a steady control strategy. It is hard to predict which effect will dominate. Therefore, the performance ratings and pilot comments collected after the experiment might provide a better insight into these effects.

4.5. Methodology

This section describes the setup and methodology of the performed exploratory study. It is important to note that the intention is not to perform a statistically sound experiment, but to gather initial data to frame the presented theoretical analysis. The goal is to use the results of the theoretical analyses of Chapters 3 and 4 to inform the design of the experimental studies performed in Chapters 5 and 6. The results of the study described in this chapter should only be treated as anecdotal evidence, not as reliable scientific findings.

4.5.1. Apparatus

The exploratory study was conducted in the SIMONA Research Simulator (Stroosma et al., 2003), shown in Figure 4.5. During the study, the simulator was set up in helicopter configuration, equipped with pedals, a cyclic stick and a collective lever. The out-the-window visual, produced by a collimated system with three LCD projectors with each a resolution of 1280×1024 and a refresh rate of 60 Hz, did not include a chin bubble and was therefore more limited than in real helicopters. The field of view of $180^{\circ} \times 40^{\circ}$ was similar to that available to pilots in cockpits of fixed-wing aircraft (see Figure 4.5, right).

The motion system of the simulator was not used. As the study focused on investigating whether the developed augmented reality displays alone contained sufficient information for pilots to achieve satisfactory hover performance, it was important to isolate the effects of the visual system as much as possible. If motion cueing would be involved as well, the information of the visual and vestibular system would be combined into an integrated perception of motion and orientation, thereby reducing the pilot’s reliance on and attention for the displays.

4.5.2. Participants

Two helicopter pilots with a commercial pilot license participated voluntarily in the study. Participants had a similar level of experience, with number of flight hours ranging from 200 to 225.

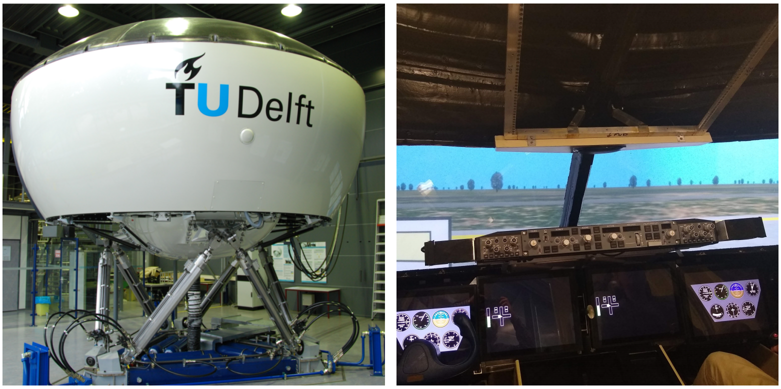


Figure 4.5: SIMONA Research Simulator.

4.5.3. Control task

The task (which is the same as in Chapter 3) and the performance boundaries were based on the hover manoeuvre described in the ADS-33 (Anonymous, 2000). Initial positions were quasi-randomised (standard deviation 10 m) around the point 100 m directly in front of the hover target, which was at a height of 10 ft. The pilots were instructed to approach the target location with the initial forward speed of 10 m/s, decelerate so as to come to a stop precisely at the hover point and then maintain a stabilised hover for 30 seconds. Pilots were encouraged to perform a smooth transition, avoiding decelerating well in advance and then slowly moving toward the target.

4.5.4. Independent variables

The independent variables in the study were *display configuration* and *vehicle dynamics*. The two developed displays were provided, one at a time, as overlays on the out-the-window view of the pilot, which was obscured by a simple simulation of a brownout cloud. A condition with good visibility and no hover display, but with the ADS-33 hover course clearly visible, served as a baseline for comparison. Pilots flew these display configurations with both a non-linear and a linear helicopter model, resulting in a total of six conditions (Table 4.5). The order of conditions was balanced between subjects to avoid measuring a structural learning effect. Each condition was repeated six times, resulting in a total of 36 runs per pilot (excluding warm-up and acclimatisation runs).

Visibility and display

The hover course described in the ADS-33 (Anonymous, 2000) served as the scenery for the good visibility conditions (see Figure 4.2a). In the remaining conditions, a simulated brownout cloud obscured the outside view and one of the displays was superimposed on the cloud. In these conditions, the visual representation of the outside scenery was removed entirely, in order to avoid it being visible momen-

Table 4.5: Investigated conditions.

Conditions Display configuration	Vehicle dynamics non-linear	 linear
Good visibility, no HUD augmentation	A	B
Brownout, display 1 (grid and box)	C	D
Brownout, display 2 (ADS-33 on HUD)	E	F

tarily in between simulated brownout clouds.

The outside scenery, brownout simulation, and hover displays were developed using the open-source 3D graphics library OpenSceneGraph in C++. A simple brownout simulation was implemented using a particle system in OpenSceneGraph, similar to the approach employed by Gerlach (2011). This system was configured to form a cloud by generating hundreds of sand-coloured particles at every time step, each particle with random initial position, rotation, velocity, rotational velocity, lifetime, and colour settings (each within a specified range). All generated particles were subject to a simple upward acceleration. The brownout condition can be considered as a as a severely degraded visual environment with occasional false motion cues due to the motion of the brownout clouds.

Vehicle dynamics

Two distinct vehicle dynamics were employed in the study. The first was an in-house non-linear six-degree-of-freedom Messerschmitt-Bölkow-Blohm Bo105 (MBB Bo 105) helicopter model (Miletović et al., 2017) with a rate-damping stabilisation system, as was used in Chapter 3. The alternative was a linear MBB Bo 105 model obtained from Padfield (1981, 2007) based on Helisim. It is the same model that was used in Chapter 3 to tune the pilot models. In this model, every degree-of-freedom is decoupled such that no cross-couplings occur. These simplified dynamics can be regarded as a model of a more heavily augmented helicopter. However, more advanced control types like attitude hold or translational rate command are not part of this design.

4.5.5. Dependent measures

The control task can be split up in two distinct phases: approach and hover. Where applicable, a separate analysis of the two phases was performed.

Hover performance was measured with the root-mean-square (RMS) error of the helicopter's vertical, longitudinal, and lateral position relative to the target location, during 30 seconds after reaching adequate performance for the first time. The boundaries for desired and adequate hover performance as stipulated in the ADS-33 are listed in Table 4.6. The relative time spent within these boundaries also served as a measure for hover performance. The differences in additional track meters travelled and in the duration of the approach phase between the various conditions were used as a metric for performance during approach.

Control activity was measured, separately during approach and hover, as the standard deviations of the longitudinal cyclic, lateral cyclic, collective and pedals.

Table 4.6: Performance boundaries from the ADS-33.

Parameter	Desired	Adequate
Longitudinal deviation	±3 ft	±6 ft
Lateral deviation	±3 ft	±6 ft
Altitude deviation	±2 ft	±4 ft

Pilot workload scores were collected after each condition with the Rating Scale Mental Effort (RSME, developed by Zijlstra and Van Doorn (1985), as cited by de Waard (1996)). Subjective scores of situation awareness were measured with the Situation Awareness Rating Technique (SART) (Taylor, 1989). A collection per condition enabled the performance of more data collection runs, compared to a collection after each run. In addition, both participants did not have extensive experience with experimental procedures — it was expected that a workload and situation awareness collection after each run (so 36 times in total) could lead to a questionnaire-"weariness" in the participating pilots, which could have negatively impacted the thought and reflection they exert to fill in the questionnaire. It was decided that these advantages of taking measurements only once per condition outweigh the disadvantages of only collecting one data point per condition, which prohibits the analysis of changes of these dependent measures between runs.

Finally, pilots were asked to fill out questionnaires about the simulator setup and the investigated conditions. These questions were rated on a seven-point scale (1 = low, 7 = high; no descriptors for intermediate values). Table 4.7 shows an overview of all collected data.

Table 4.7: Overview of dependent measures.

Category	Dependent measure
Performance	Root-mean-square of longitudinal deviation
	Root-mean-square of lateral deviation
	Root-mean-square of vertical deviation
	Root-mean-square of absolute deviation
	Time ratio spent inside desired hover boundaries
	Time ratio spent inside adequate hover boundaries
	Time ratio spent outside of hover boundaries
	Approach duration
	Additional track meters during approach
Control activity	Standard deviation of longitudinal cyclic input
	Standard deviation of lateral cyclic input
	Standard deviation of collective input
	Standard deviation of pedal input
Workload	Rating scale mental effort (RSME)
Situation awareness	Situation awareness rating scale (SART)
Pilot preference	Confidence using displays

4.5.6. Control variables

During all conditions and runs, the control task and the simulator setup remained unchanged. Figure 4.6 shows the head-down basic instrument panel which was available throughout the study.

Figure 4.6: Basic instrument panel.

4.5.7. Procedure

Before the start of the study, participants were familiarised with the questionnaires and informed on 2020's active COVID-19 protocols at the faculty. During the acclimatisation period, the pilots performed multiple practice runs for each condition in order to get acquainted with the simulator and the procedure. Every condition started with several warm-up runs, followed by six data collection runs. The RMS deviation from the target location during the 30-second hover phase was communicated to the pilots as a hover performance score when a run was completed. Runs during which the helicopter collided with the ground were immediately abandoned and restarted, their data was not used.

After the first and last run of a condition, physical well-being of the participants was assessed by asking them to rate their discomfort on the Misery Scale (Bos et al., 2005). Workload and situational awareness questionnaires were completed after each condition. At the end of the study, a pilot opinion questionnaire was distributed to obtain more insight on their subjective experience with the displays and helicopter models. Figures B.3 to B.5 in the appendix show the respective questionnaires.

4.5.8. Data processing

The control task during the study consisted of two distinct phases: the approach phase and the hover phase. To analyse each part individually, the data recordings were separated into two parts. The time step at which the participant entered the adequate performance boundaries (Table 4.6) for the first time during a run was taken as the starting point of the hover phase for that specific run.

Each participant completed the workload (RSME) and situation awareness (SART) questionnaires once for every condition. These ratings were Z-scored to have a mean of 0 and a standard deviation of 1 for each pilot, in order to compensate for possible subjective differences in scoring.

No statistical tests were performed on the results. With only two participants, such analysis was not expected to provide reliable results.

4.5.9. Hypotheses

Performance is hypothesised to decrease in degraded visual conditions relative to good visibility. Pilot situation awareness is lower than in clear conditions, due to the lack of available outside cues and the possible false cues generated by the motion of the simulated brownout clouds. In turn, reduced situation awareness, in combination with pilots using a novel display, is hypothesised to lead to higher workload and control activity. The effect is expected to be more pronounced in conditions with Display 2 (ADS-33), because the grid ground texture in Display 1 provides relatively more optical flow and edge rate information than the synthetic ADS-33 course.

The cross-couplings of the non-linear model more realistically simulate the behaviour of a conventional helicopter without sophisticated control augmentations in hover. Considering that the participants are experienced helicopter pilots, the response of the decoupled linear model may be somewhat unexpected for the pilots at first. However, participants are given ample time to get acquainted with all conditions, and, since the target location is directly ahead of the starting point, expected heading changes are minimal. This should lower the difference experienced between the models by the pilots. Moreover, linear dynamics are typically considered easier to control than non-linear types. Therefore, control activity and workload are hypothesised to decrease with the linear model, while performance is expected to increase. Due to the lower workload and control activity, also situation awareness increases.

4.6. Results

The effects of display configuration and vehicle dynamics on the dependent measures are presented in this section. First, the time trajectories of the input and state variables are analysed. Then, the measures of performance and control activity are presented. Finally, subjective pilot ratings on situation awareness and workload, and the responses to the opinion questionnaire are provided. No statistical analysis is performed, as only two pilots participated.

Runs during which pilots hit the ground were immediately abandoned. This only occurred once during the study, utilising display 2 with linear model dynamics. Because of this low number of occurrences, no analysis is based on this observation.

4.6.1. Time trajectories

As a preliminary analysis, the time recordings of the input and state variables are plotted. The hover target was positioned approximately 100 m straight-ahead from the initial location, therefore only the time trajectories of variables involved in longitudinal motion adequately capture both the approach and hover phase. Figure 4.7

shows the time traces of the variables associated with surge motion (longitudinal cyclic input θ_{1s}, longitudinal position x and velocity u, pitch angle θ and pitch rate q) for one run per condition.

Although the trajectories presented here are of one pilot and one run per condition only, comparable profiles are obtained for the other pilot and runs. Similar trends are noticeable in the position and velocity profiles, indicating that the participants employed a similar strategy regardless of condition. The pilots performed most of the deceleration during the first fifteen seconds in all conditions. However, as evidenced by the longer duration of those runs, it took the pilots considerably more effort to first reach adequate performance with Display 2 (ADS-33) than in the other conditions, despite the comparable decelerating approach.

An explanation for this difference is provided by the ground tracks, see Figure 4.8. The cluster slightly in front of the target location, clearly visible especially in the linear model curve, suggests that depth perception was worse in these conditions as the pilot was unable to accurately locate the longitudinal location of the target.

4.6.2. Performance

Hover position RMS error

The RMS distance between the target location and the helicopter position serves as a measure for task performance during the hover phase. Figures 4.9 and 4.10 show boxplots of the longitudinal (x), lateral (y), vertical (z), and combined three-dimensional position RMS error. For one run (pilot 2, Display 1, non-linear model, third run), the vertical RMS error was a factor five larger than for the other runs. Therefore, that run was considered an outlier and omitted from further analysis.

For all conditions, the longitudinal RMS error was larger than the lateral and vertical errors. One reason for this larger error is that the approach phase was longitudinal, thus the deceleration manoeuvre was also predominantly along this axis. As a result of the decelerating approach, some longitudinal oscillatory motion was likely still present. Furthermore, the start of the hover phase was defined as the first time step in which adequate performance was reached. As the optimal trajectory was a straight, purely longitudinal path, in most cases the error in x at the start of the hover phase corresponded to adequate performance at best, whereas vertical and lateral position were closer to their target values. Finally, another possible reason is that longitudinal cues were the least readily available position cues in each of the displays.

Interestingly, longitudinal performance was better and more consistent with Display 1 (grid and box) than in clear conditions (upper boxplot in Figure 4.9). Contrary to the hypothesis that performance would decrease in degraded visual conditions, performance with the grid and box of Display 1 was overall comparable or slightly better than performance in the baseline condition.

The spread of data points in the boxplots is an indication of the level of precision in performances for a certain condition. Performance was worst for runs with Display 2 (ADS-33); the RMS errors in the four plots not only generally exhibit the least precision, they were also higher in those conditions.

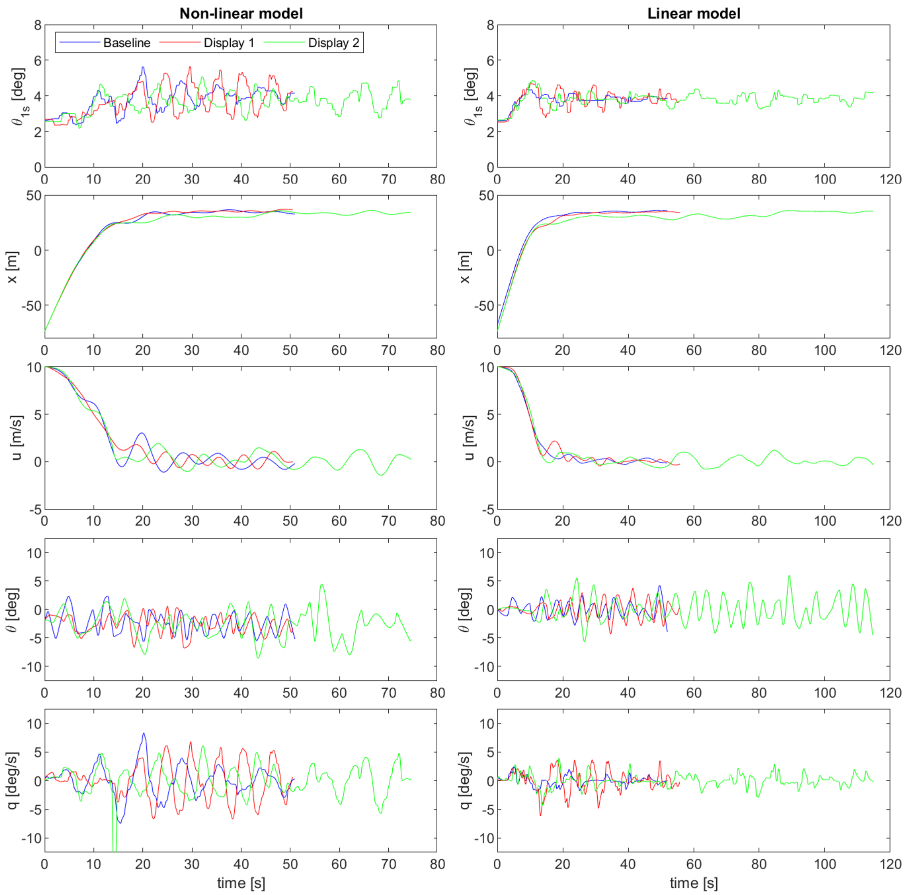


Figure 4.7: Time trajectories of surge motion variables, one run per condition. Note that the time trajectory of the shown run with Display 2 is considerably longer than the other runs because the adequate hover boundary was entered at a later point in time.

Performance is similar between the non-linear and linear vehicle models. No clear influence of vehicle dynamics is noticeable in terms of RMS errors.

Time spent inside boundaries

In general, pilots were unable to consistently remain within the adequate and desired performance boundaries stipulated in the ADS-33 (see Table 4.6) for the entire 30-second hover phase. Boxplots of the fraction of hover time spent inside these zones, depicted in Figure 4.11, demonstrate that consistent adequate performance was achieved only in conditions with Display 1. This display, in combination with the linear model, resulted on average in desired performance during approximately two-thirds of the hover time and adequate performance during the entire hover. With Display 1, time spent inside the boundaries increased with the linear model. However, no clear influence of vehicle dynamics was present in the other conditions.

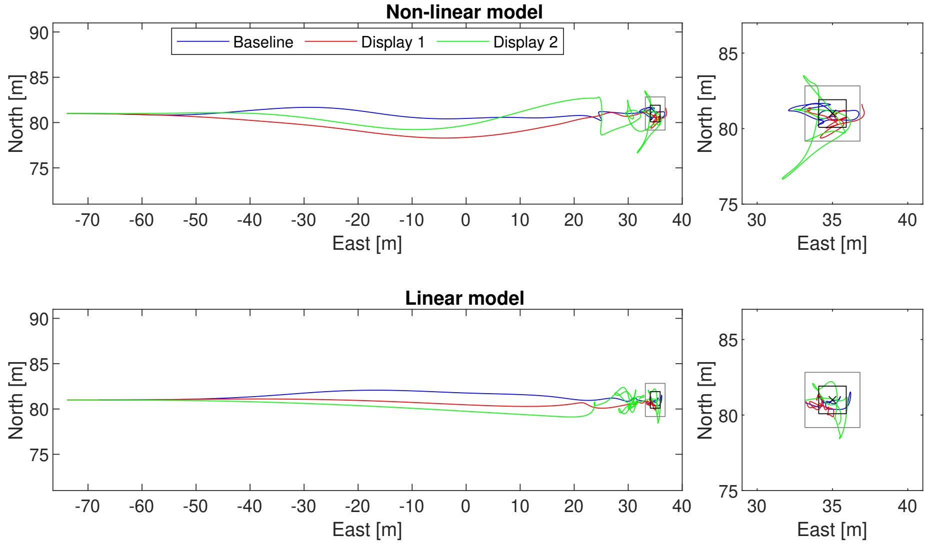


Figure 4.8: Ground tracks during full run (left) and during hover (right), one run per condition.

Pilots performed better in good visibility (baseline) than with Display 2.

Approach duration and additional track meters

The time trajectories illustrated that pilots took longer to reach the target within adequate distance in runs with Display 2. Therefore, the approach duration and the additional distance travelled relative to the shortest path were regarded as indicators of performance during the approach phase.

The average approach time, as shown in the boxplot of Figure 4.12, was longest with the Display 2 and shortest for the baseline condition. Furthermore, relative extra distance travelled (Figure 4.13) was considerably larger with Display 2. In terms of this distance metric, similar performance was achieved between conditions with Display 1 and conditions in good visibility. Regarding vehicle dynamics, no clear influence was observed in these metrics.

4.6.3. Control activity

Standard deviation of control inputs during hover

Boxplots of the standard deviations of the four input channels during hover are presented in Figure 4.14. Regarding longitudinal cyclic, the condition with Display 1 and non-linear dynamics stands out for its much higher measure of control activity than the other conditions. Moreover, a trend of decreasing control activity when switching from non-linear to linear vehicle dynamics is visible.

Whereas the standard deviation of longitudinal cyclic input θ_{1s} exhibits no clear influence of display conditions, in the lateral case control activity is lower in good visibility than with either of the developed displays. Standard deviation of lateral

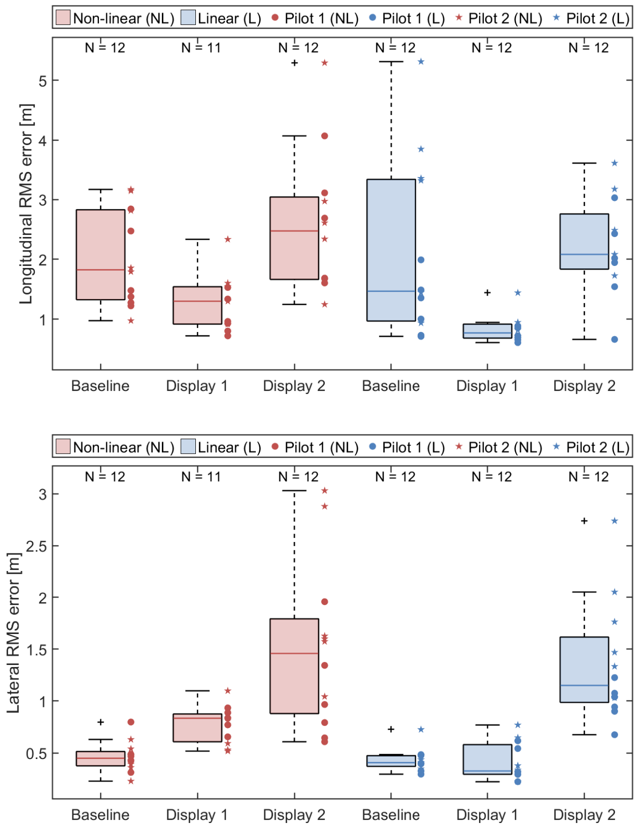


Figure 4.9: Boxplots of the RMS error in longitudinal and lateral position.

cyclic θ_{1c} was comparable between the four degraded visual conditions, and also between the two vehicle models.

Collective control activity was similar in each of the conditions and appears largely unaffected by both vehicle model and display configuration. Noteworthy, however, is the difference in control activity between the two pilots; for every condition, nearly all data points above the median belong to pilot 2. This implies that the pilots employed a somewhat different strategy during the hover phase, with pilot 2 being more reliant on the collective.

Finally, pedal control activity was higher with the non-linear than the linear model. However, this difference is at least partly explained by recalling that the linear model is a linearized and decoupled version of the non-linear dynamics. More pedal control activity is required to compensate for the cross-coupling effects present in the non-linear model.

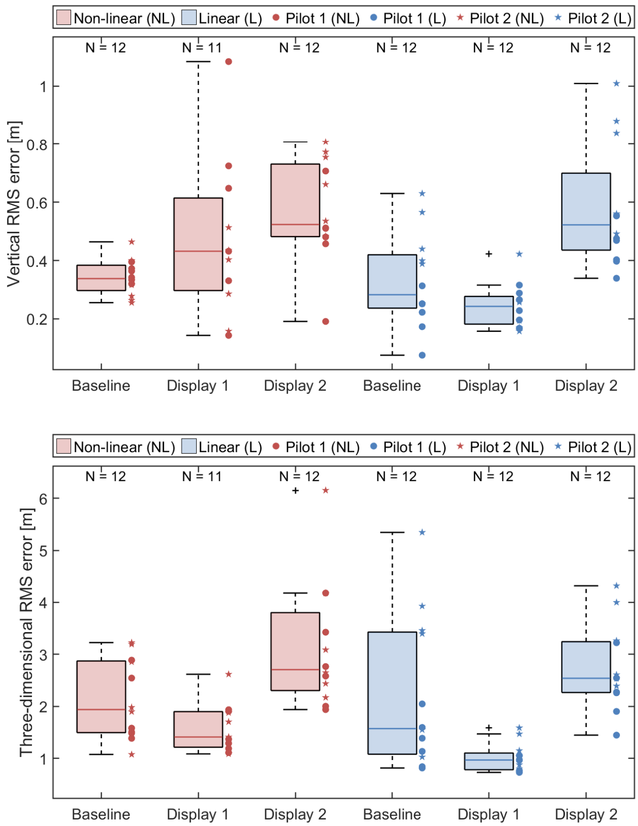


Figure 4.10: Boxplots of the RMS error in vertical and three-dimensional position.

Standard deviation of control inputs during approach

During the approach phase, an unambiguous trend of increased control activity with the non-linear model is visible in the boxplots for each of the input channels, see Figure 4.15. However, no difference in control activity can be witnessed between display conditions during the approach phase.

4.6.4. Workload

Referring to Table 4.8, pilots experienced higher mental effort in runs with the non-linear model than with the linear model. Furthermore, workload was rated higher in degraded visual conditions than in good visibility. Overall, these findings are in line with the hypotheses. However, a more noticeable difference was expected between Display 1 and 2.

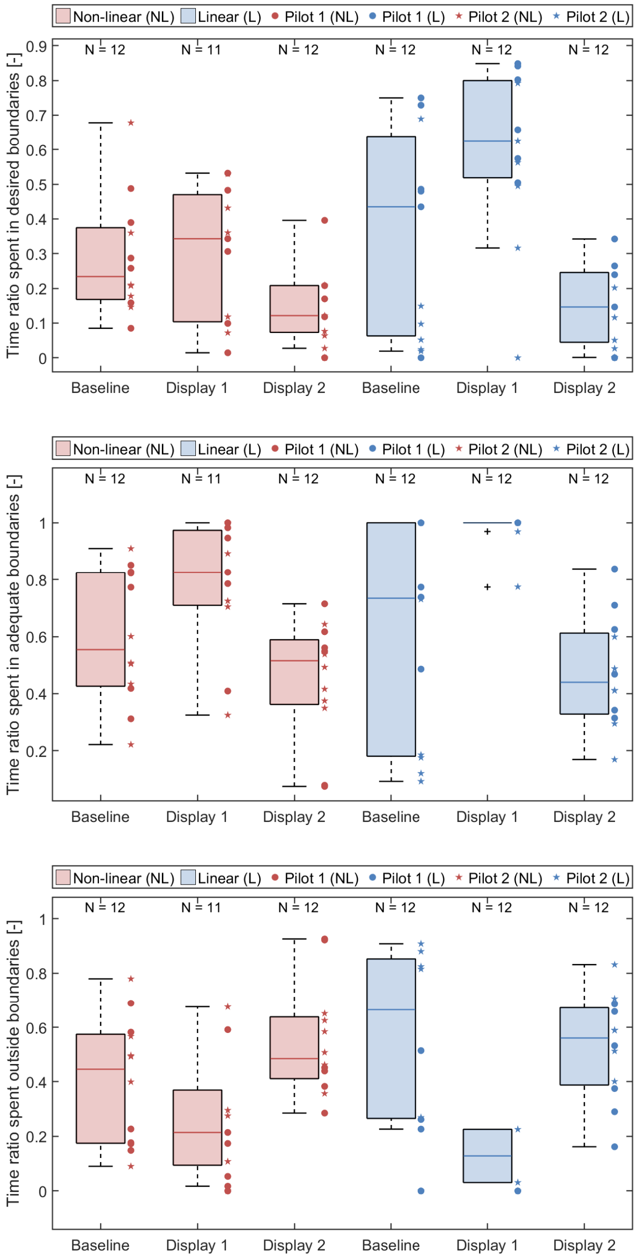


Figure 4.11: Boxplots of time spent in desired (top), adequate (middle), and inadequate (bottom) performance boundaries.

4

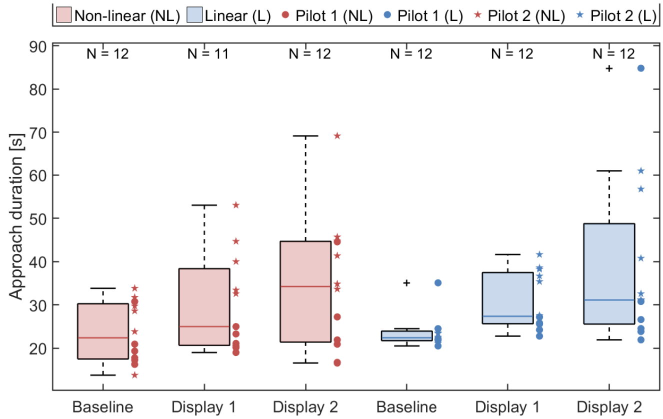


Figure 4.12: Boxplot of the approach duration.

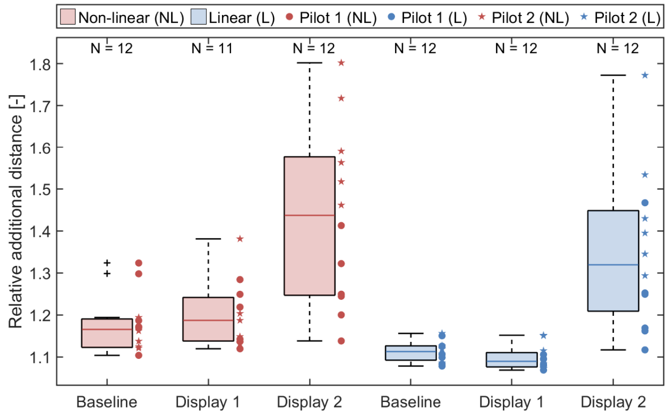


Figure 4.13: Boxplot of the additional track meters during approach.

Table 4.8: Z-scored workload ratings.

	Baseline		Display 1		Display 2	
	non-lin.	linear	non-lin.	linear	non-lin.	linear
Pilot 1	−0.81	−1.29	1.61	0.16	0.16	0.16
Pilot 2	−0.72	−1.21	0.52	−0.39	1.60	0.19
Mean	−0.76	−1.25	1.07	−0.11	0.88	0.18

4.6.5. Situation awareness

The results, shown in Table 4.9, demonstrate that pilot situation awareness was higher in good visibility than with either of the developed displays, as was expected. Furthermore, the linear model led to improved situation awareness compared to the non-linear model, confirming the hypothesis.

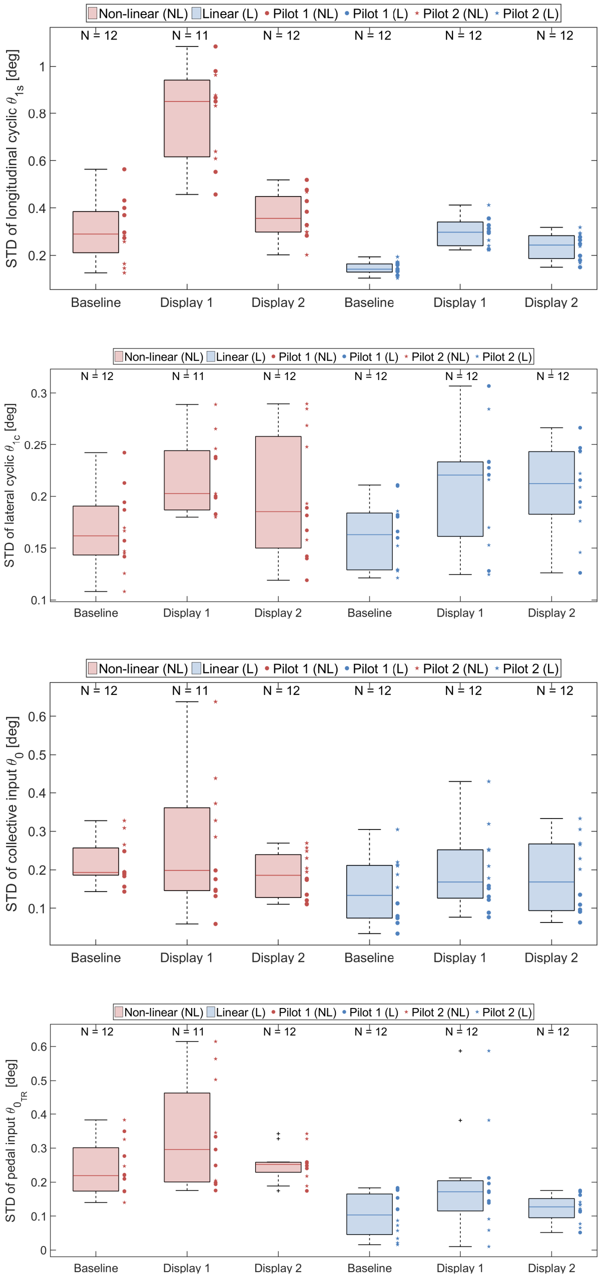


Figure 4.14: Boxplots of control input standard deviation STD during hover; from top to bottom: longitudinal cyclic, lateral cyclic, collective, pedals.

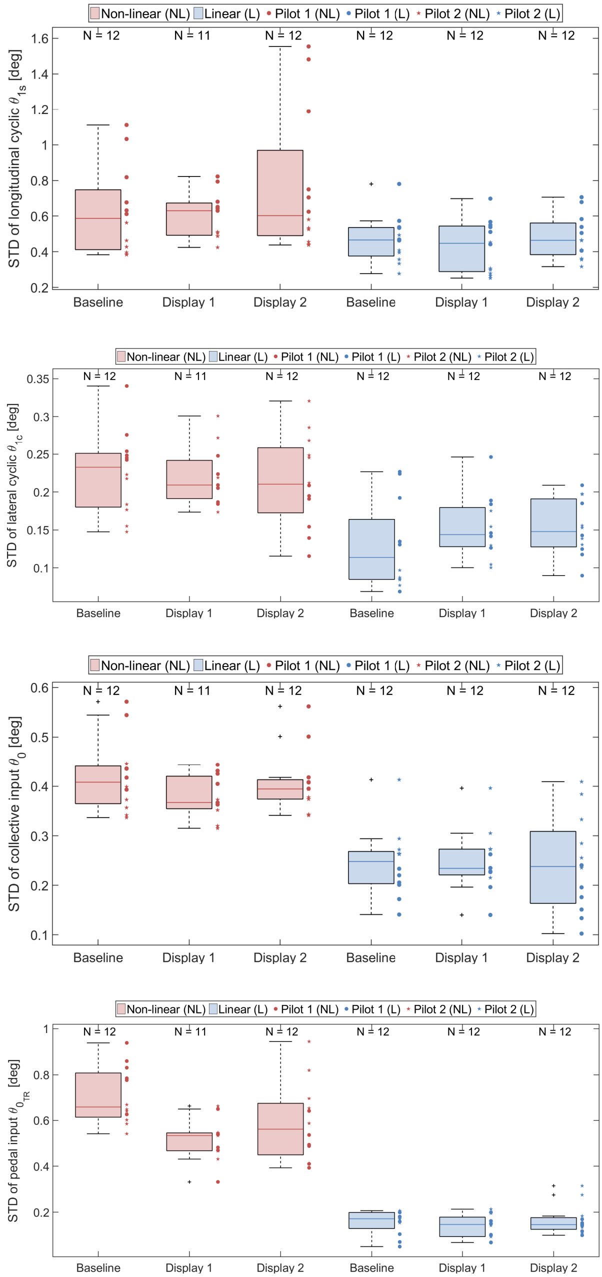


Figure 4.15: Boxplots of control input standard deviation STD during approach; from top to bottom: longitudinal cyclic, lateral cyclic, collective, pedals.

Table 4.9: Z-scored situation awareness ratings.

	Baseline		Display 1		Display 2	
	non-lin.	linear	non-lin.	linear	non-lin.	linear
Pilot 1	0.91	1.51	−1.1	−0.70	−0.30	−0.30
Pilot 2	−0.05	1.69	−0.92	0.39	−1.06	−0.05
Mean	0.43	1.60	−1.01	−0.16	−0.68	−0.18

4.6.6. Pilot opinion

The outcome of the pilot opinion questionnaires provides further information on the usefulness of the displays. One pilot reported having difficulty in judging longitudinal position with both types of ADS-33 display (i.e., both good visibility and Display 2), as it was not clear for this participant which longitudinal line (Display 2) or row of cones (baseline condition) to align with. With regards to Display 2, the same pilot further noted having difficulty perceiving altitude except when flying very close to a marker line.

Both pilots pointed out that a slight overshoot when inside the hover box of Display 1 caused them to leave the box and lose reference of the target. Interestingly, concerning his confidence in fulfilling the task, pilot 1 gave a score of 3/7 for Display 1 compared to 6/7 and 5/7 for good visuals and Display 2, respectively, while performance with that display was in fact comparable to the baseline condition. The second pilot rated all displays with the maximum 7/7.

4.7. Discussion

This theoretical analysis and exploratory simulator study investigated the effects of two conformal symbology displays and two different vehicle models on hover performance, control activity, workload, and situation awareness. The presented results provide some useful insight on the differences between the various display configurations and the two vehicle models. Table 4.10 shows a summary of the main observations.

4.7.1. Displays

Interestingly, in terms of hover performance, Display 1 (grid and box) allowed similar and at times even better performance than in good visibility. Not only did that display configuration have the lowest RMS position error, it was also the only condition that allowed pilots to consistently stay within adequate performance boundaries during hover. These results are in contrast with the hypothesis that performance would decrease in degraded visual conditions. A possible explanation for these results is that, when hovering at the target location, the cues included in the box are close-by, and the grid provides a sufficient approximation of a well visible ground texture. Therefore, a small displacement leads to relatively large apparent deviation from the target, allowing the pilots to remain closer to the target than with the ADS-33 hover board. However, a limitation of this display was the lack of references when outside the adequate hover area; if pilots moved beyond the box in

Table 4.10: Summary of main observations.

Performance	
Longitudinal deviation	Generally larger than lateral and vertical deviation
Lateral deviation	
Vertical deviation	
Absolute deviation	Display 2 showed increased deviation
Time spent in desired boundaries	
Time spent in adequate boundaries	Display 1 showed increased adequate performance, in particular with linear model
Time spent outside of boundaries	
Approach duration	Display 2 showed increased approach duration
Additional approach track meters	Display 2 showed increased approach track
Control activity	
Longitudinal cyclic input	Display 1 showed increased activity during hover, linear model showed decreased activity during hover and approach
Lateral cyclic input	Good visibility showed decreased activity during hover, linear model showed decreased activity during approach
Collective input	Linear model showed decreased activity during approach
Pedal input	Linear model showed decreased activity during hover
Workload	
RSME	Linear model and good visibility showed decreased workload
Situation awareness	
SART	Linear model and good visibility showed increased situation awareness
Pilot preference	
Confidence using displays	Display 1 showed lower confidence

certain directions, they lost all reference of the target location.

Display 2 (geometric version of the ADS-33) performed worse both during approach and during hover. Pilots reported having difficulty judging their altitude, especially in the approach phase. This was most likely due to the low amount of optic flow available in this interface, as it lacked the ground texture present in good visibility and in Display 1.

For all conditions, the RMS error was largest in the x-axis. This was in part likely due to the longitudinal approach, which caused a relatively large longitudinal error at the start of the hover phase, and which may have also led to some remnant oscillations along that axis. However, it is possible as well that longitudinal positioning cues were less readily available than lateral or vertical cues. For Display 2, this outcome is in line with results from an experiment in which a similar ADS-33 overlay was provided on a narrow field-of-view HMD (Viertler, 2017).

Considering control behaviour, pilots were found to apply a similar decelerating approach with each of the display configurations. This is further supported by the finding that, during the approach phase, control activity was comparable between display conditions. During hover, however, control activity was higher in degraded visual conditions, especially when considering inputs on the lateral cyclic. In terms of longitudinal control, Display 1 in combination with non-linear dynamics exhibited much larger control activity than other conditions. Again, this may be an effect of the close proximity of the available cues when using this display; deviations may seem larger than they are, leading to increased corrective action. Higher control activity in degraded visual conditions is in line with the hypothesis, but the difference between the two display configurations is less notable than expected.

Results of the subjective ratings on situation awareness and workload show similar trends. As predicted for degraded visual conditions, situation awareness decreased and workload increased relatively to the conditions with clear visuals.

4.7.2. Helicopter dynamics

The helicopter dynamics had a noticeable influence on control activity. Both during approach and hover, the non-linear, coupled model required considerably more control activity than the linear, decoupled model. In turn, this led the pilots to rate their workload to be higher and situation awareness to be lower in conditions with the non-linear, coupled model. These findings are in line with the hypothesis. However, it was expected to also see a clear effect of vehicle model on performance measures, but no general influence was detected. Only Display one seemed to enable an increased time spent in desired hover boundaries and a reduction of the three dimensional deviation from the target hover point when utilising linear model dynamics. This implies that vehicle dynamics were usually not a limiting factor on performance; instead, in order to ameliorate performance, the availability of positioning cues in the display configurations should be improved.

4.7.3. Control-theoretic analysis

It might be possible that the pilots did not use the visualisations of the performance boundaries, the box and the hover board/cones, for the continuous motion control, but rather the flow field information and other cues provided by the ground texture. Assuming this is true, the hover box and hover board/cone course elements only need to serve as a visualisation of the performance boundaries, against which the pilots can "check" their position occasionally. This adequacy check might be easier to perform with the hover box because its visual cues change drastically when moving towards its edges. In contrast, the geometric ADS-33 setup of Display 2 eliminates many cues typically provided by a ground texture. In addition, the visual cues of the hover board require some more mental "parsing", as the pilots need to compare the position of the top of the stick with its location on the hover board, on a relatively small portion within their visual field.

This could explain the, at first glance, contradicting result of comparable or even better hover performance with the hover box setup of Display 1, compared to the good outside visuals or Display 2. The hover performance seems most impacted by the existence of ground texture or a ground grid, which provides the natural ego motion perception cues helicopter pilots are used to, and which is absent in Display 2. The remaining course elements serve only as a visualisation of the adequate performance boundaries. It is hypothesised that with Display 1, the ground texture or grid is used for the continuous motion control, while the hover box provides unambiguous and clear cues when the performance boundaries are left. Display 1 therefore provides continuous motion cues through the ground grid which are comparable to the baseline display, while also providing a clearer performance boundary clue.

In theory, the replication of the ADS-33 hover course in Display 2, as explained in ADS-33 (Anonymous, 2000), should provide comparable results to the ADS-33 course in good visuals. However, this is not the case. That is because a critical component of visual cues, far-field references and ground textures, are not explicitly described as part of the ADS-33 course. It is clear that at least basic ground textures and visual scenery is implicitly expected, and it can be reasonably assumed that every real-world course setup includes some form of ground texture and far-field visual references. However, this is never explicitly stated in ADS-33, which explains the worse results of Display 2, the exact replication of the described course elements as a HUD. To improve the robustness of standardised course descriptions (such as in ADS-33), the underlying assumptions of available visual references should be more clearly stated.

The developed displays are focusing only on the task and the necessary parameters (position, attitude), and how these could be theoretically perceived. The setup of the study did not take into account the large influence of providing a natural representation of a typical helicopter work domain, i.e., scenery with ground texture and far-field references. Therefore, future research should investigate design philosophies that focus on the work domain and the "ecology" of helicopter operations, and compare these with more traditional, task-oriented displays and support systems. To a certain extent, this has been done inadvertently in this chapter, and should be the clear focus of the next chapters.

4.7.4. Recommendations

Although no statistical tests were performed, some trends could be discerned from the results that point to possible improvements in future versions of the visual augmentations. Longitudinal positioning cues were less readily available than lateral or vertical ones, in each of the displays. Even in good visibility, pilots described experiencing difficulties finding the right information in the ADS-33 course for accurate longitudinal positioning during hover. These issues were further amplified in the geometric ADS-33 version (Display 2), probably due to the lack of ground texture. In good visibility, pilots are instructed to use a point of reference far away in the visual field to stabilise their hover. Such a point of reference was presently not available in Display 1 (once inside the box), therefore it is recommended to adjust this configuration for future research to include one. Several methods are possible; for example, by simply adding the reference pole and hover board that are in front of the target in the ADS-33, or by extending the hover box such that it bears resemblance to tunnel-in-the-sky displays, with the end of the tunnel serving as the reference point.

As performance was found to be best in conditions with Display 1 (grid and box), it is worth investigating whether the grid (or even the entire display) would also be beneficial and improve performance in good visibility. The geometric version of the ADS-33 (Display 2) showed worst performance and should be critically evaluated. An updated version of that display should *at least* contain additional ground texture. It may be worth researching first how the ADS-33 in good visibility can be usefully augmented, before revisiting the geometric ADS-33 design of Display 2.

This chapter combined theoretic analyses with data from an exploratory study in the SIMONA research simulator. A human-in-the-loop experiment covering all presented displays would enable the analysis and discussion of verifiable experimental results, which could confirm or contradict the findings of the proof-of-concept simulator study of this chapter.

4.8. Conclusion

This chapter investigated the effectiveness of two display configurations for hover support in degraded visual conditions and the influence of helicopter dynamics. The results of a small-scale simulator experiment indicate that a display design with a grid ground texture and hover box was the best performing configuration, although it lacked visual reference when leaving the adequate performance boundaries. In terms of dynamics, decreased control activity and workload was registered with the linear model relative to the non-linear model. However, this did not lead to notably better performance.

Based on these results, it is recommended to adjust the grid and box display such that it contains an additional reference point in the far field which pilots can use to return to the optimal hover position when the box has been left. Results further indicate that an added HUD, providing increased fidelity and visibility of the ground texture, may be a beneficial addition even in good visibility.

5

Tactical Decision-Making: Obstacle Avoidance Displays

This chapter is the first chapter that directly compares advisory and constraint-based automation design approaches. The chosen obstacle avoidance task is located in the medium timescale of operation, separated from the immediate, short-term stabilisation control task on the short timescale. This task is similar to a task chosen in the fixed-wing domain to investigate ecological interface design. However, the differences between commercial fixed-wing and helicopter operations, as explained in the introduction of this dissertation, may have led to a different outcome. Pilot preference remained identical between both experiments: pilots preferred advisory automation in nominal, and constraint-based automation in off-nominal situations. Workload and situation awareness were most improved by the constraint-based approach, as was the resilience towards unexpected events. The results of this chapter suggest that in the considered task on the medium timescale, constraint-based automation led to the best results. However, the analysed task in this chapter was still directly connected to manual helicopter control, albeit on a higher level than the low-level stabilisation task. The next chapter will investigate whether results differ when performing a cognitive, decision-making task, as opposed to a skill-based manual control task.

This chapter has been published as "D. Friesen, C. Borst, M. D. Pavel, O. Stroosma, P. Masarati, M. Mulder, *Design and Evaluation of a Constraint-Based Head-Up Display for Helicopter Obstacle Avoidance*, in *AIAA Journal of Aerospace Information Systems 18(3):80-101, 2021*".

5.1. Introduction

This chapter investigates the effect of an advisory and a constraint-based obstacle avoidance display on safety, task performance, pilot workload, situation awareness, control activity, and control strategy during forward flight. It also investigates whether the switch of preference from advisory-based systems to constraint-based systems during off-nominal events, that has been observed in the fixed-wing domain, can be observed in the helicopter domain as well, even though the vehicle dynamics and control strategies differ between helicopters and fixed-wing aircraft. The results of the studies performed in Chapters 3 and 4 lead to the decision to focus solely on head-up displays in this experiment: based on the previous analyses (and in agreement with results from Minor et al. (2017)), relying on head-down displays without manoeuvre-cues as the only source of flight data information and during short-term tasks does not seem like a promising approach. Therefore, head-up displays with additional advisory or constraint-based elements are designed and evaluated in this chapter.

One way of increasing resilience is developing and employing novel automation systems that support the pilot in safety-critical situations. Head-up display (HUD) technology has been applied successfully to improve the usable cue environment-level by supplying the pilot with an additional perspective overlay based on data recorded by on-board sensor suites and/or offline maps (Szoboszlay et al., 2010; Münsterer et al., 2018; Funabiki et al., 2020). When developing novel automation systems, there are drawbacks to consider: guidance systems (e.g., manoeuvre cue-following symbology) applied in addition to existing HUD symbology suffered from sensory overload, as the two-dimensional cues were typically added on top of the augmented outside view (Minor et al., 2017). In this case, the outside view was distracting the pilot from the two-dimensional cue-following task. Current concepts of obstacle avoidance systems provide manoeuvring advice (Kahana, 2015), increase the perception of obstacles by magnifying them visually (Godfroy-Cooper et al., 2016; Münsterer et al., 2018), or provide combined visual/auditory cues (Godfroy-Cooper et al., 2018). Manoeuvre-following cues have been implemented recently in a HUD as a tunnel-in-the-sky or virtual leading aircraft (Walters et al., 2020).

It is a challenge, however, to develop automation systems that work well in off-nominal situations. Automation systems for nominal operations are often advisory systems, suggesting (or implementing) a specific optimal solution to the current situation. In contrast, design methodologies exist that focus on supporting human adaptive, resilient control. For example, systems based on ecological interface design (EID) aim at making the operational constraints tangible to the pilots, supporting their decision-making without prescribing a specific solution (Van Paassen et al., 2018).

Ecological interfaces aim to provide information about the controlled system and its environment such that the internal and environmental constraints on possible operator actions and system reactions become easily apparent (Vicente and Rasmussen, 1990, 1992). Visualised constraints are physical (e.g., avoiding flight into terrain) and intentional (e.g., staying above a predetermined safe altitude) (Comans, 2017). Borst et al. (2015) provide an up-to-date reflection on EID, the philosophy of applying EID principles to vehicle control has been summarised by Van Paassen et al. (2018). The crucial difference between ecological displays and conventional advisory systems lies in the kind of information they provide to the pilot — ecological displays provide information about possible actions and limitations, enabling the human controller to choose the most appropriate action. Conventional advisory systems typically provide one specific solution or advice. Flight directors, which propose a certain flight path, or helicopter hover displays with cue symbology, which provide a specific manoeuvre specification for the pilot to follow, are examples of conventional advisory displays.

As of now, ecological design principles have only been sparsely applied in the helicopter domain, for example for shipboard landing (Jenkins et al., 2015). Research in the domain of fixed-wing passenger aircraft by Borst et al. has shown that ecological interfaces are less desired by fixed-wing pilots during obstacle avoidance tasks in nominal flight situations. Conversely, in off-nominal situations including system failures, pilots prefer ecological interfaces (Borst et al., 2010b). There are some differences between the investigated fixed-wing task and helicopter obstacle avoidance manoeuvres: Borst et al. did not consider nap-of-the-earth operations (or helicopter operations in general). Rather, they considered a terrain avoidance task while piloting a model of a Cessna Citation 500. While the terrain avoidance decision-making in a Cessna Citation 500 can usually take tens of seconds or even minutes, the decision process often has to be much faster in the helicopter domain, especially when low-altitude flight situations are considered. Also, the task of controlling a helicopter tends to be more focused on hands-on, short-term stabilisation and control, whereas the control of fixed-wing passenger aircraft is typically more stable in the short term, freeing some cognitive resources to focus on more elaborate displays. These differences in typical vehicle dynamics and short-term attention requirement can reduce the positive preference effect of employing the constraint-based display, as compared to the advisory display.

In October and November 2019, a human-in-the-loop experiment has been conducted in the SIMONA Research Simulator, in order to evaluate two different helicopter HUD obstacle avoidance displays in different visibility conditions and during unexpected, off-nominal events. They are compared with a baseline HUD without any manoeuvre cueing. One display is a conventional **advisory display**, which provides a discrete manoeuvre suggestion to the pilot. The other one is a **constraint-based display**, which takes inspiration from ecological interface design by visualising the flight path constraint of a pull-up and climb-over manoeuvre to the pilot via a maximum effective climb angle. Employing constraint-based displays that decouple the internal constraints (e.g., performance and model dynamic restrictions) and external constraints (e.g., position and height of obstacles) of the vehicle and its environment might improve the resilience of the pilot-vehicle system to unexpected situations and subsystem faults.

The obstacle avoidance scenario is chosen for three reasons. Firstly, external environment awareness plays a major role in historic helicopter accidents (Anonymous, 2010b, 2015). Displays that support pilots in avoiding approaching obstacles can reduce the danger of collision. Secondly, the required climb-over manoeuvre can be encountered in many different helicopter missions, be it in military missions (nap-of-the-earth flying) or civil missions (approach to an unknown landing spot during helicopter emergency medical services operations, low altitude flight during search and rescue missions). It is therefore applicable to a broad range of operational environments. Lastly, it resembles the obstacle avoidance task employed by Borst et al. (2010b), which will enable the comparison of the high-level results between helicopter and fixed-wing display effects.

The chapter is structured as follows. Section 5.2 discusses the design of the displays. The experiment methodology is elaborated on in Section 5.3. Section 5.4 shows the results, which are discussed in Section 5.5. This Section also contains an outlook to possible improvements and future research activities. Section 5.6 contains a conclusion to this chapter.

5

5.2. Display design

This section elaborates on the employed displays. First, the baseline HUD and the obstacle detection and contour drawing system are explained. The following subsection details the manoeuvre constraint calculation on which both displays are based. Then, the two employed displays (advisory and constraint-based) are elaborated upon. The Messerschmitt-Bölkow-Blohm Bo105 Helicopter serves as a reference for power calculations (Padfield et al., 1996). In the last subsection, the employed displays are classified with respect to existing helicopter display systems.

5.2.1. Baseline head-up display

The baseline HUD is a control variable, shown to the pilot in every experiment condition, depicted in Figure 5.1. It is projected on top of the outside visuals, no helmet-mounted technology is used. It consists of the following elements: (i) an artificial horizon and conformal pitch ladder, indicating every 5° above and below the horizon line; (ii) an aircraft reference point, indicating the direction in which the helicopter's nose is pointing; (iii) an altimeter in feet; (iv) a speed tape in knots; (v) a flight path vector; and (vi) an obstacle detection and contour drawing system, explained in the following paragraph.

The obstacle detection and contour drawing system visualises the minimum clearance altitude above obstacles. It superimposes a red line around the obstacle in the HUD, at a distance of 10 feet, the minimum clearance, see Figure 5.2. A clearance of $10\,$ft is chosen to discourage pilots to target the exact tip of the obstacle, which could cause dangerous "near misses" of the obstacle. Its concept is based on systems described by Münsterer et al. (2018), which draw warning contours around dangerous obstacles like windmills.

