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Design and Evaluation of a Constraint-Based Head-Up Display for Helicopter Obstacle Avoidance During Forward Flight

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This paper aims to reveal the effect of different display design principles in the helicopter domain. Two different obstacle avoidance support displays are evaluated during low-altitude, forward helicopter flight: a baseline Head-Up Display (HUD) is complemented either by a conventional advisory display, or a constraint-based display inspired by Ecological Interface Design. The latter has only been sparsely applied in the helicopter domain. It is hypothesized that the advisory display reduces workload, increases situation awareness, and improves performance measures in nominal obstacle avoidance situations, while the constraint-based display increases the resilience of the pilot-vehicle system towards unexpected, off-nominal situations. Twelve helicopter pilots with varying flight experience participated in an experiment in the SIMONA Research Simulator at Delft University of Technology. Contrary to expectations, the experiment revealed no significant effects of the displays on any of the dependent measures. However, there was a trend of decreasing pilot workload and increasing situation awareness when employing any of the support displays, compared to the baseline HUD. Pilots preferred the advisory display in nominal and the constraint-based display in off-nominal situations, reproducing similar findings from research in the fixed-wing domain. The relatively short time-frame and monotony of the control-task, an already cue-rich baseline HUD condition, and similarity between the displays possibly prohibited revealing larger differences between conditions. Future research will analyze the obstacle avoidance trajectories of this experiment, possibly revealing changes in control strategy caused by the displays, even when the lumped performance measures are similar. A follow-up experiment will focus on a longer task time-frame, more variable situations, and a truly ecological display to investigate the effect of applying Ecological Interface Design and different automation systems in the helicopter domain.

Nomenclature

d_0	=	Display design variable; minimum distance for which the maneuver constraints are still valid
g	=	Gravitational constant
h_{limit}	=	Maximum altitude difference achievable within d_0 at the given forward speed V
m	=	Mass of the helicopter
p	=	Probability value of employed statistical tests

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P_{req}	=	Power required at the given forward speed V
P_{max}	=	Maximum engine power
$P_{available}$	=	Power available at the given forward speed V
V	=	Forward speed of the helicopter
x_τ	=	Pilot reaction distance
$x_{maneuver}$	=	Distance needed to attain maximum effective climb angle γ_{lim}
α	=	Significance level of statistical tests
γ_{limit}	=	maximum effective climb angle
γ_{max}	=	maximum climb angle
$\dot{\gamma}_{max}$	=	Maximum flight path quickness
$\gamma_{obstacle}$	=	Angle between the top of an obstacle's safety zone and the horizon, seen from an approaching helicopter
τ_p	=	Pilot reaction onset delay
χ^2	=	Chi-squared distribution, utilized in two-way Friedman test statistics
Ω	=	Main rotor speed

I. Introduction

This paper investigates the effect of two different helicopter Head-Up Display (HUD) obstacle avoidance displays on safety, task performance, and pilot workload during forward flight. One display is a conventional **advisory display**. The other one is a **constraint-based display**, which is inspired by Ecological Interface Design (EID) principles. The philosophy of applying EID principles to vehicle control has been summarized by Van Paassen et al. [1]. 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 controller to choose the most appropriate action. This paper's constraint-based display takes inspiration from ecological interfaces by visualizing the flight path constraint of a pull-up and climb-over maneuver to the pilot via a maximum effective climb angle (in a limited forward distance). Conventional advisory systems 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 maneuver specification for the pilot to follow, are examples of conventional advisory displays.

Research in the fixed-wing domain by Borst et al. [2] has shown that in short operational time-scales, pilots generally prefer conventional advisory displays in nominal situations, but that their preference shifts towards ecological displays in case of off-nominal, unexpected situations. As of now, ecological design principles have only been sparsely applied in the helicopter domain, for example for shipboard landing [3]. In October and November 2019, a human-in-the-loop experiment has been conducted in TU Delft's SIMONA Research Simulator (SRS) to evaluate two obstacle avoidance displays in different visibility conditions and during unexpected, off-nominal events. This experiment investigates whether the same shift of preference can be observed in the helicopter domain, even though the vehicle dynamics and control strategies differ between helicopters and fixed-wing aircraft.

This obstacle avoidance scenario is chosen for three reasons. Firstly, external environment awareness plays a major role in historic helicopter accidents [4, 5]. Displays that support pilots in avoiding approaching obstacles can reduce the danger of collision. Secondly, the required climb-over maneuver 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 HEMS operations, low altitude flight during search-and-rescue). It is therefore applicable to a broad range of operational environments. Lastly, it resembles the obstacle avoidance task employed by Borst et al., which will enable the comparison of the high-level results between helicopter and fixed-wing display effects.

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. Especially in the helicopter domain, with its high number of unknowns in many missions, for example Helicopter Emergency Medical Services (HEMS) or search and rescue, improving resilience is crucial.

The paper is structured as follows. Section II provides background information on existing obstacle avoidance support displays and the EID framework. Section III discusses the design of the displays. The experiment methodology is elaborated on in Section IV. Section V shows the results, which are discussed in Section VI. Section VII contains a conclusion to this work and an outlook to possible improvements and future research activities.

II. Background

Loss of situation awareness (by being unaware of obstacles in the flight path, or caused by bad visibility/weather) plays a role in more than 30 % of 487 helicopter accidents analyzed by the European Helicopter Safety Team [4, 5]. Flying in a Degraded Visual Environment decreases the Usable Cue Environment (UCE)-Level, which in turn leads to a decrease in Handling Qualities [6]. Head-Up Display technology has been applied successfully to increase the UCE-level by supplying the pilot with an additional perspective overlay based on data recorded by on-board sensor suits and/or offline maps [7, 8].

Guidance systems (e.g., maneuver 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 [9]. In this case, the outside view was distracting the pilot from the two-dimensional cue-following task. Current concepts of obstacle avoidance systems provide maneuvering advice [10], increase the perception of obstacles by magnifying them visually [8, 11], or provide combined visual/auditory cues [12].