5.2.2. Calculation of internal and external constraints

Both support displays are based on the maximum **effective** climb angle γ_{limit} within a certain longitudinal distance d_0. Its calculation takes into account the maximum steady-state climb angle γ_{max} based on available power, an assumed pilot reaction onset delay τ_p, and model dynamic restrictions. γ_{limit} is determined by

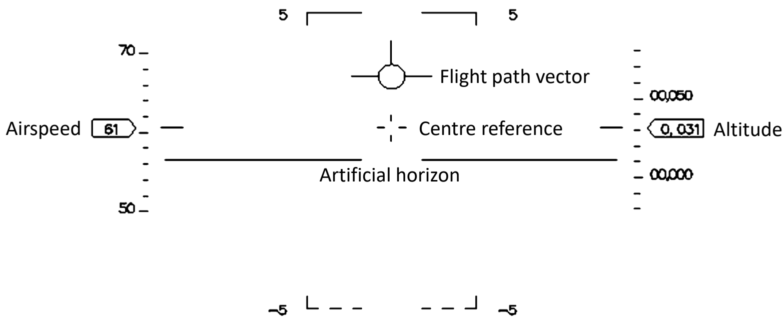


Figure 5.1: Baseline HUD elements.

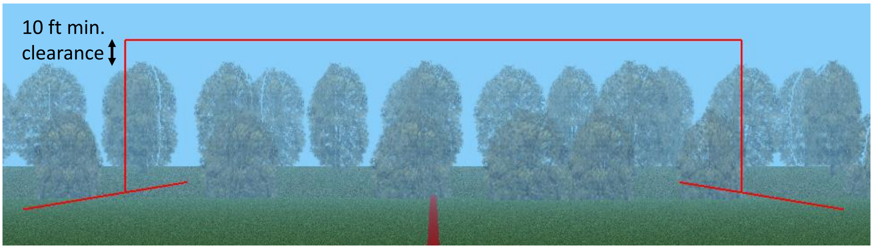


Figure 5.2: Red box around an approaching obstacle in the HUD, drawn by the obstacle detection and contour drawing system.

calculating the maximum height gain h_{limit} that can be achieved within a distance of d_0. Figure 5.3 depicts the parameters of the climb-over manoeuvre constraint calculation, with an obstacle depicted at a distance of d_0. Table 5.1 contains constant parameter values for the following calculation.

To determine the steepest climb angle γ_{max}, the power required at the given forward speed P_{req} is subtracted from $80\,\%$ of the maximum engine power P_{max}. The resulting, speed-dependent power available $P_{available}$ is transformed into an increase in potential energy (climbing). The mass of the helicopter is set to $m = 2500$ kg. Equation 5.1 details the calculation of γ_{max}.

$$\tan(\gamma_{max}) = \frac{\left(\frac{P_{available}}{mg}\right)}{V} \tag{5.1}$$

At a forward speed of 60 knots, the power required is approximately 202 kW, based on a main rotor torque of 4556 Nm and a main rotor speed of $\Omega = 44.4$ rad/s. The remaining available power to climb is approximately 268 kW. This results in a climb rate of 10.94 m/s, or a maximum climb angle $\gamma_{max} = 19.5°$.

The helicopter cannot immediately attain this climb angle. The distance over which the helicopter can climb with γ_{max} is reduced by the distance the pilot requires

Table 5.1: Constant parameter description and values for display constraint calculation.

Parameter	Explanation	Value
P_{max}	Maximum engine power	588 kW
$p_{reserve}$	Power reserve ratio for manoeuvring, tail rotor and aerodynamic power consumption	20 %
m	Mass of the helicopter	2500 kg
g	Gravitational constant	9.80665 m/s^2
τ_p	Pilot reaction onset delay	0.8 s (Hosman and Stassen, 1998)
$\dot{\gamma}_{max}$	Maximum flight path quickness	5°/s
d_0	Minimum manoeuvre distance	120 m
Ω	Main rotor speed	44.4 rad/s ≈ 424 rpm

5

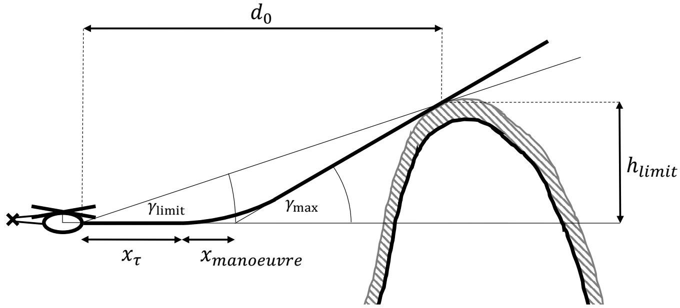


Figure 5.3: Display parameters of the climb-over manoeuvre over an obstacle's safety zone.

to react to an approaching obstacle, x_τ, and the distance that is needed to attain the maximum climb angle, $x_{manoeuvre}$. x_τ is calculated by multiplying the pilot reaction time τ_p with the current forward speed V, Equation 5.2. τ_p is set to 0.8 s, based on measurements during a reaction-onset experiment performed by Hosman and Stassen (1998).

$$x_\tau = \tau_p \cdot V \tag{5.2}$$

The manoeuvre distance $x_{manoeuvre}$ results geometrically based on $V/\dot{\gamma}_{max}$, the radius of the pull-up trajectory, and γ_{max}, the angle between initiation and completion of the pull-up manoeuvre, with the constant maximum climb path angle change $\dot{\gamma}_{max} = 5°/s$ (see Equation 5.3).

$$x_{manoeuvre} = \tan(\frac{\gamma_{max}}{2}) \cdot \frac{V}{\dot{\gamma}_{max}} \tag{5.3}$$

The maximum effective climb angle γ_{limit} can now be calculated via geometric relationships, see Equation 5.4. γ_{limit} depends on the current forward speed through a change in γ_{max}. If the forward speed decreases, γ_{max} generally increases, up to a maximum of 90° at zero forward speed, signifying the capability to increase altitude while hovering. γ_{limit} is therefore the manoeuvre limitation at the current forward speed, which is not necessarily the scenario target speed of 60 knots.

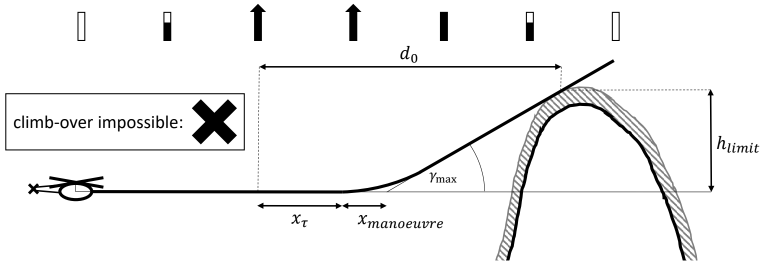


Figure 5.4: Advisory symbology for the climb-over manoeuvre, inspired by Kahana (2015).

$$\tan(\gamma_{limit}) = \tan(\gamma_{max})\left(1 - \frac{x_\tau + x_{manoeuvre}}{d_0}\right) \tag{5.4}$$

5.2.3. Advisory display

Knowing the calculated maximum effective climb angle γ_{limit}, an advisory display is developed. The advisory symbol warns the pilot about an approaching obstacle and provides a discrete suggestion when to initiate a pull-up manoeuvre. The principle design of the advisory symbol is inspired by a study conducted by Kahana (2015), Figure 5.4. The depicted empty bar at the first position is always shown to the pilot. When an obstacle approaches, the bar gradually fills up, until it gives the discrete suggestion to initiate a flight path angle change. Passing over the obstacle's edge will cause the bar to gradually empty again. If the pilot does not initiate the climbing manoeuvre in time, and a climb-over is no longer possible at the given forward speed and the given pilot and model delay constraints, the symbol will change to an X, indicating that a forward speed reduction is necessary to avoid a collision.

The fullness of the symbol is calculated based on the maximum effective climb angle γ_{limit} and the vertical angle between the helicopter and the position of the upper tip of the approaching obstacle's safety zone (10 feet above the obstacle's tip, see Figure 5.5). As an obstacle approaches, this angle $\gamma_{obstacle}$ between the horizontal plane and the obstacle's safety zone's tip increases. The advisory symbol starts filling up as the difference between $\gamma_{obstacle}$ and the effective maximum flight path angle γ_{limit} is reduced to $3°$. At a $1°$ difference, the arrowhead starts showing. If the angle of the safety zone's top is more than $1°$ larger than the maximum effective climb angle, the X symbol appears, indicating "climb-over impossible". The angle limits have been chosen iteratively to provide a reasonable arrow fill-up speed, based on the target velocity, target altitude, and obstacle height in this experiment.

5.2.4. Constraint-based display

The constraint-based display directly shows the maximum effective climb angle γ_{limit} to the pilot via a HUD-symbol. It does not incorporate any terrain- or obstacle-data but relies on the pilot to connect the visual information of γ_{limit} and the

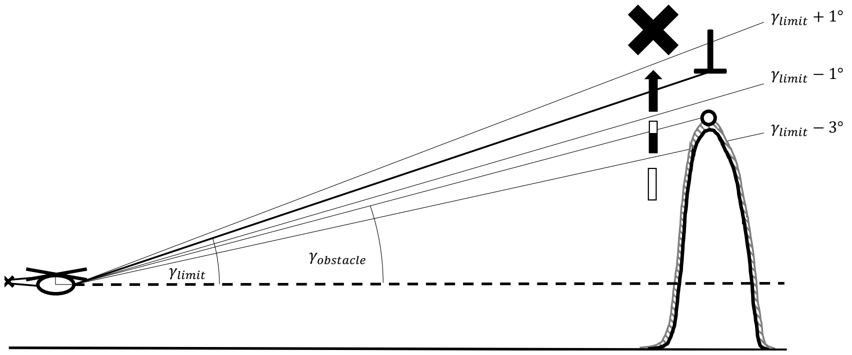


Figure 5.5: The relationship between γ_{limit}, $\gamma_{obstacle}$ and the different phases of the advisory display. The advisory symbol depends on $\gamma_{obstacle}$: as the obstacle protrudes higher and higher into the flight path, the advisory changes from the empty arrow box, to the filled arrow, to the "climb-over impossible" cross.

5

approaching obstacle to decide when to initiate a climb-over or when to reduce forward speed to avoid a collision. When a climb-over is impossible with the current forward speed (indicated by γ_{limit} being displayed in front of the obstacle, not above it), it requires the pilot to recognise this, and react accordingly by reducing speed. Figure 5.5 summarises the appearance of the two display variants, based on the maximum effective climb angle γ_{limit} and the angle between the horizontal and the obstacle's safety zone's tip. Figure 5.6 shows the two display variants as implemented in the HUD, at different distances from an approaching obstacle and constant $300\,m$ visibility.

5.2.5. Display categorisation

To relate this chapter's displays to other helicopter display types, a diagram to categorise helicopter display systems of Minor et al. (2017) is reproduced in Table 5.2. Firstly, they distinguish between helmet mounted (head-up) displays and panel mounted (head-down) displays. Secondly, they differentiate between what kind of information is shown to the pilot: either the display mainly shows primary pilotage information (e.g., altitude, attitude, airspeed, position, environmental parameters), or the display provides guidance cues, e.g., an optimal target manoeuvre trajectory. This chapter's displays fall into Category I, IV, and into the space between the two categories. The employed baseline HUD and the included obstacle detection and contour drawing system fall into Category I. The advisory symbol for obstacle avoidance falls into Category IV. Lastly, the constraint-based steepest climb indication display is located somewhere between Category I and IV, as it provides more information to the pilot than just primary pilotage information, but it does not provide a direct or discrete manoeuvre cue, giving the pilots more freedom in how to react to the approaching obstacle. Based on the provided information, the pilots need to decide themselves when to initiate the pull-up manoeuvre.

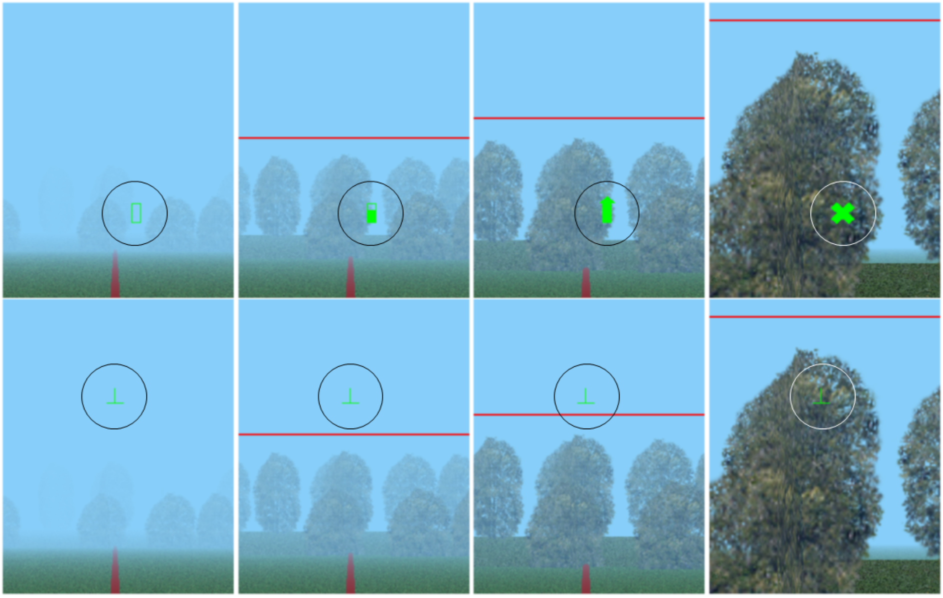


Figure 5.6: Advisory (top) and constraint-based display variant (bottom) dependent on distance to the approaching obstacle at 60 knots, highlighted by a circle (not part of HUD). From left to right: 300 m, 200 m, 150 m, 100 m between the approaching helicopter and the obstacle. (In this image, the contrast between the symbol and the sky is rather poor. In the simulator, the contrast was more pronounced and the symbology always easily visible.)

5.3. Methodology

5.3.1. Apparatus

The experiment took place in the SIMONA Research Simulator (Stroosma et al., 2003), depicted in Figure 5.7. The cockpit window set-up resembled a fixed-wing airline cockpit with a field of view of 180° by 40° — the typical chin-window view of helicopters was obstructed. The outside visual was collimated, optically appearing at or near infinity to the pilots. The HUD-symbology was projected on top of the outside view in the centre of view, no helmet-mounted technology was used. Care was being exercised that all symbology was visible during all typical pitch angles during the anticipated manoeuvres, even with the limited viewing area. The SIMONA Research Simulator in helicopter configuration contains a collective lever, a cyclic stick and pedals. During the experiment, the simulator cabin door was closed and the light was turned off. The utilised model was an in-house model of a Messerschmitt-Bölkow-Blohm Bo105 Helicopter (Miletović et al., 2017). The motion system of the simulator was deactivated. Adding motion would improve the realism of the simulation, but it could confound the experiment, as it could distract pilots from the employed visual systems. This would make it more difficult to analyse and isolate the impact of the visual augmentations on the data.

Table 5.2: Categories of display systems to support helicopter control, reproduced from Minor et al. (2017).

	Displayed image primary pilotage	Guidance algorithm primary pilotage
Helmet mounted display	**Category I**: reliable option with 1:1 magnification	**Category IV**: focusing on 2-D cues through 3-D picture can be difficult; permits coupling flight controls
Panel mounted display	**Category II**: unusable	**Category III**: excellent option for following guidance, permits coupling flight controls

Figure 5.7: SIMONA Research Simulator.

5

5.3.2. Participants

Twelve helicopter pilots with varying experience (minimum private pilot license (PPL), 100 flight hours) participated in this experiment. Table 5.3 shows some participant demographic aggregates. The participating pilots can be categorised into two distinct groups: one group of eight pilots with less than 800 flight hours, and one group of four pilots with more than 3,000 flight hours.

Table 5.3: Pilot participant demographic data.

		Flight hours		Type of licence (amount)		
Group	Number	Average	Standard deviation	PPL	CPL	other
All pilots	12	1,906	2,326	5	6	1
3000 and more flight hours	4	5025	1246	0	3	1
1000 and less flight hours	8	346	207	5	3	0

5.3.3. Task

The scenario emulated a low-altitude helicopter surveillance task to inspect oil pipelines for leakages. To quickly find the leakage, a fly-over at a low altitude of 30 feet and a speed of 60 knots had to be conducted. At intervals between 500 m and 900 m, the pipeline was covered by a rising ground slope, and a tree line with a height of 80 feet obstructed the optimal flight path. Six different obstacle courses with varying distances between obstacles were defined, as shown in Table 5.4. The first obstacle always appeared after 700 m, the following distances varied per experiment course. The obstacle courses were rotated throughout the

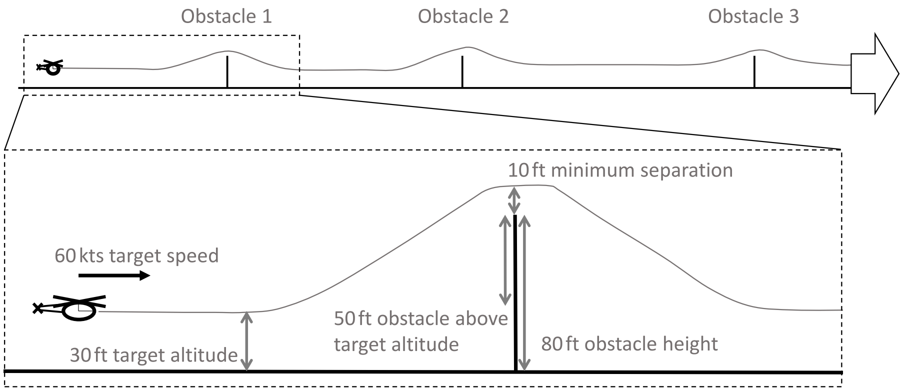


Figure 5.8: Principle obstacle course design.

experiment per run in a balanced order. Figure 5.8 shows a conceptual view of the obstacle course.

Table 5.4: Distances between obstacles of the six defined obstacle courses.

Course #	Obstacle 1	Obstacle 2	Obstacle 3	Obstacle 4	Obstacle 5	Obstacle 6
1	700 m	750 m	600 m	750 m	600 m	900 m
2	700 m	650 m	800 m	650 m	800 m	500 m
3	700 m	600 m	850 m	650 m	650 m	850 m
4	700 m	800 m	650 m	650 m	650 m	650 m
5	700 m	650 m	750 m	750 m	550 m	900 m
6	700 m	750 m	650 m	650 m	850 m	500 m

Real-world pipeline inspection tasks are not performed at this altitude–speed combination, but typically at a higher altitude as well as a higher speed. By pairing 30 feet with 60 knots, the task in this chapter is purposefully made more difficult to control. This increase in difficulty aims to provoke more different responses and pilot preferences based on the employed displays. If the task would have been very easy to perform with very good performance ratings in every condition, the performance and pilot workload differences between different displays are expected to decrease. It is important to note that this artificial increase of difficulty diminishes the task's likeness to real-world applications.

The instruction given to the pilots was:

> "The first priority is to avoid collision with any obstacle or the ground, maintaining a separation of at least 10 feet. The second priority is to maintain a forward speed of 60 knots, stay centred above the pipeline, and maintain an altitude of 30 feet, smoothly climbing over any obstacles that block your optimal flight path. After climbing over an obstacle, please try to attain the target altitude again as soon as possible."

One experiment run consisted of an obstacle course with the length of 4,700 meters which contained six obstacles at semi-random locations. After every experiment run of ca. 3 minutes, two performance scores were communicated to the pilots: the root-mean-square tracking error of the forward speed, and the root-mean-square tracking error of the target altitude. Naturally, the altitude tracking error could never reach zero, as climbing over an obstacle required a deviation from the target altitude. In addition, the minimum vertical clearance and the average vertical clearance above the obstacles were communicated to the pilots. The pilots could therefore aim to improve their scores and safety clearances between runs.

5.3.4. Independent variables

The independent variables of this experiment are *display* and *visibility*. A third independent variable *(off) nominal situation*, which introduces off-nominal situations in a small percentage of runs per experiment condition, is introduced in the following paragraph. The *display* conditions are (1) baseline HUD, (2) baseline HUD + advisory display, (3) baseline HUD + constraint-based display. The baseline HUD condition conceptually emulates current helicopter HUD systems like the one employed by Münsterer et al. (2018), including visual obstacle highlighting, but excluding any manoeuvre cues or other support tools. In this set-up, the additional value of the employed obstacle avoidance support systems, compared to a state-of-the-art baseline system, can be analysed. The *visibility* was set to 300 meters in the high condition, and to 200 meters in the low condition. The order of experiment conditions was balanced between pilots. Each experiment condition was flown five times per pilot, including one non-recorded warm-up run. Table 5.5 summarises the independent variables and experiment conditions.

Table 5.5: Experiment independent variables and resulting experiment conditions A-F.

	Experiment conditions	Visibility	
		high	low
Display	baseline HUD	A	B
	baseline HUD + advisory display	C	D
	baseline HUD + constraint-based display	E	F

To investigate the effect of off-nominal situations, failure events were deliberately inserted into some experiment runs, creating the third independent variable *(off-)-nominal situation* (nominal, off-nominal) for performance and safety measures, as described in Section 5.3.5. Some obstacles were recognised later than usual by the obstacle detection and contour drawing system (which is part of the baseline HUD), at a distance of 50 meters instead of 300 meters. This distance was chosen to force the participants to utilise only the outside visuals to detect and react to an obstacle, and to make the obstacle detection and contour drawing system practically unusable in these situations. The dependent measurements while approaching and reacting to unexpected events are cut from the remaining experiment data and analysed separately. The pilots were briefed on the possible occurrence of failures like this, and encountered one such off-nominal event during their training and acclimatisation phase.

Table 5.6 summarises the detection distances of the outside visuals and the obstacle detection and contour drawing system per experiment condition. Assuming a perfect approach at 60 kts, and 30 ft, it takes 3.9 s between the time when the obstacle contour first appears at a distance of 300 m, and when the maximum effective climb angle $\gamma_{limit} = 5.82°$ coincides with the red warning contour around the obstacle. The pilots have this time to register the appearance of the obstacle and initiate the climb-over manoeuvre at a distance and aggressiveness of their choosing.

During low visibility and off-nominal situations, the obstacle only appears visually at a distance of 200 m. The obstacle contour warning only appears at a distance of 50 m, making it deliberately unusable for a timely pull-up control action. At this point, again assuming a perfect approach, the tip of the obstacle (including the 10 ft minimum distance) appears at a $5.22°$ angle, very close to $\gamma_{limit} = 5.82°$. In order to still clear the obstacle, the pilots have to react within 0.7 s, reduce their forward speed, or exceed the limits prescribed to the constraint calculation (reacting quicker than in 0.8 s, exceeding $5°$/s flight path angle rate, and/or using more than $80\,\%$ of the available power.

These events, which require pilot actions very close, or even outside of the prescribed display limits and suggestions, enable the analysis of the robustness of the pilot-vehicle system towards system malfunction. Each condition contained four off-nominal situations, with one experiment run containing at most two off-nominal situations.

Table 5.6: Visibility and obstacle detection distances, dependent on visibility condition and unexpected events.

Condition	Visibility condition	Viewing distance	Unexpected events	Obstacle detection distance
A, C, E	high	300 m	yes	300 m
A, C, E	high	300 m	no	50 m
B, D, F	low	200 m	yes	300 m
B, D, F	low	200 m	no	50 m

5.3.5. Dependent measures

Dependent variables are *performance*, measured via the root-mean-square error, (RMS error or RMSE) from the ideal target altitude, lateral position, and speed (i.e., clearing an obstacle always causes an altitude deviation from the ideal altitude); *safety*, measured via the vertical clearance of the climb-over manoeuvres over obstacles; *workload*, measured via the subjective rating scale mental effort (RSME), given to the pilots after each condition (developed by Zijlstra and Van Doorn (1985), as cited by de Waard (1996)); and *situation awareness*, measured via the subjective scale Situation Awareness Rating Technique (SART) (Taylor, 1989), likewise given to the pilot after each experiment condition.

Although this task seems suitable to be used in a handling qualities analysis, the chosen performance metrics are deliberately defined in a simpler matter, without specifying desired or adequate boundaries. This is done in order to simplify the evaluation of the flown trajectories by the participating pilots. The employed questionnaires are neither dependent on pre-existing knowledge about handling qualities rating from the pilots, nor on the participants forming a consistent understanding about adequate and desired performance boundaries.

Control strategy is analysed by calculating the average control activity, the trajectory spread, the velocity at maximum altitude, the pull-up initiation location, and the characteristic manoeuvre parameters of fitted manoeuvres based on gap-closing τ-theory as described by Padfield et al. (2007). Table 5.7 shows an overview of the dependent measures of this experiment.

5

Table 5.7: Overview of dependent measures.

Category	Dependent measure
Performance	Deviation from ideal altitude
	Deviation from ideal lateral position
	Deviation from ideal speed
Safety	Vertical clearance over obstacles
Workload	Rating scale mental effort (RSME)
Situation awareness	Situation awareness rating scale (SART)
Control strategy	Control activity (per control axis)
	Trajectory spread
	Velocity at maximum altitude
	Pull-up initiation location
	Manoeuvre-time, coupling constant and manoeuvre gap based on τ-theory
Pilot preference	Confidence in using the displays

Workload and situation awareness were collected per condition, not differentiating between nominal and off-nominal situations. Due to the required unpredictability of off-nominal situations, these were embedded in a run with multiple nominal situations at differing intervals. Measuring workload and situation awareness separately for nominal and off-nominal situations would have either required the clear separation of off-nominal and nominal situations in the experimental process, or the participants would have had to fill in two separate assessments after each run, one for the encountered nominal, one for encountered off-nominal situations. Both approaches were deemed impractical for the envisioned experiment procedure, either because they disrupted the experimental process or because it would require the participants to separately judge two different past perceived workload and situation awareness conditions. In this experiment, the loss of separate workload and situation awareness ratings for nominal and off-nominal situations is tolerated in order to keep the off-nominal situations embedded in the regular experiment runs.

Performance, and safety, and control strategy metrics are calculated for nominal and off-nominal situations separately. After all conditions, the pilots were asked to complete a questionnaire about the whole experiment, covering their preferences between the different display systems in nominal and off-nominal situations. Figures B.3, B.4, and B.5 in the appendix depict the employed questionnaires, Table 5.8 summarises the experimental procedure.

Table 5.8: Experimental procedure, followed from top to bottom. Each group procedure was followed by two participants.

Introduction	Welcome, explanation of timetable and procedure Pre-experiment questionnaire					
Acclimatisation	Training programme in the simulator					
Preparation	Explanation of experiment questionnaires					
Group Assignment Group	1	2	3	4	5	6
Condition 1	A	F	C	B	E	D
	Warm-up runs Experiment runs Condition questionnaires (SART, RSME)					
Condition 2	B	E	D	A	F	C
	Warm-up runs Experiment runs Condition questionnaires (SART, RSME)					
Condition 3	D	C	F	E	B	A
	Warm-up runs Experiment runs Condition questionnaires (SART, RSME)					
	Break					
Condition 4	C	D	E	F	A	B
	Warm-up runs Experiment runs Condition questionnaires (SART, RSME)					
Condition 5	E	B	A	D	C	F
	Warm-up runs Experiment runs Condition questionnaires (SART, RSME)					
Condition 6	F	A	B	C	D	E
	Warm-up runs Experiment runs Condition questionnaires (SART, RSME)					
Conclusion	Post-experiment questionnaires De-briefing and goodbye					

5

5.3.6. Control variables

Control variables are comprised of the simulator set-up, task, target speed and altitude, the utilised six-degrees-of-freedom helicopter model (developed in-house, identical to the non-linear MBB Bo 105 model employed in Chapters 3 and 4, including a basic stability augmentation system SAS), and the baseline HUD with altimeter, speed tape, flight path vector, and the obstacle detection and contour drawing system, as described in Section 5.2.

5.3.7. Data processing

Workload and situation awareness ratings are collected once per experiment condition and pilot. They are normalised to a mean of 0 and a standard deviation of 1 (Z-scored) per participant, to account for subjective scaling and offset differences. Measurements from the same pilot are not treated as independent. Therefore, performance, safety, and control strategy results are averaged per experiment participant and condition, resulting in one data point per participant per experiment condition. This is done to fulfil the requirement of independent measurements of the statistical tests described in the following paragraph.

5

Anderson-Darling tests for normality of data are performed per experiment condition, separately for nominal and off-nominal cases when possible, resulting in twelve test outcomes per dependent measure. If the null hypothesis ("data are drawn from a normal distribution") is rejected in more than three out of twelve cases at $\alpha = 0.05$, non-parametric two-way Friedman tests (Friedman, 1937) are employed to analyse the data. In this case, the independent variables *display* and *visibility* are combined into one independent variable with six degrees of freedom *display x visibility*. Otherwise, a parametric three-way analysis of variance (ANOVA) is used (Girden, 1992). Figure 5.9 show the data analysis procedure for workload and situation awareness, Figure 5.10 for the collected pilot preferences.

The above methodology analyses both nominal and off-nominal situations in one combined test statistic. However, due to the difference in number of data points per pilot between nominal (20) and off-nominal (4) situations, nominal and off-nominal situations are afterwards analysed separately, as well. To account for multiple tests, a Bonferroni correction of the significance value α is carried out per dependent measure: the first statistic test, comparing all data, is carried out at $\alpha = 0.03$, the following tests for separate nominal and off-nominal situations are carried out at $\alpha = 0.01$, resulting in an overall significance value of $\alpha = 0.03 + 0.01 + 0.01 = 0.05$ for every dependent measure. Without this correction, the significance of the performed tests would be overestimated (Miller, 2012, p.67). Figure 5.11 show the complete data analysis procedure for dependent measures that differentiate between nominal and off-nominal events.

To analyse the manoeuvre strategies of the pilots in more detail, the complete trajectory is divided into three parts: *pull-up*, at a distance between $320\,m$ and $50\,m$ to the obstacle while approaching the obstacle, *fly-over*, at $\pm 50\,m$ around the obstacle, and *descent*, between $50\,m$ and $180\,m$ behind the obstacle.

In case of workload and situation awareness, no separate data points for nominal and off-nominal situations exist, which results in six test outcomes per dependent

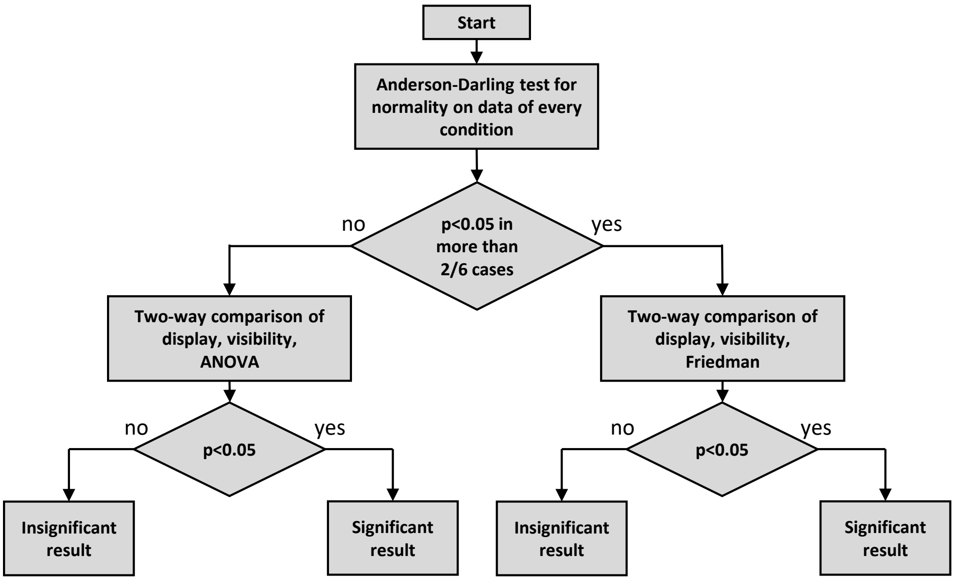


Figure 5.9: Data analysis procedure for workload and situation awareness.

5

measure. If normality is rejected in more than two cases, non-parametric two-way Friedman tests are used. Otherwise, a two-way ANOVA is used.

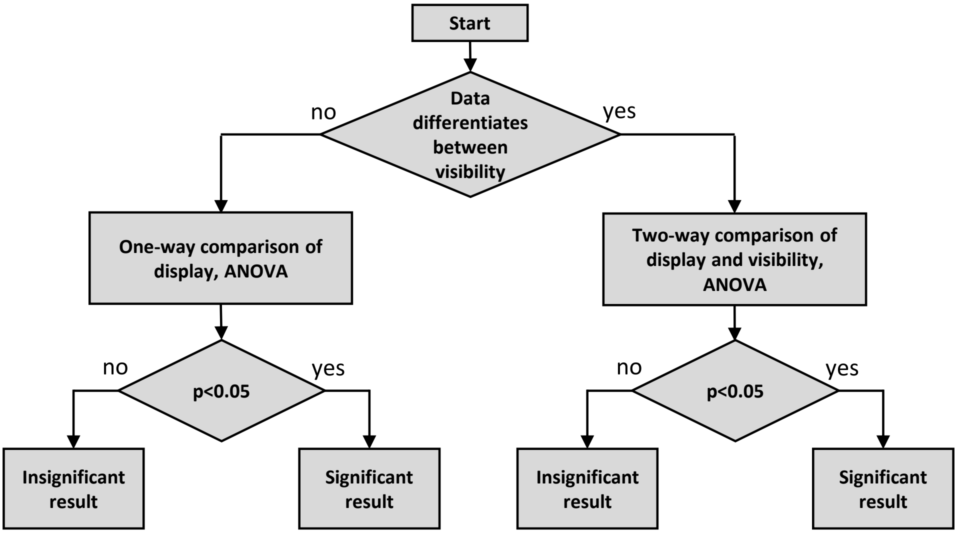
All employed statistical tests utilise a conservative baseline Type 1 error margin of $\alpha = 0.05$. Similarly, the employed Bonferroni correction and the utilisation of non-parametric tests are conservative approaches to the encountered situation. These choices lead to a decrease of the power of the employed tests. However, this reduction of power is tolerated, as it enables the formulation of strong conclusions if a statistically significant effect is found.

To enable a discussion of the power ($1 - \beta$, where β represents the Type 2-error) of the performed tests, it will be calculated for all initial tests of dependent measures, taking into account all collected data. To calculate the power ANOVA tests, a procedure presented by Faul et al. (2007) is utilised. The calculations are performed via G*Power 3[1], developed and maintained by Faul et al. To calculate the power of Friedman tests, the procedure presented by Field (2005) is used.

5.3.8. Hypotheses

Performance increases when utilising any of the support displays in nominal situations, because both displays provide more information to the pilot, enabling him or her to more consistently follow his or her preferred fly-over trajectory. The effect is stronger for the advisory system, as it requires less cognitive resources from

[1] G*Power 3 is a statistical power analyses tool, available at `https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower`, retrieved November 11th 2022.



5

Figure 5.10: Data analysis procedure for pilot preference.

the pilot, and it is easier to follow its advice. In off-nominal situations, only the constraint-based display improves performance, when compared to the baseline HUD.

Workload decreases when utilising any of the support displays, because both provide additional information to the pilot that support him or her in performing the task. The effect is stronger with the advisory display, as it provides an easy-to-follow manoeuvre advice, compared to the constraint-based display, which requires more cognitive resources from the pilot.

Situation awareness increases when utilising any of the support displays, as the pilot receives more information about his current aircraft state and its relation to the outside world (obstacles). This effect is expected to be stronger with the constraint-based display, because it enables the pilot to perceive the internal manoeuvre limitations of the helicopter (in the form of the maximum effective climb angle γ_{limit}) and to connect these to the external limitations of the approaching obstacle.

Safety is expected to behave differently between its measurement techniques. In nominal situations, the minimum clearance above obstacles decreases when utilising any of the support displays. As the pilot is made aware of the manoeuvre limitations by both support displays, the pilot might decide to reduce the safety margin (while still staying above the minimum clearance above obstacles) to increase performance. However, the percentage of unsafe clearances lower than 10 feet will decrease when utilising any of the support displays, as both displays can support the pilot in detecting and reacting to an approaching obstacle. In off-nominal situations, the percentage of unsafe clearances decreases when utilising the constraint-based display, and increase when utilising the advisory display,

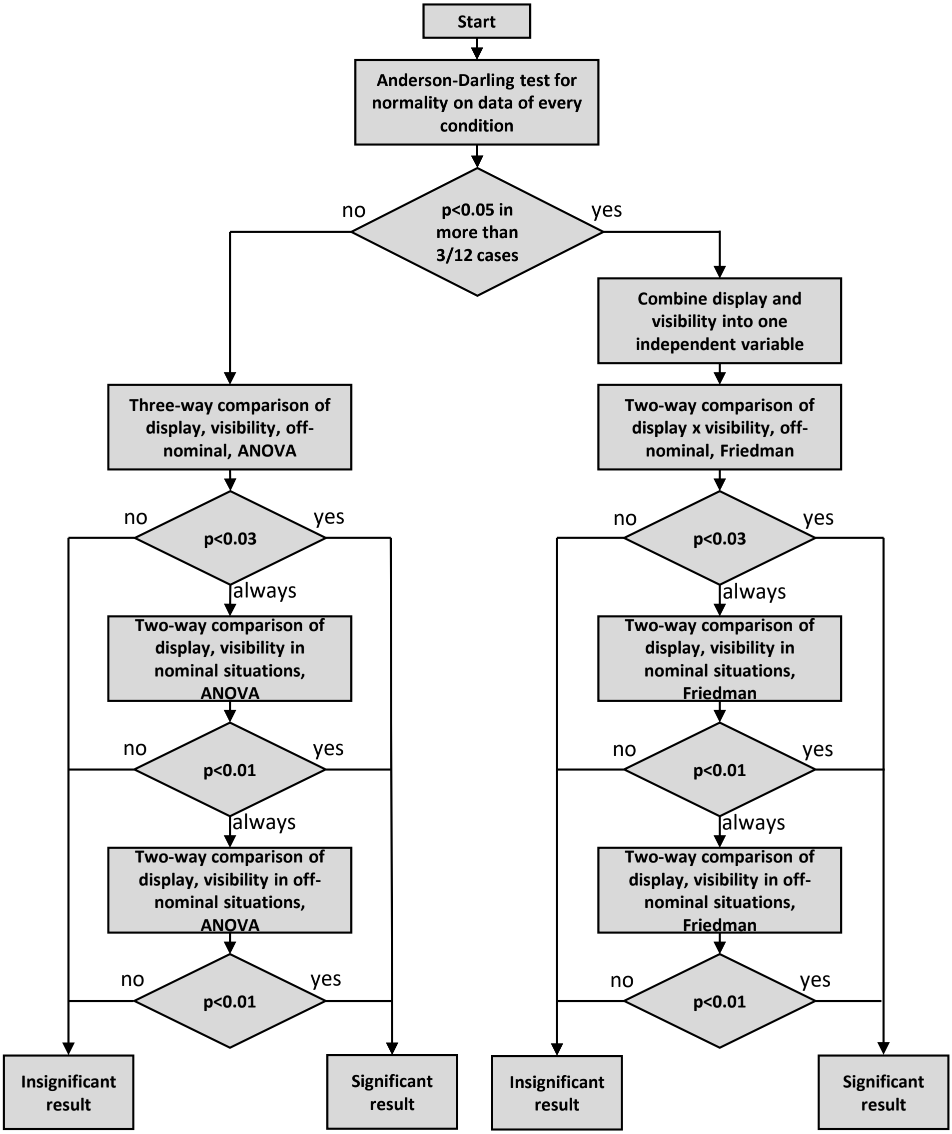


Figure 5.11: Data analysis procedure for objective measures.

compared to the baseline HUD condition. The advisory display might give a false sense of security in off-nominal situations, causing a later reaction to the obstacles than when utilising the baseline HUD. In contrast, the constraint-based display still provides the pilot with information about his or her manoeuvre capability, and its relation to outside obstacles.

Concerning **control strategy**, a decrease in visibility and off-nominal situa-

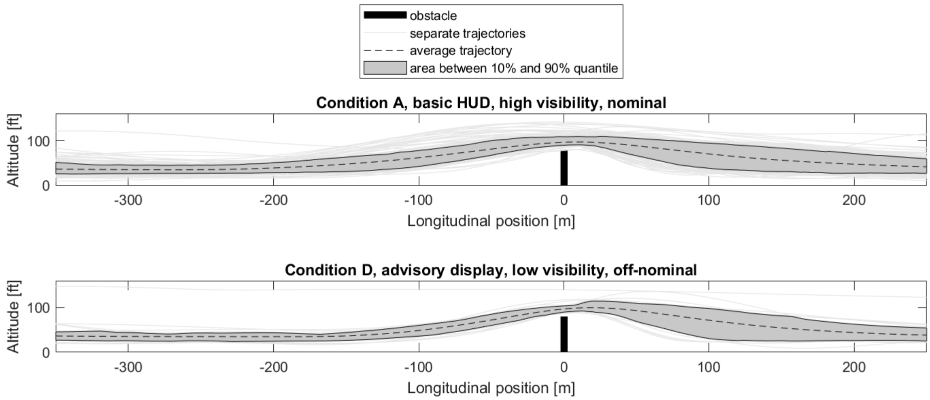


Figure 5.12: Flown trajectories in nominal cases in condition A, and off-nominal cases in condition D.

tions cause a later pull-up initiation. The advisory display causes a decrease of manoeuvre variability, the flown manoeuvres will group closely around the suggested manoeuvre. The constraint-based display will cause a broader spread of flown manoeuvres, while also enabling pilots to fly closer to the edge of possible manoeuvres, i.e., later pull-up. The constraint-based display gives the pilots the freedom to choose for themselves at what distance to the manoeuvre limit they initiate the pull-up manoeuvre.

A reduction of visibility increases workload, decreases situation awareness, reduces performance, and leads to later pull-up initiations and more fly-overs at unsafe clearances. The aforementioned hypothesised effects of displays and off-nominal situations are amplified in low-visibility conditions.

5.4. Results

Figure 5.12 shows results of two conditions: nominal, high-visibility fly-overs with the baseline HUD, and off-nominal, low-visibility fly-overs with the advisory display. At a first glance, the flown trajectories differ in spread, as well as pull-up location. The following subsections will elaborate on the effects of different display, visibility and (off) nominal situations on all dependent measures.

Analysing the dependent measures did not reveal observable difference between repeating runs of the same condition — there is no pronounced learning effect within the recorded experiment runs. The training phase seems to have been sufficient to acclimatise the pilots with the experiment. An analysis of learning effects per dependent measure is therefore omitted.

5.4.1. Workload

Figure 5.13 shows box plots of Z-scored workload measures per experiment condition. Normality is not rejected for any condition; therefore, two-way ANOVA test statistics are used. Workload seems to differ between the employed displays, es-

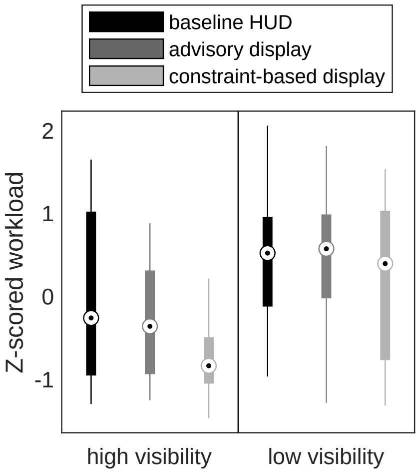


Figure 5.13: Workload questionnaire results per experiment condition, Z-scored per participant. Large Z-scored workload values correspond with large reported workload measures, and vice versa.

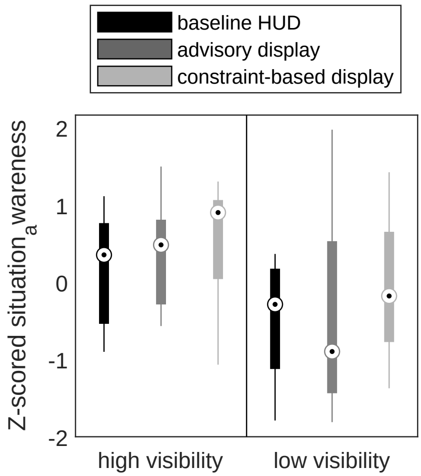


Figure 5.14: Situation awareness questionnaire results per experiment condition, Z-scored per participant. Large Z-scored situation awareness values correspond with large reported situation awareness measures, and vice versa.

5

pecially in high visibility. However, there is no significant effect, F(2,66) = 2.41, $p = 0.10$. In good visibility, there is a trend of decreasing workload when switching from the baseline HUD to the advisory display, and of a further decrease in workload when switching to the constraint-based display. In bad visibility, however, the median actually slightly increases with the advisory display, compared to the baseline HUD. Low visibility significantly increases workload (F(1,66) = 13.60, $p < 0.001$), which is in line with the expected effect of worsening visibility.

5.4.2. Situation awareness

Normality is rejected in one out of six conditions, two-way ANOVA test statistics are used. Z-scored situation awareness, as shown in Figure 5.14, is not significantly affected by *display* (F(2,66) = 1.18, $p = 0.31$). Considering the median values per condition, there is a trend of increasing situation awareness when switching from the baseline HUD to the advisory display, and a further increase when switching to the constraint-based display. Just as with workload, the median of the advisory display in bad visibility does not follow this trend and is actually lower than the medians of the baseline HUD and the constraint-based display. Lower visibility significantly decreases situation awareness (F(1,66) = 9.72, $p < 0.01$), as expected.

5.4.3. Performance

Average altitude, speed, and lateral deviation are discussed in parallel. Figure 5.15 shows box-plots of the altitude deviation per experiment condition, Figure 5.16

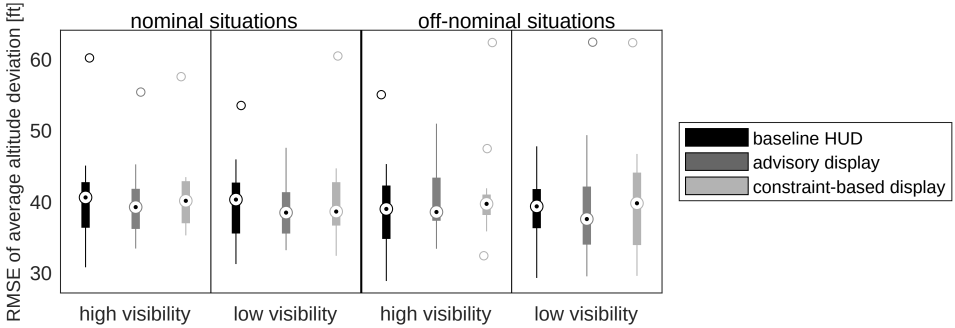


Figure 5.15: Box-plots of average altitude deviation per visibility, display, and situation.

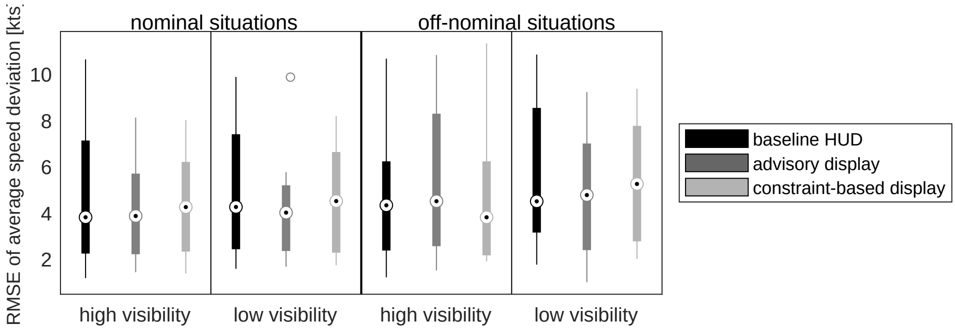


Figure 5.16: Box-plots of average speed deviation per visibility, display, and situation.

of the airspeed deviation, and Figure 5.17 shows box-plots of the lateral position deviation.

Normality is rejected in 4/12 (altitude), 0/12 (speed), and 6/12 (lateral) cases. Speed is analysed using parametric tests, altitude and lateral performance via non-parametric tests. No significant effect on average altitude or lateral deviation of *(off) nominal situation* or (*display x visibility*) is revealed, $p > 0.03$ in all cases. Likewise, there is no significant effect of *display*, *visibility* or *(off) nominal situation* on speed, $p > 0.03$. There is one trend visible: off-nominal situations increase the speed deviation, compared to nominal situations ($F(1,134) = 2.53$, $p = 0.11$). This could be explained by a change in control strategy in off-nominal situations, focusing less on maintaining forward speed, but prioritising the more important goal ("do not collide with obstacle").

Analysing only nominal situations reveals a significant effect of *visibility* on altitude deviation ($\chi^2(1,66) = 7.99$, $p < 0.01$) and lateral deviation ($\chi^2(1,66) = 7.61$, $p < 0.01$), lower visibility leads to less deviation in both measures. In off-nominal situations, no significant effects can be observed, $p > 0.01$ in all cases.

Analysing altitude, speed, and lateral deviation in the separate manoeuvre

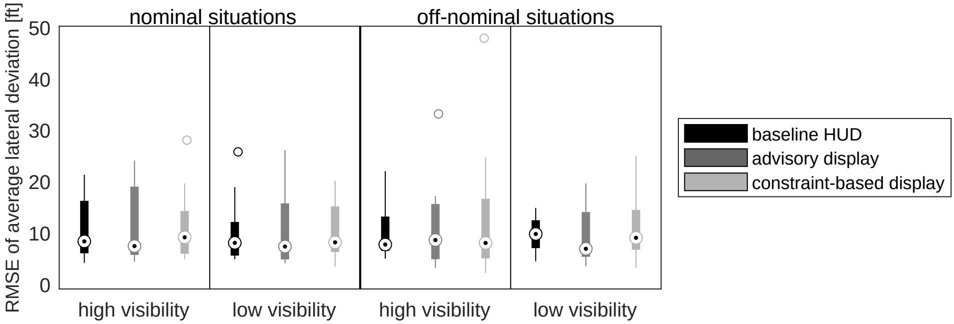


Figure 5.17: Box-plots of average lateral deviation per visibility, display, and situation.

stages reveals that only altitude deviation during the pull-up manoeuvre part is significantly affected by any of the experiment independent variables. There is also a trend visible in the effect on speed deviation during descent. Both effects are discussed below.

Figure 5.18 shows the altitude deviation during pull-up. Normality is rejected in 7/12 cases, the used two-way Friedman test reveals a significant effect of *(off) nominal situation* ($\chi^2(1{,}132) = 15.49$, $p < 0.001$) as well as of the combined *display x visibility* variable ($\chi^2(5{,}132) = 19.98$, $p < 0.03$).

Testing the nominal and off-nominal pull-up data sets separately, however, reveals that the effect of the combined *display x visibility* variable is caused solely by *visibility*. In nominal situations, bad visibility significantly decreases altitude deviation ($\chi^2(1{,}66) = 7.61$, $p < 0.01$). In off-nominal situations, the effect is even stronger ($\chi^2(1{,}66) = 39.24$, $p < 0.001$). This can be explained by the reduced distance at which the obstacle becomes visible, as explained in Table 5.6. In good visibility, the obstacle becomes clearly visible at a distance of 300 m, irrespective of nominal or off-nominal situations, which may in turn prompt the pilots to initiate an altitude change. In bad visibility and nominal situations, only the contour of the obstacle becomes visible at 300 m, the obstacle itself only becomes visible 100 m later. The appearance of only the contour line represents a less intense stimulus than the appearance of a whole line of trees directly in the current flight path. This reduction of visual stimulus and delayed visual appearance of the actual obstacle likely caused a delay in pull-up control action, leading to a smaller altitude deviation during the pull-up trajectory stage. In bad visibility and off-nominal situations, the obstacle only becomes noticeable at a distance of 200 m. The pull-up control action is delayed even further, explaining the highly significant effect of *visibility* in off-nominal situations.

Speed deviation during the descent trajectory is shown in Figure 5.19. There is a trend of increasing speed deviation during descent when encountering off-nominal events, $F(1{,}134) = 3.69$, $p = 0.06$. Even though the speed deviation was not significantly different between conditions during pull-up and fly-over, it seems like off-nominal events cause a greater speed deviation while **recovering** from an

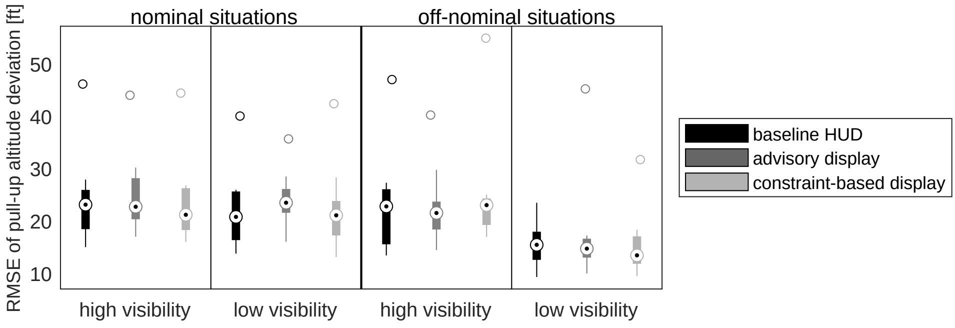


Figure 5.18: Box-plots of altitude deviation during pull-up per visibility, display, and situation.

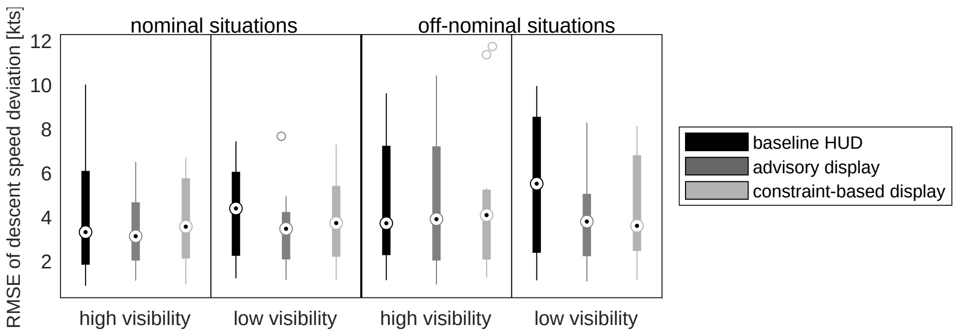


Figure 5.19: Box-plots of speed deviation during descent per visibility, display, and situation.

unexpected avoidance manoeuvre, not during the manoeuvre itself.

5.4.4. Safety

Figure 5.20 shows box plots of the averaged safety clearances. Normality is rejected in 6/12 cases, non-parametric Friedman tests are used. No significant effects can be observed, $p > 0.03$ for every independent variable. It can be observed that in bad visibility, the advisory display is the only condition whose data protrude visibly into the unsafe clearance area <10 feet. However, this is caused by the data of only two pilots — one pilot consistently undershot the safety clearance in this condition, the other pilot generally cleared the obstacle while generating two extreme outliers with negative clearance values. In other conditions, both pilots generally cleared the obstacles with sufficient clearance. The pilot who consistently undershot the clearance has one of the lowest flight hour values of the participants, which might explain his/her trouble of clearing the obstacle. However, chronologically, this condition was his/her fourth condition, and he/she completed all previous conditions without entering the unsafe clearance area so often. As this behaviour only occurred in this condition, and is only visible in this specific dependent measure, the

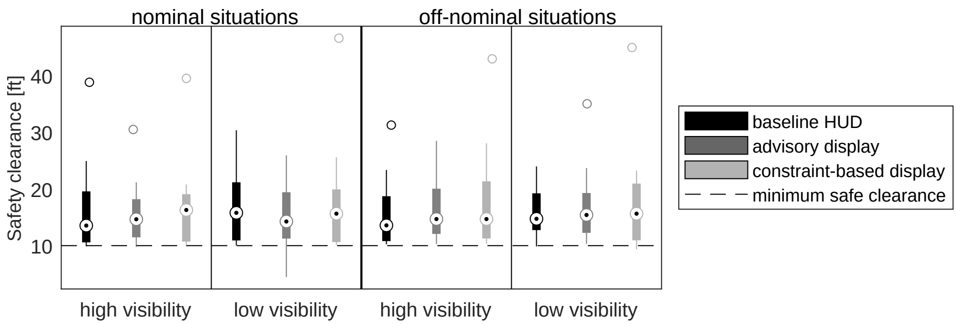


Figure 5.20: Box-plots of average safety clearances per experiment condition, in nominal and off-nominal situations.

protrusions of these two pilots into negative clearances are treated as outliers and cannot be generalised to a larger pilot population.

In off-nominal situations, the average and median safety clearance slightly increases when switching from the baseline HUD to the advisory display, and it increases further when switching to the constraint-based display. Analysing nominal and off-nominal situations separately reveals no significant effects, but trends of decreasing safety clearance when switching from high visibility to low visibility (nominal: $\chi^2(1,66) = 6.52$, p = 0.011, off-nominal: $\chi^2(1,66) = 5.84$, p = 0.016).

The relative amount of unsafe clearances <10 ft with respect to the total number of climb-over manoeuvres is shown in Figure 5.21. In nominal situations, *visibility* does not seem to influence the percentage of unsafe clearances. In off-nominal situations, using the baseline HUD leads to the highest percentage of unsafe clearances (17 % and 19 %, respectively).

Off-nominal situations consistently increase the percentage of unsafe clearances, except when using the constraint-based display in good visibility, or the advisory display in low visibility. In high visibility, using the constraint-based display leads to the lowest number of unsafe clearances, given an off-nominal situation was encountered (8 %). In low visibility, the advisory display causes the least unsafe clearances (10 %). In general, utilising the advisory or the constraint-based display seems to increase the resilience towards unexpected events, compared to the baseline HUD. The constraint-based display causes the fewest unsafe clearances in three out of four conditions.

5.4.5. Pull-up initiation

To determine the time of manoeuvre initiation, a method of Scaramuzzino et al. (2021) is used. This method calculates the manoeuvre initiation time based only on the control input data. It identifies the monotonously increasing control input section with the highest root-mean-square deviation from its starting point, in the direction of the expected manoeuvre: an increase in collective, and/or a pitch-up cyclic input. After identifying the strongest control input section, the starting time

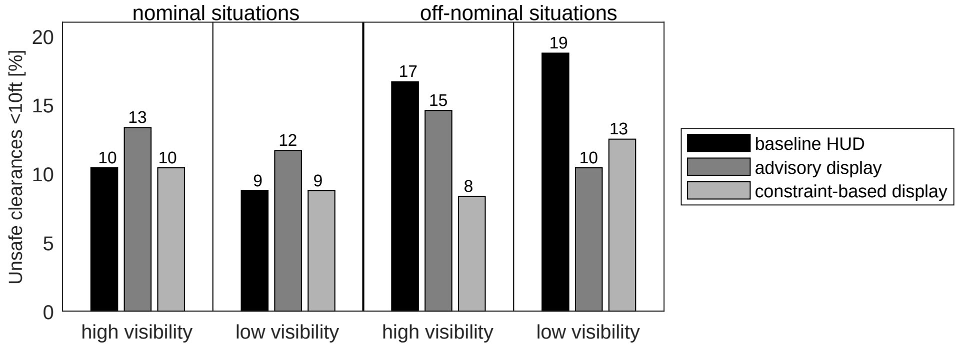


Figure 5.21: Percentage of unsafe clearances per experiment condition, in nominal and off-nominal situations.

5

of this section is defined as the manoeuvre onset.

This algorithm is applied to every obstacle approach trajectory. The data are limited to the probable location of pull-up initiation, between 320 m and 100 m in front of the obstacle. If both a collective and a cyclic pull-up initiation time is determined, the control action with the higher intensity is chosen. Control intensity is measured through the root-mean-square deviation from the manoeuvre starting position, scaled to a percentage of the respective maximum stick deflection. Figure 5.22 shows an example trajectory, including longitudinal and collective control inputs and the largest identified control actions.

The calculated pull-up initiation locations, averaged per condition, are shown in Figure 5.23. While the median pull-up location lies between 250 m and 230 m in nominal situations and high-visibility off-nominal situations, it is reduced to values between 200 m and 180 m in off-nominal situations in low visibility. There is a significant effect of *visibility* on pull-up location, $F(1,134) = 17.66$, $p < 0.001$, as well as a significant effect of *(off) nominal situation*, $F(1,134) = 17.56$, $p < 0.001$. There is also a significant interaction effect between *visibility* and *(off) nominal situation*, $F(1,134) = 11.65$, $p < 0.001$. When analysing nominal and off-nominal situations separately, it becomes apparent that *visibility* only affects pull-up location in off-nominal situations ($F(1,66) = 34.31$, $p < 0.001$), there are no significant effects in nominal situations. This can, again, be explained by the visibility onset distance of the obstacle depending on the condition, Table 5.6: only in low-visibility, off-nominal conditions is the obstacle completely undetectable at distances greater than 200 m, resulting in significantly later pull-up initiations. In the other conditions, either the obstacle itself or its contour is visible from a distance of 300 m.

5.4.6. Pull-up control strategy: cyclic vs. collective

Figure 5.24 shows a categorisation of control strategies to initiate a pull-up manoeuvre. It is based on the pull-up initiation location computed in the previous subsection. A pull-up is categorised as "cyclic only" if the algorithm did not detect any collective pull-up control action in the probable pull-up area. Likewise, it is

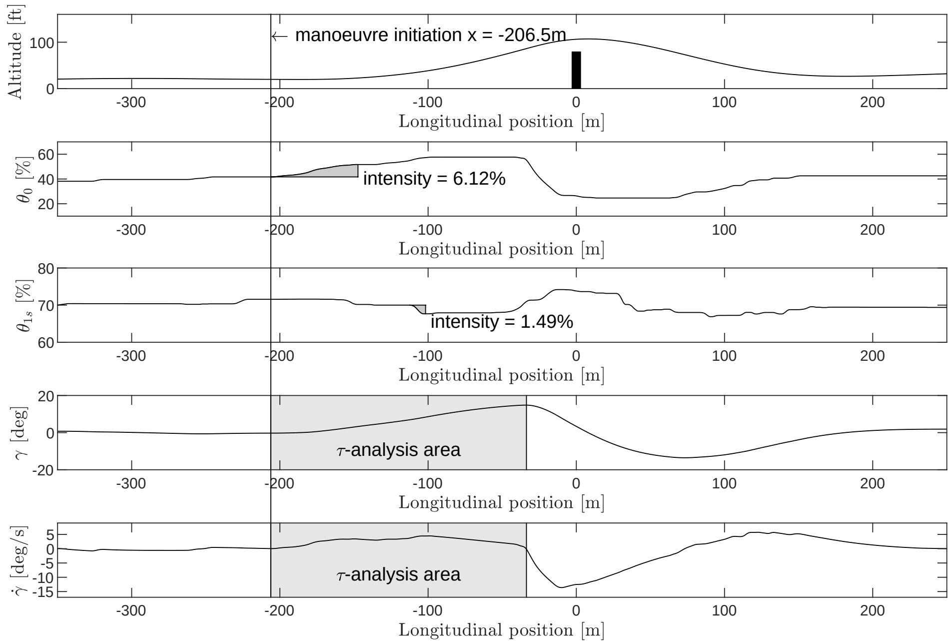


Figure 5.22: Example fly-over trajectory in good visibility, with the basic HUD, in a nominal situation.

categorised as "collective only" if no cyclic pull-up control is detected. If both collective and cyclic control actions are identified, the pull-up is categorised as "cyclic dominant" if the cyclic control intensity is greater than the collective control activity (scaled to a percentage of maximum inceptor deflection), otherwise it is categorised as "collective dominant". In low visibility, using the constraint-based display leads to a slight decrease in cyclic-only initiations, compared to the other displays. In nominal situations, the constraint-based display seems to elicit more collective-only control actions. In safety-critical off-nominal situations, the constraint-based display leads to the least cyclic-only and collective-only control actions, and to an increase of coordinated control approaches. In this dependent measure, no noticeable difference between pilots with less or pilots with more flight experience can be observed in terms of the employed control strategies.

5.4.7. Control activity

For the analysis of the results of this experiment, control activity is defined as the signal power of the control inceptor deflection in a one-second sliding window. Figures 5.25 and 5.26 show box-plots of the average cyclic and collective control activity per condition. Normality is rejected in both cases, there are no significant effects of *(off) nominal situation* or *display x visibility* on neither collective nor cyclic control activity. Analysing nominal and off-nominal situations separately likewise does not reveal any significant effects. There seems to be an increased spread of

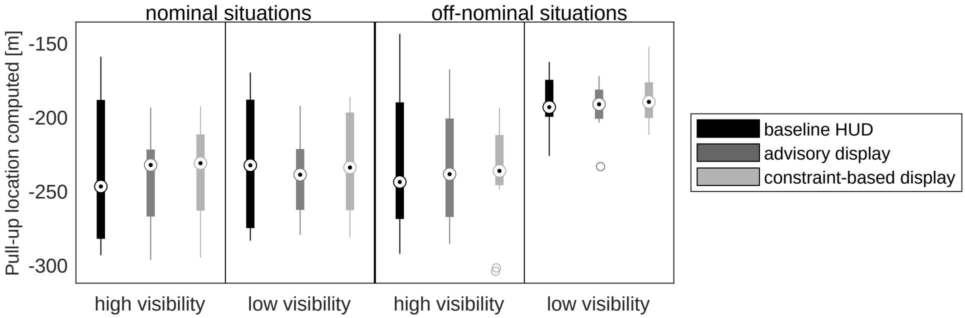


Figure 5.23: Box-plots of pull-up manoeuvre onset location per visibility, display, and situation.

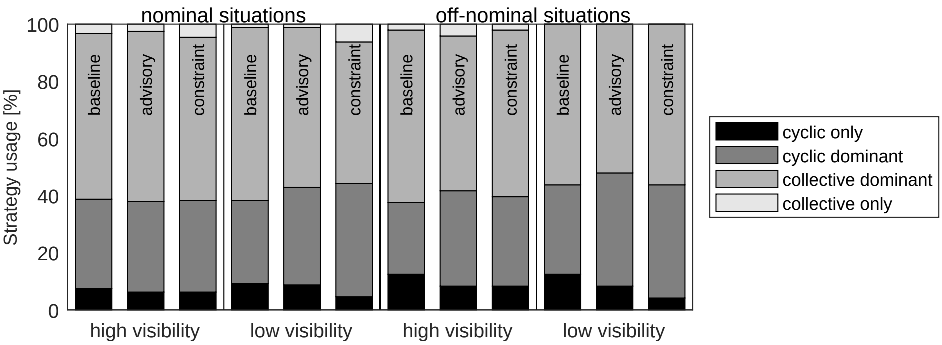


Figure 5.24: Control strategy during the pull-up manoeuvre.

5

cyclic control activity in low-visibility, off-nominal situations, possibly caused by the later detection of the obstacle, and differing coping strategies per pilot.

While there are no significant differences in average control activity, there might still be differences during the separate manoeuvre phases, especially pull-up, that could be caused by the smaller obstacle detection distance. Figures 5.27 and 5.28 show the collective and cyclic control activity during that manoeuvre phase. Normality is rejected for both parameters.

There is no significant effect of *(off) nominal situation* or *display x visibility* on cyclic or collective pull-up control activity. Analysing nominal and off-nominal situations separately, however, reveals a significant effect of *visibility* on collective pull-up control activity in nominal situations ($\chi^2(1,66) = 7.99$, $p < 0.01$). A decrease of visibility significantly increases collective control in nominal situations. The variability of cyclic control activity seems to increase in off-nominal, low-visibility situations, but this is not substantiated by a significant statistical test result.

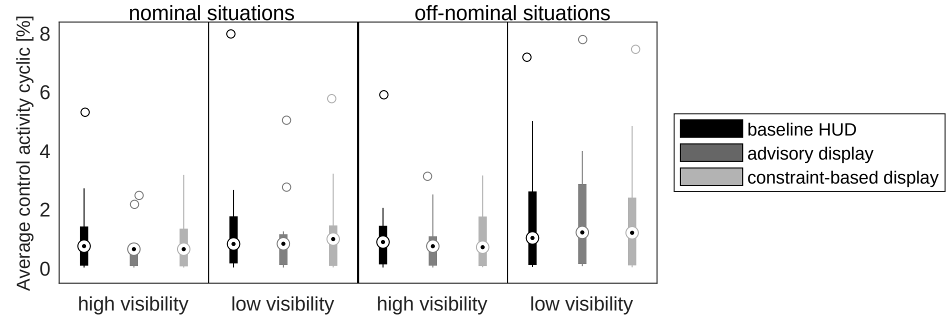


Figure 5.25: Box-plots of average cyclic control activity per visibility, display, and situation.

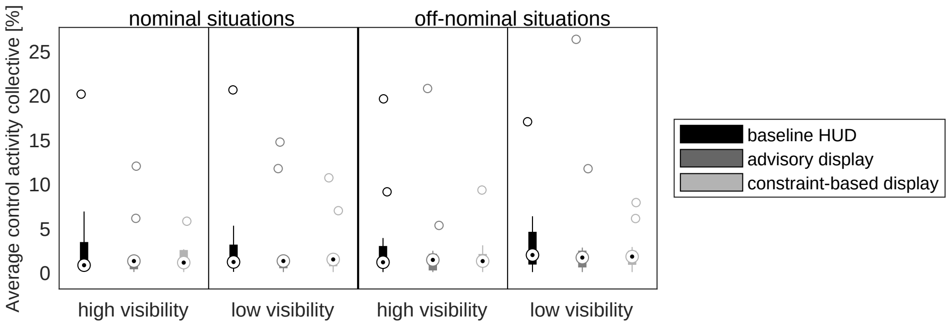


Figure 5.26: Box-plots of average collective control activity per visibility, display, and situation.

5.4.8. Trajectory spread

The average trajectory spread is calculated per pilot as the average root-mean-square difference of the flown altitude trajectories to this pilot's average altitude trajectory in this condition — it is therefore a measure of manoeuvre variability within one participant. Experiment conditions with a low trajectory spread are caused by pilots performing the task in a consistent manner. A large trajectory spread indicates diverse, non-uniform pilot reactions. Figure 5.29 shows the average trajectory spread per experiment condition.

Normality is rejected in 3/12 cases, parametric tests are used. There is no significant effect of *display*, *visibility*, or *(off) nominal situation* on the mean trajectory spread for the whole manoeuvre, $p > 0.03$ for every effect and interaction. However, when analysing only off-nominal situations (in which case normality is rejected in 3/6 cases), *visibility* has a significant effect on trajectory spread ($\chi^2(1,66) = 8.3749$, $p < 0.01$). This effect is also visible in the separate manoeuvre stages: there are no significant effects when analysing all conditions together, but a significant effect of *visibility* becomes apparent during off-nominal situations during pull-up and descent, but not during fly-over ($\chi^2(1,66) = 7.99$, $p < 0.01$;

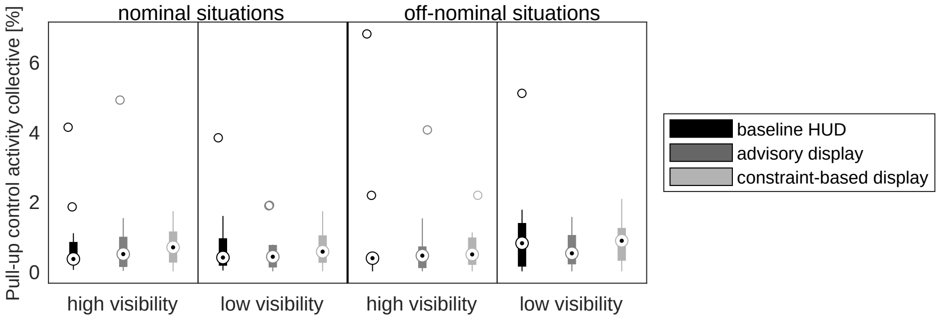


Figure 5.27: Box-plots of pull-up collective control activity per visibility, display, and situation.

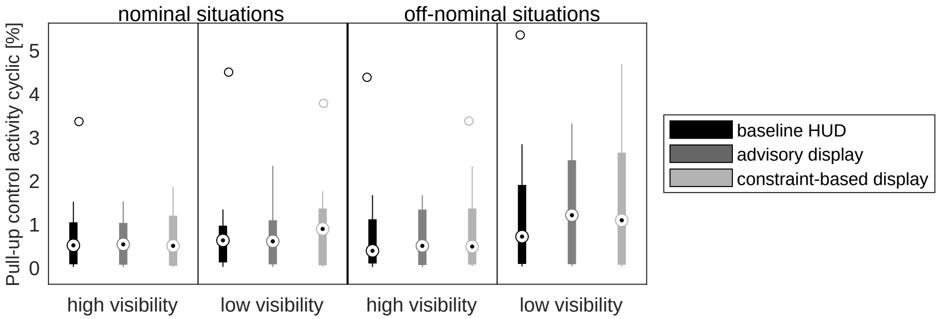


Figure 5.28: Box-plots of pull-up cyclic control activity per visibility, display, and situation.

$\chi^2(1{,}66) = 4.31$; $p = 0.038$, $\chi^2(1{,}66) = 7.79$, $p < 0.01$). Encountering low visibility or an off-nominal situation separately does not seem to impact the trajectory spread. However, encountering both at the same time consistently decreases the variability of the flown manoeuvre trajectories. The combination of the two adverse effects caused the pilots to fly closer to the edge of manoeuvre possibilities by pulling up at a later time, and therefore causing the trajectories to be grouped closer together.

5.4.9. Velocity at peak

Instead of computing an average, RMS error from the target speed, the momentary speed at maximum altitude is investigated here. If this speed is close to the target of 60 knots, the pilot was able to concentrate on managing his speed even while avoiding the obstacle. If it is below 60 knots, it presumably means that the pilot either chose or was forced to prioritise avoiding the obstacle, accepting a loss of speed in the process. Figure 5.30 shows box plots of the speed at peak altitude, averaged per pilot. Normality is rejected in 4/12 cases. The employed non-parametric tests reveal no significant effects in the overall analysis ($p > 0.03$ in all cases) or

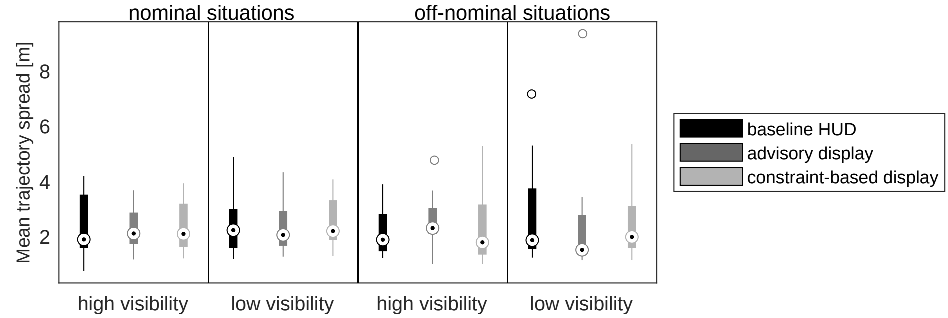


Figure 5.29: Box-plots of within-pilot trajectory spread per visibility, display, and situation.

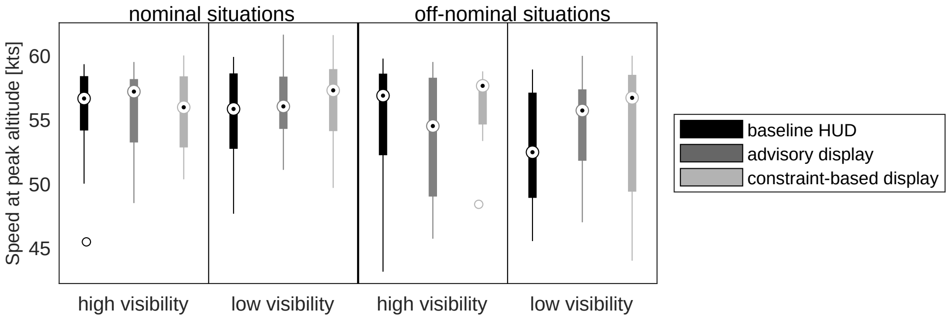


Figure 5.30: Box-plots of speed at peak altitude per visibility, display, and situation.

in the nominal/off-nominal subsets ($p > 0.01$ in all cases). Off-nominal situations seem to increase the spread of the data, but the median is not significantly affected.

5.4.10. Tau analysis

To further analyse the employed pull-up control strategy, a parameter estimation of a prescribed, *constant-acceleration* τ-guided manoeuvre is performed for every pull-up manoeuvre, see Figure 5.22. The guides are computed based on previous work by Padfield (2011). The manoeuvre time T, the manoeuvre flight path angle gap γ_{gap}, and the coupling constant k are estimated.

The pull-up manoeuvre is identified as the first stretch of data points with a positive change of flight path $\dot{\gamma} > 0$ after the previously identified manoeuvre start. The manoeuvre ends when $\dot{\gamma}$ once again reaches a value of zero for the first time. The manoeuvre time $T = t_{end} - t_{start}$ and the flight path angle gap $\gamma_{gap} = \gamma(t_{end}) - \gamma(t_{start})$ are computed based on the difference in time and flight path angle between the start and end of the manoeuvre.

To estimate the coupling parameter k, the τ trajectory of the actual flown manoeuvre, as well as the *constant-acceleration* intrinsic τ-guide have to be computed, as the coupling parameter k is defined through the relationship between $\tau_{manoeuvre}$, the instantaneous time to contact of the actually flown manoeuvre, and τ_{guide}, the prescribed τ-guide:

$$\tau_{manoeuvre} = k \cdot \tau_{guide} \tag{5.5}$$

$\tau_{manoeuvre}$ is defined as the instantaneous time to contact between the manoeuvre flight path angle and its final value. Per convention, γ_{end} is defined as zero degrees, while γ_{start} has a negative value. $\gamma_{manoeuvre}$ therefore starts at a negative value and approaches zero throughout the manoeuvre:

$$\gamma_{manoeuvre}(t) = -(\gamma_{end} - \gamma_{start}) + \gamma(t) \tag{5.6}$$

$\dot{\gamma}_{manoeuvre}$ is simply calculated as the time derivative of $\gamma_{manoeuvre}$, as γ_{start} and γ_{end} are constant:

$$\dot{\gamma}_{manoeuvre}(t) = \dot{\gamma}(t) \tag{5.7}$$

5

$\tau_{manoeuvre}$ can now be calculated through

$$\tau_{manoeuvre}(t) = \frac{\gamma_{manoeuvre}(t)}{\dot{\gamma}_{manoeuvre}(t)}. \tag{5.8}$$

The *constant-acceleration* τ-guide, as given by Padfield (2011), is

$$\tau_{guide}(\hat{t}) = -\frac{T}{2}\left(\frac{1}{\hat{t}} - \hat{t}\right), \tag{5.9}$$

with the normalised manoeuvre time $0 \leq \hat{t} \leq 1$:

$$\hat{t} = \frac{t - t_{start}}{t_{end} - t_{start}} \tag{5.10}$$

To estimate k, a least-square fit is applied to subsets of the manoeuvre data. Work by Lu et al. (2013) has shown that this approach has a number of downsides, e.g., a sensitivity to manoeuvre length, boundary conditions causing instability, and sensitivity to incomplete or oscillatory data. In this experiment, however, the analysed flight path angles show little to no oscillatory behaviour, and the employed methodology seems to provide reasonable results. Therefore, in this experiment, the aforementioned least-square fit methodology is chosen.

The least-square fit is initiated with three data points at the end of the manoeuvre. The analysis is repeated for every subset of data from three data points up until all data points between $0.2 \leq \hat{t} \leq 1$. In the region close to $\hat{t} = 0$, the τ-guide approaches minus infinity. To avoid an influence of this limit behaviour on the identification of k, at most the last $80\,\%$ of the manoeuvre are used. The final identified value of k is then chosen as the identified value of the least-square fit with the biggest number of data points that still provide an adjusted $R^2 > 0.97$. Figure 5.31 shows an example manoeuvre and fit τ trajectory.

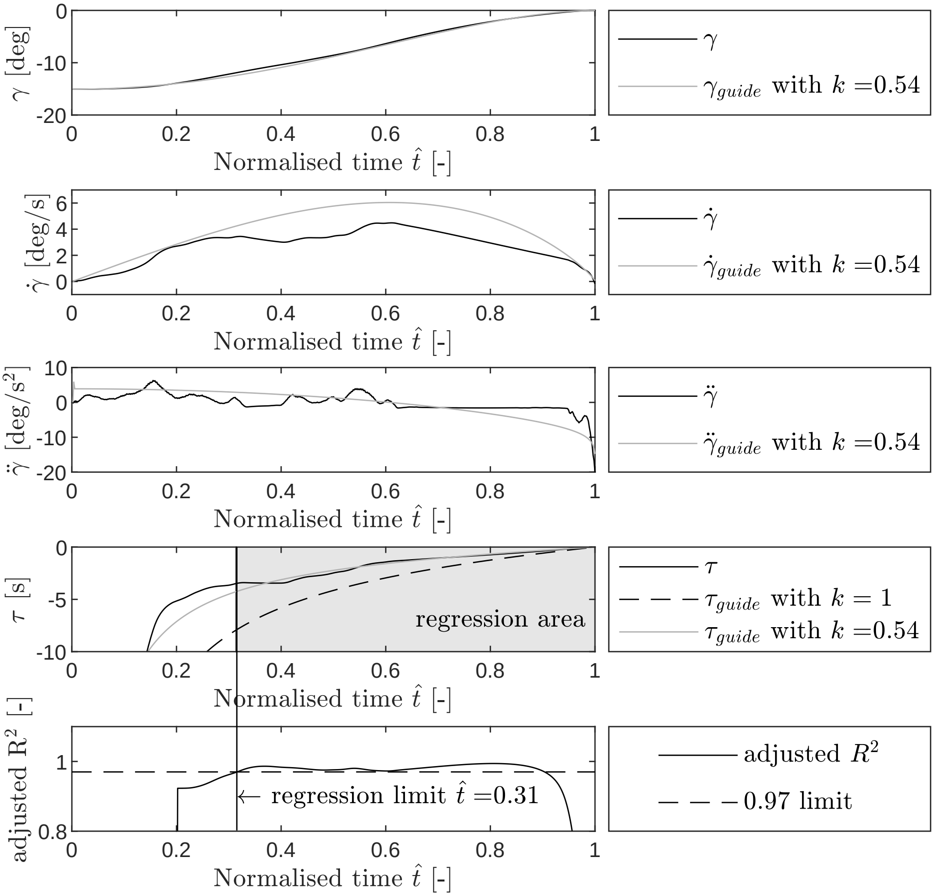


Figure 5.31: Example γ trajectory and τ-fit.

Box plots of the manoeuvre time T are shown in figure 5.32. Normality is not rejected, a three-way ANOVA does not reveal any significant effects. Likewise, analysing nominal and off-nominal situations separately does not reveal any significant effects, either. The τ-manoeuvre time T seems to be largely independent from the experiment conditions.

Figure 5.33 depicts box-plots of the manoeuvre gap γ_{gap}. Normality is rejected in no cases, parametric tests are used. *Visibility* (F(1,134) = 7.74, p < 0.01) and *(off) nominal situation* (F(1,134) = 15.63, p < 0.001) significantly affect the manoeuvre gap. There is also a significant interaction effect between *visibility* and *(off-) nominal situation*, F(1,134) = 8.28, p < 0.01. Analysing nominal situations separately, however, reveals no significant effects — the observed significant effects are caused solely by an increase of the manoeuvre gap in off-nominal situations and low visibility, revealed by a significant effect of visibility when analysing only off-

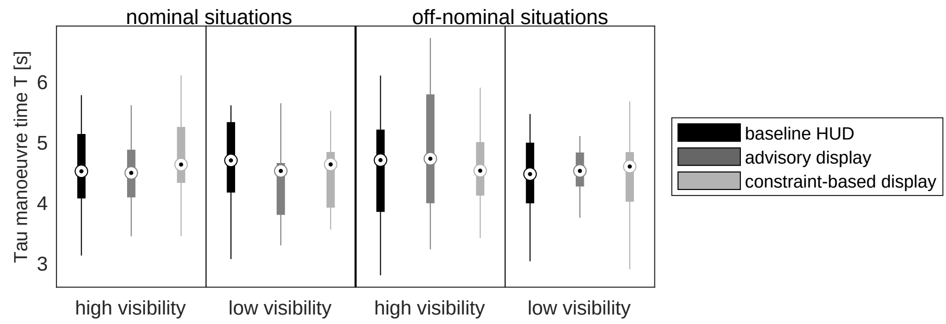


Figure 5.32: Box-plots of tau manoeuvre time T per visibility, display, and situation.

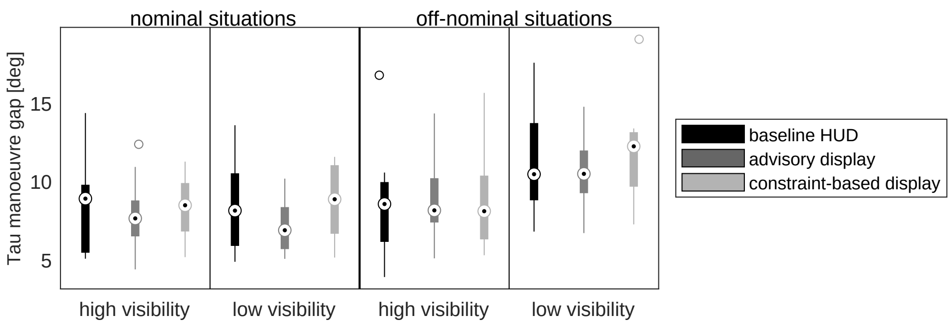


Figure 5.33: Box-plots of tau manoeuvre gap γ_{gap} per visibility, display, and situation.

nominal situations, F(1,66) = 13.34, p < 0.001. Mirroring previous results, only the combination of off-nominal situations and low visibility causes a significant change in the dependent measure. An increase in manoeuvre gap implies a larger change of γ in the initial pull-up manoeuvre. This makes sense, as the reduced obstacle detection distance necessitates a larger trajectory change in a shorter manoeuvring distance to still clear the obstacle.

The employed display seems to only have a small influence on the manoeuvre gap γ_{gap} in specific conditions, e.g., the advisory display seems to cause a smaller manoeuvre gap in nominal, low-visibility situations than the other displays. These differences are not significant, however, and not applicable in all conditions.

Figure 5.34 shows box-plots of the coupling parameter k, averaged per pilot. The larger the value of k, the later in the manoeuvre the peak acceleration occurs — at values $k > 0.5$, the acceleration guide becomes minus infinity at the end of the manoeuvre, practically meaning the guide overshoots the target. The only significant effect can be observed when analysing only off-nominal situations: in that case, *visibility* significantly affects the coupling constant k (F(1,66) = 7.45, p = 0.01). An increase of the coupling constant k makes sense when coupled with

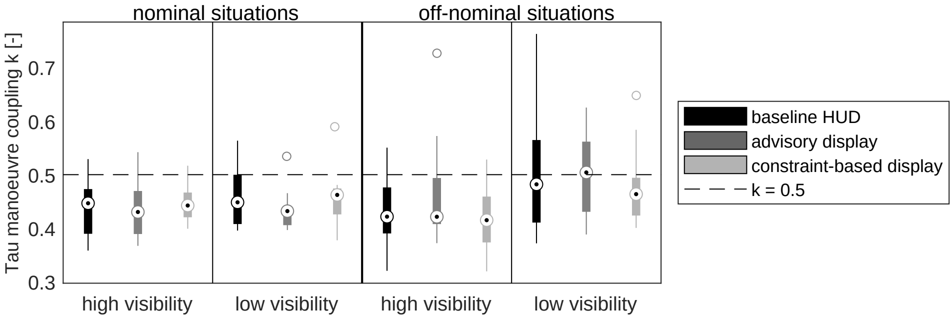


Figure 5.34: Box-plots of tau-coupling parameter k per visibility, display, and situation.

the requirement to quickly change the flight path angle when an obstacle appears at close range, as compared to the calmer manoeuvres in the other conditions.

5.4.11. Pilot preference

After the experiment, the pilots indicated their confidence in using the different displays to fulfil the task on a scale from 1 (low) to 7 (high), as shown in Table 5.9 and Figure 5.35. In general (i.e., not differentiating between nominal and off-nominal situations), pilots felt most confident using the baseline HUD (6.08) and the advisory display (5.83), followed by the constraint-based display (4.92). This difference between displays is insignificant, however, $F(2,33) = 2.35$, $p = 0.11$.

At a significance level of $\alpha = 0.05$, a two-way ANOVA covering two display conditions (advisory, constraint-based) and two situational conditions (nominal, off-nominal) reveals a significant effect of *(off-nominal) situation* on pilot rating ($F(1,44) = 5.07$, $p < 0.05$), as well as a significant interaction effect ($F(1,44) = 4.19$, $p < 0.05$). While the average pilot rating for the constraint-based display remains relatively constant between nominal and off-nominal situations (5.00 and 4.92, respectively), the rating for the advisory display drops significantly from 6.17 to 4.42. While pilots prefer the advisory display in nominal situations, they slightly prefer the constraint-based display in off-nominal situations.

It is interesting to note that the observed drop in confidence when using the constraint-based display in all and in nominal situations seems to stem completely from pilots with less than 1,000 flight hours, as shown in Figure 5.35. While the number of pilots with more than 1,000 flight hours is rather low, these results could suggest that a larger flight experience enables the pilots to more confidently use the constraint-based display.

5.5. Discussion

This experiment investigated the effect of employing a classical, advisory-based display and a constraint-based display during helicopter obstacle avoidance in forward flight. Table 5.10 summarises the results of the top-level statistical tests, as well

Table 5.9: Averaged questionnaire result to *"How confident did you feel while using the baseline/advisory/constraint-based display to fulfil the task?"*, on a scale from 1 (low) to 7 (high).

Confidence	baseline HUD	advisory display	constraint-based display
general	**6.08**	5.83	4.92
nominal		**6.17**	5.00
off-nominal		4.42	**4.92**

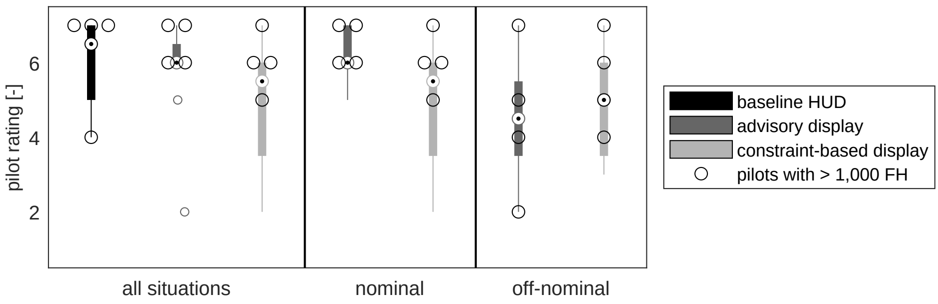


Figure 5.35: Box-plots of pilot ratings in all, nominal, and off-nominal situations.

as the statistical power $1 - \beta$ of the performed tests, calculated post-hoc. In many cases, the statistical power of the performed tests was low, signified by vales below 20 % or even 10 %. Only in cases when the test produced a significant effect) does the power reach values above 50 %[2].

These low power values can be interpreted in two different ways. First, the power could be low because there are no differences between conditions (along the lines of the tested null hypothesis). But it is also possible that there are not enough data points to draw powerful conclusions from the data, or that the utilised data analysis process is so conservative in its approach that, in order to maintain a small Type-1 error, a reduction of the power of the employed tests is accepted. The data analysis procedure in this chapter is certainly conservative, and the number of participants is not high. The results of the performed statistical tests should therefore be interpreted with caution: through the conservative approach, a reported significant result is a strong indication that there is a significant difference between conditions (stipulated Type-1 error α < 0.03/0.05, respectively). However, an insignificant result represents only a weak indication that there is no difference between conditions in reality (calculated Type-2 error 0.63<β<0.97). The presented results and discussion should be interpreted with this important limitation in mind.

Workload and situation awareness metrics are significantly affected by visibility, in accordance with the hypotheses. While the constraint-based display decreases workload and increases situation awareness according to expectations in all visibility

[2]While there are no strict rules for the required power of statistical tests, a value of $1 - \beta$=0.8 is often used as a starting point, based on convention (Field, 2005).

conditions, the advisory display improves the measures only in good visibility. In low visibility, it actually decreases the median situation awareness.

Contrary to the hypotheses, the constraint-based display reduces workload and increases situation awareness stronger than the advisory display. This is surprising, because constraint-based displays typically require more information integration from the pilot (Van Paassen et al., 2018). However, these results fit the pattern of the questionnaire answers to the pilot's confidence during off-nominal events in Table 5.9: in off-nominal situations, the constraint-based display is rated with an average score of 4.92, which is higher than the score of the advisory display in the same situations (4.42). A (subconscious) focus on the more memorable, unexpected events while filling out the questionnaires could explain these values.

Due to the chosen measurement procedure, there are no separate measurements of workload and situation awareness. For future research, it will prove valuable to collect ratings like these separately for nominal and off-nominal situations. A second possible explanation for this finding could be the higher importance of the out-of-window view for general helicopter control, compared to the more instrument-focused fixed-wing approach. Any display information that can be directly related and better conforms to the outside view (like the constraint-based display) might be preferred compared to other, non-conformal information (like the arrow of the advisory display).

Performance, safety, and control strategy are all mostly impacted by the combination of low visibility and off-nominal situation. This worst-case situation causes less altitude and lateral deviation, which can be interpreted as flying a more uniform manoeuvre with less manoeuvre spread, closer to the manoeuvre limitations and with a smaller safety clearance above the obstacle. Speed deviation increases, but only after the obstacle was cleared: as a result of the more aggressive pull-up manoeuvre, the recovery to an optimal flight path took longer. The computed pull-up location and τ-manoeuvre parameters confirm the expectation that in this worst-case scenario, a later pull-up coincides with a more aggressive pull-up manoeuvre, which covers a greater change of flight path angle to still clear the obstacle. Some pilots commented that the support displays enable them to pull up at a later time, and at a more consistent location, but other pilots reported no change in perceived behaviour at all. The data do not show clear effects of the displays in this regard.

The percentage of unsafe clearances follows this trend, with an increase of unsafe clearances in off-nominal situations. The advisory display presents an exception to this: when encountering an off-nominal situation in low visibility, the number of unsafe clearances actually decreases. A possible explanation for this could be an over-compensating pull-up manoeuvre, clearing the obstacle at a higher clearance than required and causing a larger speed and altitude deviation as a result. However, the performance measures do not reflect this expectation. The advisory display does cause a decrease of situation awareness in low visibility situations — it could be hypothesised that the increase in safety in this condition was "paid for" with some increased mental effort, which in turn lead to a decrease in mental capacity to maintain the situation awareness level. The baseline HUD causes the most unsafe trajectories when encountering unexpected events, showcasing the positive

Table 5.10: Results of initial statistical tests, taking into account all collected data. An arrow to the left implies a non-parametric test was performed, combining the analysis of display and visibility into one result. An "x" implies that the experiment design did not afford data to perform this test.

			Display		Visibility		Off-nominal	
Category	Dependent measure	α	p	$1-\beta$	p	$1-\beta$	p	$1-\beta$
Performance	Deviation from ideal altitude	0.03	0.94	0.03	<–	<–	0.56	0.06
	Deviation from ideal lateral position	0.03	0.98	0.03	<–	<–	0.87	0.03
	Deviation from ideal speed	0.03	0.81	0.05	0.64	0.05	0.11	0.27
Safety	Vertical clearence over obstacles	0.03	0.98	0.03	<–	<–	0.80	0.04
Workload	RSME	0.05	0.10	0.47	<0.001	0.95	x	x
Situation awareness	SART	0.05	0.31	0.25	<0.01	0.87	x	x
Control strategy	Control activity collective	0.03	0.90	0.03	<–	<–	0.35	0.11
	Control activity longitudinal cyclic	0.03	0.72	0.04	<–	<–	0.27	0.14
	Trajectory spread	0.03	0.96	0.03	0.52	0.07	0.67	0.04
	Velocity at maximum altitude	0.03	0.82	0.04	<–	<–	0.13	0.26
	Pull-up initiation location	0.03	0.79	0.06	<0.001	0.98	<0.001	0.97
	τ-theory manoeuvre time	0.03	0.96	0.03	0.23	0.16	0.82	0.03
	τ-theory manoeuvre gap	0.03	0.29	0.20	<0.01	0.71	<0.001	0.96
	τ-theory coupling parameter	0.03	0.33	0.06	<–	<–	0.62	0.05
Pilot preference	Confidence (irrespective of situation)	0.05	0.11	0.37	x	x	x	x
	Confidence (dependent on situation)	0.05	0.42	0.13	x	x	<0.03	0.60

5

impact of any of the support displays in these situations. The constraint-based display appears to increase the resilience of the pilot-vehicle system against unexpected events the most, considering the number of unsafe clearances: in three out of four cases, the constraint-based display causes the least unsafe clearances.

For the experiment set-up, these results indicate that the difference between nominal and off-nominal situations in high visibility was not substantial enough to elicit a significant change of the dependent measures. Conversely, in nominal situations, the difference between high and low visibility conditions was also small. This was probably caused by the inclusion of the contour box around approaching obstacles, which set the effective detection distance to 300 m across all conditions, except the worst-case scenario of low visibility and off-nominal events. Combined with the already cue-rich baseline HUD and outside visuals, the pilots received an abundance of information in all conditions but the worst, which would explain the insignificant effects of the displays in these conditions. Pilot comments support this argument: occasionally, some pilots would ignore the support displays completely, and only focus on the outside visuals and baseline HUD elements.

Considering pilot preference, the results of this chapter are in line with the aforementioned ecological design research in the fixed-wing domain (Borst et al., 2010b): pilots prefer conventional, advise-based support systems in nominal situations, but their preference shifts to constraint-based support displays in off-nominal, unexpected situations. This can be explained by the kind of information that is communicated to the pilot, even in the event of an off-nominal event: the constraint-based display still provides information about the internal manoeuvre constraints to the pilot. The advisory display does not provide any information until the obstacle is detected.

The advisory display provides easy to follow guidance on how to achieve an optimal target trajectory, but it depends on the correct detection and computation of all required data — the internal manoeuvre constraints, the external environment constraint, and their combination. The constraint-based display communicates only the internal manoeuvre constraints to the pilots, they have to acquire the external environment constraints themselves and allocate cognitive resources to derive meaning from them. This would explain why the constraint-based display is preferred in off-nominal situations. When the obstacle detection system is not functioning, i.e., fails to support the perception of the external environment constraint (by drawing the safety zone above an obstacle), pilots can still use the other half of the constraints, the internal manoeuvre constraints, to support their decision-making, leading to a more robust control performance.

The differences between the investigated displays are not statistically significant. There are some effects on workload, situation awareness, and pilot preference, but they do not afford a general conclusion concerning positive or negative effects of the displays on objective performance or safety measures. Possibly reasons for this are:

- The pilots were well able to maintain an adequate level of performance of safety across all display conditions, the only difference is a change of required mental effort. The displays might have helped the pilots in reducing the required mental effort to perform the task, but the actual task performance stays level.

- The analysed task is too focused on short-term, inner-loop control to reveal big differences, and the baseline HUD and outside visibility already provides all information that helicopter pilots use to perform the analysed task, even in off-nominal situations. The displays only provided additional information that pilots might or might not have used. Especially in hectic, fast-paced manoeuvres or reactions to obstacles, it seems plausible that pilots concentrated on the source of information they are most familiar with — the outside visuals.

- The analysed displays are quite similar to each other, as they are both based on the maximum effective climb angle γ_{limit}. This was a deliberate experiment design decision, to focus more on the different data representation philosophies, and less on differences in the actual data being displayed. utilising different data sources and constraint calculations for the displays might incur greater differences, but it also introduces the question as to which part of the display made the difference: the data itself, or its representation? In addition, the accuracy of the parameters used to calculate γ_{limit} could be improved. For example, the current pilot reaction onset time-delay is based on a one degree-of-freedom experiment, not on actual helicopter pilot performance during obstacle avoidance.

- The display design of both variants (e.g., colour, symbology, location) was rather basic, compared to current developments in helicopter HUD applications, as shown by, e.g., Münsterer et al. (2018). Improving display design aspects could increase the effect of the investigated displays. However, care has to be exerted to improve both displays to a very similar extend. Otherwise, the obtained results could be influenced more by these differing display design characteristics, and less by the different data representation mode, which was the focus of this experiment.

- The performed task was monotonous and repetitive. Even the unexpected, off-nominal situations became predictable after a few occurrences, and the first encountered unexpected events, where pilots might have been most surprised, occurred during the training phase of the experiment. Even though it was never clear to the pilot *when* an obstacle might not be detected in time, they were aware that this late detection will happen eventually and regularly, that there are no other unexpected events, and that a climb-over manoeuvre would be the only feasible avoidance trajectory. Even if positive influences of the constraint-based display are assumed, the obstacles and possible avoidance trajectories in this experiment lacked a sufficient amount of variability, and the off-nominal situations a sufficient amount of "unexpectedness", to trigger those advantages.

- Lastly, a higher number of pilot participants might increase the power of the employed test statistics, provided the results show the same trends. The number of twelve participants and the within-participants experiment design enabled the use of parametric tests, but at the cost of lower power.

In order to remedy these problems, future experiments investigating obstacle avoidance support systems should incorporate a higher variability of obstacles and possible avoidance trajectories, more varied approach speeds and tasks (e.g., hovering in obstructed areas, or approaching confined areas), and larger differences between display and visibility conditions. Off-nominal events should be designed such that neither their occurrence, nor the proper control response, can be easily predicted by the participating pilots.

This study focused on the effect of the advisory and constraint-based head-up support systems. The assumption was made that any HUD system that can include such displays would, as a standard, also show a baseline HUD with primary flight data, which is why this was chosen as the baseline condition. However, the inclusion of a condition without any HUD elements, only relying on outside visuals, could provide insight into the effects of employing a baseline HUD, and would enable the comparison of highly augmented conditions (HUD with advisory or constraint-based display) with non-augmented display conditions.

It is important to note that many results were not consistently found across all pilots, as Figure 5.36 illustrates in case of the computed pull-up location. While the pull-up location of some pilots were clearly impacted by the employed display, e.g., Pilot 3 or Pilot 7, other pilots were not impacted much by display or visibility, for example Pilot 5 and 6. While there seem to be individual preferences and different reactions to the employed displays, these reactions were not uniform, not proportional or otherwise related to pilot experience, and cannot be extrapolated to all experiment participants, let alone the general helicopter pilot population. Considering these widespread responses, an advisory display that emphasises one specific target trajectory does not seem to be able to accommodate different pilot preferences and strategies. A constraint-based or ecological interface, on the other hand, could still provide support even to pilots with different control preferences, as it emphasises only the systemic and environmental limitations — the pilots are encouraged to decide for themselves how to control the system, enabling and supporting more diverse strategies between pilots.

Improving subjective measures can be seen as a first step towards EID-based support systems in helicopters that are (i) seen favourable by pilots, by positively impacting **subjective** workload and situation awareness measures, and (ii) significantly affect **objective** task performance and safety measures. While the first step has been reached in this experiment, follow-up research should investigate the properties of helicopter automation systems that can improve both subjective and objective measures concurrently. Of special interest is a scenario on a longer timescale, requiring more rule- and knowledge-based pilot control.

5.6. Conclusion

Two helicopter obstacle avoidance displays were evaluated during low-altitude forward flight, an advisory display and a constraint-based display. Results show the

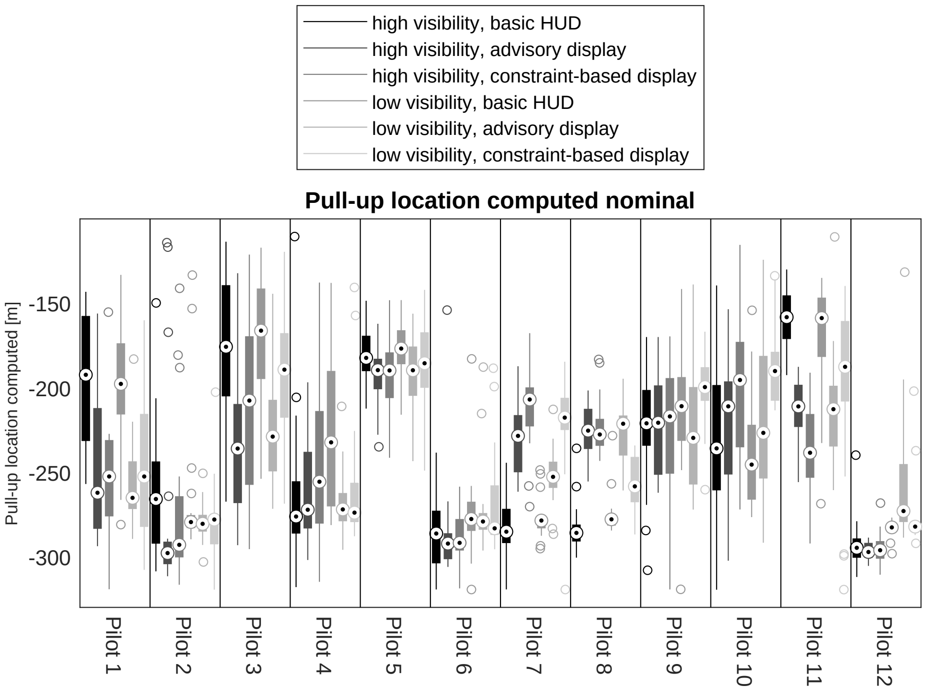


Figure 5.36: Box-plots of computed pull-up location per visibility, display, and situation, separated per pilot.

employed support displays decreased subjective ratings of workload and increased subjective ratings of situation awareness, with the constraint-based display causing larger effects. Confirming our hypothesis, pilots preferred the advisory display in nominal, the constraint-based display in off-nominal situations. While the constraint-based display seems to be the most robust display concerning safety during off-nominal events, differences were not significant. The improved subjective ratings showcase the employed displays' potential to improve the pilots' experience while performing obstacle avoiding tasks. However, contrary to our expectations, the displays in this experiment did not elicit significant changes in task performance or safety.

6

Strategic Decision-Making: Navigation Displays

This chapter investigates the effects of employing advisory and constraint-based automation design philosophies for a long-term navigation task. The focus lies on pilot trajectory decision-making in the long timescale, the manual helicopter control task on the lower timescales only acts as a workload-intensive secondary task. This setup aims to emulate the requirements of real-world helicopter operations, where pilots are required to exert control on all timescales at the same time, from short-term stabilisation to long-term navigation decisions. The results show a significant negative impact of the advisory display on pilot trajectory decision-making during unexpected events. As the temporal gap between the short-term manual control task and the performed decision-making task increases from the previous chapter (investigating medium-term obstacle avoidance) to this chapter (investigating long-term decision-making), the inadvertent negative effects of automation become more pronounced. The constraint-based display did not negatively impact the pilots' decision-making, but also failed to improve any of the other dependent metrics. This second experiment of the dissertation showcases the potential of constraint-based displays to avoid inadvertent automation effects, but also highlights their training, familiarisation, and ease-of-use issues. If constraint-based automation should be a contender for real-word helicopter automation, these issues need to be addressed.

This chapter has been presented as "D. Friesen, C. Borst, M. D. Pavel, P. Masarati, M. Mulder, *Design and Evaluation of a Constraint-Based Helicopter Display to Support Safe Path Planning*", at the *NITROS Workshop on Engineering for Rotorcraft Safety* on April 7th, 2021. Parts of it have also has been published as "D. Friesen, C. Borst, M. D. Pavel, P. Masarati, M. Mulder, *Human-Automation Interaction for Helicopter Flight: Comparing Two Decision-Support Systems for Navigation Tasks*", in *Journal of Aerospace Science and Technology, 127(19):107719, 2022*.

6.1. Introduction

As explained, a critical aspect of automation support during vehicle locomotion control is its timescale of operation Van Paassen et al. (2018). Previous helicopter automation research in this dissertation covered short-term helicopter hover control (Chapters 3 and 4) and medium-term obstacle avoidance (Chapter 5). These studies focused on the manual control behaviour of the pilots and how different head-up or head-down displays influenced this direct control behaviour. Manually controlling the vehicle on the short-term (stabilisation) and medium-term (guidance) describes the two innermost vehicle control loops described by Padfield (2007).

In contrast, this chapter investigates automation support for the remaining long-term control loop, describing navigation tasks like trajectory determination and evaluation. The focus lies on investigating the cognitive task of strategic, navigational decision-making. It is important to note that at the same time, the pilots are still required to manually close the other, shorter-term control loops: the pilots exert control on multiple timescales in parallel.

Most helicopters in operation today, in particular in the civil domain, require uninterrupted and continuous hands-on control[1]. This represents a big difference compared to studies that investigate display support in the fixed-wing (Borst et al., 2010b) or air traffic control (Klomp et al., 2016) domain. In the civil fixed-wing domain, the controlled aircraft is typically stable and does not require constant control intervention to maintain stability. Air traffic controllers do not control any one vehicle manually, they evaluate options and give instructions on a more abstract level. Both domains afford the human controller more time and cognitive resources to perform decision-making tasks. The continuous stabilisation control actions that are required by helicopters place a strain on the pilots' spare mental capacities. This might intensify possible adverse automation effects because pilots have less spare mental capacity to monitor and evaluate the automation's information and suggestions.

The goal of this chapter is to analyse what kind of automation system best supports the pilot during a long-term helicopter navigation task. Based on this analysis, recommendations for future helicopter automation can be derived. To that end, this chapter compares two different automation design philosophies, advisory automation support and constraint-based automation support.