Ecological interfaces aim to provide information about the controlled system and its environment such that the constraints on possible operator actions become easily apparent [13, 14]. Visualized constraints are physical (e.g., avoiding flight into terrain) and intentional (e.g., staying above a predetermined safe altitude) [15].

As previously stated, ecological interfaces have shown to be less desired by fixed-wing pilots during obstacle avoidance tasks in nominal flight situations [2]. Conversely, in off-nominal situations including system failures, pilots preferred ecological interfaces. There are some differences between the fixed-wing and helicopter maneuver: while fixed-wing obstacle avoidance trajectory decision making can usually take tens of seconds or even minutes, the decision process 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 stabilization and control, whereas fixed-wing control 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.

To relate this paper's displays to other helicopter display types, a diagram to categorize helicopter display systems of Minor et al. is reproduced in Table 1 [9]. 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), or the display provides guidance cues, i.e. an optimal target maneuver trajectory. This paper'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 categories I and IV, as it provides more information to the pilot than just primary pilotage information, but it doesn't provide a direct or discrete maneuver 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 climb-over maneuver.

Table 1 Categories of display systems to support helicopter control, reproduced from Minor et al. [9].

	Displayed Image Primary Pilotage (DIPP)	Guidance Algorithm Primary Pilotage (GAPP)
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

III. 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 maneuver constraint calculations on which the displays are based. Lastly, the two employed displays (advisory and constraint-based) are elaborated upon. The Messerschmitt-Bölkow-Blohm Bo105 Helicopter serves as a reference for power calculations [16].

A. Baseline Head-Up Display

The baseline HUD is a control variable, shown to the pilot in every experiment condition, depicted in Figure 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.

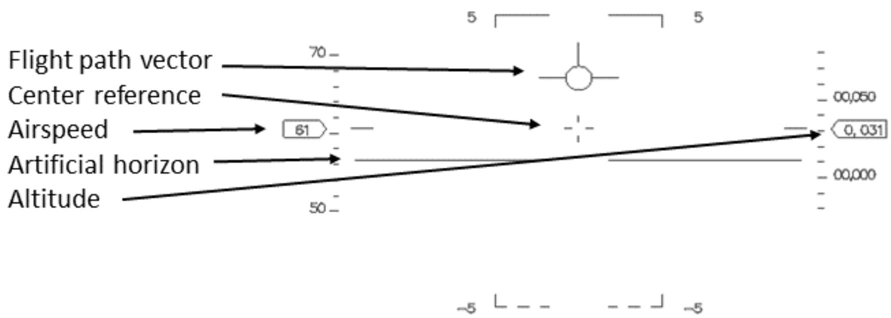

Fig. 1 Baseline HUD elements.

The obstacle detection and contour drawing system visualizes 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 2. Its concept is based on systems described by Münsterer et al. [8], which draw warning contours around dangerous obstacles like windmills. Its detection distance is set to 300 meters, and kept constant between the two visibility conditions. This distance is reduced to 50 meters in case of an unexpected, off-nominal situation.

B. 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 climb angle γ_{max} based on available power, an assumed pilot delay τ_p, and model dynamics restrictions. γ_{limit} is determined by calculating the maximum height gain h_{limit} that can be achieved within a distance of d_0. Figure 3 depicts the parameters of the climb-over maneuver constraint calculation, with an obstacle depicted at a distance of d_0. Table 2 contains constant parameter values for the following calculation.

The distance d_0 is a display design parameter. It represents the minimum distance to an obstacle at which the calculated maneuver constraint is still valid. If an obstacle is further away than d_0, γ_{limit} is a conservative estimate. With an obstacle directly at d_0, it represents the exact maneuver limit, taking into consideration the pilot and model delays. At distances smaller than d_0, it overestimates the maneuver possibilities of the aircraft within the given distance.

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

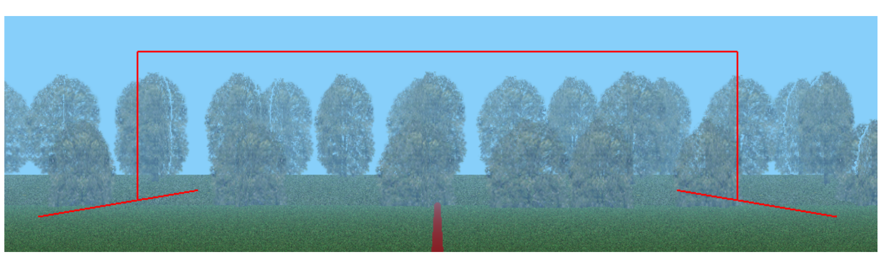

Fig. 2 Red box around an approaching obstacle in the HUD, drawn by the obstacle detection and contour drawing system.

Table 2 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 maneuvering, 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
$\dot{\gamma}_{max}$	Maximum flight path quickness	5°/s
d_0	Minimum maneuver distance	120 m
Ω	Main rotor speed	44.4 rad/s ≈ 424 rpm

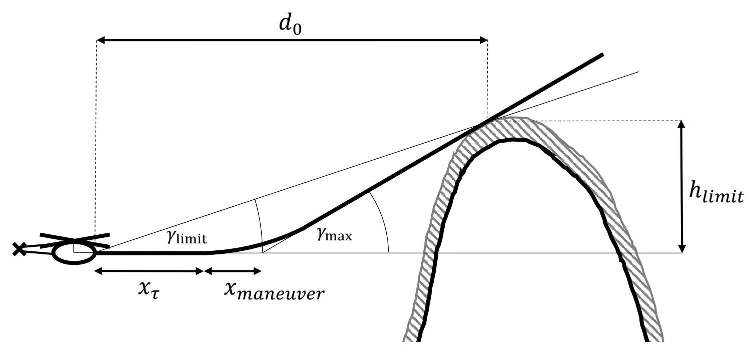

Fig. 3 Display parameters of the climb-over maneuver over an obstacle's safety zone.

into an increase in potential energy (climbing). The mass m of the helicopter is assumed to be $m = 2500$ kg. Equation 1 details how γ_{max} is calculated.