Generally speaking, advisory automation focuses on a specific, clearly defined task and provides one particular solution to it. This solution (e.g., a specific manoeuvre, flight profile, control strategy) is either communicated to the pilot or automatically implemented. Constraint-based automation, taking inspiration from ecological interface design, focuses on providing more information regarding the safe operational envelope within possible strategies and actions, but leaves the decision-making task to the pilot. It can be characterised as information automation, a term used by Parasuraman et al. (2000) to describe automation in the information acquisition and analysis stage.

Ecological interface design principles have been only sparsely applied in the he-

[1]The first full Fly-By-Wire helicopter, the NH90, was only introduced in 2006 (Lim et al., 2018).

licopter domain, for example for shipboard landing (Jenkins et al., 2015) and in this dissertation for obstacle avoidance tasks in Chapter 5. Ecological interfaces aim to provide information about the controlled system and its environment such that the constraints on possible operator actions become easily apparent (Vicente and Rasmussen, 1990, 1992). Visualised constraints can be physical (e.g., avoiding flight into terrain or bad weather) or procedural (e.g., staying above a predetermined safe altitude) (Comans, 2017). With respect to the investigated navigation task, this navigation display provides an overview of possible trajectories to the target and supports the detection of unsafe trajectories.

With respect to the helicopter navigation task, these design philosophies manifest themselves in the three different helicopter head-down navigation displays that this chapter investigates. A baseline display serves as an experimental baseline and comparison point. It only shows the most necessary information about the position of the helicopter, the target, and any navigational obstacles, which are represented through bad weather areas in this experiment. The first experimental display is based on advisory symbology and provides one particular navigational solution or trajectory to the pilots, circumnavigating navigational obstacles and providing a target trajectory to the target. The second experimental display is based on Ecological Interface Design principles and provides information about the helicopter's navigational capabilities and limitations, without prescribing one specific solution.

As previously mentioned, inadvertent effects of automation can be particularly strong during unanticipated, off-nominal events. Therefore, in this experiment, pilots will also encounter two different situations that are outside the operational envelope of both experimental displays. The first off-nominal situation the pilots encounter affords a trajectory that is more efficient than the suggested solution of the advisory display, or the most efficient solution out of the possible actions provided by the constraint-based display. The second off-nominal situation incorporates a weather area that appears mid-run and that remains undetected by automation.

Both experimental displays do not incorporate this additional weather area into their provided information. However, this does not mean that the pilot decision-making will be affected identically as well. Different automation systems can enable and incentivize different pilot control strategies and expectations. This in turn can provoke different responses: the advisory display places heavy emphasis on its suggested solution. Because of that, pilots might be quick to utilise it, also when it is inefficient or even unsafe. The constraint-based display requires more mental integration from the pilots and, as such, might make them more aware of environmental information that they would have missed otherwise. How the employed experimental displays influence the pilots' decision-making process is the focal point of this chapter.

Helicopters are inherently unstable in low-speed flight. As long as there is no complex automation support, pilots are required to fly manually, in order to stabilise the vehicle. This fact is included in the requirements for the displays in this experiment: all displays are required to work with minimal interaction, such that the pilot can in parallel pilot the helicopter. All interactions need to be performed via buttons on the cyclic or collective stick. Advanced interfacing techniques like touch-screen functionality are not considered here, as this would require the pilot to let go of one of the control inceptors. This also represents an added difficulty for the pilots: they need to plan and evaluate future trajectories while they are actively stabilising the helicopter. In particular for single-pilot operations, it is necessary to investigate systems that can be controlled and managed while manually flying the helicopter.

This represents the "engineering" challenge of this experiment: the inspiration for the constraint-based display lies in a display that was originally developed in the context of air traffic control (Klomp et al., 2016), based on in-flight trajectory modification concepts developed by Mulder et al. (2010). It requires interaction with a mouse-like "cursor" to place intermediate waypoints, a functionality which cannot be implemented easily in a standard helicopter cockpit. The original display needs to be adapted to enable interaction with only a small number of buttons, which can be reached while piloting the helicopter.

In March 2021, a human-in-the-loop experiment has been conducted in the SIMONA Research Simulator to evaluate the displays in the context of a navigation task, both during nominal operations and unexpected events. The results of this experiment provide insight into the effects of different support systems on pilot decision-making, workload, situation awareness, task performance, safety, and pilot preference.

This chapter is structured as follows. Section 6.2 provides background information relating to the proposed research. Section 6.3 describes the baseline navigation display and both experimental displays. Afterwards, an analysis of possible control strategies is performed in Section 6.4. The experimental setup is described in Section 6.4. The experiments' results are presented in Section 6.6 and discussed in Section 6.7, including recommendations for future research and automation design. Section 6.8 provides a conclusion to this chapter.

6.2. Background

This section provides an overview of existing navigation support automation systems in helicopters and highlights the peculiarities and requirements of helicopter-specific systems. Three parts of the systems are of particular interest: first, what is the operational envelope of the employed trajectory determination algorithms and what factors are not considered; second, what kind of information is shown to the pilots and in what way; and third, how do the pilots interact with the navigation system, in particular when they reject the system's proposal. For a more comprehensive review of aviation automation, please refer to Lim et al. (2018), for a review on general aviation human-machine interfaces, or to Chapter 2, for a review of helicopter-specific automation systems.

Top-down navigation displays are part of those electronic flight instrument systems that belong to second generation flight decks, which were introduced on a large scale with the Airbus A320 and the Boeing 747-400 (Lim et al., 2018). On a navigation display, a multitude of information can be displayed, for example terrain and traffic data (Lim et al., 2018), heliport/heliport locations, restricted airspace and visual flight rule waypoints (Guillanton and Germanetti, 2011), or weather and obstacle data (Haisch et al., 2009). Coupled with a flight management system, a navigation display can provide information about waypoints and courses selected by the pilots (Lim et al., 2018). Helicopter flight management systems, in particular, can offer mission-specific functions like automated flight pattern generation or the up- and down-link of flight plans with external sources (Lim et al., 2018).

Two helicopter system evaluation studies shall serve as examples of implemented helicopter navigation support systems. Haisch et al. (2009) describe the functionality of an envisioned adaptive route-planning algorithm. At the press of a button, a route from the current position to the mission target is calculated, taking into account data covering terrain, obstacles, topography, aerodromes, airspace, navigation, weather, and helicopter performance. When the system detects an additional obstacle, for example an additional bad weather area, the course is modified to evade the new obstruction. The calculated courses of this system seem to be made up of multiple straight legs between a small number of waypoints, i.e., no curved trajectories are proposed. The pilots can accept the proposed plan and "activate" it, or disregard it and insert a manual course with a joystick in the interseat console.

Takahashi et al. (2017) performed an experiment that is similar to the one proposed in this chapter, in the sense that they investigated three different levels of automation support while performing a mission: fully coupled autonomy, additive control, and piloted decoupled attitude command. Trajectories to selected waypoints or landing sites are computed with an obstacle field navigation algorithm, which analyses a three-dimensional representation of the outside world to compute an optimal route. In contrast to the previously described system, the route can be complex and curved, if the external environment warrants it. For approach and landing, it is also possible for the pilots to enter a string of desired waypoints, which is then translated into a smoothed-out trajectory by a separate path generation algorithm. The pilots interact with the system via discrete switches on the control inceptors. During full autonomy mode, they can influence the currently active waypoints and trajectories, or decouple some or all of the automated control axes. The computed trajectories can be computed automatically and either directly flown by the automated system, or communicated to the pilot via head-down, panel-mounted displays. The focus of the experimental validation lied on the vehicle behaviour during mode transition and the manual control of the aircraft in the different modes.

Automated trajectory generation algorithms can rely on many different data sources: obstacle databases (Ebel, 2019), in-flight database integrity monitor data (Vadlamani and De Haag, 2009), the distance to dangerous infrastructure like windparks (Bakker and van der Geest, 2018), the fuel cost of prospective trajectories (Murrieta-Mendoza and Botez, 2015), the acoustic footprint of prospective trajectories (Greenwood and Rau, 2020; Rolando et al., 2016; Hartjes et al., 2009; Gursky et al., 2014), or predicted fuel consumption (Halbe et al., 2018). Without going into detail, it is clear that none of the aforementioned algorithms take all existing data into account. Rather, they focus on specific data subsets, relevant to the mission. That means that even if a trajectory determination algorithm takes into account

6

all data that are deemed relevant for the mission, there is always the chance that other influences outside of the envisioned operational envelope require a change of trajectory, and the calculated trajectory is rejected. This realisation of departure from the operational envelope of the automation system falls to the pilots — the automation system is unable to react to data it is not programmed to deal with.

Heinemann et al. (2018) describe a smart autoflight control system that computes and continuously evaluates flight trajectories and assigns a supervisory control task to the human pilots. The pilots are required to acknowledge and correct the decisions made by the automatic system. They note that, on the mission planning level, communication with other actors has to be incorporated into the decision-making process by the pilot, and that the vehicle alone cannot decide its future course of action.

This analysis, and the system and operational boundaries that all automation systems naturally possess, highlight the crucial role of the pilots and their capability of adaptively reacting to the situation. When the encountered situation lies outside of the scope of the automated system, or if any kind of error prohibits the automation from working correctly, it is the pilots' responsibility to react to the situation and ensure the continued safety of the vehicle and the environment. This chapter aims to provide insight into whether the use of different automation design philosophies can support or hinder these adaptive pilot decision-making processes.

It would be unfeasible to try to design and evaluate systems that try to incorporate all of the different kinds of data listed above or faults that may occur. However, it is also not necessary, as every automation system will have a specific operational envelope, how big or small it may be, and every automation system can encounter situations outside of this boundary. The experiment of this chapter reproduces and analyses this key characteristic: the navigation support systems under consideration are designed with a particular operational envelope. They are then subsequently subjected to expected situations within the envelope and situations that lie outside of it. This enables the analysis of the pilots' reactions and decisions in a clearly defined context and how the employed automation design philosophy affects these behaviours.

6.3. Display design

This section describes the elements of the baseline display and both experimental displays in more detail. First, the fuel display and the baseline display symbology are specified. Afterwards, the algorithm to compute the advisory and constraint-based display elements is described. Lastly, the visual elements of the experimental advisory and constraint-based displays are shown.

6.3.1. Operational envelope

The operational envelope of all described displays is defined as the completion of a predetermined flight-plan, taking into account to-be-avoided weather areas, fuel constraints, and the track distance and time requirements of the chosen trajectories. The goal of the navigation system is to enable the pilots to select a safe and efficient trajectory to the next target, according to the flight plan. It should also enable the pilots to estimate the distance to future targets, provide arrival time estimations, and estimate the fuel consumption of specific trajectory implementations. The operator goals can be summarised as:

1. Perform a predetermined flight plan, which includes
   (a) flying to the target waypoints in the order defined in the flight plan and
   (b) hovering at each waypoint for ten seconds.
2. For each part of the flight plan, determine and execute a trajectory that is
   (a) safe (i.e., does not enter weather areas) and
   (b) efficient (i.e., in the constraints of this experiment, uses the path with the shortest track distance).
3. Provide regular predictions about
   (a) the estimated arrival time at the next target waypoint and
   (b) the estimated fuel use of the remaining legs of the flight plan.

The task of the pilots can be separated into two categories: 1) the manual flying task, which comprises hovering at each target and following the selected waypoints while avoiding bad weather pockets; 2) the cognitive planning task, which comprises the selection of a suitable route to the next target, the estimation of the travel time to future targets, and the evaluation of the remaining fuel with respect to the remaining legs.

A constraint is placed on the complexity of paths that will be supported by the experimental displays: only so-called "one-turn" trajectories between targets are supported. This means that at most one intermediate waypoint is placed between the ownship position and the next target, and each future trajectory between two targets also contains at most one intermediate waypoint. When following this kind of trajectory, the pilots only need to perform one turn per flight leg, not counting the rotation necessary at the starting position and the target position. Figure 6.1 (right) shows an example of a one-turn trajectory, containing one turn between the ownship position and first target, zero turns between the first and second target, and one turn between the second and the third target. The other elements of the shown display will be elaborated upon in the next section.

This particular constraint on the path complexity is chosen for a reason. A path with one intermediate waypoint is the logical first step between the most simple, direct path and more complex paths. Further steps to increase complexity then encompass increasing the number of intermediate waypoints, include curved/non-straight segments, and introduce time- and altitude constraints. The border of the operational envelope is placed on the lower end of path complexity. This is done to enable the participating pilots to quickly learn the system boundaries, to quickly be able to identify more complex path solutions outside of these boundaries, while controlling the helicopter.

Increasing the operational envelope to more complex trajectories would require the pilots to "think outside of an increasingly larger box". While this might increase the experiment realism, it would also require substantially more training and familiarisation with the proposed automation systems and the scenario. In addition, if it can be shown that certain automation systems have inadvertent negative effects in a rather straightforward navigation scenario with more complex trajectories easily conceivable, it can be assumed that these negative effects are only exacerbated in more complex scenarios with less simple solutions and unclearer system boundaries.

6.3.2. Baseline display symbology

The baseline navigation display utilised in this experiment shows a top-down representation of the outside world. Figure 6.2 shows the rendering of the outside world, depicting target waypoints one and two of the utilised example experiment course. On the display that depicts the same course, with the ownship aircraft at its bottom edge, Figure 6.1 (left), the future target waypoints and bad weather areas[2] are shown. The current leg, which comprises reaching the next target from the ownship position, is called "active leg".

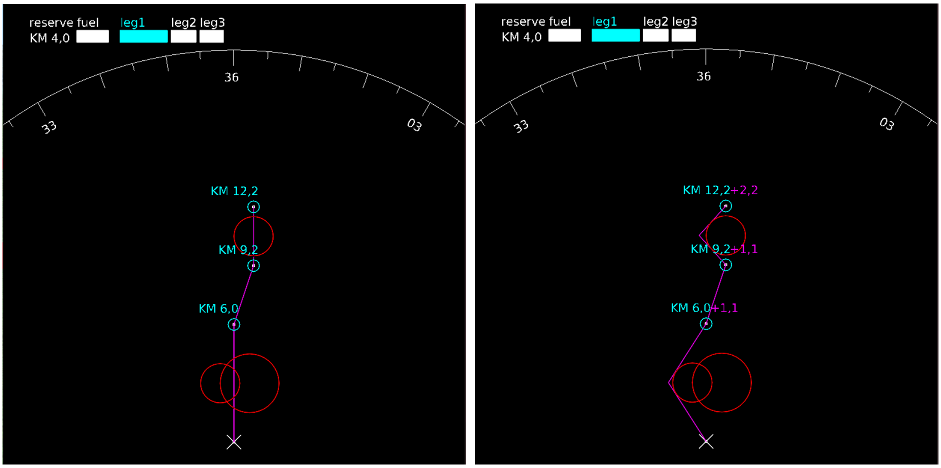


Figure 6.1: Left: baseline navigation display representation of flight plan, including obstacles (red circles) and three targets (cyan circles). Right: path calculated by the advisory display, containing at most one intermediate waypoint between targets (a "one-turn path").

By pressing the "initialise" button on the cyclic, the pilots can trigger the calculation of the remaining distance between themselves and the next waypoints (ignoring any obstacles which might be in the way). This distance is then shown next to the targets in the navigation display and the shortest, direct path from the ownship position to the still remaining target waypoints is presented in magenta.

[2] Bad weather areas do not have a graphical representation in the simulation. Rather, the default visibility of 1,500 m is gradually reduced to 100 m when entering an area designated as bad weather.

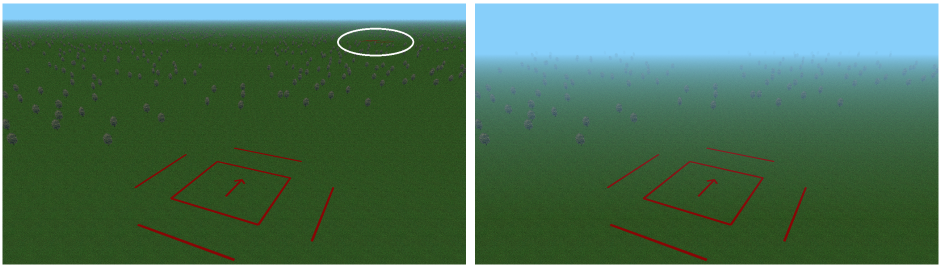


Figure 6.2: Rendering of the experiment course, looking from target 1 to target 2. Left: increased visibility to highlight the second target waypoint. The oval is inserted to highlight the target and is not visible during the experiment. Right: actual visibility employed during the experiment (1,500 m).

To identify a safe and efficient route, the pilots can only rely on the provided spatial information about the ownship position, the target position, and the position of any obstacles. The displayed direct route and the corresponding shortest distance between targets can serve as a basis for the arrival time estimation task. However, any deviations from the shortest path are not taken into account by the display, the pilots are required to estimate the additional travel distance and travel time themselves.

6.3.3. Fuel display

In every display condition, a fuel gauge shows pilots the remaining fuel which is planned for each leg and the remaining reserve fuel, see Figure 6.3. The remaining fuel is shown in terms of track kilometres. It is computed by initially defining all fuel reserves in terms of track distance. Then, the sum of flown trajectory track distance is continuously subtracting from it. This allows the direct comparison of available fuel reserves to navigational distances, which is required for the experimental task. This fuel reserve calculation method is chosen to simplify the experimental task for the participants. It is sufficient to introduce track efficiency considerations into the experiment. It does not take into account the impact of flying at different velocities, which would change the consumed fuel per distance flown, or the fuel consumption during hover.

During the mission, the fuel "container" that is currently being emptied is highlighted in cyan. The leg-specific container contains enough fuel to complete the leg without any deviations from the shortest path: every deviation due to obstacles requires the use of reserve fuel. When the leg-specific fuel has been consumed, the reserve fuel begins to be consumed. Subsequently, the reserve fuel gauge changes to a yellow colour. When all reserve fuel is used up, the gauge changes to a red colour.

Figure 6.3: Fuel gauge for reserve fuel, and fuel assigned to legs one, two, and three.

Figure 6.4 depicts the fuel gauge during different times during an example mission, when following the magenta trajectory. The reader is advised to start at the bottom of this figure. At the beginning, at the lowermost position, all containers are full. After performing the first leg (i.e., after flying from the initial position to the first target), the corresponding container is empty. As there were no major course deviations necessary, the reserve fuel container is almost full still. After performing the second leg (i.e., flying from the first to the second target), the second container is empty, and a non-negligible amount of the reserve fuel has been used. This is caused by the fact that some deviation from the optimal, direct route was necessary to avoid entering bad weather areas. The remaining reserve fuel is displayed in kilometres on the left. At the end of the course, all three leg-specific containers are empty. In this example, the leg-specific fuel was sufficient to complete the last leg, with 2.6 km of reserve fuel remaining.

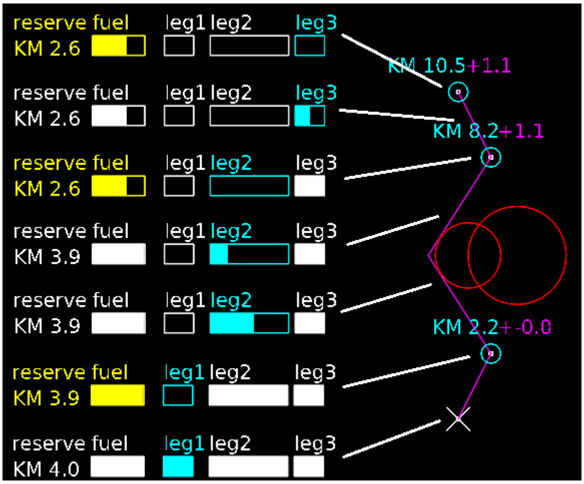


Figure 6.4: Fuel gauge at different stages of an example mission.

6.3.4. Trajectory determination and evaluation algorithm

Both experimental displays rely on the same, one algorithm that determines all one-turn trajectories to the target and that evaluates the determined trajectories with respect to safety (entry into bad weather) and efficiency (fuel consumption). This algorithm is described in this section.

The computed trajectories contain at most one turning point per leg, which corresponds to at most one intermediate course waypoint between the current position and the target. This limitation is introduced to enable the comparison between the advisory display and the constraint-based display, both of which focus on the possibilities of one-turn trajectories between each origin and target. This also enables the analysis of prospective "out-of-the-box" thinking of the participating pilots, in cases when the optimal course has more than one turn and lies outside of the operational envelope of both the advisory and the constraint-based display systems.

When the calculation of these data is triggered, the area between the ownship position and the target position is first divided into a grid of 201 (lateral) times 101 (longitudinal) point locations. The lateral expansion of the grid is determined by the outermost possible location of a one-turn intermediate waypoint, given the remaining fuel. Therefore, the grid covers all possible turn locations of one-turn trajectories between the current ownship position and the target.

Afterwards, for each point location, it is determined whether following a trajectory from the ownship position, to the point location, to the target satisfies the safety requirement of not entering any weather areas. If the trajectory is safe, it is evaluated with respect to the length of the resulting trajectory. The length of the resulting trajectory is compared to the theoretically optimal, direct trajectory length. The shorter the trajectory is, the more efficient it is.

The result of this algorithm is a grid of location points, each with a binary safety value (safe/unsafe) and a numerical efficiency value (additional travel distance, compared to theoretical optimum). These data are used both by the advisory and constraint-based display, as described below.

6.3.5. Advisory display

The advisory display shows the same information as the baseline display. However, when the "initialise" button on the cyclic stick is pressed, the most efficient, safe location point of the previously computed grid is selected, and a trajectory is plotted from the ownship position, through the location point, to the target location. The resulting path and distances are then shown on the display, as is visible in Figure 6.1 (right).

The advisory display provides the pilots with a safe and optimal one-turn route to reach the target. The additional track distance required to follow the computed path is shown next to each target in magenta. This additional track distance directly relates to the remaining reserve fuel: when this trajectory is followed precisely, the reserve fuel will be reduced by the indicated amount when reaching the respective waypoint. By visualising the additional track distance, the advisory display also supports the travel time estimation task.

6.3.6. Constraint-based display

The constraint-based display provides the pilots with graphical information about *all* possible collision-free, one-turn trajectories to reach the current target and the remaining manoeuvre capabilities for future legs, taking into account the remaining fuel. As is shown in Figure 6.5 on the left-hand side, multiple ellipsoids are shown around the prospective flight path between the ownship position and the remaining target waypoint. Flying an intermediate one-turn trajectory with a turning point on the first ellipsis results in an additional travel distance of one kilometre. Each following ellipse represents one more kilometre of travel distance. Through the size of the ellipses, the pilots can estimate the additional travel distance that is required to complete the respective path. A green area denotes the locations of all possible collision-free turning points in the active leg.

For the currently active leg, ellipses are shown at additional travel distances of 1 km, 2 km, 3 km, and 4 km. Within this area, the pilots can manually set a turning waypoint. By pressing the "select" button, the pilots can cycle through the ellipses of the current leg, as shown in Figure 6.5 on the left. By turning the helicopter, the pilots can aim the nose of the helicopter at a certain point on the selected ellipse, see Figure 6.5 in the middle. The pilots can select the intersection point of the ownship orientation and the selected ellipsis by holding the "select" button, as shown in Figure 6.5 on the right. The distance to the currently active target is then re-calculated, taking into account the selected turning point. (Note that the distances between future target points remains the direct distance, pilots can only manipulate the active leg).

For future legs, only one ellipsoid is shown. The size of this ellipsoid depends on the remaining fuel reserve, reduced by the fuel requirements of the selected course in the current leg. As such, the constraint-based display supports the selection of a safe and optimal route to reach the current target. It supports the arrival time estimation task for the currently active leg by showing the track distance of the selected trajectory. For subsequent targets, its support for the travel time estimation task is weaker: it only shows the maximum extra track distance that the remaining fuel allows — intermediate ellipses are not shown.

6

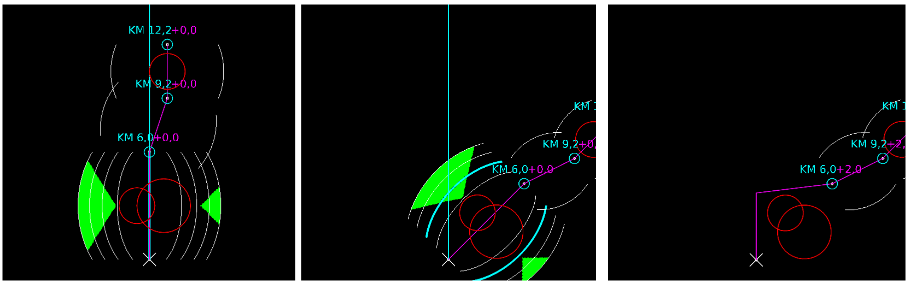


Figure 6.5: Selecting a specific waypoint by interacting with the constraint-based display.

6.4. Control strategy analysis

The designed displays afford multiple control strategies to reach the described goal. This section analyses some of the theoretically possible control strategies based on the decision ladder (DL) described by Rasmussen (1983).

Figure 6.6 depicts a DL for the path planning task, covering skill-based behaviour (SBB), rule-based behaviour (RBB), and knowledge-based behaviour (KBB). Figure 6.7 shows the corresponding control Strategies (1) - (6). Figure 6.8 visualises the control strategies in separate DLs.

6.4.1. Path planning strategies

The following paragraphs elaborate on the anticipated strategies. First, the activities of the pilots are described. Afterwards, the implication of each strategy on the

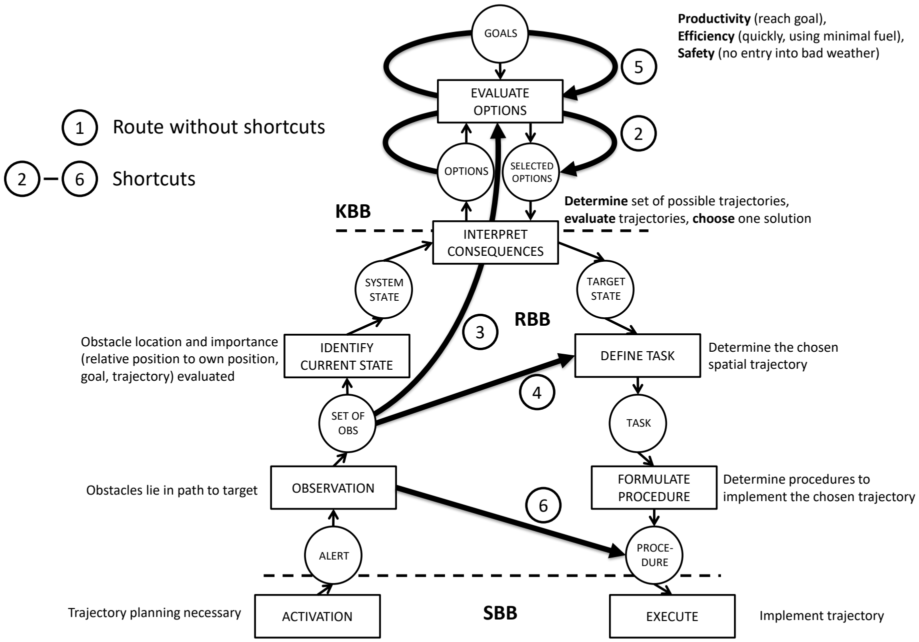


Figure 6.6: Decision ladder for the path planning task, without shortcuts, and with five with possible "automation–enabled shortcuts" (2) - (6).

secondary, arrival time estimation task is analysed. Lastly, the effect of an undetected obstacle on path safety, efficiency, and arrival time estimation is described for each strategy.

Strategies (1) and (2), as seen in Figure 6.7, can be used regardless of the employed displays. Strategy (1) comprises every step on the decision ladder, requiring knowledge-based reasoning and decision-making throughout the process. After initiating the path planning process "activation", the visible obstacles are identified, and their location and size are evaluated with respect to the ownship and target position. Then, possible solution paths are determined and evaluated. Based on the task-specific goals (safety, efficiency), one solution is chosen. This solution is then translated into an intermediate waypoint between the ownship position and the target, defining the selected path. Lastly, the chosen path needs to be implemented by the pilot by performing certain standard flying manoeuvres.

Strategy (2) is the first strategy that uses a rule-based "shortcut" in the DL. When evaluating possible path solutions, the pilots might decide to choose the first safe route they encounter, neglecting part of the efficiency evaluation and only focusing on safety. The rule can be formulated as: "If the pilots identify a safe route, then they immediately implement this route and stop searching for alternative routes". In this case, the path determination, evaluation, and selection step is significantly shortened, but at the possible expense of track efficiency.

Strategies (1) and (2) are not susceptible to obstacles that appear mid-run and

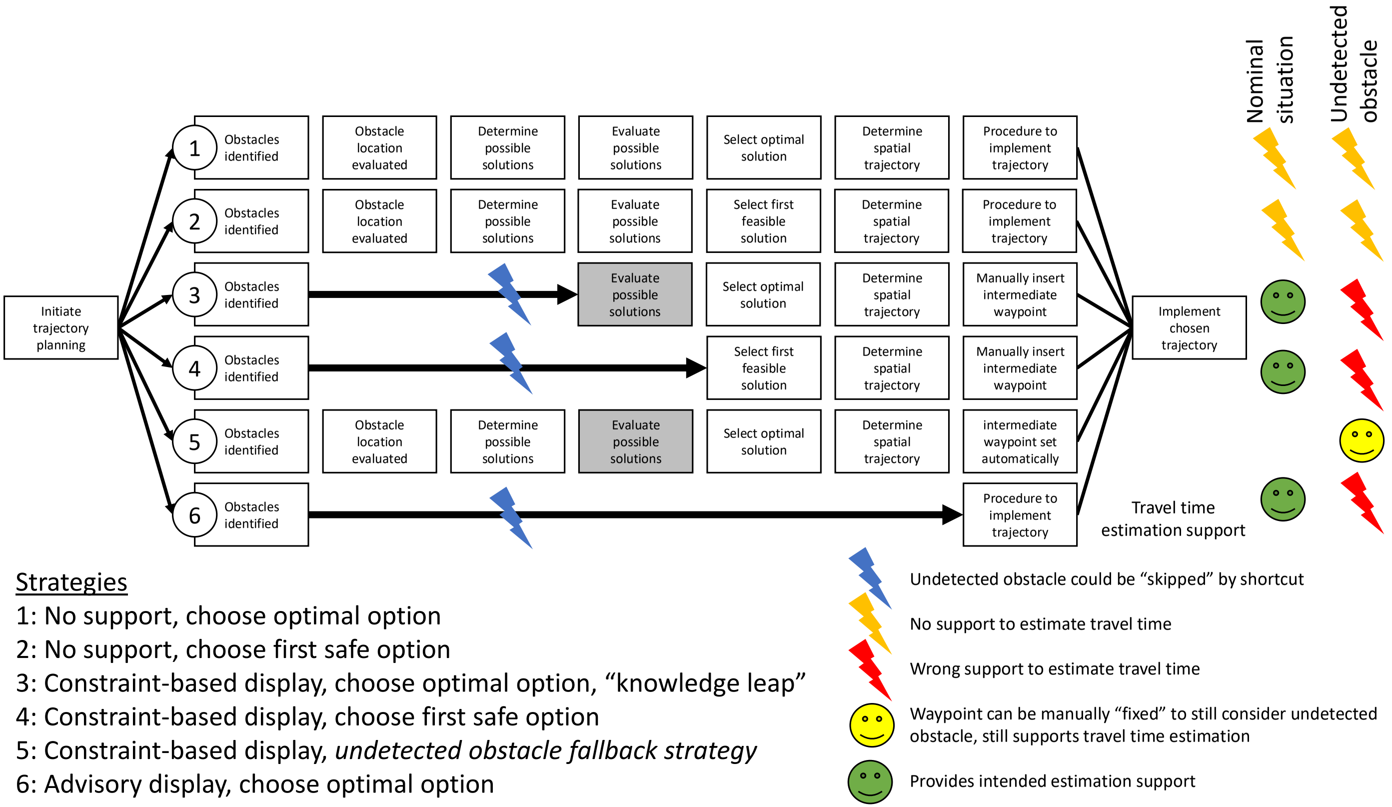


Figure 6.7: Possible strategies (1) - (6) for the path planning task based on the decision ladder. Strategy (1) represents the baseline strategy, Strategies (2) - (6) are possible automation–enabled shortcuts through the DL.

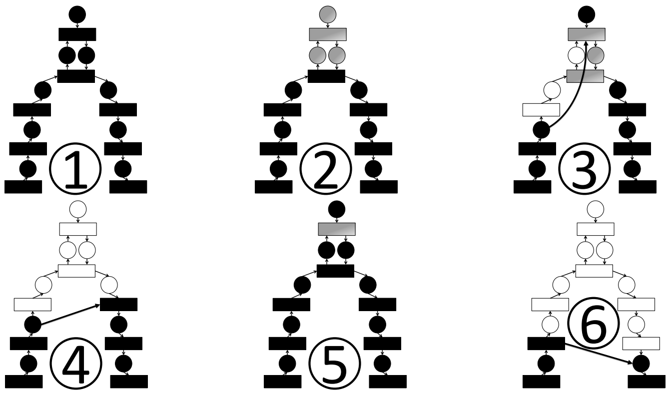


Figure 6.8: Visualisation of control Strategies (1)-(6) with respect to the Decision Ladder.

remain undetected by the experimental displays, they can always be employed by the pilots. As long as the pilots recognise all present obstacles when they initiate the planning task, the path planning strategy and the safety and efficiency of the chosen path are not impaired. The arrival time estimation task is only supported through the display of the shortest routes between targets, disregarding any obstacles. The pilots need to perform this task by integrating all additional information themselves.

Strategies (3) and (4) are enabled by the constraint-based display. With this display, after recognising the existence of an obstacle, the pilots can trigger the calculation and visualisation of all safe one-turn solutions. The pilots can immediately skip to a future step. In case of Strategy (3), they can use a "knowledge leap" to immediately skip to the path evaluation step: all safe possible one-turn paths are already calculated. The selection of the optimal path is supported through the ellipses, too, by visualising the additional track-distance of the possible turning points in one-kilometre increments. In order to choose the optimal path, the pilots need to determine the waypoint that is closest to the direct connection between the ownship position and the target, i.e., the safe waypoint that has the smallest additional track distance. After determining this waypoint, they can manually insert this waypoint into the navigation display via the provided control buttons.

The constraint-based display enables a second, larger shortcut, described in Strategy (4): instead of evaluating each proposed solution to choose the optimal route, the pilots can decide to choose the first available, safe solution. In this case, they choose and manually insert an arbitrary waypoint in the safe area. This rule-based shortcut will ensure a safe trajectory, but not an optimal one. It can be described by the following if-then-clause: "if the constraint-based display provides any safe one-turn trajectories, arbitrarily select one solution and immediately implement it."

Both Strategies (3) and (4) are vulnerable to undetected obstacles, as the calculated safe trajectories do not take this additional obstacle into account. The pilots are required to recognise the malfunction and manually adapt the suggested paths. When utilising the constraint-based display, the pilots are still required to interact with and analyse the given trajectory information on the navigation display, which increases the chance of recognising suggested trajectories that conflict with the additional obstacle. As soon as the pilots recognise the additional obstacle, they can manually fix the display's error by selecting a different waypoint. The support for the arrival time estimation task remains valid.

Strategy (5) represents a possible fallback strategy for the constraint-based display, in case an undetected obstacle appears. In this case, the spatial representation of possible intermediate waypoints is no longer valid: some of the suggested trajectories will intersect the undetected obstacle. However, if the pilots see the obstacle undetected by the algorithm, they can still utilise the ellipses indicating additional track distances to manually evaluate a trajectory with respect to its additional fuel cost. This remaining function can be represented as a shortcut within the "evaluate options" block in the DL.

Strategy (6), enabled by the advisory display, provides the fastest possible rule-based shortcut. As soon as the pilots identify the need to perform the path-planning task, they trigger the automatic path planning system. This will automatically insert a safe and optimal one-turn waypoint into the navigation display. The pilots only need to implement the proposed route. This shortcut can be described as "if the pilots cannot directly fly to the target, trigger the automatic path planning system and implement the suggested route." This large shortcut is most susceptible to undetected obstacles, because the pilots are not required to analyse and integrate the provided spatial information in any way. In order to detect the mistake, they need to consciously analyse the proposed solution for any obstacle intersections. If the proposed solution is unsafe, there is also no way of "fixing" this display error, and the provided arrival time estimation support is simply wrong. Therefore, the pilots need to disregard the display suggestions and use either Strategy (1) or (2).

As has been discussed, the advisory and constraint-based displays encourage certain control behaviours and shortcuts. Their impact on the decision-making process of the pilots depends on how prone pilots are to follow these shortcuts. How frequently do the pilots check the provided shortcuts for errors, and how frequently do they reflect on the environmental requirements for the shortcuts to work? On the one hand, relieving the pilots of some cognitive work through shortcuts could lead to an increased mental capacity to evaluate and reflect on the current course of action. On the other hand, utilising shortcuts that skip the evaluation of the chosen trajectory by the pilots themselves could lead to a decrease of the level of scrutiny the suggested trajectories are subjected to.

It is important to note that this heavily depends on the mindset of the pilots. Are they expecting errors and unsafe system behaviour all the time and on every occasion, or are they in a state of mind of generally accepting the shortcuts provided? In this experiment, while they were warned that additional obstacles might appear, it was not an emphasised element of their briefing. It can be reasonably assumed that they were mostly focused on the normal performance of the task, utilising the provided support, without questioning the provided automation support at every step of their thought process. This expectation is later translated into hypotheses covering the experiment.

6.4.2. Undetected obstacle discovery strategies

An obstacle that appears mid-run and remains undetected by the algorithm impairs the ability of both the constraint-based and the advisory display to correctly determine possible safe solutions. Depending on the utilised strategy, there are multiple modes of detection that the pilots themselves can use to detect this additional obstacle and, subsequently, the discrepancy in the solution space (when using the constraint-based display) or the suggested solution (when using the advisory display). The realisation that a chosen trajectory is unsafe would occur during the "obstacle locations evaluated" step in the DL. Any strategy that provides shortcuts within this step, or whose shortcuts skip this step entirely, are susceptible to undetected obstacles impairing the safety measures of the current leg. These are Strategies (3), (4), and (6).

The following obstacle detection modes can be used by the pilots:

1. pilot memory,
2. solution space intersects obstacle,
3. solution space contains unsafe trajectory,
4. intermediate waypoint intersects obstacle,
5. trajectory of chosen waypoint intersects obstacle, and
6. directly encountering/entering obstacle space.

"Pilot memory" describes the realisation of pilots that an additional obstacle appeared during the experiment run. If this happens, the number of obstacles visible on the display increases. If the pilots perceive this discrepancy, they detect the additional weather area. This mode of detection works across all described strategies, and it is not dependent on the utilised display.

It is important to note that in the baseline display condition, this is the only possible detection method, and that there will be no other cues during the remainder of the course. With the baseline display, after appearing at the beginning of the leg, the undetected obstacle behaves identical to previously detected obstacles. As such, it will presumably be taken into account exactly like the other existing obstacles. However, the pilots might be oblivious to the fact that they are reacting to an additional obstacle that has not been present before. Figure 6.9 depicts the appearance of an additional obstacle between leg 1 and leg 2, after hovering at the first target.

If the solution space of the constraint-based display intersects an obstacle, the pilots receive an unambiguous cue that the calculated intermediate waypoints are unsafe, see Figure 6.10 (left). This mode of detection can only occur when the solution space is shown, i.e., during the planning task.

The process of realising that an unsafe trajectory is present requires more involvement from the pilot if the solution space does not directly intersect an obstacle. However, at least one of the proposed intermediate waypoints would result in a trajectory that intersects with the obstacle. Even before selecting a specific waypoint,

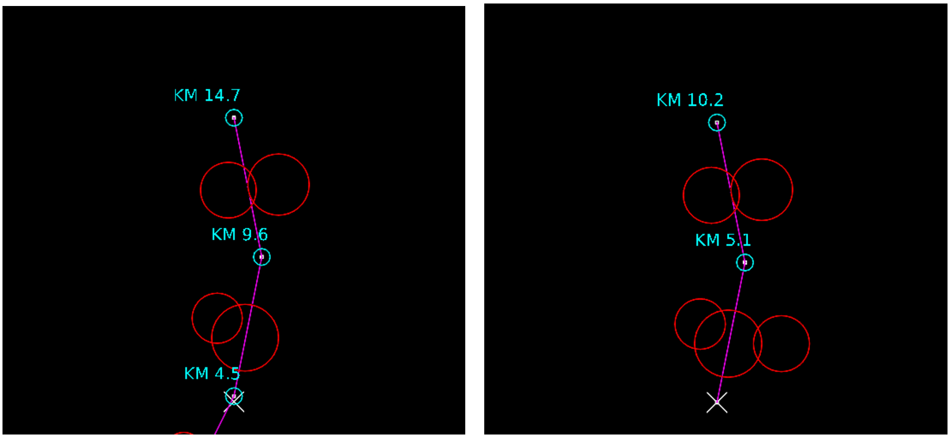


Figure 6.9: An additional bad weather area appearing as the pilots enter the corresponding leg. Left: at the end of leg 1, there are two obstacles between the ownship position and the next target. Right: at the beginning of leg 2, a third, previously invisible obstacle appeared on the right-hand side.

this might become clear to the pilots if they mentally integrate the presented information to visualise the trajectories that are possible with the given solution space. Similar to the previous mode of detection, this method only works when the solution space is visible. Figure 6.10 (right) depicts this situation.

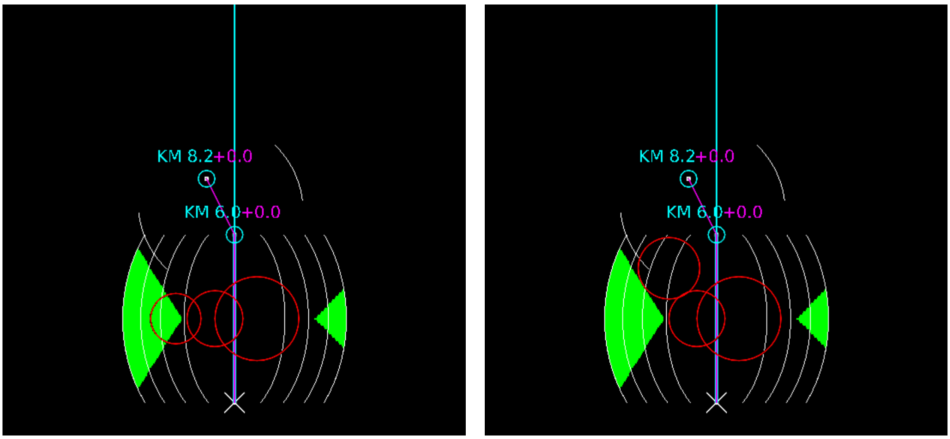


Figure 6.10: Left: the green solution space diagram directly intersects an obstacle. Right: the solution space diagram contains unsafe trajectories, but does not directly intersect an obstacle.

The next two detection modes are possible as soon as an intermediate waypoint has been determined and inserted in the display. This can happen if the intermediate waypoint is chosen manually with the constraint-based display, or if it is automatically determined and inserted by the advisory display. Unlike the previous detection modes, these two methods work both during planning and the execution of a selected trajectory. Firstly, if the selected intermediate waypoint intersects an obstacle, the graphical representation of the intermediate waypoint inside an obstacle serves as a clear clue to the pilots that the selected waypoint is unsafe. Secondly, even if the intermediate waypoint itself does not intersect an obstacle, the trajectory created by the chosen waypoint can intersect an obstacle. Again, this serves as a graphical cue for the pilots that this trajectory is unsafe. Figure 6.11 depicts both cases.

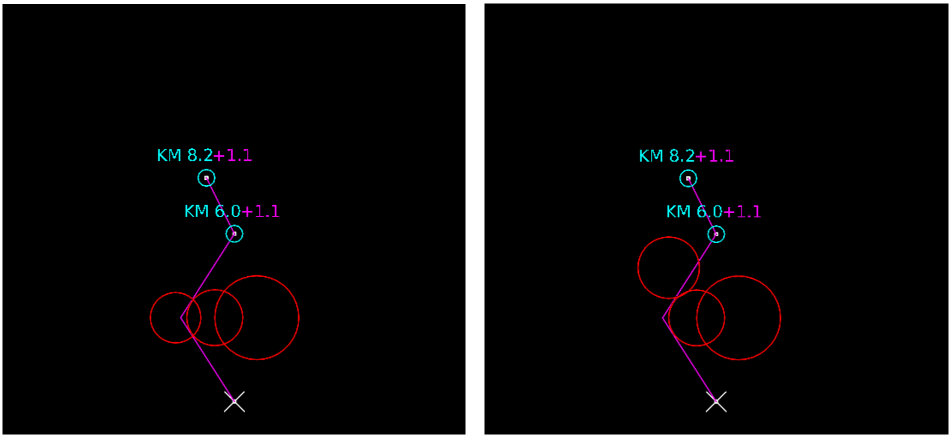


Figure 6.11: Left: the intermediate waypoint is inside an obstacle. Right: the intermediate waypoint results in a trajectory that intersects an obstacle, although the waypoint itself lies outside of it.

After realising the existence of an additional, undetected obstacle, the pilots might need to adapt their behaviour to still perform the planning task and to determine a safe trajectory. In the baseline display condition, no adaptation is needed, as long as they incorporate the newly appeared obstacle into their planning. As explained before, it is even possible that pilots do not recognise the additional, new obstacle as such, but treat it as a regular obstacle.

When using the constraint-based display, the pilots have two options. First, they could decide to neglect the additional information of the constraint-based display completely and solely rely on the baseline data representation. In this case, they would change from Strategy (3) or (4) to the baseline Strategies (1) or (2). Second, they could decide to utilise those parts of the constraint-based display that are still valid, i.e., the additional track distance ellipses. This behaviour is represented as Strategy (5).

Should pilots discover an undetected obstacle when using the advisory display, their only option is to switch to Strategy (1) or (2). No part of the advisory display can be utilised if an undetected obstacle causes wrong results.

6.4.3. Arrival time estimation strategies

The support the pilots receive for the arrival time estimation task depends on the utilised display and strategy and whether an undetected obstacle is present or not.

In case of Strategies (1) and (2), using the baseline display data, the pilots only receive information about the direct distance to the following targets — the additional track distance required to avoid any obstacles is not incorporated into this distance.

When using the constraint-based display, pilots receive two different kinds of information to estimate their future travel time. For the currently active leg, the constraint-based display shows the additional track distance of the selected trajectory. If this trajectory is safe, the given additional track distance is an accurate prediction. A safe intermediate waypoint can be the result of Strategies (3) and (4) in nominal situations and of Strategy (5) in off-nominal situations. For any future leg, excluding the current active leg, the prediction support is less precise. The constraint-based display only visualises the maximum possible deviation ellipses, based on remaining reserve fuel and the chosen trajectory in the active leg. The support is therefore more geared towards the question of whether future legs can be completed at all, not towards estimating precise arrival times.

When using the advisory display with Strategy (6), the support to estimate future travel time hinges on the existence of an undetected obstacle. In nominal situations, the advisory display provides accurate distance predictions to all future targets, strongly supporting the task. However, in off-nominal situations, the predictions are wrong and cannot be used to support the travel time estimation task.

6.4.4. Insufficient fuel discovery strategies

The baseline display does not provide any support to estimate the additional distance that is necessary to avoid obstacles. The task of estimating this extra distance and connecting it to the remaining reserve fuel is left entirely to the pilots.

The advisory display provides distance estimations for every future target. During the trajectory planning phase, if the additional distance (shown in magenta) is larger than the remaining reserve fuel, a completion of this trajectory is no longer possible.

The constraint-based display provides support to discover insufficient fuel while planning the next leg. After selecting a trajectory in the current leg, the ellipses around future legs shrink to reflect the change in available reserve fuel (see, for example, Figure 6.5). In this example, the ellipses in legs two and three do not intersect with weather areas, and the course can be completed with the remaining reserve fuel. However, if the ellipses around future legs do not afford any trajectory solutions, i.e., if they would intersect with weather areas on both sides, the remaining reserve fuel will not be sufficient to complete the corresponding leg.

6.5. Experimental setup

This section will elaborate on the experimental setup of this chapter, covering the scenario, the employed displays, and the experiment hardware, participants, and variables. Lastly, the utilised data processing and statistical analysis tools are described.

6.5.1. Scenario

The pilots are tasked to complete a predetermined flight plan which includes three target waypoints per experiment run, see Figure 6.1 (left) for an example. At each target, the pilots are asked to hover in place for ten seconds. This abstractly represents the loading/unloading of new passengers or goods. The path to the target waypoints (but not the target points themselves) can be obstructed by circular bad weather pockets (red), which must be evaded. The pilots are asked to approach each target waypoint as fast as possible, but not exceeding a maximum speed of 100 kt. That is, they need to find the shortest route, evading all bad weather pockets, from their position to the next target.

Before leaving the starting position or each target, the pilots are asked to estimate the travel time to the next target waypoint. To fulfil this task, they need to incorporate the travel speed of the helicopter and the time of acceleration and deceleration, taking into account all bad weather pockets on the way. The navigation display provides information to support this task. The provided information depends on which display (baseline, advisory, constraint-based) is active. The pilots are given a rule of thumb to complete this calculation: flying at 100 knots, it takes approximately twenty seconds to travel one kilometre. For acceleration and deceleration, pilots can factor in another twenty seconds.

During each experiment run, the helicopter only possesses a certain amount of reserve fuel (measured in travel distance, four kilometres per run). If the pilots expect to run out of reserve fuel before reaching the next target, they need to detect this and abort the mission at the current position (by telling "mission control", i.e., the experiment conductor).

It is of particular interest to investigate the effect of the employed displays on pilot decision-making during situations that do not neatly fall into the operational envelope of both displays (namely, the assumption that one-turn solutions are close to the optimal solution). To this end, two more complex obstacle arrangements are introduced.

In most cases, the one-turn solutions proposed by the displays are close to the optimal trajectory. However, depending on the location of the weather, there can be trajectories between waypoints that are more efficient than one-turn solutions, see for example Figure 6.12. At the beginning, the only suggested one-turn solutions lead completely around both obstacles, as shown by the advisory display (middle) and the constraint-based display (right). However, the most efficient route leads through the gap between the obstacles. This more efficient route is not detected by the support displays. How often pilots will detect this kind of route, and whether this depends on the used support display, is of importance for investigating pilot decision-making.

In addition to these more optimal 2-turn solutions, some additional bad weather pockets will appear for a small number of active legs. These will not be recognised by the experimental displays. This requires the pilots to detect this additional obstacle (and, when using any of the displays, the display malfunction) and perform all necessary tasks themselves. To elaborate: the obstacles will still be shown on the navigation display if they affect the currently active leg, but both the automatic path

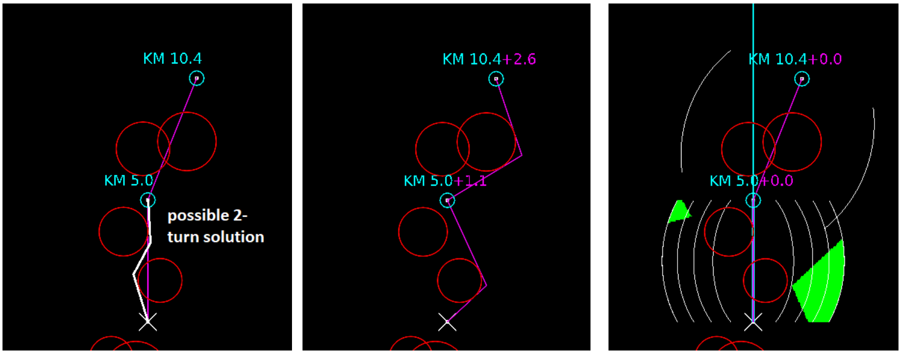


Figure 6.12: A possible 2-turn solution (added in white), afforded by the gap between the obstacles, when viewed with the baseline (left), advisory (middle), or constraint-based (right) display. Both the advisory and constraint-based displays only suggest suboptimal routes around both weather areas.

calculation of the advisory display and the area of possible intermediate waypoints of the constraint-based display will be calculated without this particular obstacle. These events will enable the analysis of the robustness of the utility of the displays towards system malfunction and inadequate reaction time to advises. Figure 6.9 depicts the appearance of a previously undetected weather area when entering the respective leg. Figure 6.13 shows how an undetected obstacle appears when using the advisory display (left) and the constraint-based display (right). For an in-depth analysis of how pilots can discover and react to this malfunction, please refer to the following section on control strategy analysis.

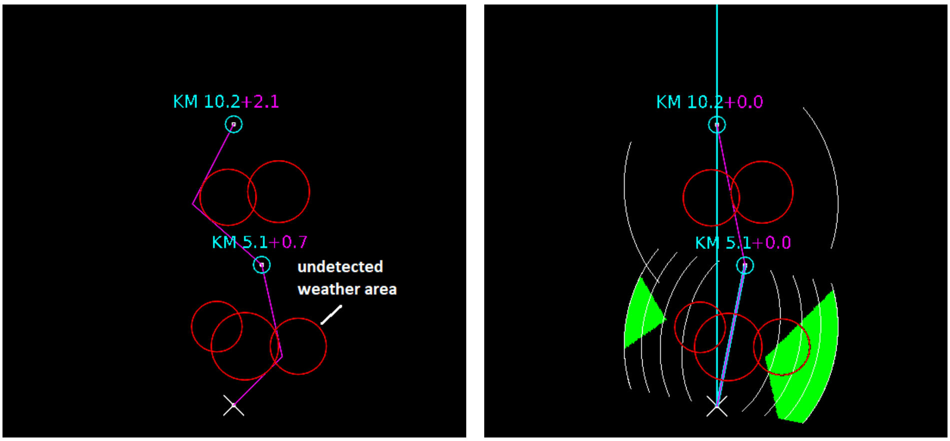


Figure 6.13: Flawed display support by the advisory (left) and constraint-based (right) display when an additional weather area appears (the third red circle at the bottom, for both displays).

6.5.2. Apparatus

The experiment took place in the SIMONA Research Simulator (Stroosma et al., 2003), shown in Figure 6.14. The outside visuals with a field-of-view of 180° by 40° are collimated, appearing at an infinite distance to the pilots. The simulator windows resemble a fixed-wing cockpit, obstructing any downward view. For the given navigation task and the very large hover area, this field-of-view limitation did not seem to play a detrimental role to the ability of the pilots to control the helicopter.

Figure 6.14: SIMONA Research Simulator. The basic instrument panel and the outside view are visible, the navigation display has been placed on the screen to the left of the right-hand instrument panel.

The participants used an authentic helicopter cyclic stick, collective stick, and pedals to control the model, which is a six-degrees-of-freedom in-house model based on a Messerschmitt-Bölkow-Blohm Bo105 Helicopter (Miletović et al., 2017). As shown in Figure 6.15, the trigger of the cyclic stick served as the "initialise" button, a button close to the resting position of the right-hand thumb served as the "select" button. Both buttons are used to interact with the experimental displays. As the focus of this experiment was long-term, strategic decision-making, the motion system of the simulator was deactivated. The additional motion cues are expected to have a negligible influence on the cognitive task of decision-making, and the added immersion was deemed insufficient to justify the added complexity and experiment duration which follows the use of the motion system.