$$\tan(\gamma_{max}) = \frac{\left(\frac{P_{available}}{mg}\right)}{V} \tag{1}$$

At a forward speed of 60 kts, 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 it takes the pilot to react to an approaching obstacle, x_τ, and the distance that is needed to attain the maximum climb angle, $x_{maneuver}$. x_τ is calculated by multiplying the pilot reaction time τ_p with the current forward speed V, Equation 2. τ_p is assumed to be 0.8 s, based on measurements during a reaction-onset experiment performed by Hosman and Stassen [17]. The maneuver distance $x_{maneuver}$ is calculated based on Equation 3, and is based on the maximum climb path angle change $\dot{\gamma}_{max} = 5°$, which is assumed to be constant.

$$x_\tau = \tau_p \cdot V \tag{2}$$

$$x_{maneuver} = \frac{V}{\dot{\gamma}_{max}} \cdot \left(\frac{1}{\sin(\gamma_{max})} - \frac{\cos(\gamma_{max})}{\sin(\gamma_{max})}\right) \tag{3}$$

The maximum effective climb angle γ_{limit} can now be calculated via equation 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° pitch up at zero forward speed. γ_{limit} is therefore the maneuver limitation at the current forward speed, which is not necessarily the scenario target speed of 60 knots.

$$\tan(\gamma_{limit}) = \tan(\gamma_{max})\left(1 - \frac{x_\tau + x_{maneuver}}{d_0}\right) \tag{4}$$

C. 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 will provide a discrete suggestion when to initiate a climb-over maneuver. The principle design of the advisory symbol is inspired by a study conducted by Kahana [10], Figure 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 maneuver 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.

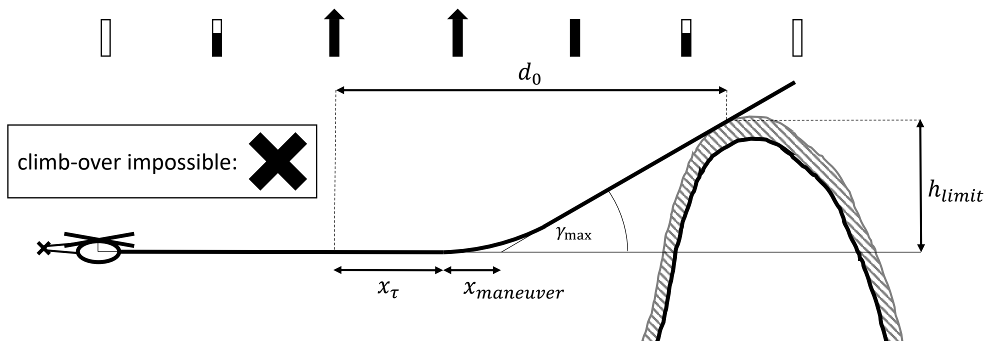

Fig. 4 Advisory symbology for the climb-over maneuver, inspired by [10].

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). 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 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".

D. 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 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 recognize this, and react accordingly by reducing speed. Figure 5 summarizes 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 6 shows the two display variants as implemented in the HUD, at different distances from an approaching obstacle.

IV. Methodology

A. Apparatus

This experiment took place in TU Delft's SIMONA Research Simulator [18], depicted in Figure 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 pilot(s). The HUD-symbology was projected on top of the outside view in the center of view, no helmet-mounted

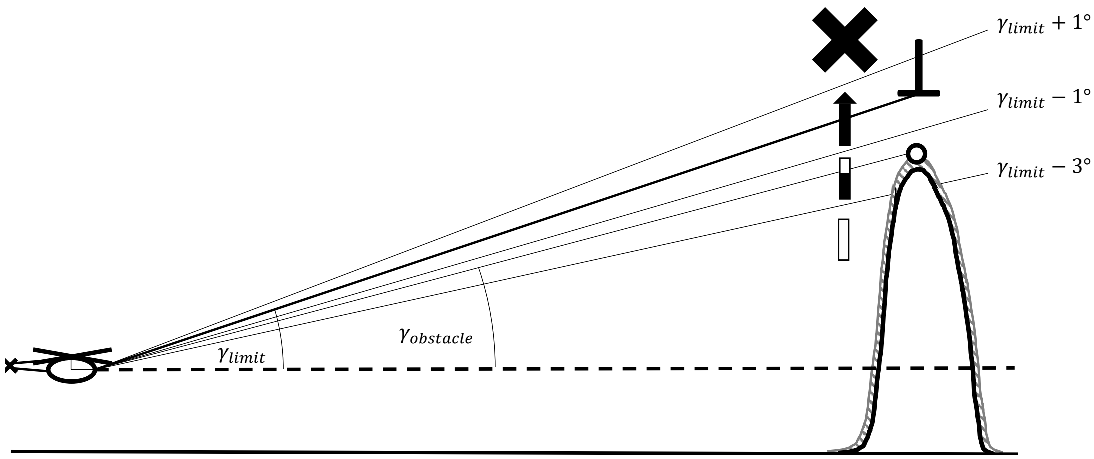

Fig. 5 The relationship between γ_{limit}, $\gamma_{obstacle}$ and the different phases of the advisory display.

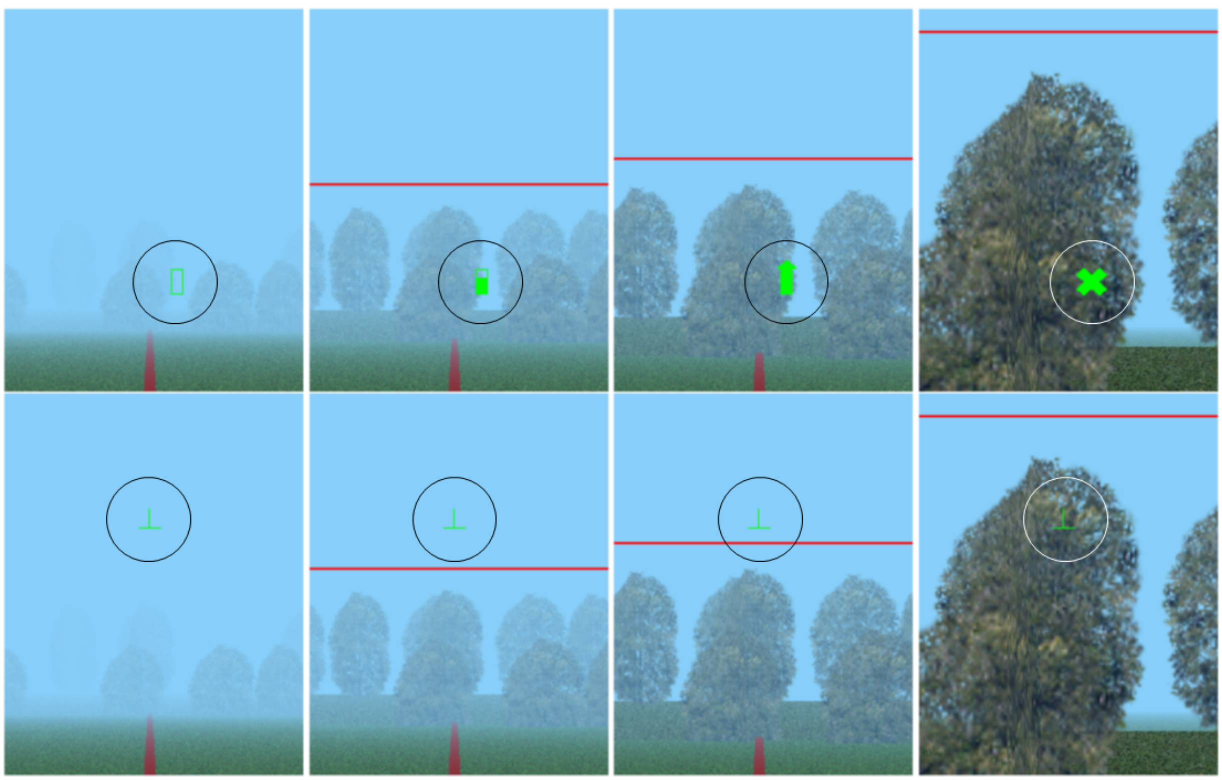

Fig. 6 Advisory (top) and constraint-based display variant (bottom) dependent on distance to the approaching obstacle at 60 kts, highlighted by a circle (not part of HUD). From left to right: 300 m, 200 m, 150 m, 100 m between the approaching helicopter and the obstacle.

technology was used. Care was being exercised that all symbology was visible during all typical pitch angles during the anticipated maneuvers, even with the limited viewing area. The SRS 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 utilized model was an analytical model of a Messerschmitt-Bölkow-Blohm Bo105 Helicopter [19], the motion system of the simulator was deactivated.

Fig. 7 SIMONA Research Simulator.

B. Participants

Twelve helicopter pilots with varying experience (minimum Private Pilot License (PPL), 100 flight hours) participated in this experiment. Table 3 shows some participant demographic aggregates. the participating pilots can be categorized into two distinct groups: one group of seven pilots with less than 800 flight hours, and one group of five pilots with more than 3000 flight hours.

Table 3 Pilot participant demographic data.

	Flight hours		Type of licence (amount)		
Number of pilots	Average	Standard deviation	PPL	CPL	other
12	1906	2326	5	6	1

C. 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 semi-random intervals, the pipeline was covered by a rising ground slope, and a tree line with a height of 80 feet obstructed the optimal flight path. Figure 8 shows a conceptual view of the obstacle course.

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 paper is purposefully made more difficult to control. This increase in difficulty aims to provoke more different responses and pilot preferences based on the currently employed display. If the task would be 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 centered 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 4700 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 at improving their scores and safety clearances between runs.

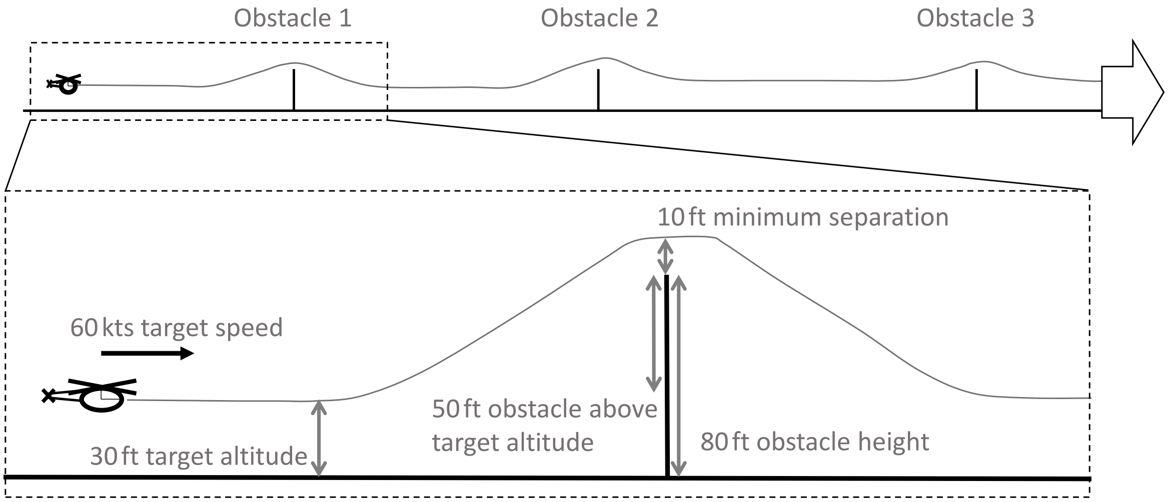

Fig. 8 Principle obstacle course design.

D. Independent variables

The independent variables of this experiment are *display* and *visibility*. A third independent variable *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 *visibility* is set to 300 meters in the high condition, and to 200 meters in the low condition. The order of experiment conditions is balanced between pilots. Each experiment condition is flown five times per pilot, including one non-recorded warm-up run. Table 4 summarizes the independent variables and experiment conditions.

Table 4 Experiment independent variables and resulting experiment conditions A-F.

Experiment conditions		Visibility high	Visibility 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 inserted into some experiment runs. Some obstacles were recognized 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. The data while approaching and reacting to unexpected events are cut from the remaining experiment data and analyzed separately, creating the third independent variable *situation* (nominal, off-nominal) for performance and safety measures, as described in Section IV.E. Table 5 summarizes the detection distances of the outside visuals and the obstacle detection and contour drawing system per experiment condition. These events 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.