6.5.3. Participants

Eight helicopter pilots with varying experience (minimum private pilot license (PPL), approximately 100 flight hours) participated in this experiment. They were recruited through personal contacts of researchers, previous experiment participants and a centrally-managed pilot database of the Section Control & Simulation at TU Delft. Five participants had a private helicopter pilot licence, three participants had a commercial or even more advanced helicopter licence. Average flight hours per participants amounted to 1,500 hours, with a standard deviation of 1,850 hours.

A briefing has been given to participating pilots before the experiment, explaining their task in great details. In summary, they were asked to complete the following task:

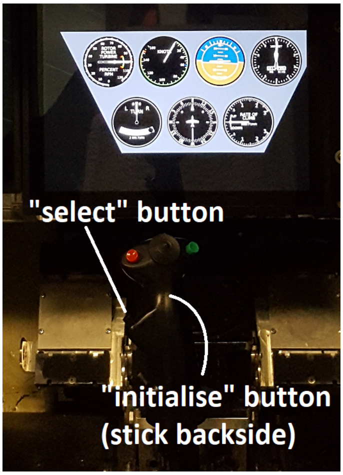


Figure 6.15: Cyclic stick, including the “initialise” trigger and the black round “select” button.

> “Please approach each subsequent target as fast as possible, without exceeding a maximum speed of 100 kn and without entering any bad weather areas. The order of targets is predetermined by the flight path. At each target, hover within the designated area for 10 seconds, to simulate loading/unloading. At the beginning of the experiment run and before departing from any target, please estimate your travel time to the next target, predict whether you will be able to reach the next target, and predict whether you will be able to complete the whole course, without exceeding the fuel reserves.”

After each run, an aggregated measure of mission time, fuel efficiency, and prediction accuracy has been communicated to the pilot.

Before the experiment, the pilots could accustom themselves with the controls, the model, and each experiment condition. The accustomisation period included shortened example runs in every experiment condition. The procedure of providing estimations of arrival times and the interaction with all displays has been explained during these runs. After the accustomisation period, the experiment procedure, as well as the workload, situational awareness and comment questionnaires have been explained to and discussed with the pilot. Afterwards, the first experiment condition would start.

It was anticipated to be a challenge to determine which strategy the pilots are following at any moment. Therefore, pilots were asked to comment on their actions and behaviours during the experiment. For example, they will be asked to call out “estimating travel time to target 2, ...”, “planning task with the display”, “There is an additional obstacle!”, etc.

6.5.4. Independent variables

The experiment utilised a within-participants design, each participant performed each condition. The independent variables of this experiment are *display* (basic, advisory, constraint-based) and *situation* (more optimal 2-turn, undetected weather). While the three displays have been explained above, the variable *situation* warrants further elaboration.

Two experiment courses have been designed, see Figure 6.16. The first course affords a more optimal 2-turn solution at the second leg. The second course contains an undetected bad weather area at the second leg, which appears when the pilots enter this leg. Depending on the flown course, the encountered situation at the second leg can therefore either be a possible, more optimal 2-turn solution, or a previously undetected weather area.

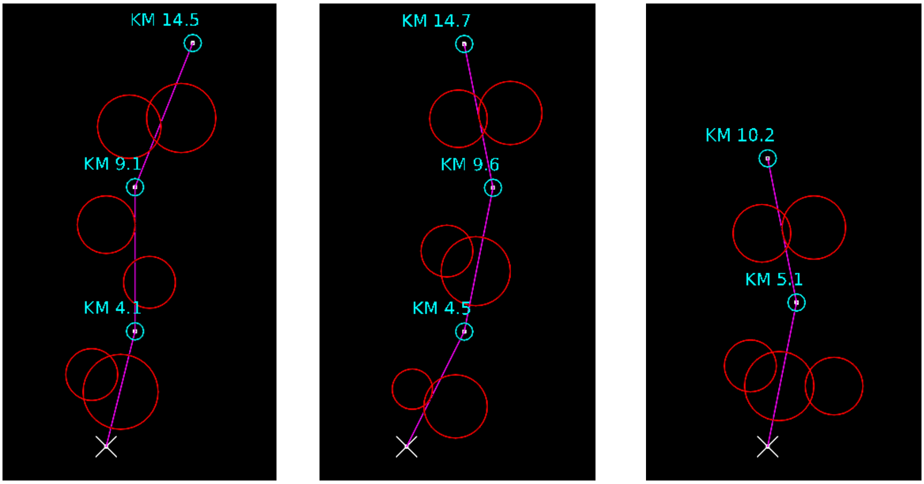


Figure 6.16: Left: first experiment course design with a 2-turn solution at leg 2. Middle: second experiment course design with an invisible additional weather area at leg 2. Right: second experiment course design, after the additional weather area appears at leg 2.

Each course is flown with each display, resulting in six experimental runs per pilot. To avoid the recognition of the same course, the course elements are rotated between displays. This does not change the distances or obstacle location relative to the leg origins and targets. The experimental setup is therefore treated as a "within subject" design, even though there are technically six different courses.

The order of experiment conditions is changed between pilots, to create a balanced experiment setup. Table 6.1 summarises the independent variables and experiment conditions.

6.5.5. Dependent measures

Dependent measures comprise of decision-making, measured through the trajectory decision the pilots make; performance, measured via track efficiency/remaining fuel, arrival time estimation duration, and arrival time estimation accuracy; safety,

Table 6.1: Experiment independent variables and resulting experiment conditions A-F.

Experiment conditions		Situation at leg 2 2-turn possible	undetected weather
Display	baseline	A	B
	advisory	C	D
	constraint-based	E	F

measured via the amount of "unsafe" fuel predictions (i.e., overestimating own capabilities); workload, measured via the subjective NASA Task Load Index (NASA TLX) (with comparison ratings collected per display), given to the pilots after each condition (Hart and Staveland, 1988; Hart, 2006); situation awareness, measured via the subjective scale Situation Awareness Rating Technique (SART) (Taylor, 1989), likewise given to the pilot after each experiment condition; and pilot preference, measured through a questionnaire given to the pilots at the end of the experiment. Figures B.6-B.12 in the appendix show the corresponding questionnaires. Table 6.2 shows an overview of the dependent measures of this experiment.

Table 6.2: Overview of dependent measures.

Category	Dependent measure
Decision-making	Trajectory decisions
Performance	Track efficiency Time efficiency Arrival time estimation duration Arrival time estimation accuracy
Safety	Number of overestimations of capability (next leg and whole course) Number of underestimations of capability (next leg and whole course) Number of correct estimations of capability (next leg and whole course)
Workload	NASA Task Load Index (NASA TLX)
Situation awareness	Situation Awareness Rating Technique (SART)
Pilot preference	Confidence using displays in all situations, with, and without additional weather Perceived path planning support Perceived weather recognition support Perceived weather reaction support Perceived arrival time prediction support Perceived fuel reserve estimation support

This experiment changes the employed workload measurement technique, compared to Chapter 5. Instead of the Rating Scale Mental Effort (RSME), the NASA TLX method is employed. By using the subscales of NASA TLX, more information about the relevant elements of the perceived pilot workload is acquired which could lead to a more thorough understanding of the perceived workload.

Decision-making, performance, and safety ratings are collected per leg and are analysed as such. Therefore, an experiment run always contains one data point for the first, nominal leg and a data point for the situation encountered at the second leg (2-turn possible or additional weather). The third leg is excluded, as some pilots were able to complete the third leg with the remaining fuel in some runs, but most pilots were not.

Workload and situation awareness ratings are collected per run and therefore always contain at least one nominal leg and one situation at the second leg as the basis for the subjective rating. The comparative ratings for the NASA TLX are only collected once per display, so three times in total. The weights are then applied to both runs with the same display. Table 6.3 shows the resulting experimental procedure.

The process of using the same scale ratings for two or more experimental runs has been described by Hart (2006). It is appropriate when the basic design (in this experiment: the display) stays identical across multiple runs. While it could be argued that encountering different kind of courses and situations constitutes a change in basic design, in this experiment it has been decided that the time saved (by only requiring the pilots to step out once per display to rate the scales) and the subsequent increase of possible run duration is worth the reduction in workload measurement accuracy.

6.5.6. Control variables

Control variables comprise the simulator set-up, task, the utilised helicopter model, the baseline navigation display elements, and the instrument panel.

6.5.7. Data processing

Given the relatively small number of eight participants, only conservative, non-parametric test statistics are used. To compare numeric measures, non-parametric two-way Friedman tests (Friedman, 1937) or, when analysing data subsets with only one independent variable, one-way Kruskal-Wallis tests (Kruskal and Wallis, 1952) are employed. To compare binary measures, Cochran-Q tests, as implemented in MATLAB by Jos[3], are utilised.

The data are treated on a "per course" basis. The course identifier is either C1, which is the experiment course with a possible 2-turn solution at the second leg; or C2, which is the experiment course with an additional weather area appearing at leg 2.

Tests are performed at an initial significance value of $\alpha = 0.05$. The initial test takes all data of one course (either C1 or C2) into account. In this arrangement, the first independent test variable is display (baseline, advisory, constraint-based), and the second independent variable is leg number (leg 1, leg 2), which corresponds to nominal and off-nominal situations, respectively. Depending on the course, the off-nominal situation is either a bad weather arrangement that affords a more efficient

[3] Jos (10584) (2021). COCHRAN Q TEST (https://www.mathworks.com/matlabcentral/fileexchange/16753-cochran-q-test), MATLAB Central File Exchange. Retrieved March 29, 2021.

Table 6.3: Experimental procedure, followed from top to bottom. The procedures of groups 1 and 2 were followed by two participants each, the procedures of groups 3 to 6 were followed by one participant each.

Introduction	Welcome, explanation of timetable and procedure Pre-experiment questionnaire					
Acclimatisation	Training programme in the simulator					
Preparation	Explanation of experiment questionnaires					
Group Assignment Group	1	2	3	4	5	6
Condition 1	A	F	D	C	E	B
	Display familiarisation Experiment run Condition questionnaires (SART, NASA TLX subscale values)					
Condition 2	B	E	C	D	F	A
	Experiment run Condition questionnaires (SART, NASA TLX subscale values) Display questionnaires (NASA TLX comparative ratings)					
	Break					
Condition 3	D	B	E	F	A	C
	Display familiarisation Experiment run Condition questionnaires (SART, NASA TLX subscale values)					
Condition 4	C	A	F	E	B	D
	Experiment run Condition questionnaires (SART, NASA TLX subscale values) Display questionnaires (NASA TLX comparative ratings)					
	Break					
Condition 5	E	C	A	B	D	F
	Display familiarisation Experiment run Condition questionnaires (SART, NASA TLX subscale values)					
Condition 6	F	D	B	A	C	E
	Experiment run Condition questionnaires (SART, NASA TLX subscale values) Display questionnaires (NASA TLX comparative ratings)					
Conclusion	Post-experiment questionnaires De-briefing and goodbye					

2-turn solution, or a weather area that appears mid-run and remains undetected by the experimental displays.

Tests that are performed post-hoc on subsets of the data are performed with a significance value of $\frac{\alpha}{n}$, where n is the number of subset tests performed. In most cases, n is equal to 5, when five subset tests are performed: three to analyse the effect of situation for each of the three separate displays and two to analyse the effect of display for each of the two situations. This Bonferroni-correction is carried out to achieve a significance value of $\alpha = 0.05$ for the combined post-hoc tests, accounting for the increased number of tests on the same data (Miller, 2012, p.67). Figures 6.17 and 6.18 show the data analysis procedure for objective and subjective dependent measures, respectively.

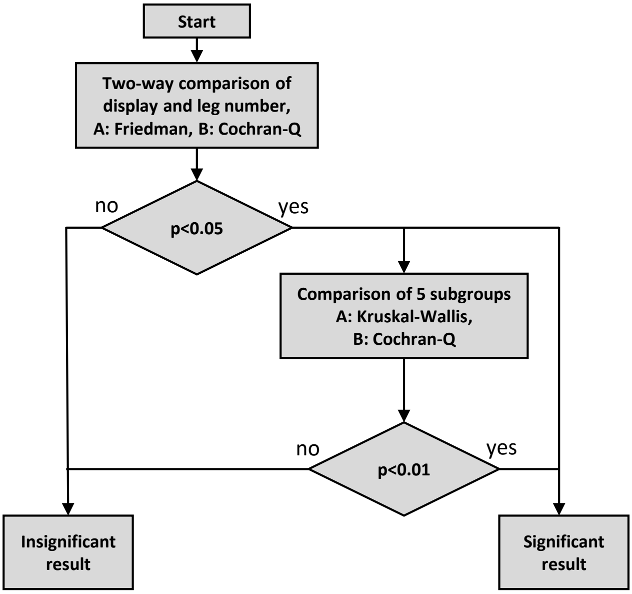


Figure 6.17: Data analysis procedure for objective dependent measures. A: non-binary measures, B: binary measures.

All employed statistical tests utilise a conservative baseline Type 1 error margin of $\alpha = 0.05$. Similarly, the employed Bonferroni correction and the utilisation of non-parametric tests are conservative approaches to the encountered situation. These choices lead to a decrease of the power of the employed tests. However, this reduction of power is tolerated, as it enables the formulation of strong conclusions if a statistically significant effect is found.

To enable a discussion of the Type 2 error β and the accompanying power $1-\beta$ of the performed tests, it will be calculated for every initial statistical test, taking into account all collected data. To calculate the power ANOVA tests, a procedure presented by Faul et al. (2007) is utilised. The calculations are performed via G*Power 3[4], developed and maintained by Faul et al. To calculate the effect size for tests relying on the χ^2-distribution, the procedure presented by Field (2005) is used. Afterwards, G*Power 3 is used to calculate the statistical power.

[4]G*Power 3 is a statistical power analyses tool, available at `https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower`, retrieved November 11th 2022.

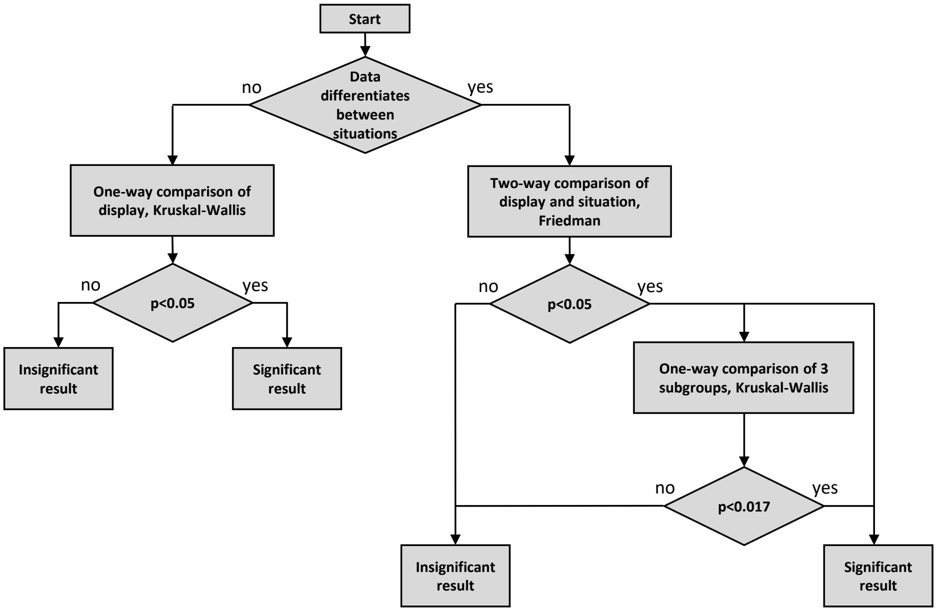


Figure 6.18: Data analysis procedure for subjective dependent measures.

6.5.8. Hypotheses

The hypotheses are based on an analysis of the control strategies that are enabled or stimulated by the different displays. The focus lies on pilot decision-making and the pilots' perception of the support the displays provide in this regard. These main hypotheses are presented first. Afterwards, secondary hypotheses for the remaining dependent measures are formulated.

Main hypotheses

In nominal situations (legs without a possible 2-turn solution and without additional weather), the advisory display will lead to the best trajectory decisions (i.e., go left or right around weather). The constraint-based display also enables good decision-making in these cases, but not as fast and direct as the advisory display.

The detection of two-turn solutions decreases when utilising the advisory display. The detection of these "unconventional" solutions takes place in the "Determine, evaluate, select solution" block in the DL, Figure 6.6, which is completely skipped with the advisory display in nominal situations, Strategy (6). With the baseline and constraint-based displays, the pilots are more involved with the spatial aspects of the prospective trajectories, which will lead them to detecting the two-turn solutions more often.

During legs with additional bad weather areas appearing, the constraint-based display will lead to the best trajectory decisions, as parts of it can still be used to judge prospective trajectories according to DL Strategy (5). Both the advisory and baseline display will lead to worse decisions, as both displays can only rely on DL Strategies (1) or (2).

It is expected that pilots prefer the advisory display in nominal situations and the constraint-based display in off-nominal situations. This outcome would reflect results obtained in the fixed-wing domain (Borst et al., 2010b).

Secondary hypotheses

Track efficiency increases when using the advisory display or the constraint-based in nominal situations. In nominal situations, both displays provide support for selecting a safe and optimal trajectory. In off-nominal situations, the advisory display does not support the pilot anymore, the performance will be similar to the baseline condition. The constraint-based display, through its fallback Strategy (5), still enables some support, performance remains higher than in the baseline condition.

In nominal situations, the planning and estimation time decrease when using the advisory display. The advisory display provides an optimal and safe solution on button press, simplifying both path planning and arrival time estimation. The constraint-based display requires pilot interaction during the path-planning task, which causes the planning phase to be larger than with the baseline display. However, arrival time estimation is supported to a higher extent than with the baseline display, through the visualisation of the track distance ellipses, which shortens the estimation time. It is hypothesised that for the constraint-based display, both effects will cancel each other out, resulting in a similar planning and estimation time.

Off-nominal situations increase the planning and estimation time of the advisory display and the constraint-based display, as both of these situations require a change of strategy. However, the strategy change is more significant for the advisory display, required a change from the highly supported Strategy (6) to the baseline Strategies (1) or (2). The constraint-based display affords fallback Strategy (5) and therefore causes a smaller planning and estimation time increase than the advisory display. For the baseline display condition, off-nominal situations do not influence the planning and estimation time.

Arrival time prediction accuracy improves when using the constraint-based display, and it further improves when using the advisory display in nominal situations, as the prediction support increases throughout these displays. In off-nominal situations, the prediction accuracy depends on the fallback strategies: in case of advisory display, Strategies (1) or (2); in case of the constraint-based display, Strategy (5). In this case, the constraint-based display is the only condition that still enables some support, and therefore it will be the only display with an improved accuracy.

Regarding safety, the distance to and time spent inside bad weather areas is expected to be not impacted by any of the displays. Even the baseline display provides enough information to avoid all obstacles.

The aggregate NASA TLX decreases with the advisory display in nominal situations. For the constraint-based display, the additional support it provides to fulfil the task is counteracted by the increased interaction and learning it requires from the pilots. In off-nominal situations, the workload is expected to increase in proportion to the severity of required strategy changes. In case of the constraint-based display, an increase is expected (switch from Strategies (3) or (4) to (5)). For the advisory display, an even higher increase is expected (strategy change from (6) to (1) or (2)).

SART scores are expected to increase with the constraint-based display in nominal situations, as it provides more information to the pilot. In off-nominal situations, SART scores will decrease for the advisory display, as it provides a large amount of wrong information. The positive effect of the constraint-based display is expected to remain visible. It is important to note that the detection of new bad weather areas and the discovery of more optimal 2-turn solutions is not part of this SART score, even though it could be argued that these behaviours are indicators for an increased pilot situation awareness.

6.6. Results

This section presents the results of the experiment, starting with the objective measures of pilot decision-making, performance, and safety. Afterwards, the subjective ratings of workload, situation awareness, and pilot preference are presented.

6

One pilot repeatedly hit the physical limits of the control inceptors in some of the runs, resulting in inconsistent helicopter model behaviour. This caused the participant to change the given performance and fuel predictions. The results of this participant are therefore only included in the decision-making category, as this specific dependent measure is expected to be independent from the encountered model behaviour changes. The results of this pilot have been omitted in all other dependent measures. This behaviour was not caused by significantly lower or higher flight experience; the participant had comparable experience to other participants who did not cause this model behaviour.

6.6.1. Pilot decision-making

The number of optimal pilot decisions is shown in Figure 6.19. Leg 1 of each course is a nominal leg, leg 2 contains either a possible 2-turn solution or an appearing additional weather area. In case of possible 2-turn solutions, the optimal pilot decision is defined as "discovering" this hidden, more optimal solution and performing it. In case of additional weather, the optimal pilot decision is defined as choosing the shorter route around the weather area. The direction of the shortest route (left or right around) changes after the additional weather area appeared.

Considering course C1, there is a significant effect of display on pilot decision ($\chi^2(2) = 8$, $p < 0.05$) and of situation on pilot decision ($\chi^2(1) = 4.5$, $p < 0.05$). The number of optimal decisions when using the advisory display drops sharply when encountering the possible 2-turn solution at leg 2, corroborated by a significant effect of display in leg 2, $\chi^2(2) = 10.3333$, $p < 0.01$. Only 2/8 pilots chose the more optimal two-turn solution with the advisory display, compared to 8/8 with the baseline and 7/8 with the constraint-based display.

Analysing course C2 reveals a similar picture, albeit somewhat less pronounced. Across all data, there is a significant effect of display ($\chi^2(2) = 8$, $p < 0.05$) and situation ($\chi^2(1) = 4$, $p < 0.05$) on pilot decision. Analysing leg 2 separately reveals

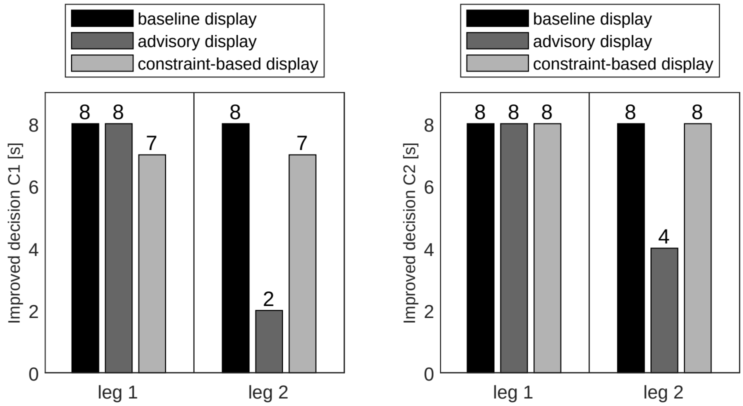


Figure 6.19: Optimal pilot decisions course C1 [s] (left); course C2 (right).

no significant effects of display ($\chi^2(2) = 8$, $p = 0.018$). However, there is a clear trend of worse decisions with the advisory display when encountering additional weather areas. Only 4/8 pilots chose the optimal route around the weather areas, the other pilots chose the less optimal direction suggested by the advisory display.

Figure 6.20 shows the questionnaire results covering the perceived display support for the subtasks of path planning, weather recognition, and the reaction to additional weather areas. The only significant effect can be observed for the path planning task: the employed display significantly affected the answer to this question ($H(2) = 9.9884$, $p < 0.01$). Both the advisory and constraint-based display have higher ratings than the baseline display.

This result seems to contradict the previous results, which highlighted the negative effect of the advisory display on the quality of trajectory decisions. There are multiple possible explanations for this apparent discrepancy. First, the pilots might have rated the theoretical, abstract capability of the displays to support their path planning and not the actual improvement they could observe during the experiment. It appears only logical that additional information, be it advisory or constraint-based, should have supported the pilots in planning prospective trajectories. This could explain why both displays have been rated higher than the baseline display.

A second possible explanation could be that the pilots did not rate the display support with regards to improved decision-making outcomes, but rather decision-making convenience. Both display variants provide shortcuts in the decision-making process that the baseline display does not offer. The pilots might also be oblivious to the fact that their chosen trajectory is non-optimal, which can lead to the subjective perception that the provided display support was useful, even though it was not.

It seems like the advisory display has a detrimental effect on pilot decision-making when encountering off-nominal situations. These worse decisions affected the performance and safety values discussed in the later sections, as the chosen trajectories were less efficient and required more fuel than the optimal route.

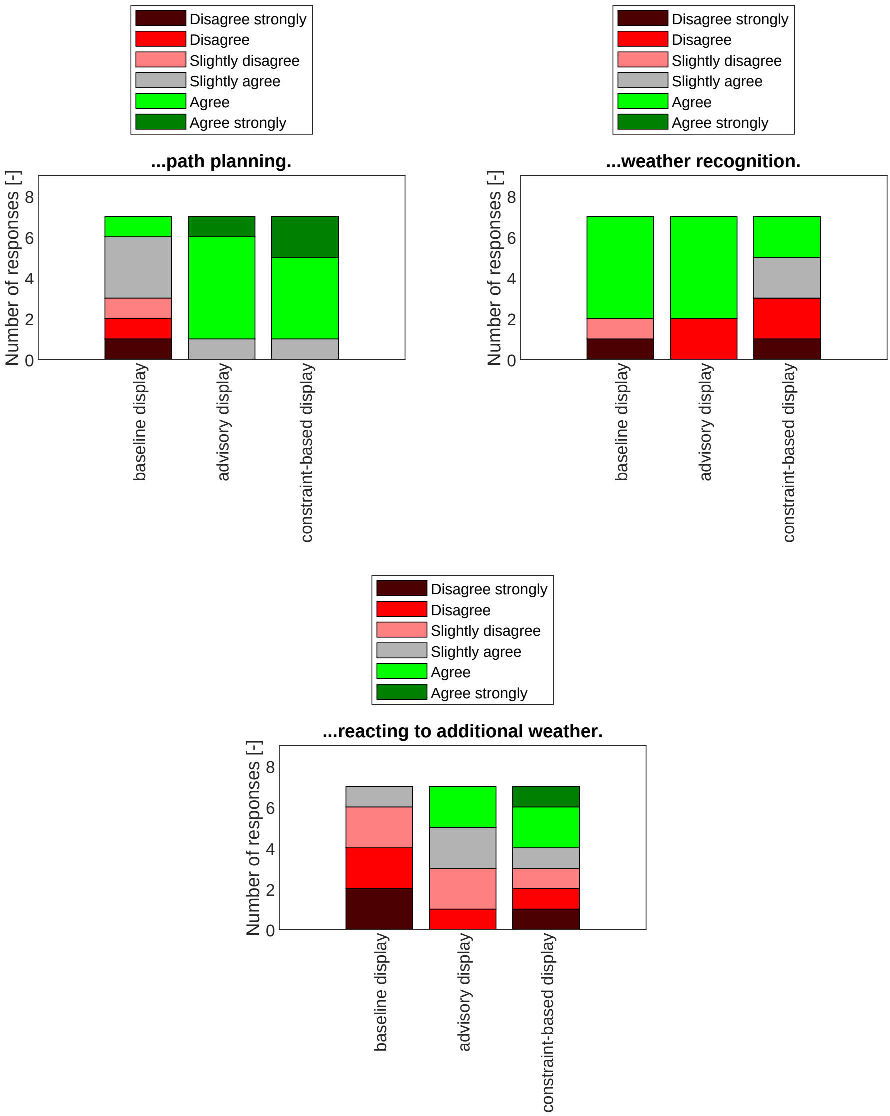


Figure 6.20: Pilot opinion on aspects of display support: path-planning, weather area recognition, and reacting to additional weather areas.

6.6.2. Performance

Performance results are presented through the analysis of four variables: the accuracy of the pilots' arrival time estimations, the track efficiency of the flown trajectories, the time efficiency of the flown trajectories, and the planning duration before each leg. All of these are only presented for legs 1 and 2, as the third leg was only completed occasionally and inconsistently by some of the pilots. This is the result of the experimental design of aborting a run when the remaining fuel is deemed insufficient to complete the next leg.

Figures 6.21 and 6.22 show the estimation accuracy data. The value shown in Figure 6.21 is the deviation of the actually flown trajectory time to the time prediction the pilots gave at the beginning of the leg. A positive value means that the pilots took longer than predicted, a negative value the opposite. No significant effects can be observed, $\alpha > 0.05$ for every effect in both courses. In both legs in course C1, as well as in leg 1 in course C2, pilots tended to overestimate their travel time, resulting in mostly negative deviation values.

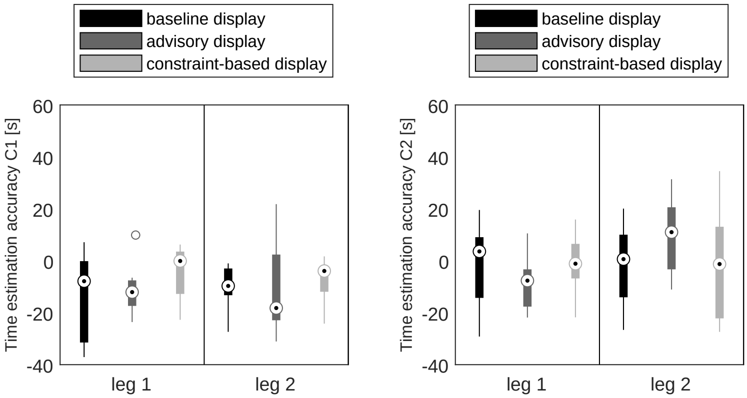


Figure 6.21: Time estimation accuracy course C1 [s] (left); course C2 (right).

Figure 6.22 shows the estimation deviation in absolute values. These values are per definition always larger than zero. There is a significant effect of display on absolute estimation deviation in course C1, $\chi^2(2) = 7.7069$, $p < 0.05$. Analysing legs 1 and 2 separately does not reveal any significant effects, $p > 0.01$ for every subset test. However, there seems to be a trend of larger deviations with the advisory display during leg 2, where a 2-turn solution is possible. It appears that in this situation, using the advisory display caused the pilots' estimations to deviate further from the actual travel time than in other nominal situations or than in leg 2 of course C2. In course C2, no significant effects can be observed.

Figure 6.23 depicts the questionnaire results covering the arrival time prediction support the displays provided. The employed display significantly affects the outcome, $H(2) = 14.6791$, $p < 0.001$. Both the advisory and constraint-based display score much higher than the baseline display. This difference is not visible in the objective experiment data. Comparable to the decision-support questionnaire result, this might be caused by the pilots rating the theoretical possibility, rather than the actual implementation, of improved estimation support. However, this could also be explained by assuming that the prediction task was not inherently hard, and the pilots were able to perform it with a comparable accuracy across all conditions. In

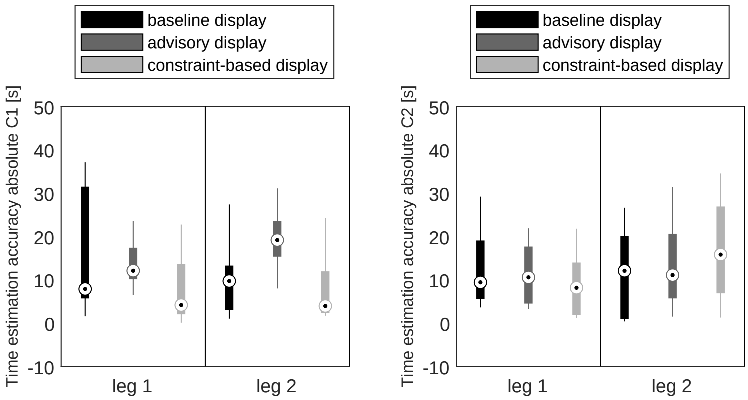


Figure 6.22: Time estimation accuracy absolute course C1 [s] (left); course C2 (right).

this case, the provided display support would only reduce the pilots' task-specific workload, without affecting the outcome.

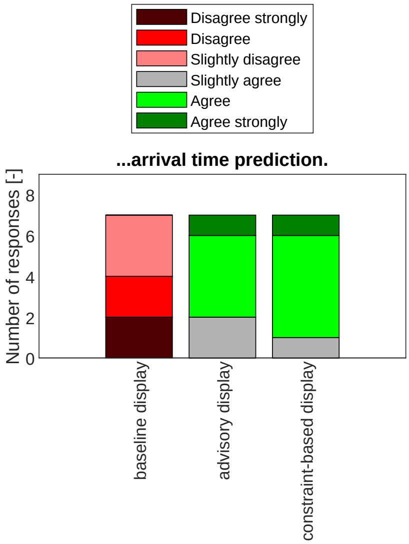


Figure 6.23: Pilot opinion on aspects of display support: arrival time prediction.

Figure 6.24 shows the track efficiency of the flown trajectories, measured in the difference to the shortest possible one-turn trajectory. For course C1, there is a significant effect of situation on track efficiency, $\chi^2(1) = 5.0626$, $p < 0.05$. In leg 2 of course C1, where a more optimal 2-turn trajectory is possible, the trajectories of both the baseline and the constraint-based display are on average 750 m shorter than the values of the advisory display. This is easily explained by the number of optimal pilot decisions in this case: 8/8 with the baseline, 7/8 with the constraint-based, but only 2/8 with the advisory display. Making the optimal decision of taking the 2-turn trajectory results in a shorter trajectory, while following the advisory display's suggestion results in a trajectory close to the suggested 1-turn solution.

For course C2, no significant effects can be observed, $p > 0.05$. However, the influence of the different trajectory decisions with the advisory display in leg 2 (when reacting to additional weather areas) manifests itself in a large spread of track efficiency. Four pilots decided on the optimal direction of circumnavigation, which resulted in track efficiency values close to 0 m. The remaining four pilots chose the suboptimal route around the weather area, which resulted in extra travel distances up to 2,000 m.

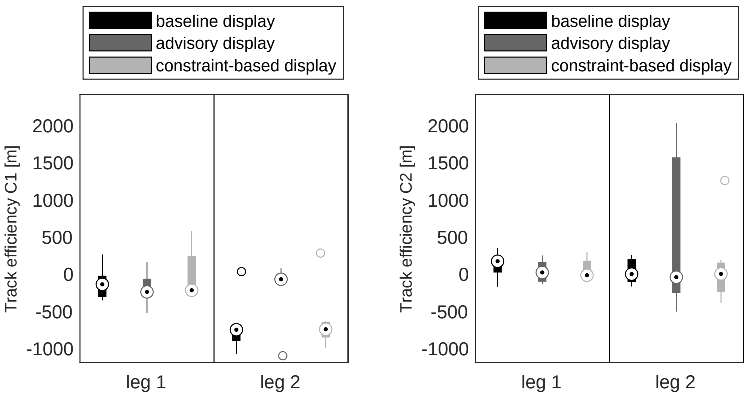


Figure 6.24: Track efficiency course C1 [s] (left); course C2 (right).

Figure 6.25 shows the time efficiency of the flown trajectories, measures in the deviation from a prescribed, "optimal" track duration based on the rule of thumb pilots used to estimate their travel time: twenty seconds per kilometre, plus twenty seconds for accelerating and decelerating. For course C1, there is a significant effect of situation on time efficiency, $\chi^2(1) = 5.7483$, $p < 0.05$. Encountering the possible 2-turn situation seems to have afforded the pilots more opportunities to undercut the benchmark time. Interestingly, there is no trend visible of improved trajectory times when choosing more optimal trajectories, which occurred more often with the baseline and constraint-based display than with the advisory display. This could be explained by the already large spread of time efficiency values (in the range of 30 to 40 seconds from minimum to maximum value) and the comparatively low time difference a track increase of 500 metres or one kilometre translates to. For course C2, no significant effects are observed, $p > 0.05$ for both variables.

In Figure 6.26, the planning duration for every course and leg is shown. For course C1, there is a significant effect of display on planning duration, $\chi^2(2) = 10.9981$, $p < 0.01$. While separate tests for both legs do not reveal a

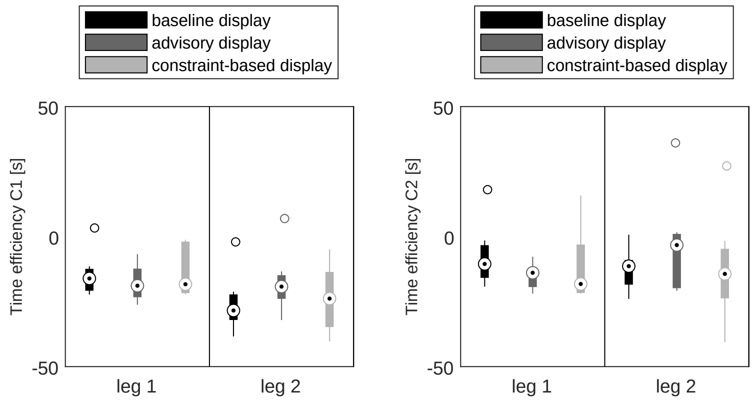


Figure 6.25: Time efficiency course C1 [s] (left); course C2 (right).

significant effect of the employed display (leg 1: H(2) = 6.0779, p = 0.048; leg 2: H(2) = 7.2356, p = 0.027), there seems to be a trend of an increased planning time when using the constraint-based display, in particular during leg 2 when a more optimal 2-turn solution is possible. This makes sense, as the constraint-based display requires more pilot interaction than the baseline or advisory display.

No significant effects can be observed for course C2, p > 0.05 for both variables. Considering leg 2, when additional weather appears, there seems to be a trend of increased planning duration for both the advisory display and the constraint-based display, compared to the baseline display. This result can be explained by the requirement to "change strategy" according to the process described in the previous section. Both the advisory and constraint-based displays clearly give faulty information, which requires the pilots to re-evaluate the provided information and employ a different strategy. In contrast, the control strategy with the baseline display stays identical, there is only one more weather area to consider.

6.6.3. Safety

Two different fuel predictions were made by the pilots. They needed to predict whether the remaining fuel is sufficient to complete the next leg, and they needed to predict whether the remaining fuel is sufficient to complete the whole course.

To determine the safety of the pilots' fuel predictions considering the next leg, three possible outcomes are considered. First, the pilots could overestimate their fuel capabilities. In this case, they predicted that they could finish the next leg, but they actually ran out of fuel before doing so. The number of these cases is shown in Figure 6.27. For course C1, no significant effects are observed, p > 0.05 for both variables. Both the baseline and constraint-based display caused one overestimation each in the third leg.

When encountering additional weather in course C2, the number of overestimations increases from zero to four. This is substantiated by a significant effect of

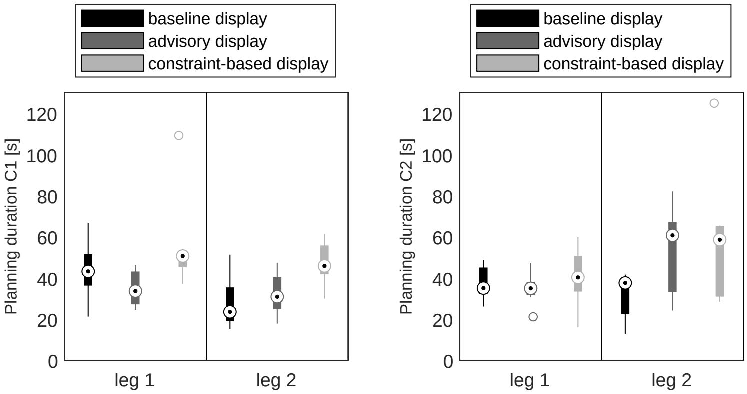


Figure 6.26: Planning duration course C1 [s] (left); course C2 (right).

situation on the number of overestimations, $\chi^2(2) = 8$, $p < 0.05$. There is no significant effect of display on the amount of overestimations, $\chi^2(2) = 4.6667$, $p = 0.097$. However, a clear trend is visible. Most overestimations took place when using the advisory display (3/7), followed by the constraint-based display (1/7). The difference between the baseline and the advisory display is particularly striking, as the advisory display contains all information of the baseline display, as well. Still, in this situation, having access to more information through the advisory display actually led to worse decisions. All three overestimations took place when the pilots chose the less optimal direction of circumnavigation, i.e., made a non-optimal trajectory decision.

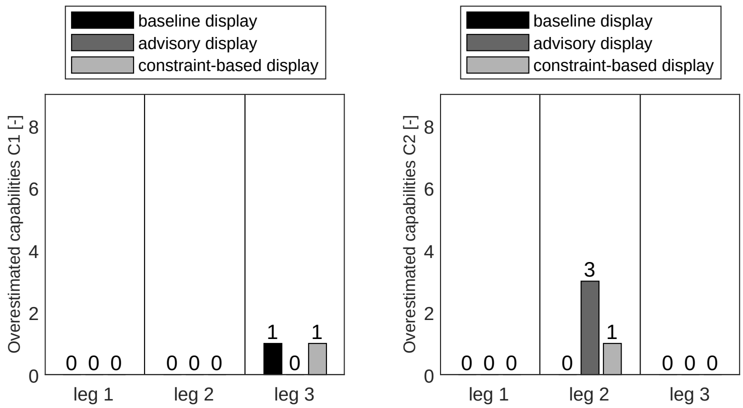


Figure 6.27: Pilot overestimated capabilities course C1 [s] (left); course C2 (right).

The second outcome occurs when pilot underestimate their capabilities. In this case, they judge their fuel insufficient to complete the next leg, even though the remaining fuel would actually be sufficient to complete the shortest one-turn solution to the next target. The data are shown in figure 6.28. No significant effects can be observed. Pilots underestimated their capabilities twice with the baseline display. It is important to note that underestimations are not necessarily wrong, they can also be a sign of caution. It is possible that the pilots realised that the fuel is theoretically sufficient to complete the leg, but their previous experience taught them that they require a certain additional amount of fuel, because it is impossible to perfectly follow the considered 1-turn path.

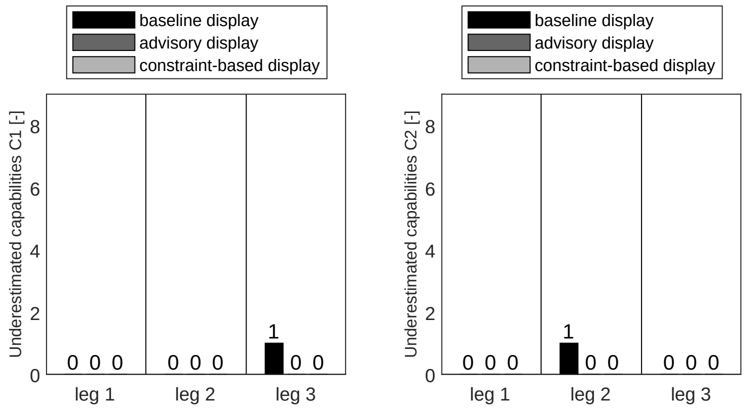


Figure 6.28: Pilot underestimated capabilities course C1 [s] (left); course C2 (right).

The third and last outcome occurs when the pilot prediction turns out to be accurate at the beginning and true in the end, i.e., the pilots neither overestimated nor underestimated their capabilities. The resulting numbers are shown in Figure 6.29. For course C1, there is a significant effect of leg number on the number of true predictions, $\chi^2(2) = 6$, $p < 0.05$. Three wrong estimations took place in leg 3: two overestimations (one with the baseline, one with the constraint-based display) and one underestimation (with the baseline display).

For course C2, there is also a significant effect of leg number ($\chi^2(2) = 10$, $p < 0.01$). Five wrong estimations happened during leg 2, when the additional weather area appeared. One of these was an underestimation with the baseline display. The remaining wrong estimations were overestimations: three with the advisory, one with the constraint-based display. While the test statistic is not significant, $H(2) = 6$, $p = 0.050$, there seems to be a trend of a larger number of wrong estimations when using the advisory display in this situation.

The pilots were also asked to predict their capability of completing the remainder of the course, at the beginning of leg 1 and leg 2. The number of overestimations is shown in Figure 6.30. Considering full-course overestimations in course C1, there is a significant effect of the employed display ($\chi^2(2) = 6$, $p < 0.05$). The baseline display caused four, the constraint-based display five overestimations, while the

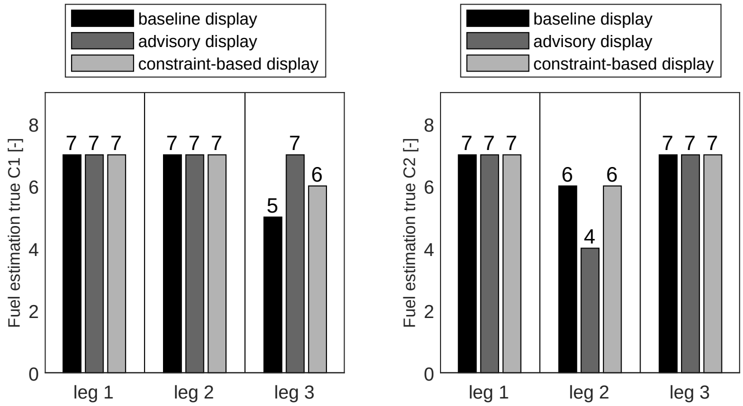


Figure 6.29: Pilot estimation was true course C1 [s] (left); course C2 (right).

advisory display caused none. In situations without additional bad weather, the advisory display seemed to be very helpful in determining the remaining course capabilities.

Naturally, there is a significant number of overestimations in leg 1 of course C2, compared to the second leg, $\chi^2(1) = 14$, $p < 0.001$. These are caused by the not yet visible additional weather areas in leg 2. In this case, the pilots are acting on incomplete information and are unable to provide accurate estimations. Across both legs, the effect of display is significant, too ($\chi^2(2) = 8.4$, $p < 0.05$). However, analysing only leg 2 estimations reveals no significant effects of display, $H(2) = 4.6667$, $p = 0.097$. The advisory display caused three, the constraint-based display two overestimations, while the baseline display caused none.

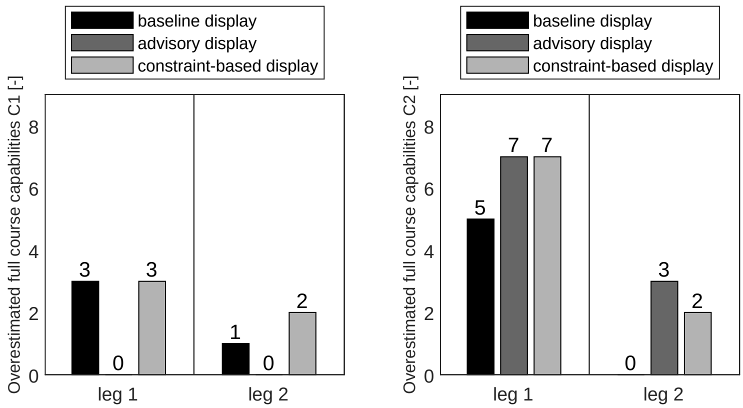


Figure 6.30: Pilot overestimated full course capabilities course C1 [s] (left); course C2 (right).

Full-course underestimations happened rarely, as seen in Figure 6.31: twice with the advisory display and twice with the constraint-based display. No significant effects are observed.

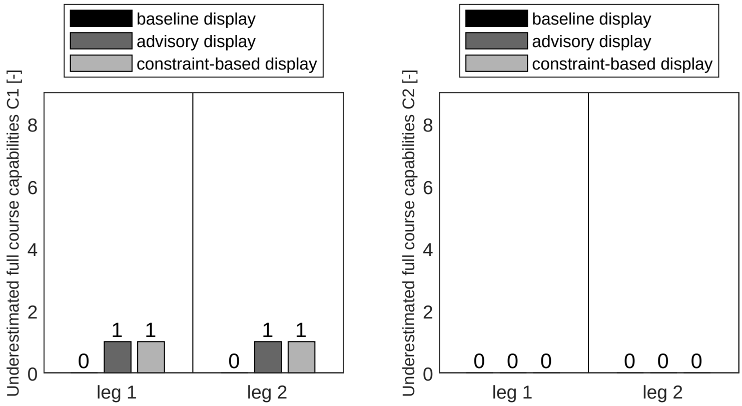


Figure 6.31: Pilot underestimated full course capabilities course C1 [s] (left); course C2 (right).

Cases in which pilots neither overestimated nor underestimated their full course capabilities are shown in Figure 6.32. For course C1, no significant effects are observed, $p > 0.05$ for every variable. For course C2, both display ($\chi^2(2) = 8.4$, $p < 0.05$) and leg number ($\chi^2(1) = 14$, $p < 0.001$) have a significant effect. As previously explained, the small number of correct estimations in leg 1 is explained by the additional weather area that will appear at leg 2. At leg 2, the baseline display caused zero wrong predictions, while the advisory display caused four and the constraint-based display caused two. The differences are not significant, $H(2) = 4.6667$, $p = 0.097$.

In Figure 6.33, the questionnaire results covering the fuel reserve estimation support of the displays, is shown. Mirroring results from the arrival time estimation task, the advisory and constraint-based display are rated significantly higher than the baseline display ($H(2) = 14.1411$, $p < 0.001$). Again, this difference is not visible in the objective experiment metrics, where each display contributed equally to some false predictions. In this case, having the additional information of the advisory or constraint-based display might have increased the pilots' confidence in their predictions, or decreased the required workload, without actually influencing the prediction accuracy.

6.6.4. Workload

The NASA TLX workload rating is shown in Figure 6.34 (left). No significant effects are observed. There seems to be a slight trend of a lower workload rating with the advisory display in 2-turn courses, which would be in line with the hypothesis. Considering all conditions, however, the subjective workload seems largely independent from both situation and display. For reference, the NASA TLX subscales

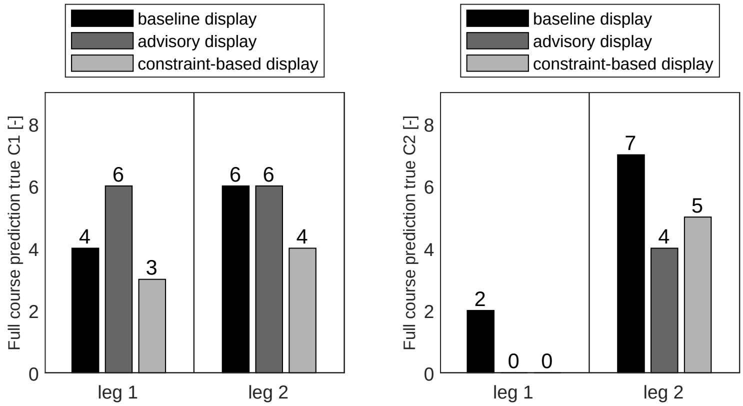


Figure 6.32: Pilot estimation full course true course C1 [s] (left); course C2 (right).

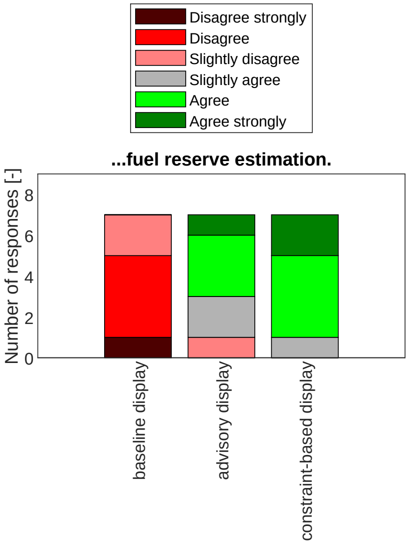


Figure 6.33: Pilot opinion on aspects of display support: fuel reserve estimation.

are depicted in Figures 6.36 to 6.38 at the end of this Chapter.

6.6.5. Situation awareness

The situation awareness ratings, based on SART, are shown in Figure 6.34 (right). Once again, no significant effects are observed. There is a small trend of an increased situation awareness rating in 2-turn situations with the advisory display, mirroring the workload ratings.

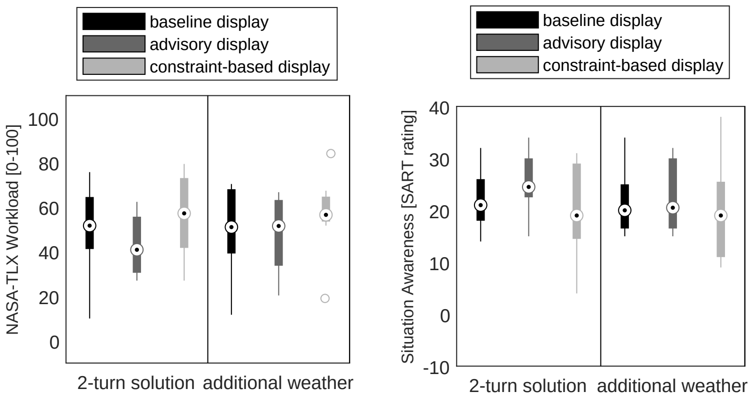


Figure 6.34: Subjective pilot ratings per course, each containing either a possible 2-turn solution or an additional weather area at the second leg. Workload [NASA TLX] (left); situation awareness [SART rating] (right).

6.6.6. Pilot preference

Pilot preference was determined through the questionnaire question:

> *"(In general/Without additional weather/with additional weather), I felt confident using the display."*

The display referred in the question is written on the top of the corresponding questionnaire page. The answers to this question are shown in Figure 6.35. Both display ($\chi^2(2) = 11.9433$, $p < 0.01$) and situation ($\chi^2(2) = 6.6141$, $p < 0.05$) significantly impact the approval rating. In general, pilot preference was largest for the advisory display. In nominal situations, all displays were preferred equally, no significant effect of display can be observed ($H(2) = 3.5$, $p = 0.1737$). However, in cases with additional bad weather, the results diverge. Analysing the displays separately, encountering additional bad weather reveals a trend of decreasing preference rating of the baseline display ($H(2) = 4.4842$, $p = 0.1062$), both the constraint-based display ($H(2) = 3.0054$, $p = 0.2225$) and the advisory display ($H(2) = 0.5832$, $p = 0.7471$) retain their high approval ratings.

This result is surprising, as the advisory display is actually the least helpful in these situations, purely based on the information it provides. The trajectory advice it gives in these situations is obviously wrong (and the pilots were aware of this), and the suggested direction leads to a larger circumnavigation manoeuvre. Nonetheless, and particularly in these situations, pilots preferred the "wrong advice" of the advisory display over the minimal but correct information of the baseline display and also over the partly wrong, but still usable information of the constraint-based display. This result is in stark contrast to the hypothesis as well as to the other dependent measures and will be discussed in detail in the following section.