E. Dependent measures

Dependent variables are *performance*, measured via the deviation (root-mean-suqare-error, RMSE) of the target altitude, lateral position, and speed; *safety*, measured via the vertical clearance of the climb-over maneuvers over obstacles, as well as the number of intrusions into the minimum clearance zone or the obstacle itself; *workload*, measured via the subjective Rating Scale Mental Effort (RSME), given to the pilots after each condition (developed by Zijlstra and Van Doorn [20], as cited by [21]); and *situation awareness*, measured via the subjective scale Situation Awareness

Table 5 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

Rating Technique (SART) [22], likewise given to the pilot after each experiment condition.

Workload and situation awareness were collected per condition, not differentiating between nominal and off-nominal situations. Performance and safety metrics were 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, and how those impacted the perception of their control strategy.

F. Control variables

Control variables are comprised of the simulator set-up, task, target speed and altitude, the utilized six-degrees-of-freedom helicopter model, and the baseline HUD with altimeter, speed tape, flight path vector, and the obstacle detection and contour drawing system, as described in Section III.

G. Hypotheses

The first paragraph of this Section provides a high-level overview of the hypotheses. They are elaborated upon in detail in the following paragraphs and highlighted in **bold**.

The advisory display is expected to better support the pilot in nominal situations, while the constraint-based display is expected to support the pilot better in off-nominal situations, when compared to the baseline HUD. In nominal situations, the advisory display gives an easy-to-follow, discrete advice on when to initiate a climb maneuver, requiring little cognitive resources from the pilot. The advisory system stops working in off-nominal situations, however — it depends on the timely detection of an obstacle, to compute its advice. Without a timely obstacle detection, the advice will show much too late for the pilot to react to. He or she has to identify the fault, and initiate the maneuver based on the outside visual scenery alone. The constraint-based display is expected to increase resilience of the pilot-vehicle system towards a late obstacle detection. It requires the pilot to connect the visualized internal helicopter maneuver constraint, γ_{limit}, with the external limitations of the obstacle course. This takes more cognitive resources from the pilot, but it also enables the pilot-display system to dynamically react to an obstacle that is not detected in time: instead of comparing γ_{limit} to the red box created by the obstacle detection and contour drawing system, the pilot can compare γ_{limit} directly with the tip of the approaching obstacle.

Performance increases when utilizing any of the support displays, 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 the pilot, and it is easier to follow its advice. **Low visibility decreases performance in every condition**, as it becomes more difficult to control the helicopter with reduced visibility cues. Both display conditions lose less performance than the baseline HUD condition, because the extra display information substitutes some of the information that is lost due to lower visibility. **Off-nominal situations decrease performance in every condition**.

The constraint-based display increases resilience to off-nominal situations, compared to the other two display options. In case of a reduced obstacle detection distance, the advisory display will not give any advice at all. The constraint-based display, however, is not reliant on obstacle detection: it can still be used in junction with the tip of the actual obstacle approaching. In off-nominal situations, it should therefore provide better support (and enable better performance) than the other display variants.

Workload decreases when utilizing 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 expected to be stronger with the advisory display, as it provides an easy-to-follow maneuver advice, compared to the constraint-based display, which requires more cognitive resources from the pilot to translate the given maximum effective climb angle and the location of the looming obstacle into a maneuver advice. **Low visibility increases workload**, with the baseline HUD condition experiencing the highest increase, again because of reduced visibility cues.

Situation awareness increases when utilizing 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 maneuver limitations of the helicopter (in the form of the maximum effective climb angle γ_{limit}), and connect these to the external limitations of the approaching obstacle. In comparison, the advisory display only provides an action suggestion at a specific point in time, without revealing the underlying maneuver attributes. **Low visibility decreases situation awareness**, the reason being similar to an increase in workload: lower visibility makes it more difficult to perceive the current aircraft state, and project it into the future.

Safety is expected to behave differently between its measurement techniques. On the one hand, **the minimum clearance above obstacles decreases when utilizing any of the support displays**. As the pilot is made aware of the maneuver 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. On the other hand, **the percentage of unsafe clearances lower than 10 feet will decrease when utilizing 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 utilizing the constraint-based display, and increase when utilizing the advisory display, 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 utilizing the baseline HUD. In contrast, the constraint-based display still provides the pilot with information about his or her maneuver capability, and its relation to outside obstacles, even when they are not detected and visually amplified by the obstacle detection and contour drawing system. The constraint-based system is therefore expected to decrease the number of unsafe clearances, compared to the baseline HUD. **Low visibility decrease all measures of safety in every condition**.

V. Results

Workload and situation awareness ratings are collected once per experiment condition and pilot. They are normalized to a mean of 0 and a standard deviation of 1 (Z-scored) per participant, to account for subjective scaling and offset differences. Performance and safety results are averaged per experiment participant and condition, resulting in one data point per participant per experiment condition.

There are twelve data points per condition, with a total of six conditions (*display x visibility*), in case of workload and situation awareness, or twelve conditions (*display x visibility x (off-nominal) situation*), in case of performance and safety measures. Anderson-Darling tests for normality reject the null hypothesis of a normal distribution in 23 cases at an $\alpha = 0.05$ significance level, across 84 measurements of dependent variables (27,38 %). Therefore, non-parametric tests are employed to analyze the data.

If not otherwise specified, two-way Friedman test statistics are computed and analyzed. To account for the third independent variable *situation*, the six display and visibility combinations are treated as a single independent variable with six degrees of freedom. The selected significance value is chosen to be $\alpha = 0.05$.

A. Workload

Figure 9 shows box plots of Z-scored workload measures per experiment condition. Low visibility seems to increase workload, and workload seems to differ between the employed displays, especially in high visibility. However, there are no significant effects of visibility or display on workload. 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 ($\chi^2(66) = 3.4448, p = 0.1786$). In bad visibility, this trend is only true for the average value — the median actually slightly increases with the advisory display, compared to the baseline HUD. Considering the averages, this trend is in line with the hypothesized effect of visibility on workload. There is also a trend of increasing workload as visibility decreases, ($\chi^2(66) = 3.6395, p = 0.0564$). This is in line with the expected effect of worsening visibility on workload.

B. Situation awareness

Z-scored situation awareness, as shown in Figure 10, is not significantly affected by visibility or display. As with workload, there are trends visible for an effect of visibility ($\chi^2(66) = 1.2627, p = 0.2611$) and of display ($\chi^2(66) = 2.8969, p = 0.2349$). Lower visibility causes lower situation awareness rating averages and medians. Considering the mean 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 doesn't follow this trend, and is actually lower than the medians of the baseline HUD and the constraint-based display.

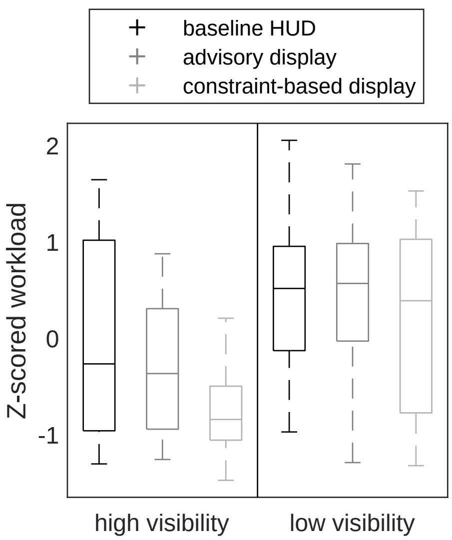

Fig. 9 Workload questionnaire results per experiment condition, Z-scored per participant.

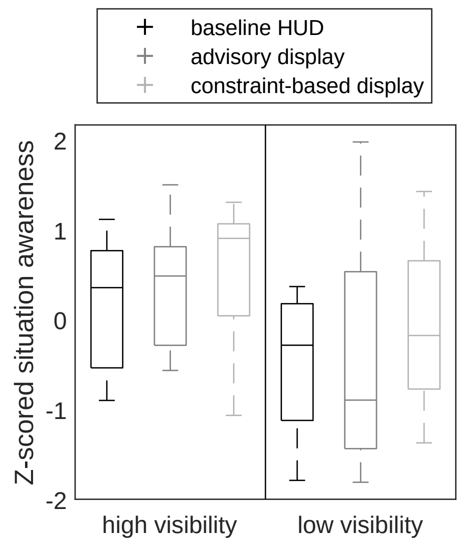

Fig. 10 Situation awareness questionnaire results per experiment condition, Z-scored per participant.

C. Performance

In the Appendix, Figure 13 shows box-plots of the altitude deviation per experiment condition, Figure 14 of the airspeed deviation, and Figures15 show box-plots of the lateral position deviation.

No significant effect of *situation* or (*display x visibility*) is revealed, $p > 0.5$ in all cases but one. The single p-value smaller than 0.5, bit still bigger than 0.05, can be observed in the effect of *situation* on speed deviation, $\chi^2(132) = 2.205, p = 0.1376$. In off-nominal situations, the average speed deviation is slightly higher, compared to nominal situations. This could be explained by a change in control strategy in off-nominal situations, from a coordinated pull-up that requires both collective and longitudinal cyclic input, to a cyclic-only pull-up maneuver, during which the forward speed naturally drops. This second, cyclic-only maneuver is the typical way of performing climb-over maneuvers in helicopters, according to multiple participants. While most participants tried to fly coordinated, keeping airspeed at 60 knots during the climb-over, they might have reverted to a cyclic-only control strategy in those off-nominal situations that were more hectic and required a quicker control reaction.

D. Safety

Figure 11 shows box plots of the averaged safety clearances. No significant effects can be observed, $p > 0.05$ for every independent variable. There is a weak trend of the advisory display lowering the average safety clearance in nominal situations, compared to the other two displays. The median only follows this trend in bad visibility, in

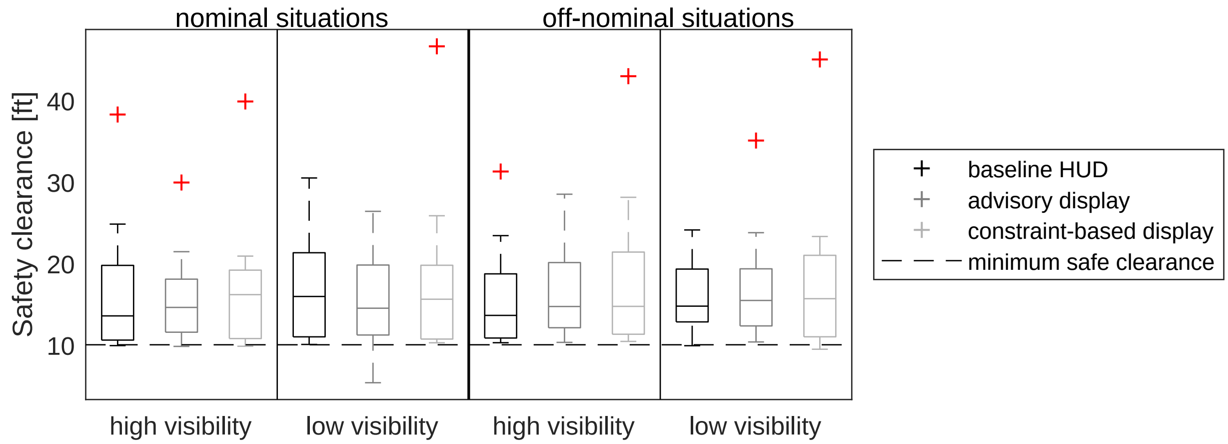

Fig. 11 Box-plots of average safety clearances per visibility visibility, display, and situation.

good visibility the median continuously rises from baseline HUD to advisory display, to constraint-based display. It can also be observed that in bad visibility, the advisory display is the only condition whose data protrude visibly into the unsafe clearance area < 10 feet. In off-nominal situations, the average and median safety clearance slightly increases when switching from the baseline HUD to the advisory display, and increases further when switching to the constraint-based display. All of these observations are not substantiated by significant test statistics, or even low *p*-values of the corresponding tests.