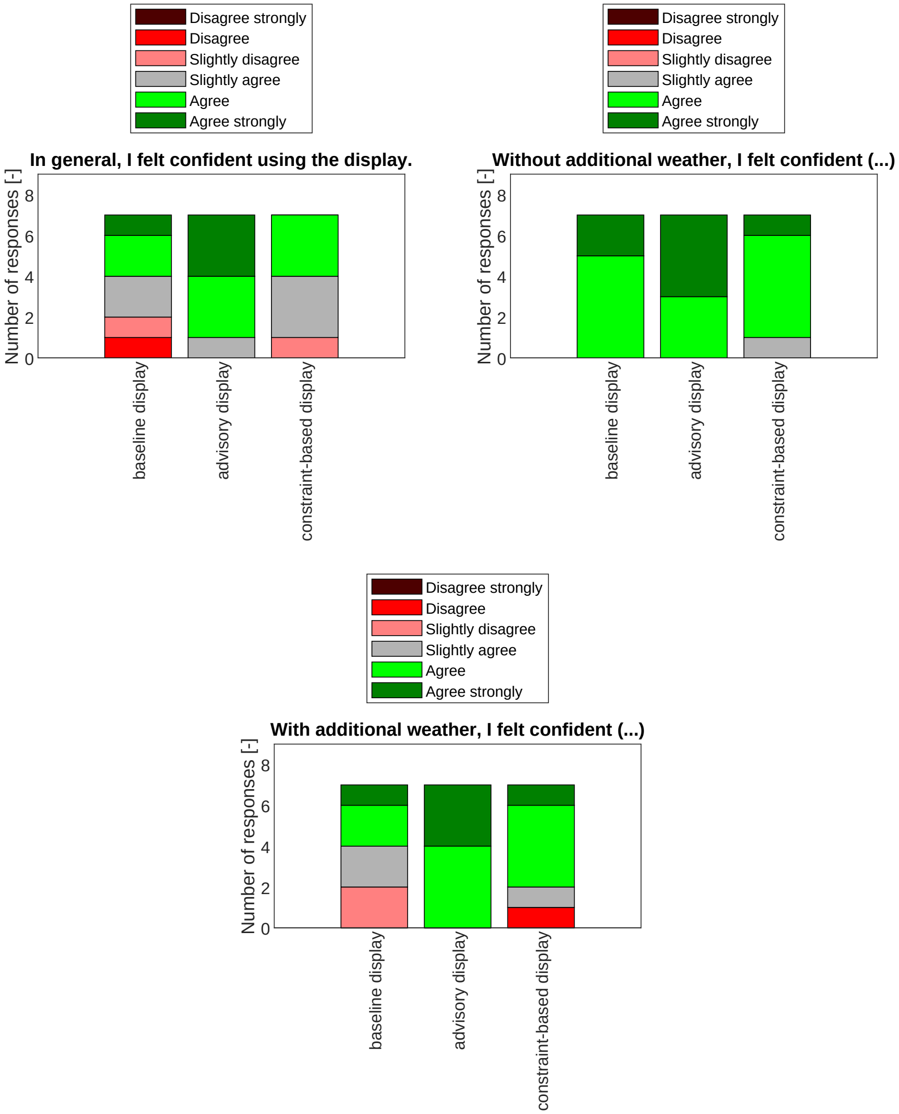


Figure 6.35: I felt confident using the display. In general; without additional weather; with additional weather.

6.7. Discussion

Tables 6.4 and 6.5 summarise the results of the initial statistical tests of this experiment, taking into account all collected data, as well as the statistical power $1 - \beta$ of the performed tests, calculated post-hoc. For dependent measures with insignificant test results, it shows values between 0.05 and 0.41. While the power of the

Table 6.4: Results of initial statistical tests, taking into account all collected data.

Category	Dependent measure	Display p	Display $1-\beta$	Situation p	Situation $1-\beta$
Workload	NASA TLX	0.30	0.14	0.54	0.09
Situation awareness	SART	0.32	0.13	0.45	0.12
Pilot preference	Confidence using displays	<0.01	0.32	<0.05	0.23

performed tests is higher than in Chapter 5, it is still well below the value of 0.8, which is often used based on convention (Field, 2005).

Again, these high values for potential Type-2 errors ($0.59 < \beta < 0.95$) limit the relevance of tests that produced an insignificant result. This experiment used a conservative approach to data analysis and statistical testing, including using a stringent Type-1 error bound of α=0.05, using non-parametric tests, and utilising the conservative Bonferroni modification of the significance levels of performed post-hoc tests. This was done in order to strengthen the relevance of significant test results: when a significant difference is detected, this is a strong indication that there is a difference between conditions. At the same time, this approach reduces the power of insignificant test results, which only present a weak indication that there is no difference between conditions in the ground truth.

The most important finding of this experiment is the influence of the employed automation system on the decision-making of the participating pilots. Results show that employing the advisory display significantly and negatively impacts the pilots' decision-making process in both off-nominal situations: a possible two-turn solution and an additional appearing obstacle. Critically, most pilots were unaware of their worse decisions, in particular during situations with possible two-turn solutions. A few pilots commented mid-run on their decision (e.g., *"I think I should have gone the other way."*, *"Why did I fly this way around? I think through the middle would have been faster."*), and some more pilots made references to "wrong suggestions" in the final questionnaire, but not during the run itself. In order to analyse these decisions, the following discussion refers to the control strategies as described in Section 6.4.

When encountering additional bad weather, the advice was always obviously wrong, as it crossed straight through an additional weather area. However, even in these situations, pilots were inclined towards following the direction of the suggested trajectory. This might be explained through a "priming" effect of the previously correct and still visible trajectory suggestion. In order to change their opinion about which direction to fly, the pilots were required to abandon the convenience of control Strategy (6) (and the large shortcut through the DL) and utilise Strategies (1) or (2). Being used to a nicely presented solution through the advisory display, they might have been inclined to utilise Strategy (2), choosing the first viable solution, instead of utilising the more mentally demanding Strategy (1), choosing the optimal solution. Being aware of the incorrectness of the large shortcut through the DL, the pilots might have been primed to select a control strategy that still provides the largest shortcut possible, without violating the safety requirements. By utilising this

Table 6.5: Results of initial statistical tests, taking into account all collected data. An arrow to the left implies the test was performed simultaneously for courses 1 and 2. An "x" implies that the experiment design did not afford data to perform this test. A "-" implies no difference in the data, which means the test could not be performed.

	Course 1				Course 2			
	Display		Leg number		Display		Leg number	
Dependent measure	p	$1-\beta$	p	$1-\beta$	p	$1-\beta$	p	$1-\beta$
Decision-making								
Trajectory decisions	<0.05	0.26	<0.05	0.56	<0.05	0.26	<0.05	0.52
Performance								
Track efficiency	0.69	0.08	<0.05	0.61	0.41	0.12	0.36	0.15
Time efficiency	0.89	0.06	<0.05	0.67	0.23	0.15	0.85	0.05
Arrival time estimation duration	0.00	0.31	0.13	0.33	0.49	0.11	0.36	0.15
Arrival time estimation accuracy	0.29	0.14	0.28	0.19	0.87	0.06	0.64	0.07
Arrival time estimation absolute deviation	<0.05	0.25	0.53	0.10	0.96	0.05	0.85	0.05
Safety								
Number of overestimations (next leg)	0.61	0.09	0.14	0.18	0.10	0.19	<0.05	0.26
Number of overestimations (remaining course)	<0.05	0.22	0.08	0.41	<0.05	0.27	<0.001	0.96
Number of underestimations (next leg)	0.37	0.12	0.37	0.12	0.37	0.12	0.37	0.12
Number of underestimations (remaining course)	0.37	0.12	-	-	-	-	-	-
Number of correct estimations (next leg)	0.22	0.15	<0.05	0.22	0.14	0.18	<0.01	0.29
Number of correct estimations (remaining course)	0.12	0.18	0.08	0.41	<0.05	0.27	<0.001	0.96
Pilot preference								
Perceived path planning support	<0.01	0.29	x	x	<−	<−	x	x
Perceived weather recognition support	0.31	0.13	x	x	<−	<−	x	x
Perceived weather reaction support	0.11	0.19	x	x	<−	<−	x	x
Perceived arrival time prediction support	<0.001	0.36	x	x	<−	<−	x	x
Perceived fuel reserve estimation support	<0.001	0.35	x	x	<−	<−	x	x

6

shortcut, they (possibly subconsciously) sacrificed trajectory efficiency for a quicker trajectory determination control strategy.

In this case, the first viable solution seems to be influenced by the still visible, albeit wrong, advisory suggestion. The solution that is closely related to this wrong suggestion is the trajectory that follows the same direction and just incorporates an additional track around the newly appeared obstacle. Half of the pilots implemented this suboptimal trajectory.

The pilots preferred the direct trajectory suggestion of the advisory display, in particular in situations with additional bad weather, where this advice was clearly wrong. At first glance, this seems to be a contradiction: in situations where the advice was clearly wrong, pilots preferred the display even more. Conversely, the baseline and constraint-based display were rated less favourably, even though the information of the baseline display was not influenced by the additional weather area, and the majority of constraint-based information was still usable. Clearly, the differences in approval rating are not based on the usability of the provided information alone.

In general, the way in which the question is posed in the questionnaire might have caused a difference. Even though there was no (baseline) or little (constraint-based) difference in support between situations with and without additional bad weather, pilots might have felt inclined to rate the displays worse in situations with additional bad weather, simply because this theoretically presented a complication in determining the next trajectory. In case of the advisory display, this negative effect might have been counteracted by the natural "convenienceness" of a nicely presented trajectory suggestion, even if the suggestion was wrong. As previously discussed, this wrong suggestion could have acted as an anchor point to determine the "next best" solution quickly and without the requirement to completely change the control strategy and put more cognitive effort into it.

The constraint-based display did not cause significant differences in dependent measures, when compared to the baseline display. In terms of decision-making, there were only two instances of "wrong" trajectory decisions. Pilots commented on a variety of advantages and disadvantages of the constraint-based display. Some examples include:

- *"The display is hard to learn and use"* (aural remark: *"caused by the novelty of the data type and representation"*)
- *"The presented data is appreciated, but using it correctly causes a lot of work-load"*
- *"It gives a lot of information, but you must calculate and do too much during hover and flight."*
- *"More accurate calculation of reserve and planning options, but a lot of lines. So you have to choose the best option by yourself (no advisory in it)."*

Generally, the pilots appreciated to goal of the display and commented on the theoretical usefulness of the information. However, using the display correctly was hard to learn and required a lot of workload. Consequently, usage of the display differed between pilots. Some pilots used the display extensively, setting "test waypoints" to the right and left of obstacles to support their decision-making. Conversely, some pilots did not set intermediate waypoints at all and only utilised the information about additional travel distance signified by the ellipses. In addition, some pilots commented on the usefulness of the "future leg constraints", whereas other pilots did not use this information at all. In conclusion, it seems like this display concept may have potential, but it requires further improvement in terms of data representation and the workload of the required pilot interaction, as well as more intense training in understanding and using novel data representations.

This experiment clearly shows the disadvantages of subjective ratings of situation awareness and system preference. When analysing situation awareness, it is impossible for the participants to judge the amount of information they did not perceive or understand. They might have the subjective sense of perceiving and understanding all necessary information, as they are, obviously, not aware of all the information they did not perceive. This might be a reason for the relatively high values of SART ratings for the advisory display: the pilots are presented with an easy-to-follow suggestion, which causes a sense of solving the situation quickly and efficiently. Consequently, the subjectively reported SART ratings are high. However, the pilots are, at this moment, not aware of the existence of a more efficient trajectory. While this might have been caught by more objective measures of situation awareness, the subjective scale in this experiment has no way of incorporating this "unknown unknown".

Subjective measures of system value or acceptance can be misleading, as seen in this experiment. The advisory display led to the worst decisions, but it was most favoured by the pilots. It is then unclear whether the pilots preferred the advisory display in spite of the worse decisions, or because they were unaware of the negative impact on their decision-making. It is therefore important to consider the state of information the pilots have while judging their system preference: does it incorporate the pilots' performance, or is it solely based on convenience? This is exceptionally important when designing new displays for actual operation: the convenience or ease-of-use of an automation system clearly does not correlate with the quality of its support and the resulting system performance and safety.

This is clearly not a new result. The possible downsides of automation have been discussed extensively (Bainbridge, 1983; Baxter et al., 2012; Strauch, 2018). However, it is important to always analyse and discuss these general findings while taking into consideration the actual system design and characteristics. In case of this experiment, it is important to consider the typical human-machine interface of helicopters and how its characteristics could influence the effect of automation systems.

In this experiment, and in many helicopters that are used privately and commercially, helicopter pilots are required to fly "hands-on" the vast majority or all parts of a mission. As such, they have little to no capacity to use intricate touchscreen functions or other mechanisms that would require them to let go of one of the control inceptors. Because they are required to manually control the vehicle, it is conceivable that this human-machine system is increasingly susceptible to those ironies of automation, as described by Bainbridge (1983), that deal with trust in automation and automation reliability. As their manual workload of controlling the (typically unstable) helicopter is already high, any form of automation function that reduces the requirements on the pilots' mental capacities might be strongly appreciated.

This is in particular true for the advisory display of this experiment: it takes and completely solves the trajectory determination task for the pilots, greatly reducing the strain on their cognitive resources. As this effect is so positive, pilots might be inclined to accept the suggested solution even if it could theoretically be (or actually is) wrong. The results of this experiment indicate that even when the suggested solution is clearly wrong, it can still be appreciated as a "starting point" for the finding of the next trajectory. Conversely, the constraint-based display places more requirements on the cognitive resources of the pilots. In these cases, even if the provided information is theoretically useful, the pilots rather not use it and rely on the easier usage of baseline display information.

Lastly, the requirements of continuously controlling the helicopter might also impair the capacity of pilots to ad-hoc analyse the response of automation systems and examine their behaviour in search for inconsistencies. It is also conceivable, and supported by the results of this experiment, that pilots differentiate between different degrees of accepted automation failure. 6/8 pilots accepted less efficient trajectories when encountering possible two-turn solutions, resulting in worse mission efficiency. However, only 4/8 pilots accepted flawed suggestions when encountering additional weather, the rest of the pilots invested more cognitive resources to modify their decision. Lastly, none of the pilots followed a flawed suggestion into a bad weather area: analysing and correcting the automation suggestion always took preference over impairing safety, the pilots always compensated this element of the automation system's failure.

6.8. Conclusion

This chapter experimentally compared a baseline, advisory, and constraint-based helicopter navigation display. The eight participating helicopter pilots preferred the advisory display, even in situations where its advice was wrong. The advisory display caused the most suboptimal trajectory decisions, in particular in situations that afforded a more efficient trajectory without introducing additional navigational hazards. The complex information that the constraint-based display provided was appreciated by the pilots. However, this did not result in improved performance or decision-making, and the pilots commented on the difficulty of learning and utilising the display. The negative impact of the advisory display was clearly visible and warrants intense scrutiny for future system designers to avoid these negative influences of future automation systems in actual operation. The constraint-based display of this experiment has shown theoretical potential to better inform pilots decisions. However, its data representation and the required high workload to correctly use it barred it from being more useful than the baseline display.

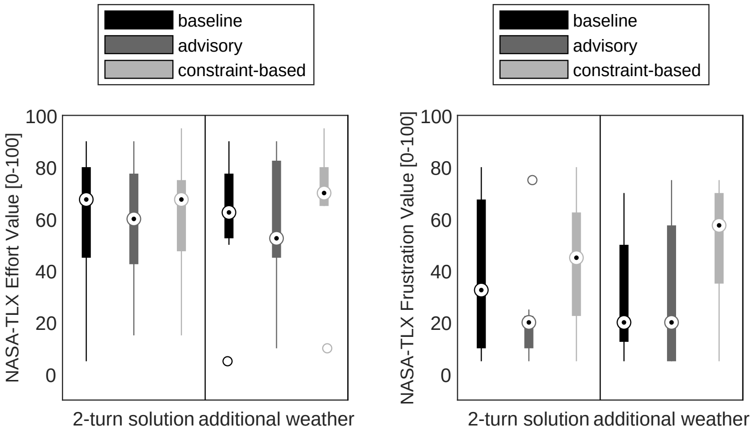


Figure 6.36: Workload Effort and Frustration ratings per course.

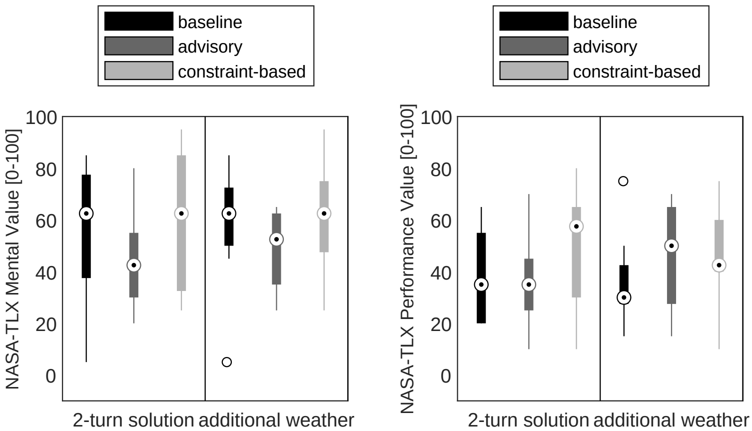


Figure 6.37: Workload Mental and Performance ratings per course.

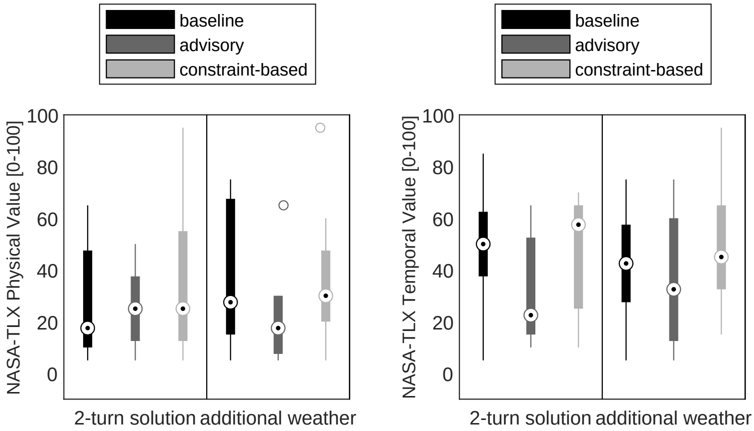


Figure 6.38: Workload Physical and Temporal ratings per course.

7

Discussion, Recommendations, and Conclusion

7.1. Main research question

At the beginning of this dissertation, a main research question and three subquestions have been defined. This chapter is structured to follow the posed questions, starting with reiterating the main research question, and subsequently answering subquestions one to three. The main research question has been defined as:

> **Main research question**
>
> How can advisory and constraint-based automation design philosophies improve helicopter safety at different timescales of operation?

As the first step to answer the main research question, a literature review has been performed, analysing helicopter control peculiarities and existing automation systems (Chapter 2). Afterwards, two exploratory studies and two human-in-the-loop experiments have been performed to analyse different automation design philosophies in scenarios on different timescales: short-term (Chapters 3 and 4), medium-term (Chapter 5) and long-term (Chapter 6).

This conclusion is separated into multiple sections. Section 7.2 discusses helicopter automation and control peculiarities and investigates how these differences influence the results of this dissertation. Section 7.3 examines the employed methods to evaluate helicopter automation. The results of the separate studies and experiments of this dissertation are combined in Section 7.4 to discuss automation across timescales. Section 7.5 recalls different reasons for pilots to question the given automation advice, and how these reasons affect the likelihood of corrective pilot action. Sections 7.6 and 7.7 formulate recommendations for future helicopter automation design and research, respectively. Lastly, Section 7.8 concludes this chapter and, by extension, the complete dissertation.

7.2. Helicopter automation peculiarities

The first subquestion has been defined as:

> **Subquestion 1**
>
> What are the peculiarities of helicopter automation?

This dissertation investigates ecological interface design (EID) principles as a possible avenue of automation design in the helicopter domain. EID has been applied in different control domains like civilian fixed-wing aircraft, but not often in the helicopter domain. The first subquestion therefore investigates whether results from other control domains can be directly applied in the helicopter domain, or whether there are peculiarities of the typical helicopter control task and of automation-supported functions that warrant renewed investigation of basic EID effects in this domain.

The performed literature review revealed a broad range of helicopter automation systems. From obstacle avoidance to path planning systems, and from full-authority autopilots to digital map and navigation displays, every aspect of helicopter operation has been the focus of research and evaluation. This does not mean, however, that automation support for helicopter pilots has been "solved". Many publications focus on very specific operational scenarios and simplifications, only providing evaluation results for narrowly defined tasks. In addition, new automation functions are often only compared to a baseline condition without any automation support.

Comparing typical helicopter and typical commercial fixed-wing aircraft control activities reveals significant differences, such as:

1. vehicle dynamics,
2. extent of required manual control inputs,
3. possible trajectories,
4. distance/time-to-contact to obstacles, and
5. mission variability.

The first two points manifested themselves in very different activities that pilots perform while utilising automation. For helicopters, a larger requirement for manual control, coupled with a less stable vehicle, leads to an increased focus on short-term manual control and decreased attention to supervisory automation monitoring. Pilots are focused on "solving the problem" manually and quickly, with or without automation support. This might be a result of the typical focus of helicopter pilots on the outside visuals, especially during low-speed manoeuvring and hovering: pilots need to continuously monitor the position and attitude of the helicopter and enact precise control inputs to maintain stability.[1]

7

The performed obstacle avoidance experiment provides anecdotal evidence of this: even when faced with automation malfunctions, pilot approval of the advisory system did not decrease. Instead, pilots quickly adjusted and "solved the problem" by relying on other information sources. Generally, the performed studies and experiments in the short and medium timescale found that a natural representation of the outside world, possibly augmented by conformal information, provides the best support to pilots. This held true as long as this information was sufficient to perform the task, as was the case for short-term hovering and medium-term obstacle avoidance.

These results imply that helicopter pilots are predominantly focused on their immediate surroundings which can be directly perceived visually, at least when performing tasks that can be solved with this information. In the investigated short-term and medium-term tasks, no additional tasks like energy management, fuel management, or long-term trajectory management were necessary. The tasks focused on the immediate reaction of the helicopter to their environment, and the

[1]Using the outside visuals to hover in place represents a large part of initial helicopter pilot training. On average, it takes about 10 hours of training to "begin to master" hovering ("A Hovering Helicopter: How Does It Do That?", Rick James, `https://pilotteacher.com/a-hovering-helicopter-how-does-it-do-that/`, retrieved July 6th 2022). during this time, helicopter pilots in training rely on the outside visuals to perform the hover manoeuvre.

participating pilots were more than capable of performing these tasks by utilising the visual perception of said environment. Additional automation functions like the advisory obstacle avoidance display were treated as a side note and not as an integral part of the control task.

Point 3, the availability of different kinds of trajectories with helicopters when compared to commercial fixed-wing aircraft, did not play an important role in any of the performed studies and experiments. In fact, the calculation of the constraints of the pull-up manoeuvre during the obstacle avoidance experiment were based on similar calculations for fixed-wing aircraft performed by Borst et al. (2010b). Of course, automation systems need to be modified to encompass the manoeuvring capabilities of helicopters. The availability of different kinds of trajectories by itself, however, did not seem to impact the effect of ecologically inspired displays.

The only notable difference observed in this dissertation is the theoretically indefinite planning time helicopter pilots can have while hovering in place. While it is true that commercial fixed-wing aircraft are typical at much larger distances to obstacles, both temporally and spatially (see point 4), they are required to fly with a minimum forward velocity for their wings to generate enough lift. Commercial fixed-wing pilots may typically have more time to make navigational decisions or to react to unforeseen events, but they will never have an indefinite amount of time.

In contrast, when helicopters are able to enter a stable hover, the pilots are in theory able to hold their position for as long as they see fit, freeing them from the temporal decision-making limitation. This has been the case in the performed long-term navigation experiment, and the effect was visible in the behaviour of the pilots: some of them took only a few seconds to decide on their next trajectory, while others extensively used the automation at their disposal to investigate and evaluate all their navigational options before making a decision.

The closer vicinity to obstacles and the typically shorter available reaction time of helicopter operations cause a focus on the immediate surroundings and the spatial information of conformal outside visuals. Obstacles and other aircraft in the vicinity do not afford long planning actions when a collision is imminent. Rather, the situation needs to be resolved quickly. As elaborated upon before, helicopter pilots seem to excel at this kind of control, and they appreciate automation systems that can seamlessly integrate into this control loop.

This is in stark contrast to commercial fixed-wing operations, where the out-of-window view offers much less useful information, especially at cruising altitudes. Other aircraft are far away and barely visible, and at most altitudes, the ground is not visible and provides no meaningful information. Commercial fixed-wing pilots are therefore more dependent on their flight instruments to perceive basic flight data. This dependence on flight instruments changes how commercial fixed-wing pilots utilise displays in general, and ecological interfaces in particular, when compared to helicopter pilots. Commercial fixed-wing pilots might be more inclined to use or trust more abstract flight data representations. Helicopter pilots heavily favour conformal, natural work domain representations, presumably because a significant amount of initial hover training is spent honing the skill of controlling the helicopter based on outside visuals.

As another effect of point 4, the sense of "urgency" and "risk" differs between commercial fixed-wing and helicopter pilots. Time-to-contacts that are unacceptable in the fixed-wing domain are more accepted or even required in the helicopter domain to perform specific manoeuvres. As Joseph et al. (2012) describe, helicopter and fixed-wing pilots exhibit different correlations between risk perception/attitude and the number of hazardous events/risk-seeking tendencies. They conclude that "helicopter operations during peacetime may be inherently more risky than fixed-wing operations" (Joseph et al., 2012, p. 18).

Aggravating this risk difference is the fact that some helicopter missions are planned in less detail and require more ad-hoc reactions than commercial fixed-wing missions. As an example, a pilot performing helicopter emergency medical services (HEMS) missions is, at the start of flight, not aware of the required landing manoeuvres, which will be dictated by the as-of-yet unknown landing zone. This difference yet again reinforces the dependence of helicopter pilots on the immediate surroundings. Based on visual information, helicopter pilots need to decide how to proceed with their mission. In the example of the HEMS pilot, he/she will need to evaluate possible landing zones and decide where to land based on the information perceived on-location and immediately before landing. In contrast, commercial fixed-wing operations are more abstract, caused by the larger distances, longer turn-times, and less reliance on outside visuals. Helicopter flying is more hands-on, direct, and dependent on the immediate surroundings of the helicopter, predominantly perceived visually.

Subjective experience and conversations of a pilot who transferred from fixed-wing to helicopter operations[2] suggest that helicopters "require a greater skill level and demand more airmanship", when compared to fixed-wing operations. This is caused by, among other things, the prevalence of low-altitude flight close to obstacles and the inherent instability of helicopters in particular during hover. According to his experience, "proficient utility helicopter pilots (...) possess a situational (sic) awareness most pilots do not".

In addition to a different "baseline" of workload and situation awareness, Walker's article examines the fact that when an emergency occurs during helicopter operations, pilots have much less time to react to it. While fixed-wing pilots might be stabilising the aircraft after an engine failure to diagnose the situation, helicopter pilots need to immediately enact the required autorotation manoeuvres or risk entering unrecoverable and catastrophic flight states.

Considering the covered differences between helicopter and commercial fixed-wing pilots, ecological interfaces have different effects on each pilot population. For example, visualising the operational boundaries of operation (either physical or organisational) can cause pilots to "migrate to the limits of safe system performance" (Borst et al., 2015, p. 160), as they are now directly available to them. If helicopter and fixed-wing pilots have different concepts of risk and urgency, how does that influence their limit-seeking behaviour? Are helicopter pilots less susceptible

[2]"The truth about going from flying airplanes to helicopters", by Stephen Walker, January 21st, 2021, https://www.thedrive.com/the-war-zone/38695/the-cold-hard-truth-about-going-from-flying-fixed-wing-airplanes-to-helicopters, retrieved October 10th, 2021.

7

to this effect, because the potentially catastrophic consequences can manifest on a much shorter timescale? Or are they more prone to accept these risks as regular helicopter operations seem to inherently be more risky anyway? The number of passengers might also play a role in pilots' view on risk — commercial aviation pilots can be responsible for hundreds of passengers, while helicopter pilots often operate alone or in pairs. On the one hand, helicopter pilots might be more familiar with operating close to risky operational boundaries and be more prone to accept operating even closer to these limits. On the other hand, the normal, continuous operation close to operational boundaries might make them wary to accept an even greater amount of risk by reducing the distance to those boundaries.

While the studies and experiments performed in this dissertation did not give a clear answer to these specific questions, they do highlight the requirement to investigate commercial fixed-wing displays and helicopter displays separately. Hypotheses regarding the effect of different automation design concepts in original research, as presented in this dissertation, should be carefully formulated with these differences in mind. The specific results of fixed-wing research covering ecological interface design cannot be used directly to guide the transition to more automation in the helicopter domain.

7.3. Methods to evaluate helicopter automation

The second subquestion has been defined as:

> **Subquestion 2**
>
> How do different automation design philosophies influence safety (and other parameters) in helicopters during short-, medium-, and long-term scenarios?

To answer subquestion two, it is first required to address possible evaluation metrics and methods of automation systems and their effects. The observed differences in helicopter and commercial fixed-wing control (and the resulting differences in pilot "baselines") influence the appropriateness of different measurement techniques.

In every experiment of this dissertation, and in most initiatives that investigate automation in a human-machine context, multiple evaluation metrics are employed. To briefly recapitulate, this dissertation uses the following metrics:

1. subjective pilot workload;
2. subjective pilot situation awareness;
3. subjective pilot approval and acceptance;
4. objective task-related performance metrics such as manoeuvre accuracy, manoeuvre time, and trajectory efficiency;
5. objective task-related safety metrics such as minimum distance to the ground, obstacle clearance altitude, and fuel prediction accuracy; and

6. objective task-related optimal decision-making capabilities.

There are many other metrics that can be used in experimental evaluations of automation systems. Both workload and situation awareness can be measured through many other subjective pilot rating questionnaires or more objective measures and methods. How to optimally measure workload and situation awareness is an active research field, and each method focuses on different aspects of workload and situation awareness (Gawron, 2008; Stanton et al., 2006, as cited by van Dijk et al., 2011). The obtained, subjective results should therefore be seen as an indication, but not as the absolute truth regarding the automation effects on workload and situation awareness.

7.3.1. Subjective and objective metrics

Subjective pilot ratings of situation awareness and automation system support, in particular, have inherent drawbacks that revealed themselves during the experiments of this dissertation. While subjective ratings of workload are useful to determine the perceived mental and/or physical demand, it is impossible for pilots to rate their own situation awareness beyond their own impression. They cannot rate the degree to which they perceived and understood a situation, as they could be completely unaware of those parts of a situation they did not perceive or understand. As has been shown in the long-term navigation experiment, this "unknown unknown" represents a major hurdle in using subjective ratings of situation awareness: it is impossible for humans to accurately describe the extent of information they are ignorant of.

Subjective ratings of automation system usefulness and acceptance have a similar problem. A system might be very convenient and intuitive to use, which results in high pilot approval ratings. However, this perceived usefulness and convenience does not take into account the actual effect of the evaluated automation system on other mission parameters. The long-term navigation experiment showed that an automation system can give pilots the impression that they are quickly and efficiently performing tasks, while in actuality, they perform worse than with other systems (that they rated worse).

What do these results implicate for future research and automation design? It is important to evaluate the effect of prospective automation systems on every mission parameter and pilot rating. A system might be preferred by pilots and reduce perceived workload, but it might also lead to worse decisions in critical situations, as has been shown with the advisory navigation system in the long-term navigation experiment. Another system might produce the best workload and situation awareness ratings, but pilots might only prefer it in off-nominal situations, as has been shown with the constraint-based display in the obstacle avoidance experiment.

Before designing novel helicopter automation systems, it is important to investigate *which combination of evaluation parameters* is desirable in the investigated scenario. Only then can an automation system truly be evaluated and judged with regard to its overall usefulness and impact. Using only a small number of evaluation metrics can hide potentially adverse effects of automation. The timescale of the investigated scenario will influence the meaning of workload and situation awareness, too: in short-term scenarios, both metrics are predominantly based on the performed manual control task. In medium- and long-term scenarios, situation awareness requires the perception and projection of more and more variables and their interactions. The perceived workload will not only comprise the short-term burden of the manual control task, but also the cognitive load of medium- and long-term decision-making processes.

7.3.2. Timescale as a tool to choose evaluation metrics

The framework of short-, medium-, and long-term automation presented in this dissertation can support system designers in choosing how to evaluate and judge prospective automation systems. As has been seen in this dissertation, different task timescales change the applicability and usefulness of different evaluation tools. On the short timescale of the hover task, for example, the parameters of tuned pilot models can be used to estimate the real-world implication of changing visual representations. The analysis of available visual cues (and how they are influenced by different display representations and multidimensional observer movement) can give insight into the parameters of the short-term manual control task. For both performed short-term investigations, the narrowly defined and executed hover task enables the use of task-specific performance and safety metrics such as hover position deviation and minimum altitude.

Experiments on medium timescales, like the performed obstacle avoidance experiment, require different types of evaluation metrics. In contrast to the hover manoeuvre in the previous studies, an ideal trajectory for obstacle avoidance is less easily defined, even if the possible manoeuvre space is restricted to longitudinal and vertical directions. For tasks and manoeuvres on the medium timescale, this dissertation found that τ-theory is a useful tool to determine probable pilot manoeuvring behaviour and compare different trajectories. Performance and safety metrics can be easily defined, but their meaning requires more interpretation and definitions. For example, how important is lateral course precision compared to the speed deviation during the manoeuvre?

As experimental manoeuvre complexity increases, the number of possible evaluation metrics and their possible meaning also increase. Interpreting the wide array of metrics requires a thorough understanding of the experimental task, typical and preferred pilot behaviour, and the impact that high or low values of one metric can have on other parts of the manoeuvre. In this thesis, for example, a later pull-up location usually led to a more pronounced altitude "overshoot". Both metrics need to be analysed in parallel and should not be discussed in isolation.

The performed long-term navigation experiment provided an example of an experiment on a long timescale. It investigated many interconnected dependent measures that required thorough interpretation. The most important dependent measure, pilot decision-making, is an abstract label assigned to a trajectory and in stark contrast to strict, task-dependent performance measures. Rather, it is a measure of "decision-making quality", determined by analysing the final flown trajectories.

Other performance and safety measures such as fuel consumption/distance travelled, time required, or speed accuracy were only secondary in nature, albeit more grounded and more easily available from the flight data. If the importance of decision-making quality has not been identified and considered during the discussion of the results, the experiment could have reached a more muddled or conflicting conclusion. In order to analyse long-term pilot control strategies and behaviour, this dissertation employed methodologies like the decision ladder and qualitative control strategy predictions. In contrast to strictly task-related performance measures or τ-theory-based analyses on the short and medium timescale, these tools are more conceptual, procedural, and are better suited for long-term experimental investigations.

To summarise, the evaluation of performance, safety, and other metrics depends on the experimental timescale. Short-term, task-related measures evaluate only that: the task itself. These metrics do not consider their implication on longer-term metrics, e.g., fuel efficiency, comfort, or pilot workload. However, if a judgement is to be made about a system's applicability in real-world helicopter operations, it is important to analyse its impact on longer-term measures, too. A hover display that works perfectly for hover might obstruct the pilots' view of other important environmental elements, or it might tire out the pilot when used for a longer period of time. Fuel-optimal evasive trajectories might be incredibly hard to fly manually, or they might cause unnecessary strain on the fuselage or passengers. Just like the usefulness of automation systems depends on their operational timescale, so do the relevance and significance of automation evaluation methods.

7.4. The effect of automation across timescales

This section briefly summarises the setup of the performed studies and experiments. Afterwards, the effect of different automation design philosophies across timescales is discussed. To structure the analysis, the performed investigations are located at a specific Level of Control Sophistication (LoCS). The timescales associated with each LoCS are:

- LoCS 2 (Chapters 3 and 4): short-term operation,
- LoCS 3 (Chapter 5): medium-term operation, and
- LoCS 4 (Chapter 6): long-term operation.

7.4.1. Experimental setup

Both performed short-term studies investigated a clearly defined hover task on LoCS 2, without significant interactions with higher timescales. Figure 7.1 shows this task and its interfaces across timescales. No errors or unexpected situations occurred, the studies focused on different ways of perceiving the system state through representations of the outside world (through good visuals, a hover display, or conformal HUDs) and acting on it.

The employed automation systems of both exploratory studies do not yet follow the "advisory — constraint-based" dichotomy. Rather, they can be classified into

Level of Control Sophistication				
1 System Readiness	2 Controlled Locomotion	3 Flying	4 Navigation	5 Mission
Different helicopter dynamic response: Experiment 1: no SAS vs. SAS Experiment 2: non-linear & coupled vs. linear & decoupled	**Hover** Different representations of required parameters through displays Experiment 1: Good outside visuals Head-down hover display Experiment 2: Good outside visuals Head-up ADS-33 display Head-up hover box display	Prescribed approach-to-hover manoeuvre	*no interface*	*no interface*

Figure 7.1: The hover task of both exploratory studies and its interfaces with adjacent LoCS.

"task-centred" and "ecology-centred" design approaches. The task-centred designs (the hover display and the ADS-33 based HUD implementation) focus on clearly visualising system states that directly relate to the hover task: longitudinal, lateral, and vertical position and adequacy boundaries. The ecology-centred displays (good visibility, hover box HUD) focus on providing visual cues that closely resemble the actual work domain of a helicopter, without placing a large focus on the hover task itself.

In both the medium-term and long-term experiments, EID principles were used to both design interfaces and design the algorithms that determine what is shown on the displays. This highlights the fact that utilising EID principles is not only about designing a display for existing support functions, but it is also about designing the support algorithms in accordance with what should be shown on the display. Ideally, the support algorithms and display functions align to create a "window" into the work domain that clearly shows both action possibilities and constraints, according to the principles of EID (Vicente and Rasmussen, 1990).

The medium-term experiment investigated an obstacle avoidance task on LoCS 3, see Figure 7.2. Again, interactions with higher timescales were limited: the long-term navigation course was clearly defined (straight and level) and did not change. Interactions with lower LoCS existed in terms of the longitudinal/vertical pull-up manoeuvre that was considered by both automation systems. For the first time, system malfunctions were included in the experiment. Also, for the first time, the two different automation design paradigms "advisory" and "constraint-based" were compared.

In the long-term experiment, a navigation task on LoCS 4 was investigated, see Figure 7.3. This cognitive task was the only investigated task completely separated from the manual control of the helicopter: the pilots needed to divide their attention between manually piloting the helicopter and planning their next navigational action. The focus of this experiment lied not on the manual flying performance of the pilots, but on their decision-making capabilities.

Level of Control Sophistication				
1 System Readiness	2 Controlled Locomotion	3 Flying	4 Navigation	5 Mission
no interface	Prescribed solution: pull-up manoeuvre	**Obstacle Avoidance** System evaluated under hypothetical faults, reduced reliability Different augmentation of outside visuals through head-up displays: Baseline contour display Advisory symbol Constraint-based symbol	Prescribed straight course, no navigational or fuel considerations	*no interface*

Figure 7.2: The task of the obstacle avoidance experiment and its interfaces with adjacent LoCS.

Level of Control Sophistication				
1 System Readiness	2 Controlled Locomotion	3 Flying	4 Navigation	5 Mission
no interface	*no interface*	Trajectory implementation left to the pilots	**Trajectory evaluation and selection** System evaluated under hypothetical faults, reduced reliability Different representation of work domain through head-down displays: Baseline navigation display Advisory display Constraint-based display	Fuel and time included in decision-making

Figure 7.3: The task of the navigation experiment and its interfaces with adjacent LoCS and levels of abstraction, located in the abstraction-control decomposition.

7.4.2. Combining timescales

In short and medium timescales, the best results were achieved by automation systems that focus on representing or enhancing the visual natural work ecology, or on systems that integrate their ecological information into a conformal representation of the outside world. For longer timescales, when the manual flying of the helicopter and the investigated task are more cognitively separated, the results start to resemble the results obtained in the fixed-wing domain, with advisory automation systems offering enormous potential to decrease workload and support the pilots in nominal situations. However, the observed inadvertent negative effects were clearly visible, and might have been exacerbated by the peculiarities of helicopter control: the mental capacities of the pilots seem to be divided between the two tasks of manually controlling the helicopter and performing the cognitive task of supervising advanced automation functions. This double task load, both

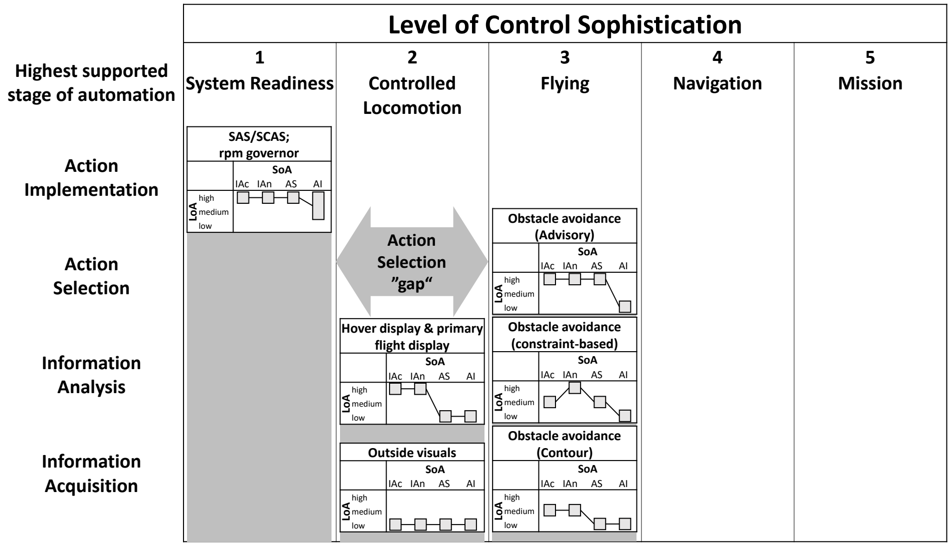


Figure 7.4: Conceptual representation of automation support in the medium-term obstacle avoidance scenario, highlighting the action selection "gap" when advisory automation is employed.

manually/physically and mentally/cognitively, could explain the observed negative effect of advisory automation. Those include the susceptibility to over-reliance on automation and the tendency of reduced automation supervision by the pilots.

7

Both the medium- and long-term experiments introduced automation systems that supported the action selection and action implementation stage of automation on a longer timescale, while still depending on the pilot to fulfil these functions on the shorter timescales. This created a "gap" of automation coverage in the helicopter control loop: the manual control task of the pilots is "trapped" in the short timescale underneath the action selection and implementation advice on a longer timescale. On the short timescale, the task of the pilots is reduced to executing the commands of the automation system. Figures 7.4 and 7.5 visualise this phenomenon by arranging the automation systems of both experiments according to their highest supported stage of automation.

Given the inherently unstable nature of helicopters in low-speed regimes, this short-term flying task still comes with significant manual control demands. The results might be different if the control setup of helicopters moves towards more automation integration on the shorter timescale. If the low-level flying functions would be completely automated, for example through a full authority autopilot, the pilots would be freed of the manual flying task. They then have more mental capacity to perform the automation supervisory task across all timescales of operation, monitoring and correcting both short-term autopilot systems and long-term navigation systems. The helicopter pilot task would then more closely resemble the pilot task in typical, highly automated passenger airliner cockpits, where the pilots have the spare mental capacity and time to perform the supervisory role with more

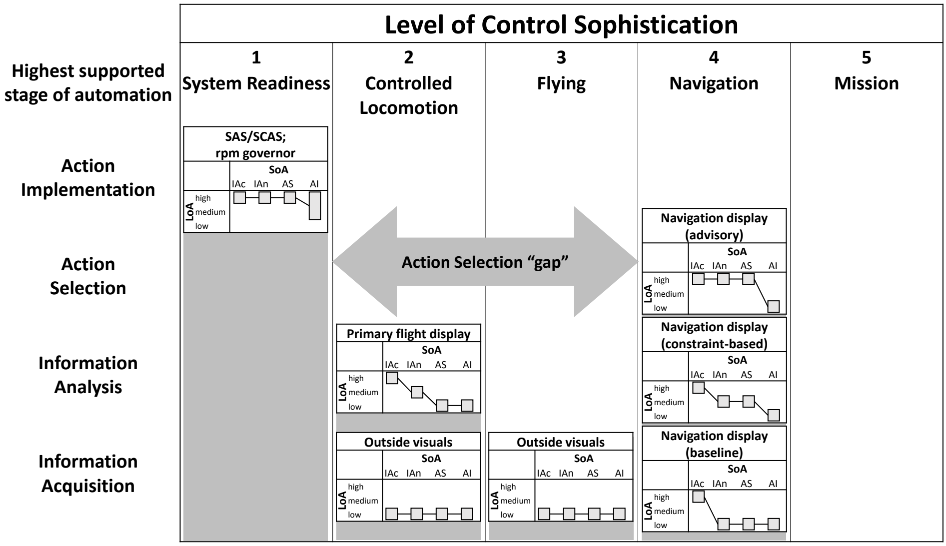


Figure 7.5: Conceptual representation of automation support in the long-term navigation scenario, highlighting the action selection "gap" when advisory automation is employed.

rigour.

It is important to consider, of course, that this kind of supervisory control task is not the final goal of automation development in aviation. Even with ample cognitive resources and few manual control requirements, passenger airliner accidents still happen, and in many accidents, human-automation interaction contributed to the outcome. The outlined possible transition from predominantly manual helicopter control to a more supervisory role only represents a trajectory to a *different* use of automation in the helicopter, not necessarily a *better* one.

7.5. Failure vs. leaving operational envelope

Before formulating recommendations for helicopter automation design and future research in the following section, this section investigates a phenomenon predominantly encountered in the long-term navigation experiment: the pilots' varying reactions to off-nominal situations and events. Off-nominal, unexpected events often contribute to or cause catastrophic accidents, and therefore deserve intense and dedicated attention.

In this dissertation, two different categories of off-nominal situations have been considered. In the medium-term obstacle avoidance experiment, the detection distance of the obstacle avoidance system was drastically reduced in some cases. This simulated an automation malfunction: the automation system did not work according to its normal way of operation, and the pilots needed to react to this. The pilots were required to detect the malfunction by recognising that the obstacle warning contour in the HUD was not drawn at the same distance as during normal operation. Afterwards, depending on the utilised display, they needed to modify their control behaviour to still avoid the obstacle safely.

In the long-term navigation experiment, two different kinds of off-nominal situations were simulated:

1. automation malfunctions, in the form of obstacles that appeared mid-run and were not recognised by the advisory and constraint-based displays, and

2. situations outside of the operational envelope of the experimental advisory and constraint-based displays.

In the case of the simulated automation malfunction, the displays suggested trajectories that intersected a bad weather area. These trajectories were clearly unsafe, as the display representation of the suggested course (advisory display) or the safe intermediate waypoints (constraint-based display) clearly intersected an obstacle. All pilots reacted to this visual cue of a malfunction by selecting a different, safe trajectory. However, the employed display changed the way that pilots reacted to this malfunction. Both the baseline and constraint-based display always led to optimal trajectory decisions, even when faced with obstacles that appear mid-run and are not recognised by the constraint-based display. In case of the advisory display, half of the pilots still followed the general direction of the suggested trajectory. They only modified the trajectory to *also* circumvent the additional obstacle. The pilots did not re-evaluate all available trajectory options, but only modified the automation's suggestion.

During situations outside of the operational envelope of the experimental displays, the negative effect of the advisory display was even stronger. This situation was simulated in the experiment by arranging the obstacles in such a way that a more optimal, two-turn solution was afforded. As both displays only considered one-turn trajectories, these more complex trajectories were not considered by the experimental displays. In these cases, there was no obvious visual cue on the display that the automation system encountered a situation outside of its operational envelope, and that the suggested trajectory is not optimal. With the advisory display, only two out of eight pilots re-evaluated the suggested route with respect to its efficiency, and "discovered" the more optimal two-turn trajectory. The baseline and constraint-based display, in contrast, led pilots to almost always (15/16 cases) discover the more optimal trajectory.

Considering the data of both experiments, there seems to be a hierarchy of priorities that pilots check the advisory suggestion against. The safety of the helicopter was never compromised: every pilot still tried evading obstacles, and no pilot entered bad weather for extended periods of time, in particular not in cases where the suggested route led through an obstacle. However, when faced with situations that were not safety critical, but merely compromised mission efficiency, the results diverted. When confronted with clear visual cues that the automation malfunctioned, only 50 % of pilots re-evaluated the advisory suggestion and completely disregarded its advice with respect to mission efficiency. If such a clear visual cue was missing, only 25 % performed this re-evaluation. The observed pilot behaviour when using advisory-based automation can be summarised in the following rules. Rules 1, 3, and 4 are based on the long-term navigation experiment, rule 2 is based on the medium-term obstacle avoidance experiment.

1. All pilots re-evaluated automation decisions with respect to **safety** when there was a clear visual cue that the automation suggestion was erroneous.

2. Almost all pilots re-evaluated automation decisions with respect to **safety** when there were ambiguous or delayed visual cues that the automation suggestion was erroneous.

3. A mediocre percentage of pilots (50 %) re-evaluated automation decisions with respect to **efficiency** when there was a clear visual cue that the automation suggestion was erroneous.

4. A small percentage of pilots (25 %) re-evaluated automation decisions with respect to **efficiency** when there was no clear visual cue that the automation suggestion was erroneous.

All pilots maintained the vehicle's safety, regardless of automation suggestion. I.e., they still avoided approaching obstacles, and they did not follow the advised trajectory into bad weather. With regards to efficiency, however, the pilot behaviour was negatively influenced by the advisory automation. They often still followed the suggestion, or only modified the suggestion slightly to maintain safety, disregarding the impact this decision has on efficiency. This reaction to advisory automation might be caused by multiple factors:

1. **The workload reduction of advisory automation when following its advice.** As pilots are always busy with controlling the unstable helicopter dynamics on the short-term control loop, they might highly appreciate any way of reducing the required mental workload on the shorter timescales. An advisory system enables a huge shortcut through the required mental decision ladder steps and immediately provides a feasible solution.

2. **The convenience and easy-of-use of advisory automation.** At the press of a button, the encountered situation is "solved". This is irrespective of the efficiency of the suggested route, the system still gives the impression that the suggested route is a "good one" and should be followed. This effect might be exacerbated by the immense workload reduction that results from taking this trajectory determination an evaluation task completely out of the hands of the pilots.

3. **Completely re-evaluating an advisory suggestion requires at least as much workload as performing the complete trajectory determination and evaluation task.** In addition to performing the "base" task, pilots also need to make sure to free themselves of any priming effects that the suggested trajectory might have had on them, consciously or subconsciously. This priming effect was clearly visible in the long-term navigation

experiment, where even in case of clear visual cues of erroneous suggestions, half of the pilot still followed the general direction of the advice and did not reconsider changing course completely.

In parallel to what Wickens et al. (2009) describe, the appearance of a secondary task can influence the operator reaction to automation. This effect might therefore be stronger in the helicopter domain, compared to commercial fixed-wing operation. In the case Wickens et al. (2009) describe, the secondary task increased the negative impact of false alarms of a collision warning system. In the helicopter case, it is possible that the secondary, often demanding manual control task increases the susceptibility to inadvertent, negative automation effects, as explained above.

It is important to note that without advisory automation support, the pilots always chose the most efficient route. The discussed hierarchy of supervision/checking of routes is only introduced with the advisory automation. The reduced workload and improved pilot opinion most likely stems from the omission of these cognitively demanding steps from their task load. The positive pilot ratings of these systems do not take into account the effect of worse decision-making and mission efficiency.

7.6. Automation design recommendations

The aforementioned negative effects of advisory automation present a dilemma for system designers of future helicopter automation: the best results would be obtained if the pilots re-evaluate every automation suggestion, in particular when safety is compromised. However, if one provokes and encourages such pilot behaviour, the workload and ease-of-use benefits of advisory automation are largely lost. This might represent the fundamental difference between helicopter automation and passenger airliner automation. In passenger airliners, the workload reduction of advisory automation frees up pilots' cognitive resources to focus on other tasks, for example automation supervision and management. In helicopters, however, the pilots already perform a task that can consume large amounts of cognitive resources: the continued manual control of the helicopter, which requires manually closing the control loop and perceiving the system state and any control input effects from the outside visuals. As long as this demanding manual control task persists, pilots might be eager to allocate freed up mental resources to this task, and not to other, cognitively demanding automation supervision tasks.

What are the implications of these results for automation design? The last subquestion has been defined as:

Subquestion 3

How can the gathered exploratory and experimental results be incorporated into guidelines for helicopter automation design?

This dissertation provides suggestions for automation design in the short-term, medium-term, and long-term domains separately. However, it also showcased the untapped potential of systems that integrate the positive aspects of support on all timescales into one system. Both aspects are discussed in the following sections.

7.6.1. Highlight the work ecology

The short-term exploratory studies and the medium-term experiment clearly indicate that for automation support on these timescales, the focus should lie on the work ecology, on enriching conformal visual cues, and on including artificial/additional automation cues in such a way that they seamlessly integrate into the visual work domain. The focus should lie on the general work domain, not on specific tasks. The goal should be to support the perception of the natural work domain, and, if necessary, to augment this natural representation with conformal information or symbols that can be used as continuous control inputs for the short- and medium-term helicopter control.

For short- and medium-term automation support, task-specific visualisations and non-conformal, two-dimensional symbology on top of the outside world view should be avoided. While they theoretically provide all necessary information, they can detract the pilots' attention away from the natural motion perception and control response that pilots are highly skilled in. If task-specific symbology is necessary, it should be designed such that it can serve as a quick "performance adequacy check" for the pilots, without requiring a large amount of cognitive resources to understand. The use of task-specific and/or non-conformal symbology as continuous control cues lead to decreased task performance and cannot be recommended, as long as a conformal outside view is available to the pilots.

This recommendation changes when no good outside visuals or an artificial conformal representation of the work domain is available. As Minor et al. (2017) already noted, head-down displays can work well when paired with continuous trajectory advice and manoeuvre-specific control cues. They do not work well, however, as a provider of continuous control cues or as the sole source of primary pilotage information without manoeuvre-specific suggestions. This dissertation reproduced this specific result and discovered that only adding flight state information like a velocity vector and acceleration cue to a head-down display is not sufficient to make these displays more viable.

7

7.6.2. Prevent the pitfalls of advisory automation

For long-term tasks like navigation, the above-mentioned suggestions change. In the long-term navigation experiment, the constraint-based display did not provide a significant improvement over the evaluated baseline display. It appears that the full potential of EID-inspired, constraint-based navigation displays has not been reached in this experiment. In general, the pilots appreciated the extra information this display provided, and positively commented on the additional functions it enabled. However, these additional data, novel data representations, and uncommon functionality also required a large workload and learning investment from the pilots.

Based on these results and on this long timescale, no clear recommendation for the constraint-based automation design approach can be given. While it did not cause significantly worse decisions, and the pilots generally appreciated all additional information, it also presented its information in an unfamiliar manner to the pilots. Further developments of the display design and an improved training and familiarisation regime might be able to rectify these drawbacks and enable the pilots to fully utilise the additional provided information.