The relative amount of unsafe clearances < 10 feet with respect to the total number of climb-over maneuvers is shown in Figure 12. In good visibility, encountering an off-nominal situation consistently increases the percentage of unsafe clearances. In bad visibility, encountering an off-nominal situation actually decreases the percentage of unsafe clearances, except with the constraint-based display, in which case the percentage is still increased.

The percentage of unsafe clearances seems to be sensitive to off-nominal events, but only under certain conditions. The largest increase of unsafe clearances can be observed with the baseline HUD and the advisory display in good visibility, increasing by 6 % and 10 %, respectively. Conversely, the baseline HUD and the advisory display increased the resilience to off-nominal events in bad visibility. The constraint-based display consistently caused an increase in unsafe clearances when encountering off-nominal events, with an increase of 2.4 % in good visibility and 4.2 % in bad visibility.

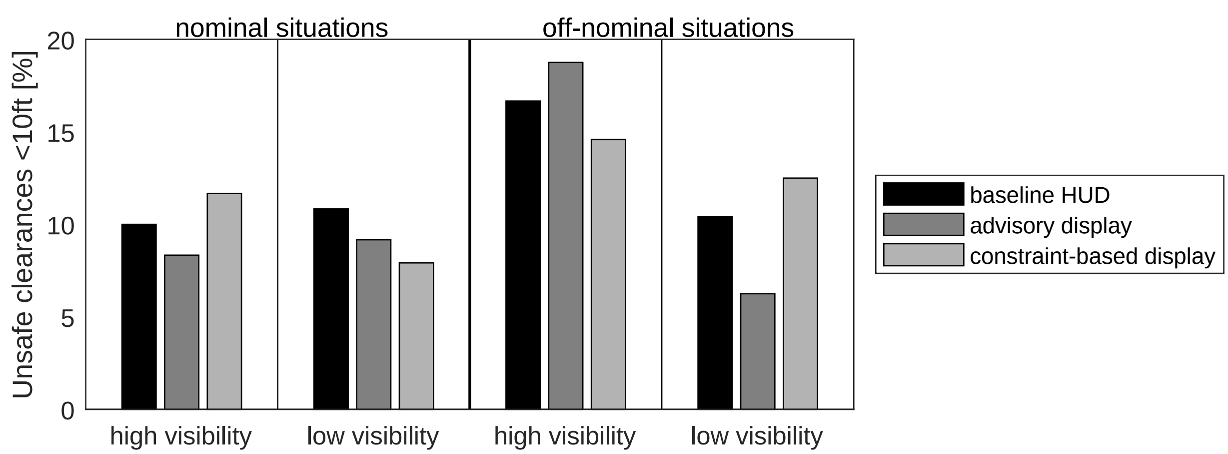

Fig. 12 Percentage of unsafe clearances per experiment condition, in nominal and off-nominal situations.

E. Control strategy

The speed deviation performance results already indicated that the experiment conditions might have impacted the employed control strategy of the pilots. Figures 16 and 17 in the Appendix show the climb-over trajectories for all conditions, as well as the average, 10 % and 90 % quantile altitudes. Depending on the condition, different trajectory distributions can be observed.

For example, compare conditions A and B: while the trajectory distribution in condition A looks rather symmetric with respect to the obstacle, in condition B, there is a much higher altitude spread behind the obstacle (positive x-values) than before it. This difference is apparently caused by the different visibility in conditions A (high) and B (low). Another difference can be observed between the off-nominal trajectories of condition A, C, and E, differing in the employed display: compared to the baseline HUD in condition A, the trajectory spread seems to decrease with the advisory display in condition C, and increase with the constraint-based display in condition E.

This data suggest that there are differences in control strategy caused by the difference in experiment conditions, that are not captured sufficiently by the employed performance or safety measurements. Section VI discusses these implications.

F. Pilot preference

After the experiment, the pilots indicated their confidence in using the different displays to fulfill the task on a scale from 1 (low) to 7 (high), as shown in Table 6. In general, pilots felt most confident using the baseline HUD (6.08) and the advisory display (5.83), followed by the constraint-based display (4.98). In nominal situations, pilots likewise prefer the advisory display (6.17) to the constraint-based display. In off-nominal situations, however, pilot confidence was slightly stronger with the constraint-based display (4.92), compared to the advisory display (4.42), whose confidence value dropped from 6.17 to 4.42.

Table 6 Pilot questionnaire result to *"How confident did you feel while using the baseline/advisory/constraint-based display to fulfill 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

VI. Discussion

The performed two-way Friedman tests reveal no significant effects on workload, situation awareness, performance or safety. Nonetheless, there are some trends in the data that are worth discussing.

The advisory display seems to decrease workload and increase situation awareness, when compared to the baseline HUD, with a stronger trend observable in good visibility. This has been hypothesized correctly, presumably because this display provides additional, easy to follow advice for pilots to perform the task.

Contrary to the hypotheses, the constraint-based display reduces workload and increases situation awareness even more, compared to the advisory display. This is surprising, because the constraint-based display requires more information integration from the pilot. However, these results fit the pattern of the questionnaire answers to the pilot's confidence during off-nominal events in Table 6: 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 would explain these values. For future research, it might prove valuable to collect ratings like these separately for nominal and off-nominal situations. A second possible explanation for this 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 is directly relatable to the outside view (like the constraint-based display) might be preferred compared to other, non-related information (like the arrow of the advisory display).

Performance and safety measures are not significantly affected by any of the experiment independent variables. Some variations in average or standard deviation magnitude can be observed in performance measures like airspeed deviation, but these differences are not useful to draw any generalized conclusion.

The percentage of unsafe clearances is influenced by the visibility condition, the employed display, and the situation. The advisory display shows the highest increase of unsafe clearances when encountering an off-nominal event in good visibility, while the constraint-based display leads to the most unsafe clearances in bad visibility conditions. The hypotheses concerning the number of unsafe clearances are rejected.