The peculiarities of helicopter control might have exacerbated this diminishing of the positive effects of the display. Instead of focusing on the learning and understanding of the novel display concept, pilots already had a viable target (the manual control of the helicopter) for any spare cognitive capacity they had. Even given these drawbacks, the constraint-based display did not lead to significantly worse decisions. It is therefore expected that if a constraint-based display is accompanied by a more intense training regime and more intuitive interaction methods, it could surpass the baseline display in its support for pilots' decision-making, without incurring the negative effects of advisory displays.

7.6.3. Visualise automation function and intent

In long-term tasks, advisory automation should be employed only very carefully. The risk of incurring inadvertent negative effects seems to be even larger than in the passenger fixed-wing domain, where it already is a hotly debated topic. The increasingly large gap between the manual control requirements in the short-term control loops and the supervisory control requirements in the long-term control loops placed on the pilots, and the split of attention this warrants, seems to intensify the potential negative effects of automation on the longer timescales. Rather, future automation design should focus on automation that is transparent in which information it uses, and how its information and suggestions are computed. The supervisory task of checking the automation system should be as easy as possible. Alternatively, it is desirable to keep the pilot in the decision-loop while providing automation support in the earlier stages of automation, like the constraint-based display in the performed long-term navigation experiment aimed to do.

7.6.4. Close or avoid the "action selection gap"

The previous recommendations are based on the assumption that the short-term control loop of the helicopter still needs to be performed by the human pilots. In this case, the aforementioned temporal gap between the manual control of the helicopter and the cognitive, longer-term tasks lead to an increase in negative advisory automation effects. This might change when the manual control requirements are lifted from the pilot, for example through the application of a full authority autopilot. Without this obvious first "sink" of their attention and freed up cognitive resources, pilots might be more able to concentrate on performing a supervisory role across all timescales. Having to perform only supervisory control tasks reduces the number of tasks that have to be performed in parallel, effectively transforming a multi-task environment into a single-task environment with two consecutive supervisory tasks.

Figures 7.4 and 7.5 show a conceptual representation of automation support in the performed short-term studies. In both scenarios, the manual control on the lower LoCS is left to the pilots. Through the outside world, the primary flight display, and conformal display additions in case of the performed obstacle avoidance experiment, the pilots only receive support in the information acquisition and information analysis stage.

However, if advisory automation is included, pilots are required to perform both a supervisory control task on the higher LoCS (3 or 4, depending on the experiment) and a manual control task on the lower LoCS. In nominal situations, the pilots are required to simply implement the suggestion they received by the advisory automation system. In contrast, off-nominal situations require the pilots to recognise the off-nominal situation, disregard the received suggestion, and implement their own chosen control actions on the lower LoCS. This task allocation can make it hard for the pilots to leave their allotted role of executing automation suggestions and actively supervise and question the automation advice they receive.

Translated into design recommendations, this outcome suggests that longer timescale control loops should not be supported in the action selection stage (advisory automation, as used in this dissertation) if shorter timescale control loops are still required to be closed manually by the pilots. Helicopter automation support should be built according to a hierarchy of the highest supported stage of automation, with the highest automation support on the shorter timescale control loops. Moving to longer timescale control loops should never increase the highest supported stage of automation, but always stay identical or decrease. This paradigm would ensure that pilots are never degraded to the function of simply implementing manual control suggestions from longer timescale automation, which could limit their tendency to perform supervisory control actions on longer timescales.

7.6.5. Address visually conformal long-term automation

Could this kind of navigation display be implemented as a head-up display, too, following the recommendations of the previous experiments? The goal of any constraint-based or ecology-centred display should be to represent the part of the work domain that is relevant for the supported task.

Consider the example of a conformal, long-term navigation aid. This display could visualise the prospective course in the outside world (e.g., via a tunnel-in-the-sky), connect it with the visible parts of the outside world, and aim to create one consistent representation of the work domain. The trajectory length could be shown through conformal waypoints or ground trajectories. However, future obstacles and waypoints could lie spatially behind each other, making their individual identification very hard.

Another possible issue of this approach is the distraction long-term conformal elements can cause. An elaborate tunnel-in-the-sky and the visualisation of long-term navigational targets and obstacles might distract pilots from looking at the actual work domain and their immediate surroundings. If there is indeed an "action selection gap" in automation coverage, it is possible that the proposed long-term trajectory intersects with obstacles in the immediate vicinity that have not been taken into account on the long-term timescale. The pilots are therefore required to constantly check the long-term trajectory for short-term obstacles. Showing the proposed long-term solution conformally in the work domain might support this checking task (e.g., when the tunnel-in-the-sky intersects with the ground or an obstacle), but it might also hinder it (caused by visual clutter, or when pilots focus their attention predominantly on the optimal, artificial tunnel instead of on the remaining parts of the work domain).

Based on these considerations, it seems that showing long-term information conformally in the work domain can only avoid these pitfalls when there is no "action selection gap", i.e., the system takes all shorter timescale considerations into account when calculating the suggested trajectory. Otherwise, the shown trajectories imply a false level of safety and precision. Avoiding the "action selection gap" either requires the focus on only information automation functions, or it requires that any implementation of decision automation does not "skip" timescales: if long-term advisory trajectory information is shown to the pilots, it should be computed with all lower timescale constraints considered.

7.6.6. Manage automation activation and deactivation

Another question that arises when implementing multiple automation systems in parallel is how to enable, disable, and transition between these systems. As Sheridan (2011) summarises, automation capabilities might be controlled adaptively (through the automation), in an adaptable manner (controlled by the human controller), or this responsibility might be shared between the two. Naturally, adaptive automation adds more complexity to the automation system itself, and the pilots will be required to supervise and monitor this automation subsystem, as well. Mirroring discussion points from the effect of different automation approaches, adaptive automation may work well in nominal situations, but encountering off-nominal situations that trigger suboptimal automation capabilities could have catastrophic consequences. If the pilots can adapt automation capabilities manually, they stay in control and in the loop, but receive yet another task to perform in parallel to controlling the helicopter on every timescale. Based on the results of this thesis, it appears that avoiding additional potential automation-induced adverse effects should take precedence, and the pilots should manually control automation functions if necessary. Ultimately, it might be better to move towards a minimum number of separate systems and to aim to integrate information automation functions across timescales and operational scenarios. This would reduce the requirement for automation function switching and make the available functions applicable in as many scenarios as possible.

As a hypothetical example, imagine a conformal visual system that highlights relevant positions and infrastructure in the environment. This would include visualising possible landing spots. This information can then be used by the pilots for a variety of tasks, for example for the short-term manoeuvre-sample landing (short-term), the medium-term mission task element approach (medium-term), or the long-term mission phase of navigating towards a landing point. Obstacles in the immediate environment would also be highlighted, supporting the avoidance of collisions. The inclusion of some form of universally useful performance-related information (like the maximum achievable climb angle or variations of similar concepts) would support the selection of suitable evasive control actions and manoeuvres. The goal of these systems would be to make their information accessible and useful at every point of helicopter operation, and usable on all timescales. Important requirements would be, of course, to avoid visual clutter, and to ensure the mentioned applicability and relevance of all shown information.

7.6.7. Learn from fixed-wing automation where applicable

Will helicopter automation ever "rise up" to the level of commercial fixed-wing automation? Based on the discussed significant operational differences, this question appears to rely on the false assumption that automation follows a linear path that is similar across operational domains. However, as this dissertation has shown, the parameters of automation systems with "optimal" outcomes vary greatly between commercial fixed-wing and helicopter operations, and even between different timescales of operation. Instead of pursuing ever-increasing automation capabilities, the direction of helicopter automation development and application points towards a continued increase of support for helicopter pilots. This support will be different than that employed in the commercial fixed-wing domain. Helicopter automation will therefore never "rise up"' to commercial fixed-wing automation, as their goals are different. Both automation development trajectories should aim to best support the pilots in their specific operational domain.

Nonetheless, are there lessons already learned in the fixed-wing or automotive automation research that can inform helicopter design recommendations? As extensively discussed in this chapter, helicopter operations differ significantly from commercial fixed-wing operations: their mission phases and elements are often defined in less detail, they possess more uncertainty and variety, take place closer to obstacles, and contain more elements that are hard to automatically predict. Rather than following the path of evolutionary development employed in the fixed-wing domain, resulting in a large number of separate automation systems for different functions (Lim et al., 2018), a more revolutionary approach might be warranted. Instead of developing task-centred automation systems separately, the goal would rather be to develop information automation that supports pilots in as many situations as possible, leaving behind the notion of separate, "task-centred" automation systems that completely take over control in specific situations and remove the pilots from the control loop. This approach is more akin to suggestions formulated in the automotive domain by Walch et al. (2017), who recommend the development of "cooperative interfaces" that avoid the many issues of control handovers from automated systems to human drivers. This approach would aim to support the adaptive problem-solving skills of the pilots, while keeping them actively engaged in the control loop.

7.6.8. Focus on information automation

Based on results obtained by Onnasch (2015), there seems to be an increase of adverse automation effects when automation competencies cross from information automation, focusing on improving pilot situation awareness, to automation that focuses on decision automation, supporting the action selection and action implementation phase. For helicopters, specifically, this cut-off point might be already visible when investigating short-term control scenarios on LoCS 2. For helicopter missions with varying goals and capabilities on the higher LoCS, it appears to be optimal to not implement decision automation above universal manoeuvring support functions like stability augmentation, control augmentation, and basic manoeuvre aids like attitude/position hold. This keeps the pilot in the control loop and actively engaged with all timescales of operation. For short-term and medium-term scenarios, this support is best employed through conformal visualisations. For long-term scenarios, the supporting system can be detached from the conformal work domain representation, but its focus should still lie on information automation, not decision automation.

The last, and maybe most prevalent, design recommendation is therefore the design of automation systems that support the information acquisition and information analysis stage of automation across all time scales. This recommendation holds irrespective of the provided support on higher stages of automation in the same timescale. If the higher stages of automation remain unsupported, and the task lies with the pilots, automation support on the information acquisition and analysis stage enables the pilots to spend less cognitive resources on acquiring and analysing information, and more resources on continuously controlling and evaluating the helicopters movements and position. If the higher stages of automation are also supported, for example through an advisory automation system, a strong support in the information acquisition and analysis stage increases the transparency of the suggestions of the advisory automation. It enables the pilots to better perform the required supervisory control task, and to better avoid possible inadvertent automation effects in the face of off-nominal situations.

7.7. Research recommendations

Naturally, the research performed in this dissertation has been subject to limitations. Some of these limitations were consciously set. Others only became apparent during the research and while analysing the results of the performed studies and experiments. This section discusses limitations of this dissertation that future research into helicopter automation could address. Next to these points of improvement, this section also identifies novel or particularly worthwhile research avenues, based on the results of the performed research.

7.7.1. Points of improvement

Research experiments are almost always limited in both the number of participants and the time that is allotted for each participant. This places a limit on the amount of data obtainable for each experiment, which can reduce the statistical significance of observed differences. The limited time available requires the design of very efficient experiment schedules. The goal is to maximise the time spent with the actual experiment conditions, while minimising the required training and familiarisation time to enable all participants to confidently and uniformly perform the experiment task. With respect to this dissertation, the extension of the exploratory studies covering the short timescale of operations into statistically relevant experiments would generate more reliable results. The results of both studies informed the design of the medium-term and long-term experiment, but only their theoretical results can be utilised and generalised. The performed proof-of-concept simulator studies only provided anecdotal information, not significant results.

Similarly, the relatively low number of participants limited the diversity of experiment participants. Different educational backgrounds, cultural influences, or other standard operating procedures might influence the results obtained. Before generalising the results of this dissertation to more diverse pilot populations, it is paramount to investigate whether parts of the assumptions made in this dissertation still hold true, and whether a homogeneous response of pilots can be expected across different operational, procedural, and cultural backgrounds. This might prove particularly relevant for subjective measures of workload, situation awareness, or display approval, as these could change based on the individual background of pilots.

The implication of relatively low participant numbers can be seen in the statistical analysis of the performed simulator experiments, too. Combined with the rather conservative approach employed in both experiments, this led to the following limitation in data interpretation: while significant test results are a strong indication that differences between experimental conditions exist, insignificant results are only a weak indication that no differences between conditions exist. The postulated Type-1 error α (indicating significant differences when in actuality, there are none) is much smaller than the resultant Type-2 error β (indicating no significant differences, even though there are some).

In the experiments performed in this dissertation, this was a conscious choice: if significant differences were found, this conclusion should be strong and clearly visibly from the data. This was the case in the long-term navigation experiment, producing significant indication that pilot decision-making is negatively impacted by advisory automation support. However, the same conservative approach led to very few significant differences between conditions in the medium-term obstacle avoidance experiment. A less conservative data analysis approach could have enabled the formulation of more significant results, but it also would have weakened the significant results that have been found. an increase of the number of experiment participants would have reduced the Type-2 error margin without negatively affecting the strength of significant results, but as explained before, finding willing experiment participants with the required qualification was not easily achieved.

In line with previous research in ecological interface design in the fixed-wing domain (Borst et al., 2015), the constraint-based automated systems highlighted the need for longer training and familiarisation regimes. Pilots need time and practice to use and understand novel representations of vehicle capabilities and constraints, as employed here. While the training regimes in both experiments with EID-inspired displays were sufficient to avoid any negative impacts of using constraint-based systems, in both cases, the lack of extensive practice runs probably prohibited those systems to fully reach their potential.

Rectifying this limitation is neither easy nor straightforward. Increasing the training regime would require much longer experiment sessions. This, in turn, can reduce the number of available pilot participants, as the necessary time commitment grows even more. For every future experiment, this balance between experiment time, training time, and participant number needs to be newly found and optimised.

As a next point of improvement, the simulator realism could be improved. The setup of the SIMONA simulator closely resembles a commercial fixed-wing cockpit. Even though helicopter control inceptors were installed, the instrument and window arrangement was not representative for a typical helicopter cockpit. Changing the cockpit window setup to include downward-facing chin windows, as are common on helicopters, would increase the available visual cues and might change the control behaviour of pilots. All pilots who participated in the short-term hover experiments, and some of the pilots who participated in the medium-term obstacle avoidance experiment, commented on this simulator limitation. In contrast, based on pilot comments, it seems to have been a much smaller issue in the long-term navigation task.

This aligns with the respective focus on the manual control task during the experiments: when the short-term control task is the sole performed task, or when the experiment requires rapid control reaction to obstacles, missing visual cues limit the pilots' capacity to adequately react. During long-term control tasks, the pilots seemed more content with the limited visual cues, as they were focusing more on the cognitive task, and the available visual cues were sufficient to perform the required manoeuvres. Therefore, as the timescale of the experimental task increases, the importance of the simulator visual setup seems to decrease, and vice-versa.

In the experiments performed in this dissertation, the motion system was always deactivated. It was expected that the positive aspect of added realism would not counteract the negative aspects of increased experiment complexity and experiment time. Each experiment also focused on visual displays and augmentations — the inclusion of motion could have distracted the pilots from the visual cues. Nonetheless, an increased experiment realism could also lead to more natural and realistic pilot responses. Ultimately, performing some of the described experiments in real-world helicopters would drastically increase experiment complexity and costs, but would likewise lead to much more realistic experimental situations and more robust results.

An eye-tracking device would have strengthened the analyses of the performed experiments, in particular with respect to the hypothesised usage of the displays by the pilots. At the time of conducting the experiments, an eye tracker of high quality that could operate in the SIMONA research simulator (having challenging lighting conditions) was not available. The eye tracker would need to be able to discriminate gaze patterns between the interface symbols that are dynamically moving across a relatively small screen size. Unlike static areas of interest (e.g., a speed or altitude tape having a fixed position on a PFD), measuring reliable gaze patterns for dynamic areas of interest (that are sometimes less than 0.5 degrees apart) is challenging for most eye trackers. These are some of the reasons eye-tracking functionality is, as of now, not available for the SIMONA research simulator.

In this research, control-theoretic analyses and cognitive work analyses were performed to identify what information needs to be shown to successfully "close the loop" and what results could be expected in terms of observed (manual) control behaviour and decision-making. The emphasis of the work in this dissertation was therefore placed on the design aspects of information systems. Based on controlled experiments, where the information shown on the displays is carefully controlled, it was already possible to observe notable differences in control behaviour and decisions based on the different displays alone. However, eye tracking data could have provided more information on what exact display elements pilots looked at more frequently and thus could have helped determine the relevance of each visual cue.

In each study and experiment, the task was clearly defined, and apart from a small number of off-nominal situations, the task remained identical throughout each experiment. This was done to enable the detailed analysis of pilot behaviour in this specific task, but it of course does not represent actual helicopter operation, which encompasses a multitude of different manoeuvre samples, mission task elements, and mission phases, each of which can differ greatly from the preceding task. Designing an experiment that takes many different tasks and timescales of operations into account presents a big challenge, but it might also produce unique insights that cannot be gained when analysing only one task on one timescale in isolation.

Lastly, the concluding results and discussions of the dissertation have not been validated experimentally. In particular in this conclusion chapter, hypotheses about the general working principles of different helicopter automation systems are presented. These are backed up by the performed experiments. However, they only represent one task on each operational timescale. To strengthen the obtained results, more experiments on each timescale could be performed, covering different tasks but employing similar automation design approaches. It would be of great interest to determine whether the obtained results hold valid across different tasks, or whether they only hold for the specific tasks considered in this dissertation.

7.7.2. Future research directions

At the beginning of this dissertation, a number of limitations and assumptions have been made. Loosening one or more of these constraints will alter the results or enable entire new research directions, depending on the specific constraint. Moving from carefully designed simulator situations to real-world helicopters, for example, will lead to the breach of many, if not all, of the below assumptions. These assumptions were:

1. Only single pilot operations are considered, all automated systems need to be controlled and managed by the pilot flying. Considering multi-pilot operations will, on the one hand, significantly increase the complexity of the possible pilot-pilot and pilot-system interactions. On the other hand, it will make the performed research applicable to multi-pilot helicopter operations, increasing its significance and possible impact. Workload- and attention-related issues with respect to the investigated automation systems will play out differently, as the second pilot can perform monitoring or other supporting functions.

2. No advanced control augmentations (like position hold or translational rate command) are employed, the helicopter dynamics broadly behave like attitude rate control systems, and the pilot is always required to manually control the helicopter. Releasing this constraint has already been discussed when aiming to close the "action selection gap": allowing advanced control augmentations or even full authority autopilots will free up pilots' mental resources to perform other functions, e.g., supervisory control tasks, more effectively. As with the previous constraint, considering these additional operational circumstances would increase the applicability of the performed research.

3. Unless otherwise specified, helicopter systems work 100 % reliably, and flight instruments and sensors are 100 % accurate. Violating this constraint does not seem helpful — introducing malfunctions or failures that are not specifically accounted for in the experiment design could be argued to increase the experimental realism, but it would significantly hinder the analysis of the obtained experimental results. Introducing sensor or flight instrument inaccuracies could increase the experimental realism, and it might change the behaviour of automation systems that rely on accurate data. Depending on the experimental setup and scenario, this could lead to new insights.

4. Wind and its effects, as well as aerodynamic interactions with the environment (ground, structures, foliage) are not considered. Changing this assumption would increase the experimental realism. It also enables the analysis of wholly new scenarios, e.g., landing under crosswind or navigating in ground effect, and how automation systems could support the pilots in these.

7

5. Engine or drive train dynamics are not considered, the rotor rpm is assumed to be constant and nominal. Allowing engine and drive-train dynamics would allow the analysis of a broader range of scenarios, e.g., the autorotation manoeuvre.

6. The utilised helicopter model is either an in-house generic six degrees-of-freedom helicopter flight dynamics model, run with a Messerschmitt-Bölkow-Blohm Bo 105 Helicopter (MBB Bo 105) parameter set (Miletović et al., 2018), or a linear MBB Bo 105 model presented by Padfield (1981, 2007), based on Helisim. Changing the utilised helicopter model would change the control requirements for the pilot, and it would influence the workload and concentration that is required to perform different manoeuvres. Unless the vehicle dynamics change drastically, however, the general results of an experiment performed with one model should still be applicable.

This dissertation investigated tasks on three separate timescales of operation, and it combined the obtained results to hypothesise on the effect of different automation design approaches across timescales and tasks. One way of validating the made hypotheses would be, of course, to develop and experimentally investigate automation systems that span multiple timescales at once. Identified automation functions that are similar across timescales are:

1. in-flight information acquisition,
2. in-flight information analysis,
3. trajectory determination,
4. trajectory visualisation/communication, and
5. trajectory implementation.

Investigating different automation approaches that integrate one or more of these functionalities across timescales of operation will potentially change the obtained results. On the one hand, it is possible that the inadvertent effect of advisory automation on longer timescales is reduced when the system seamlessly integrated short timescale information, reducing the cognitive gap. On the other hand, the operational envelope of integrated systems might be even less clearly defined or observable than the boundaries of single timescale systems, exacerbating inadvertent negative effects. Nonetheless, developing integrated automation support across timescales might be the way forward to avoid cognitive gaps in control and reduce the effort that is required of pilots to integrate information across all timescales.

The constraint-based systems investigated in the medium-term and long-term experiments showed potential, but their usefulness was limited because of their novel and unfamiliar mode of data representation. This caused an increase in pilot workload to comprehend and use the provided information. Some pilots even decided to not use the provided information at all, as it was deemed not worth the effort. Future research should investigate how constraint-based systems can be better integrated into the operational context of helicopter pilots — be it through increased training and familiarisation, or through different ways of communication system capabilities and constraints to the pilot. This dissertation showed the potential of constraint-based systems, but it did not develop an immaculate constraint-based display design that could or should be integrated into real-world missions right away.

The studies and experiments of this dissertation covered tasks on the timescale of manoeuvre samples, mission task elements, and mission phases, covering LoCS 2 to 4. Automation systems on the lowest timescale of operation, system readiness, and on the highest timescale, mission, have not been investigated. Automation functions on these two timescales differ greatly from the functions provided on the “middle” LoCS 2 to 4. Future helicopter automation research could therefore investigate different control augmentations on LoCS 1, and mission-level automation support in LoCS 5.

Throughout this dissertation, one stage of automation was not considered: action implementation, the last stage of automation. This resulted from the set assumptions and limitations, which required that the (single) pilot flying always needs to be in manual control of the helicopter. Future developments in helicopter automation support and mission profiles make evident that automated systems that fully take over certain tasks or flight phases are not out of reach. This is true not only for current advanced military helicopter types, but also for future developments in personal aerial mobility and novel rotorcraft configurations.

7.8. Final concluding remarks of this dissertation

This dissertation set out to "understand the use of automation in helicopters", and to investigate how EID principles could improve helicopter operational safety. After reviewing existing automation approaches on different operational timescales, two exploratory studies and two human-in-the-loop experiments have been conducted. Each investigation compared task-centred and ecology-centred automation (in the short timescale) or advisory and constraint-based automation (in the medium and long timescale). The investigations covered the tasks of hover, obstacle avoidance, and navigation.

Results suggest that the peculiarities of helicopter control (the requirement of constant, hands-on control actions in parallel to the use of any automation system on-board) and the broader operational envelope influence the effect of the employed automation. Ecology-centred and constraint-based automation generally enabled the pilots to successfully complete the task with acceptable performance, albeit there is room for improvement with respect to the systems' ease-of-use. Advisory automation was generally preferred by the pilots, but it produced significant negative effects on navigational decision-making when confronted with unexpected, off-nominal situations.

It is hypothesised that the "cognitive gap" between the requirement of manually controlling the helicopter on the short timescale and the requirement of supervising advisory automation on the long timescale exacerbated inadvertent, negative effects of automation. To increase operational safety, future helicopter automation should focus on supporting the pilots' information acquisition and analysis tasks across all timescales, while leaving the final action selection and implementation to the pilots. It should implement action selection and implementation support on a specific timescale only when the same process is supported at least as strong on the neighbouring lower timescale. This avoids the requirement of performing a manual control task on a short timescale of operation and a supervisory control task on a longer timescale of operation, and thus avoids creating a "cognitive gap" between the required pilot tasks. Supporting pilots in the suggested way should enable them to employ their control and decision-making skills to the best of their (extensive) capabilities, and therefore increase helicopter operational safety.

This dissertation provides analyses, examples, and results to "understand the use of automation in helicopters". As is the case with many research projects, the process of answering some questions led to an array of new questions being posed in turn. However, this dissertation contributes to taking a next step towards understanding automation in helicopters, and towards improving helicopter automation by supporting its well-reasoned development and application.

A

Bo105 model and control characteristics

This appendix contains bode plots for the decoupled, linear MBB Bo 105 model utilised in Chapter 3. System structures are set up to control surge ($\theta_{1s} \rightarrow u \rightarrow x$), heave ($\theta_0 \rightarrow w \rightarrow z$), roll/sway ($\theta_{1c} \rightarrow \phi \rightarrow v \rightarrow y$) and yaw ($\theta_{TR} \rightarrow r \rightarrow \psi$). Table A.1 shows the target system state per loop. Figures A.1 and A.2 show the inner loop controlled element and pilot model transfer functions, respectively, Figure A.3 shows the resulting inner loop open loop transfer functions. Figures A.4 and A.5 show the inner, middle, and outer loop closed loop transfer functions without and with a stability augmentation system (SAS), respectively.

Table A.1: Target system state of every controlled loop.

System	Loop	Target
Surge	Inner	θ
	Middle	u
	Outer	x
Heave	Inner	w
	Middle	z
Sway	Inner	ϕ
	Middle	v
	Outer	y
Yaw	Inner	r
	Middle	ψ

A

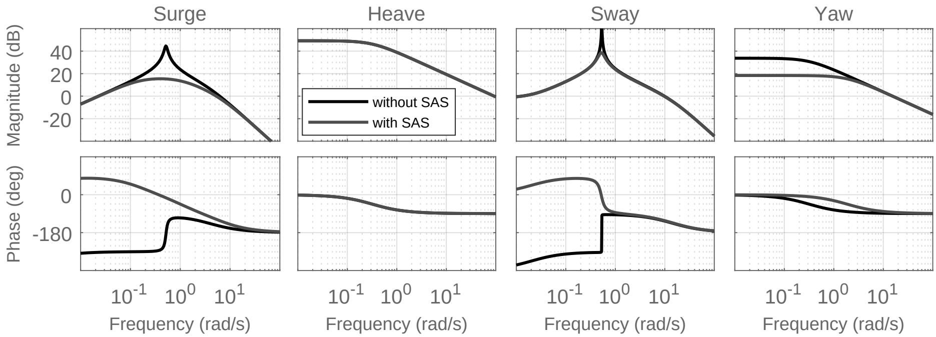


Figure A.1: Bode plots of the inner loop controlled element transfer function $Y_{c,inner}$ for surge, heave, sway, and yaw.

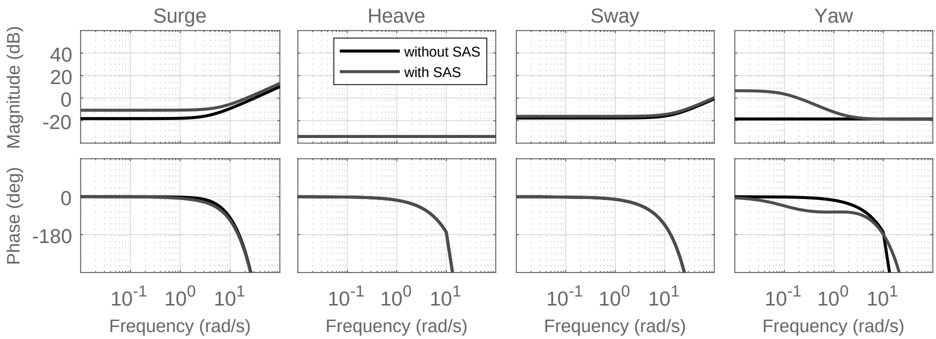


Figure A.2: Bode plots of the inner loop pilot model transfer function $Y_{p,inner}$ for surge, heave, sway, and yaw.

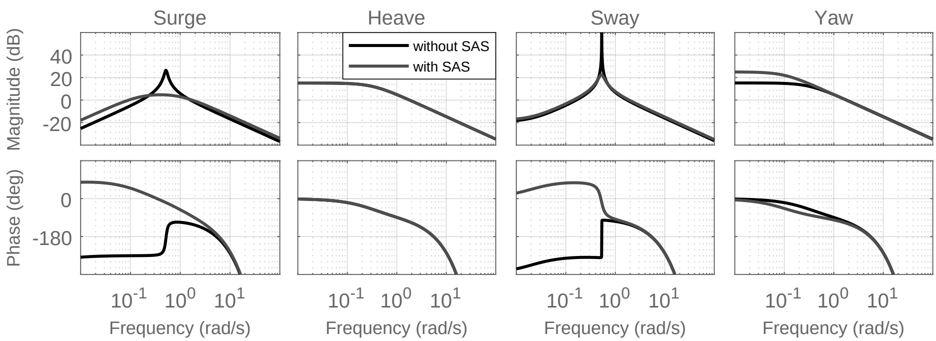


Figure A.3: Bode plots of the inner loop open loop transfer function $Y_{OL,inner}$ for surge, heave, sway, and yaw.

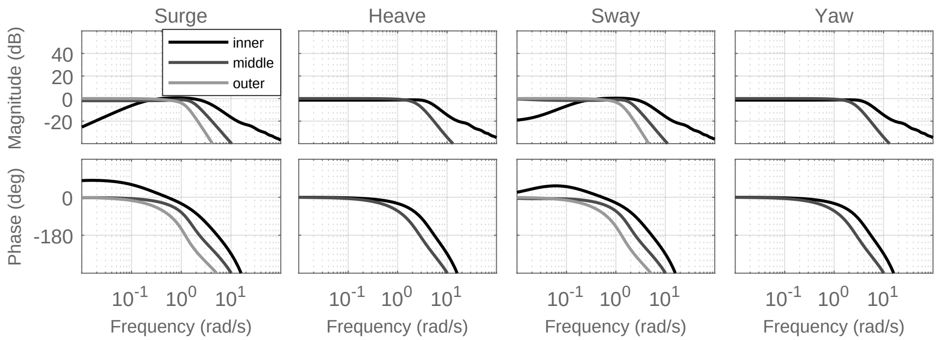


Figure A.4: Bode plots of the inner, middle, and outer loop closed loop transfer functions Y_{CL} for surge, heave, sway, and yaw without SAS.

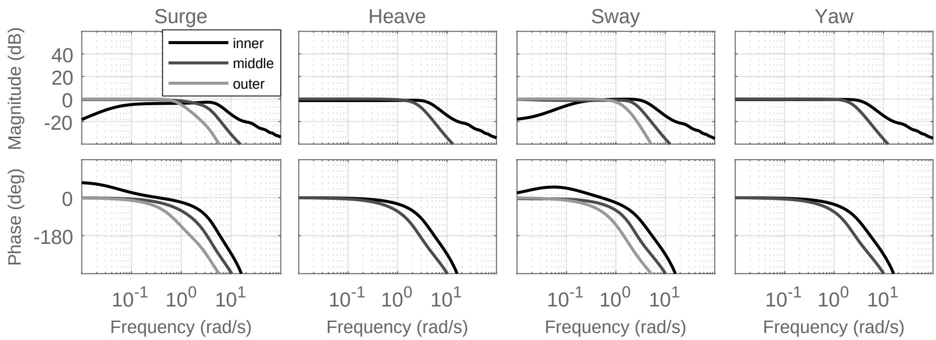


Figure A.5: Bode plots of the inner, middle, and outer loop closed loop transfer functions Y_{CL} for surge, heave, sway, and yaw with SAS.

B

Experiment documents

This appendix contains the experiment questionnaires utilised in Chapters 4 to 6. In Chapter 3, the pilots were provided with questionnaires, but the answers were not utilised in this dissertation.

Experiment 2: Head-up hover displays

Code

SART (Situation Awareness Rating Scale)

Please rate the level of each component of situation awareness that you had when you performed the task (without sensor failure) by circling the appropriate number for each component.

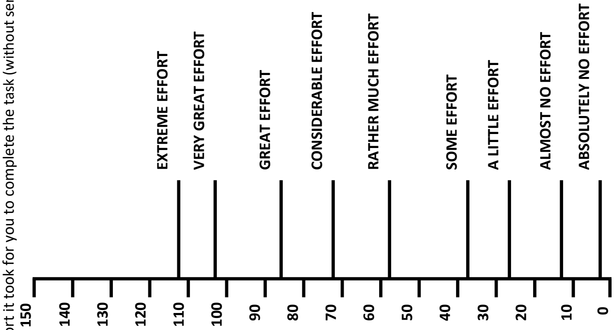
DEMAND									
Instability of situation Likeness of the situation to change suddenly	Low	1	2	3	4	5	6	7	High
Variability of situation Number of variables that require your attention during the task	Low	1	2	3	4	5	6	7	High
Complexity of situation Degree of complication (number of closely connected or coupled elements) of the situation	Low	1	2	3	4	5	6	7	High

SUPPLY									
Arousal Degree to which you are ready for activity; ability to anticipate and keep up with the flow of events	Low	1	2	3	4	5	6	7	High
Spare mental capacity Amount of free mental capacity available during the task to apply to new and different tasks	Low	1	2	3	4	5	6	7	High
Concentration Degree to which your thoughts are brought to bear on the situation; degree to which you focus on important elements and events	Low	1	2	3	4	5	6	7	High
Division of attention Ability to divide your attention among several key issues during the mission; ability to concern yourself with many aspects of current and future events simultaneously	Low	1	2	3	4	5	6	7	High

UNDERSTANDING									
Information quantity Amount of knowledge received and understood (e.g. attitude, aircraft & obstacle position, speed and direction of flight, information about future aircraft states)	Low	1	2	3	4	5	6	7	High
Information quality Degree of goodness, value, usefulness of information communicated	Low	1	2	3	4	5	6	7	High
Familiarity Degree of acquaintance with the situation	Low	1	2	3	4	5	6	7	High

RSME (Rating Scale Mental Effort)

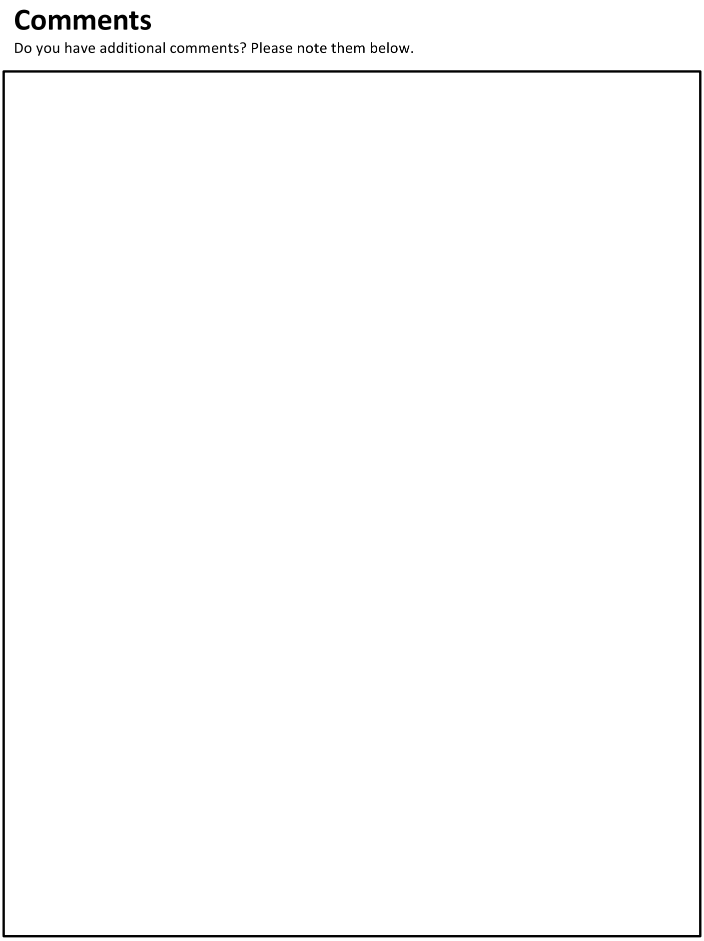
Please indicate, by marking the vertical axis below, how much effort it took for you to complete the task (without sensor failure).



Comments

Please see the backside of this questionnaire.

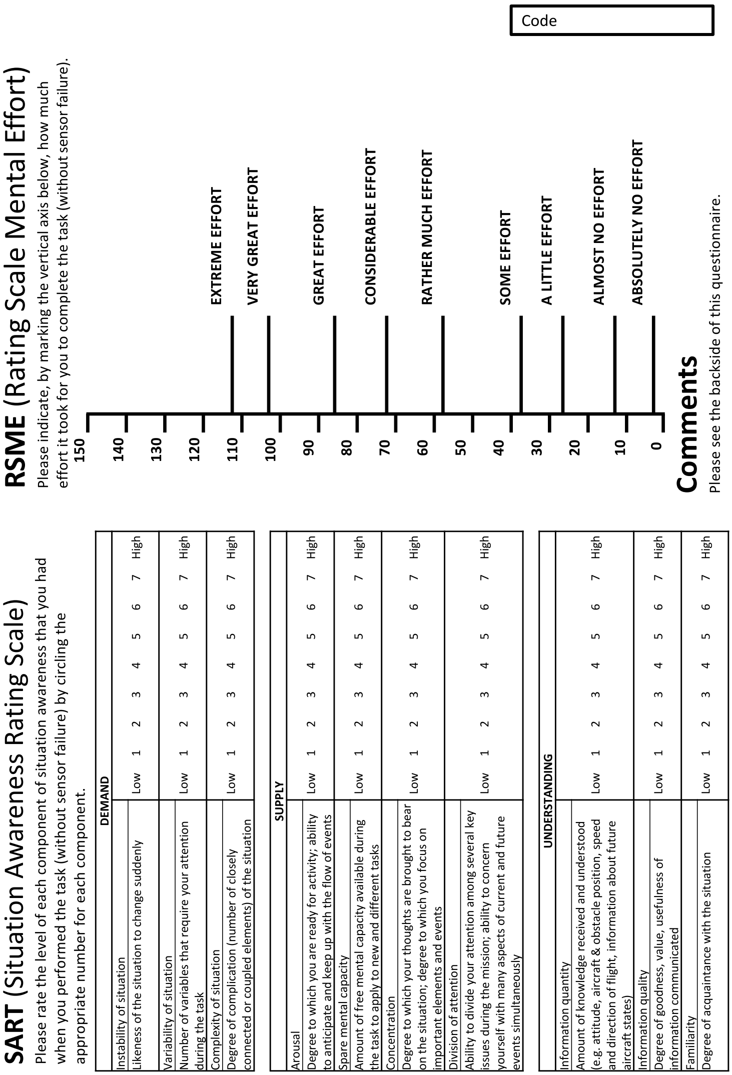
Figure B.1: Questionnaire filled out by participating pilots after each condition (front side).


Comments

Do you have additional comments? Please note them below.

Figure B.2: Questionnaire filled out by participating pilots after each condition (back side).

Experiment 3: Head-up obstacle avoidance


Code

SART (Situation Awareness Rating Scale)

Please rate the level of each component of situation awareness that you had when you performed the task (without sensor failure) by circling the appropriate number for each component.

DEMAND									
Instability of situation Likeness of the situation to change suddenly	Low	1	2	3	4	5	6	7	High
Variability of situation Number of variables that require your attention during the task	Low	1	2	3	4	5	6	7	High
Complexity of situation Degree of complication (number of closely connected or coupled elements) of the situation	Low	1	2	3	4	5	6	7	High

SUPPLY									
Arousal Degree to which you are ready for activity; ability to anticipate and keep up with the flow of events	Low	1	2	3	4	5	6	7	High
Spare mental capacity Amount of free mental capacity available during the task to apply to new and different tasks	Low	1	2	3	4	5	6	7	High
Concentration Degree to which your thoughts are brought to bear on the situation; degree to which you focus on important elements and events	Low	1	2	3	4	5	6	7	High
Division of attention Ability to divide your attention among several key issues during the mission; ability to concern yourself with many aspects of current and future events simultaneously	Low	1	2	3	4	5	6	7	High

UNDERSTANDING									
Information quantity Amount of knowledge received and understood (e.g. attitude, aircraft & obstacle position, speed and direction of flight, information about future aircraft states)	Low	1	2	3	4	5	6	7	High
Information quality Degree of goodness, value, usefulness of information communicated	Low	1	2	3	4	5	6	7	High
Familiarity Degree of acquaintance with the situation	Low	1	2	3	4	5	6	7	High

RSME (Rating Scale Mental Effort)

Please indicate, by marking the vertical axis below, how much effort it took for you to complete the task (without sensor failure).

Comments

Please see the backside of this questionnaire.

Figure B.3: Questionnaire filled out by participating pilots after each condition (front side).

Comments

Do you have additional comments? Please note them below.

Figure B.4: Questionnaire filled out by participating pilots after each condition (back side).

B

Baseline HUD									
How confident did you feel in using only the outside visuals, the baseline head-up display (HUD), and the obstacle boxes to fulfil the task?	Low	1	2	3	4	5	6	7	High
Do you have additional comments on the simulation realism, the outside visuals or the baseline head-up display?									

Arrow symbology									
In general, how confident did you feel in using the arrow symbology to fulfill the task?	Low	1	2	3	4	5	6	7	High
In cases **without faults**, how confident did you feel in using the arrow symbology to fulfill the task?	Low	1	2	3	4	5	6	7	High
In cases **with faults**, how confident did you feel in using the arrow symbology to fulfill the task?	Low	1	2	3	4	5	6	7	High
Do you have any additional comments on the arrow symbology?									

Steepest climb symbol									
In general, how confident did you feel in using the steepest climb symbol to fulfill the task?	Low	1	2	3	4	5	6	7	High
In cases **without faults**, how confident did you feel in using the steepest climb symbol to fulfill the task?	Low	1	2	3	4	5	6	7	High
In cases **with faults**, how confident did you feel in using the steepest climb symbol to fulfill the task?	Low	1	2	3	4	5	6	7	High
Do you have any additional comments on the steepest climb symbol?									

Figure B.5: Questionnaire filled out by participating pilots after the experiment.

Experiment 4: Head-down navigation displays

Professional Experience Information (to be filled before the experiment)

To be able to put the results in relation to experience, you are asked to fill in this anonymous questionnaire.

1. Age: ____________________
2. Gender:
   - ☐ Female
   - ☐ Male
3. Based on your experience as a pilot, please provide the following information:
   (a) Helicopter license type:
   - ☐ PPL
   - ☐ CPL
   - ☐ Other: ____________________

   (b) Total helicopter flight hours: ____________________
4. Have you ever participated in a research experiment?
   - ☐ Yes
   - ☐ No

   If yes, please elaborate on the type of experiment. (handling qualities, motion cueing, ...)

   ____

   ____

Figure B.6: Pre-experiment questionnaire.

Pilot ID

Baseline Display, run 1

Situation Awareness Rating Scale (SART)

Please rate the level of each component of situation awareness that you had when you performed the task by circling the appropriate number for each component.

DEMAND									
Instability of situation Likeness of the situation to change suddenly	Low	1	2	3	4	5	6	7	High
Variability of situation Number of variables that require your attention during the task	Low	1	2	3	4	5	6	7	High
Complexity of situation Degree of complication (number of closely connected or coupled elements) of the situation	Low	1	2	3	4	5	6	7	High

SUPPLY									
Arousal Degree to which you are ready for activity; ability to anticipate and keep up with the flow of events	Low	1	2	3	4	5	6	7	High
Spare mental capacity Amount of free mental capacity available during the task to apply to new and different tasks	Low	1	2	3	4	5	6	7	High
Concentration Degree to which your thoughts are brought to bear on the situation; degree to which you focus on important elements and events	Low	1	2	3	4	5	6	7	High
Division of attention Ability to divide your attention among several key issues during the mission; ability to concern yourself with many aspects of current and future events simultaneously	Low	1	2	3	4	5	6	7	High

UNDERSTANDING									
Information quantity Amount of knowledge received and understood (e.g. absolute and relative position of aircraft, bad weather areas, targets, prospective manoeuvres)	Low	1	2	3	4	5	6	7	High
Information quality Degree of goodness, value, usefulness of information communicated	Low	1	2	3	4	5	6	7	High
Familiarity Degree of acquaintance with the situation	Low	1	2	3	4	5	6	7	High

NASA Task Load Index (NASA TLX)

Please rate the level of each component of workload that you experienced when you performed the task by marking the scales with an X.

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure B.7: Per-course questionnaire, SART and NASA TLX.

NASA Task Load Index (NASA TLX)

Rating Scale Definitions

Title	Endpoints	Descriptions
MENTAL DEMAND	Low/High	How much mental and perceptual activity was required (e.g,. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	Low/High	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	Low/High	How much time pressure did you feel due to the rate or pace at which the task or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	good/poor	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	Low/High	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION LEVEL	Low/High	How insecure, discouraged, irritated, stressed, and annoyed versus secury, gratified, content, relaxed, and complacent did you feel during the task?

Figure B.8: Per-course questionnaire, NASA TLX factor descriptions.

B

Questionnaire to be filled at the end of the experiment

1. Baseline Display

1.1 In general, I felt confident using this display.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

1.2 In cases with **NO** undetected bad weather areas, I felt confident using this display.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

1.3 In cases with **AT LEAST ONE** undetected bad weather area, I felt confident using this display.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

1.4 This display supported the **path-planning** task.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

1.5 This display supported the **arrival time estimation** task.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

1.6 This display supported the **fuel reserve estimation** task.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

1.7 This display supported the **recognition** of undetected bad weather areas.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

1.8 This display supported **reacting to** undetected bad weather areas. I.e., the re-planning of the path and the re-estimation of arrival times and fuel reserves after recognising an undetected bad weather area.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

1.9 Do you have general comments regarding this display?

____

____

____

Figure B.9: Post-experiment questionnaire page 1/4.

2. Advisory Display

2.1 In general, I felt confident using this display.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

2.2 In cases with **NO** undetected bad weather areas, I felt confident using this display.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

2.3 In cases with **AT LEAST ONE** undetected bad weather area, I felt confident using this display.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

2.4 This display supported the **path-planning** task.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

2.5 This display supported the **arrival time estimation** task.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

2.6 This display supported the **fuel reserve estimation** task.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

2.7 This display supported the **recognition** of undetected bad weather areas.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

2.8 This display supported **reacting to** undetected bad weather areas. I.e., the re-planning of the path and the re-estimation of arrival times and fuel reserves after recognising an undetected bad weather area.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

2.9 This display changed my control strategy and decision-making process, compared to the baseline display.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

2.10 Please explain why this display did or did not impact your control strategy and decision-making process.

____

2.11 Do you have general comments regarding this display?

____

Figure B.10: Post-experiment questionnaire page 2/4.

B

3. Constraint-Based Display

3.1 In general, I felt confident using this display.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

3.2 In cases with **NO** undetected bad weather areas, I felt confident using this display.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

3.3 In cases with **AT LEAST ONE** undetected bad weather area, I felt confident using this display.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

3.4 This display supported the **path-planning** task.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

3.5 This display supported the **arrival time estimation** task.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

3.6 This display supported the **fuel reserve estimation** task.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

3.7 This display supported the **recognition** of undetected bad weather areas.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

3.8 This display supported **reacting to** undetected bad weather areas. I.e., the re-planning of the path and the re-estimation of arrival times and fuel reserves after recognising an undetected bad weather area.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

3.9 This display changed my control strategy and decision-making process, compared to the baseline display.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

3.10 Please explain why this display did or did not impact your control strategy and decision-making process.

3.11 Do you have general comments regarding this display?

Figure B.11: Post-experiment questionnaire page 3/4.

B

4. General comments

4.1 The **path-planning** task resembles activities I encounter during real helicopter operations.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

4.2 The **arrival time estimation** task resembles activities I encounter during real helicopter operations.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

4.3 The **fuel reserve estimation** task resembles activities I encounter during real helicopter operations.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

4.4 The **recognition of undetected bad weather areas** resembles activities I encounter during real helicopter operations.

☐ Disagree strongly ☐ Disagree ☐ Slightly disagree ☐ Slightly agree ☐ Agree ☐ Agree strongly

4.5 Do you have general comments regarding the experiment?

____

____

____

Figure B.12: Post-experiment questionnaire page 4/4.

Bibliography

Abildgaard, M. and Binet, L. (2009). Active Sidesticks Used for Vortex Ring State Avoidance. In *Proceedings of the 35th European Rotorcraft Forum, Hamburg, Germany*.

Alfred, J., Celi, R., Gordon Leishman, J., and Leishman, J. G. (2017). Flight Path Optimization for Brownout Mitigation Using a High-Fidelity Simulation Model. *Journal of the American Helicopter Society*, 62(3):1–15.

Amelink, M. H. J. (2010). *Ecological Automation Design: Extending Work Domain Analysis*. PhD thesis, Delft University of Technology.

Anonymous (1993). Official Report Into the Accident on 20 January 1992 near Mont Sainte Odile (Bas-Rhin) of the Airbus A.320 Registered F-GGED Operated by Air Inter. Technical Report November, French Ministry of Transport and Tourism.

Anonymous (2000). Aeronautical Design Standard - 33E PRF, Performance Specification, Handling Qualities Requirements for Military Rotorcraft. Technical report, US Army AMCOM, Redstone, Alabama, United States.

Anonymous (2010a). Crashed During Approach, Boeing 737-800, near Amsterdam Schiphol Airport, 25 February 2009. Technical report, The Dutch Safety Board.

Anonymous (2010b). Final Report - EHEST Analysis of 2000-2005 European Helicopter Accidents. Technical report, European Helicopter Safety Team.

Anonymous (2011a). The Compendium Report: The U.S. JHSAT Baseline of Helicopter Accident Analysis: Volume I. Technical report, U.S. Joint Helicopter Safety Analysis Team.

Anonymous (2011b). The Compendium Report: The U.S. JHSAT Baseline of Helicopter Accident Analysis: Volume II. Technical report, U.S. Joint Helicopter Safety Analysis Team.

Anonymous (2012). Final Report On the Accident on 1st June 2009 to the Airbus A330-203 Registered F-GZCP Operated by Air France flight AF 447 Rio de Janeiro - Paris. Technical report, Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile.

Anonymous (2015). Final Report - EHEST Analysis of 2006-2010 European Helicopter Accidents. Technical report, European Helicopter Safety Team.

Anonymous (2018). Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles. Technical report, SAE International.

Anonymous (2019a). Annual Safety Review 2019. Technical report, EASA.

Anonymous (2019b). FAA Annual Safety Review Data 2017 (Part 121 Operations). Technical report, United States Federal Aviation Administration.

Anonymous (2019c). The European Plan for Aviation Safety (EPAS 2020-2024). Technical report, EASA.

Anonymous (2020). Safety Report (August 2020). Technical report, United States Helicopter Safety Team.

Aponso, B. L., Lee, D., and Bachelder, E. N. (2007). Evaluation of a Rotorcraft Autorotation Training Display on a Commercial Flight Training Device. *Journal of the American Helicopter Society*, 52(2):123–133.

Atyeo, S., Sinha, A. K., and Young, K. (2004). An Intelligent System for the Pre-Mission Analysis of Helicopter Emergency Medical Service Operations: Status Report One. In *Proceedings of the 30th European Rotorcraft Forum, Marseille, France*.

Atyeo, S., Sinha, A. K., and Young, K. (2005). Pre-Mission Analysis for Helicopter Emergency Medical Service Operations. In *Proceedings of the 31st European Rotorcraft Forum, Florence, Italy*.

Bainbridge, L. (1983). Ironies of Automation. *Automatica*, 19(6):775–779.

Bakker, R. and van der Geest, P. (2018). Determining a Safe-Distance Guideline for Helicopters Near a Wind Turbine and Wind Park. In *Proceedings of the 44th European Rotorcraft Forum, Delft, The Netherlands*.

Barendswaard, S., Pool, D. M., Van Paassen, M. M., and Mulder, M. (2019). Dual-Axis Manual Control: Performance Degradation, Axis Asymmetry, Crossfeed, and Intermittency. *IEEE Transactions on Human-Machine Systems*, 49(2):113–125.

Baxter, G., Rooksby, J., Wang, Y., and Khajeh-Hosseini, A. (2012). The ironies of automation: still going strong at 30? In *Proceedings of the 30th European Conference on Cognitive Ergonomics - ECCE '12*, page 65, New York, New York, USA. ACM Press.

Bazargan, M. and Guzhva, V. S. (2011). Impact of Gender, Age and Experience of Pilots on General Aviation Accidents. *Accident Analysis and Prevention*, 43(3):962–970.

Beyer, R., Bondurant III, R. A., Huddleston, J. H. F., McGregor, D. M., Sterk, F. J., and Walters, D. J. (1972). AGARD Report 594: V/STOL Displays for Approach and Landing. Technical report, North Atlantic Treaty Organization, London.

Billings, C. E. (1991). Toward a Human-Centered Aircraft Automation Philosophy. *The International Journal of Aviation Psychology*, 1(4):261–270.

Blumen, I. J. and UCAN Safety Committee (2002). *A Safety Review and Risk Assessment in Air Medical Transport, Air Medical Physician Handbook 2002*. Air Medical Physicial Association, Salt Lake City, Utah, United States.

Borst, C., Flach, J. M., and Ellerbroek, J. (2015). Beyond Ecological Interface Design: Lessons From Concerns and Misconceptions. *IEEE Transactions on Human-Machine Systems*, 45(2):164–175.

Borst, C., Mulder, M., and van Paassen, M. (2010a). A Review of Cognitive Systems Engineering in Aviation. *IFAC Proceedings Volumes*, 43(13):221–226.

Borst, C., Mulder, M., and Van Paassen, M. M. (2010b). Design and Simulator Evaluation of an Ecological Synthetic Vision Display. *Journal of Guidance, Control, and Dynamics*, 33(5):1577–1591.

Bos, J. E., MacKinnon, S. N., and Patterson, A. (2005). Motion Sickness Symptoms in a Ship Motion Simulator: Effects of Inside, Outside, and No View. *Aviation Space and Environmental Medicine*, 76(12):1111–1118.

Bottasso, C. L. and Montinari, P. (2015). Rotorcraft Flight Envelope Protection by Model Predictive Control. *Journal of the American Helicopter Society*, 60(2):1–13.

Burns, C. M. and Hajdukiewicz, J. R. (2004). *Ecological interface design*. CRC Press.

Byrne, D. (2001). Enhancing Helicopter Mission Effectiveness. In *Proceedings of the 27th European Rotorcraft Forum, Moscow, Russia*.

Celi, R. (2010). Rotorcraft Dispatching in Large-Scale Emergencies Using Sequential Linear Assignment Techniques. *Journal of the American Helicopter Society*, 55(3):032004.

Charlesworth, S., Kusumo, R., Sinha, A. K., and Atyeo, S. (2005). Crew Capability Evaluation for Helicopter Emergency Medical Service Operations. In *Proceedings of the 31st European Rotorcraft Forum, Florence, Italy*.

Comans, J. (2017). *Visualizing Rules, Regulations, and Procedures in Ecological Information Systems*. PhD thesis, Delft University of Technology.

Cooper, J., Horn, J. F., Yomchinda, T., and O'Neill, E. P. (2014). Handling Qualities Evaluation of an Adaptive Disturbance Compensation System for Ship-Based Rotorcraft. *Journal of the American Helicopter Society*, 59(2):1–12.

Couch, M. and Lindell, D. (2010). Study on Rotorcraft Safety and Survivability. In *Proceedings of the 66th American Helicopter Society Forum*, Phoenix, Arizona, United States.

Craig, G., Carignan, S., and Brulotte, M. (2011). Flight Task Performance with High and Low Gain Night Vision Goggles. In *Proceedings of the 37th European Rotorcraft Forum, Cascina Costa, Italy*.

Craig, G., Gubbels, B., Prystay, M., Ball, A., Carignan, S., Swail, C., Ellis, K., Erdos, R., Jennings, S., and Macuda, T. (2007). Flight Test of a Video-Based Automatic Station-Keeping System: Tracking Targets on the Ground. In *Proceedings of the 33rd European Rotorcraft Forum, Kazan, Russia*.

Crawford, J. and Neal, A. (2006). A Review of the Perceptual and Cognitive Issues Associated With the Use of Head-Up Displays in Commercial Aviation. *The International Journal of Aviation Psychology*, 16(1):1–19.

Curtis, M. T., Jentsch, F., and Wise, J. A. (2010). Aviation Displays. In *Human Factors in Aviation*, pages 439–478. Elsevier, Burlington, Massachusetts, United States.

De Bernardi, S. M. and Ferroni, M. (2018). Skyflight Mobile: A Service to Enhance the Leonardo Flying Experience. In *Proceedings of the 44th European Rotorcraft Forum, Delft, The Netherlands*.

De Reus, A. and Van Witzenburg, M. (2007). Pilot-in-the-Loop Evaluation of a Novel Acceleration Symbol for the RNLAF AS-532 U2 Cougar Helicopter HUD. In *Proceedings of the 33rd European Rotorcraft Forum, Kazan, Russia*.

de Waard, D. (1996). *The Measurement of Drivers' Mental Workload*. PhD thesis, Rijksuniversiteit Groningen, The Netherlands.

de Winter, J. C. F. and Dodou, D. (2014). Why the Fitts List has Persisted Throughout the History of Function Allocation. *Cognition, Technology & Work*, 16(1):1–11.

Dekker, S. W. (2003). Accidents are Normal and Human Error Does Not Exist: A New Look at the Creation of Occupational Safety. *International Journal of Occupational Safety and Ergonomics*, 9(2):211–218.

D'Intino, G., Olivari, M., Bülthoff, H. H., and Pollini, L. (2020). Haptic Assistance for Helicopter Control Based on Pilot Intent Estimation. *Journal of Aerospace Information Systems*, 17(4):193.

Döhler, H.-U., Knabl, P. M., Schmerwitz, S., Eger, T., and Klein, O. (2012). Evaluation of DVE Landing Display Formats. In *Airborne Intelligence, Surveillance, Reconnaissance (ISR) Systems and Applications IX*, volume 8360, page 83600P.

Döhler, H.-U., Peinecke, N., Schmerwitz, S., and Lüken, T. (2013). ALLFlight-Imaging Sensors Fused with Ladar Data for Moving Obstacle Detection. In *Proceedings of the 39th European Rotorcraft Forum, Moscow, Russia*.

Döhler, H.-U., Schmerwitz, S., and Lüken, T. (2014). Visual-Conformal Display Format for Helicopter Guidance. In Güell, J. J. and Sanders-Reed, J., editors, *Degraded Visual Environments: Enhanced, Synthetic, and External Vision Solutions 2014*, volume 9087, page 90870J.

Dorneich, M. C., Dudley, R., Letsu-Dake, E., Rogers, W., Whitlow, S. D., Dillard, M. C., and Nelson, E. (2017). Interaction of Automation Visibility and Information Quality in Flight Deck Information Automation. *IEEE Transactions on Human-Machine Systems*, 47(6):915–926.

Drop, F. M. (2016). *Control-Theoretic Models of Feedforward in Manual Control*. PhD thesis, Delft University of Technology.

Ebel, T. (2019). Technical Note: Obstacle Databases for Instrument Flight: A Risk Analysis. *Journal of Aerospace Information Systems*, 16(10):437–440.

Eshow, M. M. and Schroeder, J. A. (1993). Improvements in Hover Display Dynamics for a Combat Helicopter. In *Piloting Vertical Flight Aircraft: A Conference on Flying Qualities and Human Factors*, pages 235–250.

European Helicopter Safety Team (2010). EHEST Training Leaflet HE4: Decision Making for Single-Pilot Helicopter Operations.

Faul, F., Erdfelder, E., Lang, A. G., and Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods 2007 39:2*, 39(2):175–191.

Federal Aviation Administration (2019). Basic Flight Maneuvers. In *Helicopter Flying Handbook*, chapter 9, pages 9.1–9.20. U.S. Department of Transportation, Oklahoma City, Oklahoma, United States.

Feltman, K. A., Curry, I., Bernhardt, K., Hayes, A., Kirby, S., Davis, B., Sapp, J., Durbin, D., and Hartnett, G. (2018). Integrated Cueing Environment: Simulation Event Four. Technical report, (ARL-TR-8538), Fort Rucker, Alabama, United States: U.S. Army Aeromedical Research Laboratory.

Field, A. P. (2005). *Discovering Statistics Using SPSS, 2dn Edition*. Sage Publications, London.

Fillias, F., Gillet, M., and Pire, R. (2011). Low Level Flight Solutions for Civilian Missions. In *Proceedings of the 37th European Rotorcraft Forum, Cascina Costa, Italy*.

Flach, J. M., Warren, R., Garness, S. A., Kelly, L., and Stanard, T. (1997). Perception and Control of Altitude: Splay and Depression Angles. *Journal of Experimental Psychology. Human Perception and Performance*, 23(6):1764–1782.

Flemming, R. J. (2003). A Jistory of Ice Protection System Development at Sikorsky Aircraft. *SAE Technical Papers*.

Friedman, M. (1937). The Use of Ranks to Avoid the Assumption of Normality Implicit in the Analysis of Variance. *Journal of the American Statistical Association*, 32(200):675–701.

Funabiki, K., Tsuda, H., Shimizu, A., Sugihara, Y., Tawada, K., and Hasebe, K. (2020). Objective Flight Evaluation of Visual Cue for DVE Helicopter Operation. In *AIAA Scitech 2020 Forum, Orlando, Florida, United States*.

Funabiki, K., Tsuda, H., Tawada, K., and Hasebe, K. (2018). Research on Vision System for Degraded Visual Environment. In *Proceedings of the 44th European Rotorcraft Forum, Delft, The Netherlands*.

Gaffal, R. and Gollnick, V. (2003). Comparison of Flight Guidance Symbologies for Helicopter-Low-Level-Flight. In *Proceedings of the 29th European Rotorcraft Forum, Friedrichshafen, Germany*.

Gatter, A. (2015). Edge-Based Approach to Estimate the Drift of a Helicopter During Flight. In *Proceedings of the 41st European Rotorcraft Forum, Munich, Germany*.

Gatter, A. (2019). Preventing Dynamic Rollover in Brownout. In *Proceedings of the 45th European Rotorcraft Forum, Warsaw, Poland*.

Gawron, V. J. (2008). *Human Performance, Workload, and Situational Awareness Measures Handbook*. CRC Press, Taylor and Francis Group, Boca Raton, Florida, United States, 2nd edition.

Gerlach, T. (2011). Visualisation of the Brownout Phenomenon, Integration and Test on a Helicopter Flight Simulator. *The Aeronautical Journal*, 115(1163):57–63.

Germanetti, S., Godard, M., and Cognet, J. (2002). A New Avionics System for the EC225/725 Cougar - An "Advanced Helicopter Cockpit and Avionics System". In *Proceedings of the 28th European Rotorcraft Forum, Bristol, United Kingdom*.

Gibson, J. J. (1950). *The Perception of the Visual World*. The Riverside Press, Cambridge, Massachusetts, United States.

Girden, E. R. (1992). *ANOVA: Repeated Measures*. Sage Publications, Newbury Park, California, United States.

Gmelin, B. L. and Pausder, H.-J. (1985). AGARD LS-139: Mission Requirements and Handling Qualities. Technical report, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e.V.

Godfroy-Cooper, M., Miller, J. D., Bachelder, E., and Wenzel, E. M. (2018). Isomorphic Spatial Visual-Auditory Displays for Operations in DVE for Obstacle Avoidance. In *Proceedings of the 44th European Rotorcraft Forum, Delft, The Netherlands*.

Godfroy-Cooper, M., Miller, J. D., Szoboszlay, Z., and Hartnett, G. (2019). Multimodal Pilot Cueing for 360° Situation Awareness. In *Proceedings of the 45th European Rotorcraft Forum, Warsaw, Poland*.

Godfroy-Cooper, M., Szoboszlay, Z., Kahana, A., and Rottem-Hovev, M. (2016). Terrain and Obstacle Avoidance Displays for Low-Level Helicopter Operations in Degraded Visual Environments. In *Proceedings of the American Helicopter Society 72nd Forum, West Palm Beach, Florida, United States*.

Greenwood, E. and Rau, R. (2020). A Maneuvering Flight Noise Model for Helicopter Mission Planning. *Journal of the American Helicopter Society*, 65(2):1–10.

Greiser, S., Wolfram, J., and Gestwa, M. (2011). Classification of Pilot Requirements Used for Takeoff Planning. In *Proceedings of the 37th European Rotorcraft Forum, Cascina Costa, Italy*.

Guillanton, E. and Germanetti, S. (2011). System Architecture for new Avionics on Eurocopter Fleet Based on IMA Supporting Civil and Military Missions. In *Proceedings of the 37th European Rotorcraft Forum, Cascina Costa, Italy*.

Gursky, B. I., Olsman, W. F., and Peinecke, N. (2014). Development of a Tunnel-in-the-Sky Display for Helicopter Noise Abatement Procedures. *CEAS Aeronautical Journal*, 5(2):199–208.

Haisch, S., Hess, S., Jank, S., and Kreitmair-Steck (2009). Pilot Assistance for Rotorcraft. In *Proceedings of the 35th European Rotorcraft Forum, Hamburg, Germany*.

Halbe, O., Haroch, M., Kleinitz, D., and Astruc, J. (2018). Development of Integrated Avionics Functions for External Situation Awareness in Civil Helicopter Missions. In *Proceedings of the 44th European Rotorcraft Forum, Delft, The Netherlands*.

Harris, F. D. (2007). No Accidents—That's the Objective; The 26th Alexander A. Nikolsky Lecture. *Journal of the American Helicopter Society*, 52(1):3–14.

Hart, S. G. (2006). Nasa-Task Load Index (NASA-TLX); 20 Years Later. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 50(9):904–908.

Hart, S. G. and Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. *Advances in Psychology*, 52(C):139–183.

Hartjes, S., Visser, H. G., and Pavel, M. D. (2009). Optimization of Simultaneous Non-Interfering Rotorcraft Approach Trajectories. In *Proceedings of the 35th European Rotorcraft Forum, Hamburg, Germany*.

Haverdings, H., Vorst, J. V., and Gille, M. (2006). Design and Execution of Piloted Simulation Tests of Steep Segmented and Curved Rotorcraft IFR Procedures at NLR. In *Proceedings of the 32nd European Rotorcraft Forum, Maastricht, The Netherlands*.

Heinemann, S., Müller, H. A., and Suleman, A. (2018). Toward Smarter Autoflight Control System Infrastructure. *Journal of Aerospace Information Systems*, 15(6):353–365.

Hess, R. A. and Gorder, P. J. (1990). Design and Evaluation of a Cockpit Display for Hovering Flight. *Journal of Guidance, Control, and Dynamics*, 13(3):450–457.

Hitomi, K. (1994). Automation - Its Concept and a Short History. *Technovation*, 14(2):121–128.

Hoh, R. H., Smith, J. C., and Hinton, d. A. (1987). The Effects of Display and Autopilot Functions on Pilot Workload for Single Pilot Instrument Flight Rules (SPIFR) Operations (NASA Contractor Report 4073). Technical report, National Aeronautics and Space Administration.

Hosman, R. J. A. W. and Stassen, H. G. (1998). Pilot's Perception and Control of Aircraft Motions. *IFAC Proceedings Volumes*, 31(26):311–316.

Inagaki, T. (2006). Design of Human-Machine Interactions in Light of Domain-Dependence of Human-Centered Automation. *Cognition, Technology & Work*, 8(3):161–167.

Inagaki, T. and Sheridan, T. B. (2019). A Critique of the SAE Conditional Driving Automation Definition, and Analyses of Options for Improvement. *Cognition, Technology & Work*, 21(4):569–578.

Itoh, J., Sakuma, A., and Monta, K. (1995). An Ecological Interface for Supervisory Control of BWR Nuclear Power Plants. *Control Engineering Practice*, 3(2):231–239.

Jenkins, M. P., Hogan, C., and Kilgore, R. (2015). Ecological Display Symbology to Support Pilot Situational Awareness During Shipboard Operations. In *Proceedings of the 2015 IEEE International Multi-Disciplinary Conference on Cognitive Methods in Situation Awareness and Decision, Orlando, Florida, United States*, pages 213–219.

Jeram, G. J. and Prasad, J. V. R. (2005). Open Architecture for Helicopter Tactile Cueing Systems. *Journal of the American Helicopter Society*, 50(3):238.

Joseph, C., Verma, R., and Chandana, C. R. (2012). Risk Perception and Safety Attitudes in IAF Rotary and Fixed Wing Aviators. *Indian Journal of Aerospace Medicine*, 56(2):9–20.

Jump, M., Alam, M., Rogers, J., and Eberle, B. (2018). Progress in the Development of a Time-to-Contact Autorotation Cueing System. In *Proceedings of the 44th European Rotorcraft Forum, Delft, The Netherlands*.

Kahana, A. (2015). Obstacle-Avoidance Displays for Helicopter Operations: Spatial Versus Guidance Symbologies. *Journal of Aerospace Information Systems*, 12(7):455–466.

Kaletka, J., Kurscheid, H., and Butter, U. (2005). FHS, the New Research Helicopter: Ready for Service. *Aerospace Science and Technology*, 9(5):456–467.

Kerler, M. and Erhard, W. (2014). Evaluation of Helicopter flight Missions with Intended Single Engine Operation. In *Proceedings of the 40th European Rotorcraft Forum, Southampton, United Kingdom*.

Kessler, C. (2015). Helicopter Emergency Medical Service: Motivation for Focused Research. *CEAS Aeronautical Journal*, 6(3):337–394.

Klomp, R., Borst, C., Van Paassen, R., and Mulder, M. (2016). Expertise Level, Control Strategies, and Robustness in Future Air Traffic Control Decision Aiding. *IEEE Transactions on Human-Machine Systems*, 46(2):255–266.

Kong, Z. and Mettler, B. (2013). Modeling Human Guidance Behavior Based on Patterns in Agent-Environment Interactions. *IEEE Transactions on Human-Machine Systems*, 43(4):371–384.

Kruskal, W. H. and Wallis, W. A. (1952). Use of Ranks in One-Criterion Variance Analysis. *Journal of the American Statistical Association*, 47(260):583.

Labun, J., Soták, M., Kurdel, P., and Draxler, D. (2011). Radar-Altimeter in the Function of Anticollision System. In *Proceedings of the 37th European Rotorcraft Forum, Cascina Costa, Italy*.

Lam, T. M. (2009). *Haptic Interface for UAV Teleoperation*. PhD thesis, Delft University of Technology.

Lantzsch, R., Greiser, S., Wolfram, J., Wartmann, J., Müllhäuser, M., Lüken, T., Döhler, H.-U., and Peinecke, N. (2012). ALLFlight: Helicopter Pilot Assistance in All Phases of Flight. In *Proceedings of the 38th European Rotorcraft Forum, Amsterdam, The Netherlands*.

Lantzsch, R., Hamers, M., and Wolfram, J. (2014). Flight Control and Handling Qualities Evaluations Considering Air Resonance. *Journal of the American Helicopter Society*, 59(2):022001.

Larish, J. F. and Flach, J. M. (1990). Sources of Optical Information Useful for Perception of Speed of Rectilinear Self-Motion. *Journal of Experimental Psychology: Human Perception and Performance*, 16(2):295–302.

Lim, Y., Gardi, A., Sabatini, R., Ramasamy, S., Kistan, T., Ezer, N., Vince, J., and Bolia, R. (2018). Avionics Human-Machine Interfaces and Interactions for Manned and Unmanned Aircraft. *Progress in Aerospace Sciences*, 102:1–46.

Lockett, H. A. (2010). *the Role of Tau-Guidance During Decelerative Helicopter Approaches*. PhD thesis, University of Liverpool.

Lopez, M. J., Tischler, M. B., Takahashi, M. D., Cheung, K. K., and Prasad, J. V. (2019). Development and Evaluation of a Full Flight Envelope Integrated Flight and Vibration Controller. *Journal of the American Helicopter Society*, 64(1):012001.

Lu, L., Jump, M., and Jones, M. (2013). Tau Coupling Investigation Using Positive Wavelet Analysis. *Journal of Guidance, Control, and Dynamics*, 36(4):920–934.

Lüken, T., Döhler, H.-U., and Lantzsch, R. (2010). ALLFlight-Fusing Sensor Information to Increase Helicopter Pilot's Situation Awareness. In *Proceedings of the 36th European Rotorcraft Forum, Paris, France*.

Lüken, T., Ernst, J. M., and Döhler, H. U. (2015). Virtual Cockpit Instrumentation Using Helmet Mounted Display Technology. In *Proceedings of the 41st European Rotorcraft Forum, Munich, Germany*.

Lüken, T., Schmerwitz, S., Halbe, O., Hamers, M., Bonel, R., and Ganille, T. (2019). Flight Evaluation Of Advanced Sbas Point-In-Space Helicopter Procedures Facilitating Ifr Access In Difficult Terrain And Dense Airspaces. In *Proceedings of the 45th European Rotorcraft Forum, Warsaw, Poland*.

Mämpel, M., Münsterer, T., Kramper, P., Kress, M., and Wegner, M. (2011). A New Approach to a Smart Helicopter Terrain Awareness and Warning System. In *Proceedings of the 37th European Rotorcraft Forum, Cascina Costa, Italy*.

McEwen, T. R., Flach, J. M., and Elder, N. C. (2014). Interfaces to Medical Information Systems: Supporting Evidenced Based Practice. In *Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics, San Diego, California, United States*, pages 335–340.

McRuer, D. T. and Jex, H. R. (1967). A Review of Quasi-Linear Pilot Models. *IEEE Transactions on Human Factors in Electronics*, HFE-8(3):231–249.

Miletović, I., Pavel, M. D., Stroosma, O., Pool, D. M., Van Paassen, M. M., Wentink, M., and Mulder, M. (2018). Eigenmode Distortion as a Novel Criterion for Motion Cueing Fidelity in Rotorcraft Simulation. In *Proceedings of the 44th European Rotorcraft Forum, Delft, The Netherlands*.

Miletović, I., Pool, D. M., Stroosma, O., Pavel, M. D., Wentink, M., and Mulder, M. (2017). The Use of Pilot Ratings in Rotorcraft Flight Simulation Fidelity Assessment. In *Proceedings of the American Helicopter Society 73rd Forum*, Fort Worth, Texas, United States.

Miller, D. G., De Brun, E. T., Lu, Y., and Hagar, M. P. C. (2010). V-22 Roll-on-Deck Control Law Design. *Journal of the American Helicopter Society*, 55(2):022004.

Miller, J. D., Godfroy-Cooper, M., and Szoboszlay, Z. P. (2019). Augmented-Reality Multimodal Cueing for Obstacle Awareness: Towards a New Topology for Threat-Level Presentation. In *Proceedings of the American Helicopter Society 75th Forum, Philadelphia, Pennsylvania, United States*.

Miller, R. G. J. (2012). *Simultaneous Statistical Inference*. Springer Series in Statistics. Springer New York.

Minor, J., Morford, Z., and Harrington, W. (2017). Sensor Data/Cueing Continuum for Rotorcraft Degraded Visual Environment Operations. In Sanders-Reed, J. J. N. and Arthur, J. T. J., editors, *Proceedings Volume 10196, Degraded Environments: Sensing, Processing, and Display 2017, SPIE Defense + Security*, volume 10197, page 101970Y, Anaheim, California, United States.

Mulder, M., Winterberg, R., van Paassen, M. M., and Mulder, M. (2010). Direct Manipulation Interfaces for In-Flight Four-Dimensional Navigation Planning. *International Journal of Aviation Psychology*, 20(3):249–268.

Müllhäuser, M. (2018). Tactile Cueing with Active Cyclic Stick for Helicopter Obstacle Avoidance: Development and Pilot Acceptance. *CEAS Aeronautical Journal*, 9(1):27–37.

Münsterer, T., Kress, M., and Klasen, S. (2013). Sensor Based 3D Conformal Cueing for Safe and Reliable HC Operation Specifically for Landing in DVE. In *Proceedings of SPIE 8737, Degraded Visual Environments: Enhanced, Synthetic, and External Vision Solutions 2013*, Baltimore, Maryland, United States.

Münsterer, T. R., Singer, B., Zimmermann, M., and Gestwa, M. (2018). NIAG DVE Flight Test Results of LiDAR Based DVE Support Systems. In Sanders-Reed, J. J. N. and Arthur, J. T. J., editors, *Proceedings Volume 10642, Degraded Environments: Sensing, Processing, and Display 2018, SPIE Defense + Security*, volume 106420, page 18, Orlando, Florida, United States.

Murrieta-Mendoza, A. and Botez, R. M. (2015). Methodology for Vertical-Navigation Flight-Trajectory Cost Calculation Using a Performance Database. *Journal of Aerospace Information Systems*, 12(8):519–532.

Naito, N., Itoh, J., Monta, K., and Makino, M. (1995). An Intelligent Human-Machine System Based on an Ecological Interface Design Concept. *Nuclear Engineering and Design*, 154(2):97–108.

Nascimento, F., Majumdar, A., Ochieng, W., and Schuster, W. (2014). Initial Evidence-Based Analysis of Risk Levels per Phases of Flight, Recency Requirements and Visual Approach Design in Nighttime Offshore Helicopter Operations. In *Proceedings of the 40th European Rotorcraft Forum, Southampton, United Kingdom*.

Nascimento, F. A. C. (2014). *Hazard Identification and Risk Analysis of Nighttime Offshore Helicopter Operations*. PhD thesis, Imperial College London, United Kingdom.

Negrin, M., Grunwald, A. J., and Rosen, A. (1991). Superimposed Perspective Visual Cues for Helicopter Hovering Above a Moving Ship Deck. *Journal of Guidance, Control, and Dynamics*, 14(3):652–660.

Nguyen, T., Sinha, A. K., Young, K., Laycock, K., and Hogan, P. (2003). An Intelligent System for the Pre-Mission Analysis of Helicopter Emergency Medical Services. In *Proceedings of the 29th European Rotorcraft Forum, Friedrichshafen, Germany*.

Okuno, Y., Kobayashi, K., and Ishii, H. (2016). Development of a Helicopter Operations Management System for Disaster Relief Missions. *Journal of the American Helicopter Society*, 61(1):1–9.

Onnasch, L. (2015). Crossing the Boundaries of Automation—Function Allocation and Reliability. *International Journal of Human-Computer Studies*, 76:12–21.

Onnasch, L., Wickens, C. D., Li, H., and Manzey, D. (2014). Human Performance Consequences of Stages and Levels of Automation: An Integrated Meta-Analysis. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 56(3):476–488.

Padfield, G., Clark, G., and Taghizad, A. (2005). How Long do Pilots Look Forward? Perspective Visual Guidance in Terrain-Hugging Flight. In *Proceedings of the 31st European Rotorcraft Forum, Florence, Italy*.

Padfield, G., Dequin, A.-M., Haddon, D., Kampa, K., Basset, P.-M., von Grünhagen, W., Haverdings, H., and McCallum, A. (1996). Predicting Rotorcraft Flying Qualities through Simulation Modelling. A Review of Key Results from GARTEUR AG06. In *Proceedings of the 22nd European Rotorcraft Forum, Brighton, United Kingdom*.

Padfield, G. D. (1981). Theoretical Model of Helicopter Flight Mechanics for Application to Piloted Simulation, RAE TR 81048. Technical report, Royal Academy of Engineering (RAE).

Padfield, G. D. (2007). *Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modelling*. American Institute of Aeronautics and Astronautics, 2nd edition.

Padfield, G. D. (2011). The Tau of Flight Control. *The Aeronautical Journal*, 115(1171):521–556.

Padfield, G. D. (2013). Rotorcraft Handling Qualities Engineering: Managing the Tension between Safety and Performance 32nd Alexander A. Nikolsky Honorary Lecture. *Journal of the American Helicopter Society*, 58(1):1–27.

Padfield, G. D., Clark, G., and Taghizad, A. (2007). How Long Do Pilots Look Forward? Prospective Visual Guidance in Terrain-Hugging Flight. *Journal of the American Helicopter Society*, 52(2):134–145.

Parasuraman, R. and Riley, V. (1997). Humans and Automation: Use, Misuse, Disuse, Abuse. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 39(2):230–253.

Parasuraman, R., Sheridan, T., and Wickens, C. (2000). A Model for Types and Levels of Human Interaction with Automation. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, 30(3):286–297.

Pavel, M. D., Shanthakumaran, P., Chu, Q., Stroosma, O., Wolfe, M., and Cazemier, H. (2020). Incremental Nonlinear Dynamic Inversion for the Apache AH-64 Helicopter Control. *Journal of the American Helicopter Society*, 65(2):022006.

Prinzel, L. J. and Risser, M. (2004). Head-Up Displays and Attention Capture. Technical report, (NASA TM-2004-213000), Hampton, Virginia, United States: NASA Langley Research Center.

Quaranta, G., Barakos, G., White, M., Pavel, M., and Mulder, M. (2018). NITROS: An Innovative Training Program to Enhance Rotorcraft Safety. In *Proceedings of the American Helicopter Society 74th Forum, Phoenix, Arizona, United States*.

Rakotomamonjy, T., Binet, L., and Müllhäuser, M. (2016). Onera-DLR Joint Research on Tactile Cueing for Reactive Obstacle Avoidance Dedicated to Low Speed Helicopter Maneuvers. In *Proceedings of the 42nd European Rotorcraft Forum, Lille, France*.

Rasmussen, J. (1983). Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and Other Distinctions in Human Performance Models. *IEEE Transactions on Systems, Man, and Cybernetics*, SMC-13(3):257–266.

Rataj, J., Bender, K., and Kohrs, R. (2000). A Helicopter Pilot Assistant System for Inflight Mission Planning. In *Proceedings of the 26th European Rotorcraft Forum, The Hague, The Netherlands*.

Riberon, O. (2016). Heli Clearvision a Revolutionairy Onboard Enhanced Flight Vision System. In *Proceedings of the 42nd European Rotorcraft Forum, Lille, France*.

Rolando, A., Rossi, F., Trainelli, L., Leonello, D., Maisano, G., and Redaelli, M. (2016). Demonstration and Testing of the Pilot Acoustic Indicator on a Helicopter Flight Simulator. In *Proceedings of the 42nd European Rotorcraft Forum, Lille, France*.

Roos, C. and de Reus, A. (2015). Effects of On Board Tablet Use During Helicopter Operations. In *Proceedings of the 41st European Rotorcraft Forum, Munich, Germany*.

Ruffier, F. (2005). Automatic Landing and Take Off at Constant Slope Without Terrestrial Aids. In *Proceedings of the 31st European Rotorcraft Forum, Florence, Italy*.

Ruffier, F. and Franceschini, N. (2004). Optic Flow Based AFCS for Rotorcraft Automatic Manoeuvring (Terrain Following, Take-Off and Landing). In *Proceedings of the 30th European Rotorcraft Forum, Marseille, France*.

Safety Regulation Group (2007). PAPER 2007/03 Helicopter Flight in Degraded Visual Conditions. Technical report, Civil Aviation Authority.

Sahasrabudhe, V., Horn, J. F., Sahani, N., Faynberg, A., and Spaulding, R. (2006). Simulation Investigation of a Comprehensive Collective-Axis Tactile Cueing System. *Journal of the American Helicopter Society*, 51(3):215–224.

Scaramuzzino, P. F., Pavel, M. D., Pool, D. M., Stroosma, O., Mulder, M., and Quaranta, G. (2021). Effects of Helicopter Dynamics on Autorotation Transfer of Training. *Journal of Aircraft*, 59(1):73–88.

Schmerwitz, S., Knabl, P., Lüken, T., and Döhler, H.-U. (2015a). Amplified Ego Motion Drift Indication for Helicopter Landing. In *Proceedings of the 41st European Rotorcraft Forum, Munich, Germany*.

Schmerwitz, S., Knabl, P. M., Lüken, T., and Döhler, H.-U. (2015b). Drift Indication for Helicopter Approach and Landing. In Sanders-Reed, J. and Arthur, J. J., editors, *Degraded Visual Environments: Enhanced, Synthetic, and External Vision Solutions 2015*, volume 9471. SPIE.

Schuchardt, B. I. (2019). Workload Reduction through Steering Wheel Control for Rotorcraft. *CEAS Aeronautical Journal*, 10(3):893–902.

Sheridan, T. B. (2011). Adaptive Automation, Level of Automation, Allocation Authority, Supervisory Control, and Adaptive Control: Distinctions and Modes of Adaptation. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, 41(4):662–667.

Sheridan, T. B. and Verplank, W. L. (1978). Human and Computer Control of Undersea Teleoperators (Technical Report).

Sinha, A. K., Kusumo, R., Laycock, K., and Hogan, P. (2002). An Automated System Framework for Pre-Mission Success Evaluation of Medical Emergency Helicopters Operations-Pre-Mission Success Evaluation Sub-Module. In *Proceedings of the 28th European Rotorcraft Forum, Bristol, United Kingdom*.

Smith, C. A. (2006). An Ecological Perceptual Aid for Precision Vertical Landings (MSc thesis), Massachusetts Institute of Technology.

Smith, C. A., Cummings, M., Forest, L. M., and Kessler, L. J. (2006). Utilizing Ecological Perception to Support Precision Lunar Landing. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 50(1):91–95.

Soneson, G. L., Horn, J. F., and Zheng, A. (2016). Simulation Testing of Advanced Response Types for Ship-Based Rotorcraft. *Journal of the American Helicopter Society*, 61(3):032011.

Stanton, N. A., Plant, K. L., Roberts, A. P., Allison, C. K., and Harvey, C. (2018). The Virtual Landing Pad: Facilitating Rotary-Wing Landing Operations in Degraded Visual Environments. *Cognition, Technology & Work*, 20(2):219–232.

Stanton, N. A., Salmon, P. M., Rafferty, L. A., Walker, G. H., Baber, C., and Jenkins, D. P. (2006). *Human Factors Methods: A Practical Guide for Engineering and Design*. Ashgate, Brookfield V, 2nd edition.

Stevens, J. M. G. F. and Vreeken, J. (2014). The Potential of Technologies to Mitigate Helicopter Accident Factors - An EHEST Study. Technical report, Netherlands Aerospace Centre (NLR).

Strauch, B. (2018). Ironies of Automation: Still Unresolved After All These Years. *IEEE Transactions on Human-Machine Systems*, 48(5):419–433.

Strohmaier, T., Lantzsch, R., and Greiser, S. (2010). Assisted Landing for Helicopters in Confined Areas. In *Proceedings of the 36th European Rotorcraft Forum, Paris, France*.

Stroosma, O., van Paassen, M. M., and Mulder, M. (2003). Using the SIMONA Research Simulator for Human-Machine Interaction Research. In *Proceedings of the AIAA Modeling and Simulation Technologies Conference and Exhibit*, Austin, Texas, United States.

Sunberg, Z. N., Miller, N. R., and Rogers, J. D. (2015). A Real-Time Expert Control System For Helicopter Autorotation. *Journal of the American Helicopter Society*, 60(2):022008.

Sweet, B. T. (2013). A Model of Manual Control with Perspective Scene Viewing. In *AIAA Modeling and Simulation Technologies (MST) Conference*, Boston, Massachusetts, United States.

Szoboszlay, Z., Davis, B., Fujizawa, B., Minor, M. J., Osmon, M. M., and Morford, M. Z. (2017). Degraded Visual Environment Mitigation (DVE-M) Program, Yuma 2016 Flight Trials in Brownout. *Proceedings of the American Helicopter Society 73rd Forum, Fort Worth, Texas, United States*.

Szoboszlay, Z., Fujizawa, B. T., Ott, C. R., Savage, J. C., Goodrich, S. M., McKinley, R. A., and Soulup, J. R. (2014). 3D-LZ Flight Test of 2013: Landing an EH-60L Helicopter in a Brownout Degraded Visual Environment. In *Proceedings of the American Helicopter Society 70th Forum*, Montréal, Québec, Canada.

Szoboszlay, Z. P., McKinley, R. A., Braddom, L. S. R., Harrington, W. W., Burns, H. N., and Savage, J. C. (2010). Landing an H-60 helicopter in Brownout Conditions Using 3D-LZ Displays. In *Proceedings of the American Helicopter Society 66th Forum*, Phoenix, Arizona, United States of America.

Takahashi, M. D., Abershitz, A., Rubinets, R., and Whalley, M. S. (2013). Evaluation of Safe Landing Area Determination Algorithms for Autonomous Rotorcraft Using Site Benchmarking. *Journal of the American Helicopter Society*, 58(3):032007.

Takahashi, M. D., Goerzen, C. L., Whalley, M. S., Hossein Mansur, M., Schulein, G. J., Minor, J. S., Ott, C. R., and Morford, Z. G. (2018). Full-Scale Flight-Test Results for a Rotorcraft Safe Landing Area Determination Algorithm for Autonomous and Piloted Landing Approaches. *Journal of the American Helicopter Society*, 63(4):042001.

Takahashi, M. D., Whalley, M. S., Mansur, H., Ott, C. R., Minor, J. S., Morford, Z. G., Goerzen, C. L., Schulein, G. J., Ott, L. C., Minor, M. J. S., and Morford, M. Z. G. (2017). Autonomous Rotorcraft Flight Control with Multilevel Pilot Interaction in Hover and Forward Flight. *Journal of the American Helicopter Society*, 62(3):032009.

Task Group HFM-162 (2012). Rotary-Wing Brownout Mitigation: Technologies and Training. Technical report, (RTO-TR-HFM-162), Brussels, Belgium: NATO.

Taylor, R. M. (1989). Situational Awareness Rating Technique (SART): The Development of a Tool for Aircrew Systems Design. In *Proceedings of the AGARD AMP Symposium on Situational Awareness in Aerospace Operations, CP478*, Copenhagen, Denmark.

Thomas, A. and Voinchet, O. (2019). Performance Class 2 With Defined Limited Exposure for Offshore Operation: Use Case and Perspectives. In *Proceedings of the 45th European Rotorcraft Forum, Warsaw, Poland*.

Thorndycraft, D. C. and Craig, G. (2004). Trial Iguana-A Flight Evaluation of Conformal Symbology Using Display Night Vision Goggles. In *Proceedings of the 30th European Rotorcraft Forum, Marseille, France*.

Trapsilawati, F., Wickens, C., Chen, C.-H., and Qu, X. (2017). Transparency and Conflict Resolution Automation Reliability in Air Trffic Control. In *Proceedings of the 19th International Symposium on Aviation Psychology*, Dayton, Ohio, United States.

Tristrant, D. and Greiller, M. (2016). What Technologies to Improve Helicopter Flight Safety? In *Proceedings of the 42nd European Rotorcraft Forum, Lille, France*.

Truong, Q. H., Rakotomamonjy, T., and Biannic, J.-M. (2016). Visually Controlled Helicopter: A Control Scheme for Helicopter Landing. In *Proceedings of the 42nd European Rotorcraft Forum, Lille, France*.

Vadlamani, A. K. and De Haag, M. U. (2009). Terrain Elevation Data Integrity Monitor and Referenced Navigation. *Journal of Aerospace Computing, Information and Communication*, 6(4):307–327.

van der Meer, B., Yilmaz, D., Stoop, J. A. A. M., and Pavel, M. D. (2011). Helicopter Safety: A Contradiction in Terms? – an Overview of the Status at the Beginning of the 21st Century. In *Proceedings of the 37th European Rotorcraft Forum, Cascina Costa, Italy*.

van Dijk, H., van de Merwe, K., and Zon, R. (2011). A Coherent Impression of the Pilots' Situation Awareness: Studying Relevant Human Factors Tools. *The International Journal of Aviation Psychology*, 21(4):343–356.

Van Paassen, M. M., Borst, C., Ellerbroek, J., Mulder, M., and Flach, J. M. (2018). Ecological Interface Design for Vehicle Locomotion Control. *IEEE Transactions on Human-Machine Systems*, 48(5):541–555.

Varnes, D. J., Duren, R. W., and Wood, E. R. (2000). An Onboard Warning System to Prevent Hazardous "Vortex Ring State" Encounters. In *Proceedings of the 26th European Rotorcraft Forum, The Hague, The Netherlands*.

Veillette, P. (2001). Human Error Cited as Major Cause of US Commercial EMS Helicopter Accidents. *Flight Safety Digest*, 20(4-5):1–38.

Vicente, K. J. (1999). *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work*. Lawrence Erlbaum Associates, Mahwah, New Jersey, United States.

Vicente, K. J. and Rasmussen, J. (1990). The Ecology of Human-Machine Systems II: Mediating "Direct Perception" in Complex Work Domains. *Ecological Psychology*, 2(3):207–249.

Vicente, K. J. and Rasmussen, J. (1992). Ecological Interface Design: Theoretical Foundations. *IEEE Transactions on Systems, Man, and Cybernetics*, 22(4):589–606.

Viertler, F. and Hajek, M. (2017). Evaluation of Visual Augmentation Methods for Rotorcraft Pilots in Degraded Visual Environments. *Journal of the American Helicopter Society*, 62(1):012005.

Viertler, F., Krammer, C., and Hajek, M. (2015). Analyzing Visual Clutter of 3D-Conformal HMD Solutions for Rotorcraft Pilots in Degraded Visual Environment. In *Proceedings of the 41st European Rotorcraft Forum, Munich, Germany*.

Viertler, F. X. (2017). *Visual Augmentation for Rotorcraft Pilots in Degraded Visual Environment*. Ph.D. dissertation, Fakultät für Maschinenwesen, Technische Universität München, Munich, Germany.

Villeneuve, E., Volat, C., and Ghinet, S. (2020a). Numerical and Experimental Investigation of the Design of a Piezoelectric De-Icing System for Small Rotorcraft Part 1/3: Development of a Flat Plate Numerical Model with Experimental Validation. *Aerospace*, 7(5):62.

Villeneuve, E., Volat, C., and Ghinet, S. (2020b). Numerical and Experimental Investigation of the Design of a Piezoelectric De-Icing System for Small Rotorcraft Part 2/3: Investigation of Transient Vibration during Frequency Sweeps and Optimal Piezoelectric Actuator Excitation. *Aerospace*, 7(5):49.

Villeneuve, E., Volat, C., and Ghinet, S. (2020c). Numerical and Experimental Investigation of the Design of a Piezoelectric De-Icing System for Small Rotorcraft Part 3/3: Numerical Model and Experimental Validation of Vibration-Based De-Icing of a Flat Plate Structure. *Aerospace*, 7(5):54.

von Grünhagen, W., Schönenberg, T., Lantzsch, R., Lusardi, J. A., Lee, D., and Fischer, H. (2014). Handling qualities studies into the interaction between active sidestick parameters and helicopter response types. *CEAS Aeronautical Journal*, 5(1):13–28.

Vreeken, J. and Haverdings, H. (2013). Helicopter Flight in a Degraded Visual Environment. In *Proceedings of the 39th European Rotorcraft Forum, Moscow, Russia*.

Vreeken, J., Haverdings, H., and Joosse, M. (2013). Helicopter Flight in a Degraded Visual Environment. Technical report, Netherlands Aerospace Centre (NLR).

Waanders, T., Qian, Q., Scheiblhofer, R., Koerber, R., Giere, A., Schubert, F., and Ziegler, V. (2012). Miniaturized and Low-Cost Obstacle Warning System. In *Proceedings of the 38th European Rotorcraft Forum, Amsterdam, The Netherlands*.

Waanders, T., Qian, Q., Scheiblhofer, R., van Noort, B., Koerber, R., Giere, A., Schubert, F., and Ziegler, V. (2013). Helicopter Miniaturized and Low-Cost Obstacle Warning System. *CEAS Aeronautical Journal*, 4(4):373–383.

Waanders, T., Roth, F., Singer, B., Fadljevic, D., Plorin, J., Shpak, M., Hasharoni, O., and Limonad, A. (2019). Integration and Test of a Degraded Visual Environment System on H145. In *Proceedings of the 45th European Rotorcraft Forum, Warsaw, Poland*.

Waanders, T., Scheiblhofer, R., Qian, Q., van Noort, B., Ziegler, V., Schubert, F., and Koerber, R. (2015). Helicopter Rotorstrike Alerting System. In *Proceedings of the 41st European Rotorcraft Forum, Munich, Germany*.

Walch, M., Mühl, K., Kraus, J., Stoll, T., Baumann, M., and Weber, M. (2017). From Car-Driver-Handovers to Cooperative Interfaces: Visions for Driver–Vehicle Interaction in Automated Driving. In Meixner, G. and Müller, C., editors, *Automotive User Interfaces. Human–Computer Interaction Series*, pages 273–294. Springer, Cham.

Walko, C. and Schuchardt, B. (2019). Increasing Helicopter Flight Safety in Maritime Operations With a Head Mounted Display. In *Proceedings of the 45th European Rotorcraft Forum, Warsaw, Poland*.

Walters, R., McCandless, J., and Feigh, K. M. (2020). Pilot Cueing for Rotorcraft Shipboard Landings. In *AIAA Scitech 2020 Forum, Orlando, Florida, United States*. American Institute of Aeronautics and Astronautics (AIAA).

Warren, R. (1982). Optical Transformation During Movement: Review of the Optical Concomitants of Egomotion. Technical report, (AFOSR-TR-82-1028), Columbus, Ohio, United States: Ohio State University, Department of Psychology, Aviation Psychology Laboratory.

Whalley, M. S. and Howitt, J. (2002). Optimization of Partial Authority Automatic Flight Control Systems for Hover/Low-Speed Maneuvering in Degraded Visual Environments. *Journal of the American Helicopter Society*, 47(2):79–89.

Wickens, C. D., Rice, S., Keller, D., Hutchins, S., Hughes, J., and Clayton, K. (2009). False Alerts in Air Traffic Control Conflict Alerting System: Is There a "Cry Wolf" Effect? *Human Factors*, 51(4):446–462.

Wiener, E. L. and Curry, R. E. (1980). Flight-Deck Automation: Promises and Problems. *Ergonomics*, 23(10):995–1011.

Windridge, D., Shaukat, A., and Hollnagel, E. (2013). Characterizing Driver Intention via Hierarchical Perception-Action Modeling. *IEEE Transactions on Human-Machine Systems*, 43(1):17–31.

Yamaguchi, M. and Proctor, W. R. (2010). Compatibility of Motion Information in Two Aircraft Attitude Displays for a Tracking Task. *The American Journal of Psychology*, 123(1):81.

Zhou, C., Lu, Y., and Huang, S. (2019). Helicopter Forward-Looking Warning Method based on Image Matching for Urban Low-Altitude Flight. In *Proceedings of the 45th European Rotorcraft Forum, Warsaw, Poland*.

Zijlstra, F. R. H. and Van Doorn, L. (1985). The Construction of a Scale to Measure Perceived Effort. Technical report, Delft University of Technology.

Zimmermann, M., Gestwa, M., Klasen, S., and Lederle, A. (2018). Avoiding Obstacles during Approach: DVE-Mitigation Flight Trials and Beyond. In *Proceedings of the Americal Helicopter Society 74th Forum, Phoenix, Arizona, United States*.

Zimmermann, M., Gestwa, M., König, C., Wolfram, J., Klasen, S., and Lederle, A. (2019). First Results of LiDAR-Aided Helicopter Approaches During NATO DVE-Mitigation Trials. *CEAS Aeronautical Journal*, 10(3):859–874.

Zimmermann, M. and König, C. (2016). Integration of a Visibility Graph Based Path Planning Method in the ACT/FHS Rotorcraft. *CEAS Aeronautical Journal*, 7(3):391–403.

Zimmermann, M. and Peinecke, N. (2015). Dynamic Landing Site Ranking for Helicopter Emergency Situations. In *Proceedings of the 41st European Rotorcraft Forum, Munich, Germany*.

Zoppitelli, P., Mavromatis, S., Sequeira, J., Anoufa, G., Belanger, N., and Filias, F.-X. (2018). Embedding Intelligent Image Processing Algorithms: the New Safety Enhancer for Helicopters Missions. In *Proceedings of the 44th European Rotorcraft Forum, Delft, The Netherlands*.

Acknowledgements

Where to start... what a daunting task this is, trying to find words to thank the people who have made this incredible journey possible. There are those who were actively involved in my work, and those who cheered me on from the sideline. Those who supported me content-wise, methodically, emotionally, or a combination of all. If our paths crossed at all in the past years, I am certain you will be able to find yourself in at least one, if not more of the following situations and occasions.

Thank you to my supervisory team, comprising of members from both TU Delft and PoliMi. Thank you for introducing me to being a PhD at TU Delft, for supporting me in finding structure and purpose, and for providing both encouraging feedback and harsh comments. The papers that I published in the course of this PhD contain five different co-authors, and each of them provided different support, be it challenging or supporting. In the end, it is this feedback that formed my academic thinking in the past years, and I am grateful to have received it from such a diverse supervisory team.

Thank you to everyone in NITROS, the project that defined my PhD and many activities in it. I would like to thank the NITROS coordinators and organisational support staff for providing insights into the wider research environment I was working in. Thank you for providing interesting and engaging activities throughout the years, be it summer schools, webinars, or project-related meetings. I never had the feeling I was working alone in a small room without windows, somewhere detached from the rest of the world, and part of the reason for that were the activities and stimuli originating from NITROS. I particularly want to thank my co-"Early-Stage-Researchers" for making me feel like I'm not alone in all of this, for sharing laughs and frustrations, and for all the support I received in particular from the Italian and Milan-based colleagues during my rather short stay at PoliMi. While I was happy to be home in the situation we found ourselves in Spring 2020, I wish I could have spent more time with you in Milan.

Jumping back to the Netherlands, I would like to wholeheartedly thank all the staff members at TU Delft who were not directly involved with my PhD, but who contributed to its success nonetheless. This happened either through direct support or by providing me with an environment in which I was stimulated to investigate, question, and discuss many different ideas and topics. An especially loud "thank you" belongs to the SIMONA support staff for ensuring that my code would run and that my experiments could take place in sometimes extremely challenging situations. In addition to this, it cannot be understated how the quick and efficient organisational and IT-related support contributed to a great working environment.

I would like to thank all helicopter pilots who took the time and energy to participate in my experiments. You provided valuable feedback and ideas during the

experiments and beyond, and even invited me to one of your flight schools. Without your help and participation, my work would not have been possible.

To all other PhD students that I crossed path with, be it at the very beginning, the very end, or anytime in between my time in Delft: Thank you so, so much for making me feel like I belong, and for becoming colleagues and friends in a new country. Thank you for uncountable coffee corner talks and discussions, for much needed lunch breaks at the faculty or at the sports centre, and for forming a mutual support group for question, problems, and issues large and small. Thank you for providing a fun and engaging culture around the faculty and around PhD defences, including gifts, commemorative plaques, and any other "unproductive" office activities that are yet so vital for a meaningful, rich, and complete PhD experience. It was sad to see many elements of this culture disappearing during the unavoidable work-from-home time the past years, but I hope and I am confident that future generations will be able to enjoy this culture once again, and hopefully throughout their whole PhD trajectory.

Before continuing, I want to spend some time recalling particular events that will always stay dear to me. The first meetings I want to mention, both temporally and in their frequency, are the ones with NITROS colleagues and partners across a multitude of events. Conferences, summer schools, NITROS meetings: it was great to have a network of colleagues and friends no matter what scientific event I attended, and to further get to know my "collaborators" with every meeting. My personal highlight has to be the AIAA Scitech conference in January 2020 in Florida: Spending time there with so many colleagues and friends across so many disciplines and experience levels was invigorating. I am particularly thankful that I was able to have an experience like this before the events of 2020 unfolded, and made this kind of activity impossible for a long time.

Next to these big events, there were many smaller, yet equally important events that deserve mention. Thank you for all the BBQ's (C&S and otherwise), VrijMiBo's, coffees, birthday parties, board game evenings and weekends, drinks and dinners, and everything in between. These were the events that made my PhD journey alive, and that provided the foundation for genuine friendships that developed over the course of the last years. I fondly recall attending weddings in China and in Italy, making quite a few travels to Belgium (not only for the beer), spending excessive amounts of time standing bent over a world map of the Mediterranean, and finding spicy chicken sandwiches all across the world. Thank you to everyone who played a big or small part in making these events become reality.

I would not be the person I am today without my friends in Germany and beyond, in person or virtual. From elementary school to high school to university, I am tremendously grateful for the personal connections that developed and endured until today. I cherish everything we do, from quiet walks in the forest to partying through the night, from cosy talks over tea and coffee to having a blast at music festivals, from talking about our daily struggles to philosophising about the most fantastical ideas, and from serious heart-to-heart talks to gaming the nights away. You provide joy, connection, and support whenever I need it. Thank you for being there for me.

Last but not least, I cannot write acknowledgements without focusing on my family. Dad, thank you for supporting me in everything I ever did, unquestioningly and relentlessly encouragingly, for as long as you could. I know what you would have said after these years, just like after every milestone in my life. Finding my way into aerospace, going abroad, finding myself, finding love, becoming a father myself, and now finishing this year-long project... I know you would have been thrilled to experience this with me. I can hear you say the words that you would have said, and that you said so many times before. Thank you for instilling this certainty in me, I appreciate it more and more with every passing year.

Mom, thank you for always providing that anchor I occasionally needed back home. Thank you for supporting me in every decision and at any point, no matter where they would lead me, be that the US, Germany, or the Netherlands. You have been a constant in my life since I can think, and it made me into the person I am today.

It seems almost impossible to find words that adequately describe my feeling of thankfulness for my immediate family, my wife and son. Throughout all of this journey, all its fun and its hardships, all its elation and frustration, through all the time I spent with you hurled up in an apartment in Delft or the time I spent apart from you, your love and support never wavered. I literally would not have had this position if it would not have been for your help, and I could not have made it without your never-ending support. We went through this journey together. We mastered every hurdle the world threw at us, and it made us stronger in the end. Thank you, from the bottom of my heart. I love you.

Yours is a long road, my friend, and it stretches on to places beyond imagining. With your every step, these grand adventures shall grow more distant and faint. And there may come a day when you forget the faces and voices of those you have met along the way. On that day, I bid you remember this...

That no matter how far your journey may take you, you stand where you stand by virtue of the road that you walked to get there. For in times of hardship, when you fear you cannot go on... the joy you have known, the pain you have felt, the prayers you have whispered and answered... they shall ever be your strength and your comfort.

— G'raha Tia, *Final Fantasy XIV*

Curriculum Vitæ

Daniel Friesen

10-08-1989	Born in Wuppertal, Germany

Education

2017–2022 Ph.D. Aerospace Engineering
Delft University of Technology, The Netherlands
Politecnico di Milano, Italy
Thesis: Understanding the Use of Automation in Helicopters
Promotors: dr. M. D. Pavel, prof. P. Masarati, dr.ir. C. Borst

2014–2017 M.Sc. Mechanical and Process Engineering
Technical University of Darmstadt, Germany

2015–2016 Graduate Certificate Aerospace System Engineering (study exchange)
University of Illinois at Urbana-Champaign, United States of America

2012–2014 B.Sc. Industrial Engineering
Technical University of Darmstadt, Germany

2010–2014 B.Sc. Mechanical and Process Engineering
Technical University of Darmstadt, Germany

Experience

2021–today Lecturer & Researcher
Amsterdam University of Applied Sciences, The Netherlands

2017–2021 PhD Candidate & Researcher
Delft University of Technology, The Netherlands
Politecnico di Milano, Italy

2016–2017 M.Sc. thesis collaboration
2014–2015 Internship
Lufthansa Technik AG, Frankfurt a.M., Germany

List of Publications

6. **Friesen, D.**, Borst, C., Pavel, M. D., Masarati, P., Mulder, M. (2022) Human-Automation Interaction for Helicopter Flight: Comparing Two Decision-Support Systems for Navigation Tasks. Journal of Aerospace Science and Technology, 129(10):107719.

5. **Friesen, D.**, Borst, C., Pavel, M. D., Stroosma, O., Masarati, P., and Mulder, M. (2021). Design and Evaluation of a Constraint-Based Head-Up Display for Helicopter Obstacle Avoidance. Journal of Aerospace Information Systems, 18(3):80–101.

4. Meima, N., Borst, C., **Friesen, D.**, and Mulder, M. (2021). Augmented Reality to Support Helicopter Pilots Hovering in Brownout Conditions. Available online as part of the Master of Science Thesis of the same name by N. Meima, Education Repository of Delft University of Technology.

3. **Friesen, D.**, Pavel, M. D., Borst, C., Stroosma, O., Masarati, P., and Mulder, M. (2020). Design and Evaluation of a Constraint-Based Head-Up Display for Helicopter Obstacle Avoidance During Forward Flight. AIAA Scitech 2020 Forum, Orlando, Florida, United States of America.

2. **Friesen, D.**, Pavel, M. D., Borst, C., Masarati, P., and Mulder, M. (2019). Pilot Model Development and Human Manual Control Considerations for Helicopter Hover Displays. Proceedings of the 45th European Rotorcraft Forum, Warsaw, Poland.

1. Morelli, M., Ghiasvand, S., Nabi, H. N., Taymourtash, N., Masarati, P., Quaranta, G., Barakos, G., Fasiello, S., Huercas, S., White, M., Akel, E., Yu, Y., **Friesen, D.**, Scaramuzzino, P. F., and Pavel, M. D. (2018). Assessment of the Feasibility of an Extended Range Helicopter Operational Standard for Offshore Flights. Proceedings of the 44th European Rotorcraft Forum, Delft, The Netherlands.


COURSE
A/T ARM
IAS/MACH
V NAV
HEADING
L NAV
ALTITUDE
VERT SPEED
A/P ENGAGE
CMD A
CWS A
DISENGAGE
VOR LOC
APP
HDG SEL
LVL CHG
SPEED
N1
F/D
OFF
ALT HLD
V/S
RADIO
MINS
BARO
FPV
MTRS
MAP
PLN
VOR 1
ADF 1
VOR 2
ADF 2
WXR
TERR