Considering pilot preference, the results of this paper are in line with the aforementioned ecological design research in the fixed-wing domain [2]: 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 maneuver 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, but it depends on the correct detection and computation of all required data — the internal maneuver constraints, the external environment constraint, and their combination. The constraint-based display communicates only the internal maneuver constraints to the pilot, he or she has to acquire the external environment constraints him-/herself 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, failing 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 maneuver constraints, to support their decision making.

The differences between the investigated displays are not statistically significant. There are trends in workload, situation awareness, and pilot preference, but they don't afford a general conclusion concerning positive or negative effects of the displays. Five possibly reasons for this are: (i) The difference is not visible in aggregate scores, but in the employed control strategy. Even though the performance stayed the same, pilots possible pulled up at different distances to the obstacle, or changed the shape of their maneuver. (ii) The analyzed 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 analyzed task. The displays only provided additional information that pilots might or might not have used. Especially in hectic, fast-paced maneuvers or reactions to obstacles, it seems plausible that pilots concentrated on the source of information they are most familiar with — the outside visuals. (iii) The analyzed displays are very 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. Utilizing 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? (iv) The performed task was monotonous and repetitive. Even the unexpected, off-nominal situations became predictable after a few occurrences. 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, and that there are no other unexpected events. Even if positive influences of the constraint-based display are assumed, the off-nominal situations in this experiment probably lacked a sufficient amount of "unexpectedness" to trigger those advantages. (v) Lastly, a higher number of pilot participants might increase the significance of the employed test statistics, provided the results show the same trends.

In follow-up research activities with these data, analyzing the control strategy of the pilots in more depth might still reveal differences. Options include calculating/identifying control activity, pull-up time, or other metrics based on the fly-over trajectories.

VII. Conclusion

This experiment did not reveal significant effects of the considered displays on the aggregate dependent measures. Trends indicate a reduction in subjective workload and an increase in subjective situation awareness ratings when switching from the baseline HUD to the advisory display, and when switching from the advisory display to the constraint-based display. The displays' effect on safety requires more attention, however, as there were different trends (upwards and downwards) visible in different visibility conditions and situation.

The results of this experiment indicate that in the analyzed control task of low-altitude helicopter flight and obstacle avoidance, differences in data representation of additional displays don't play a major role in supporting the pilot. The baseline HUD was considered largely satisfactory to complete the task by the participants. For a follow-up experiment, increasing the time-frame of the task and introducing more complex problems (including more variants of unexpected events) is expected to better reveal the difference between conventional and ecological display philosophies.

Acknowledgments

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Appendix

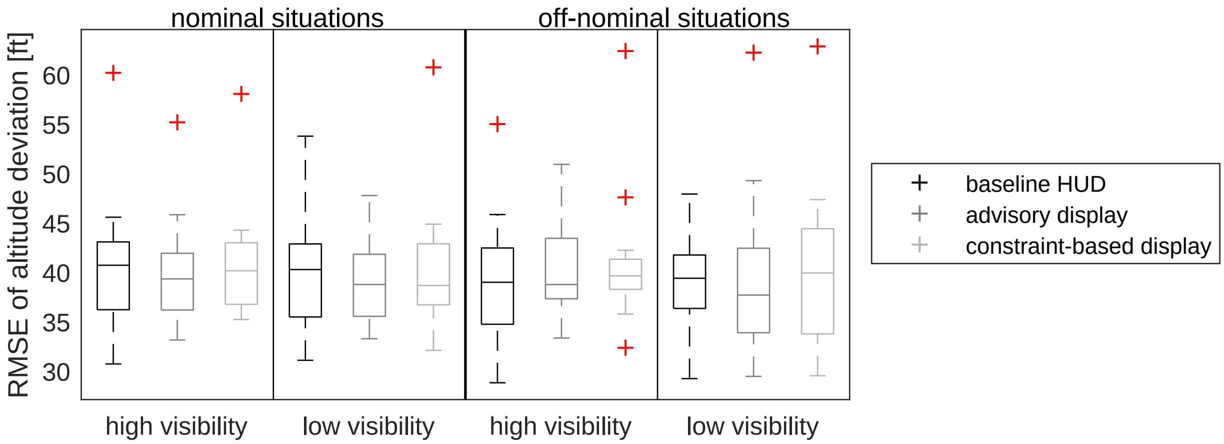

Fig. 13 Box-plots of altitude RMSE per visibility, display, and situation condition.

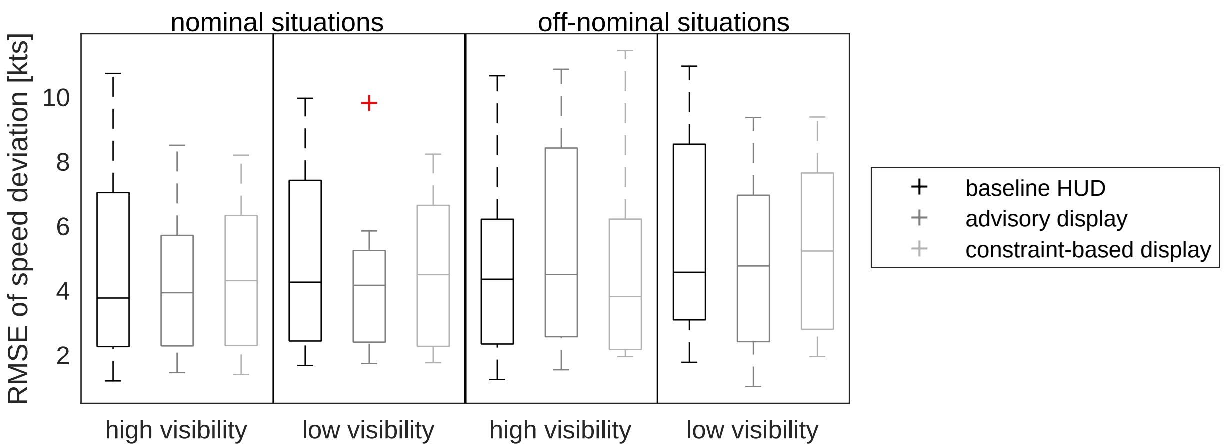

Fig. 14 Box-plots of forward speed RMSE per visibility, display, and situation condition.

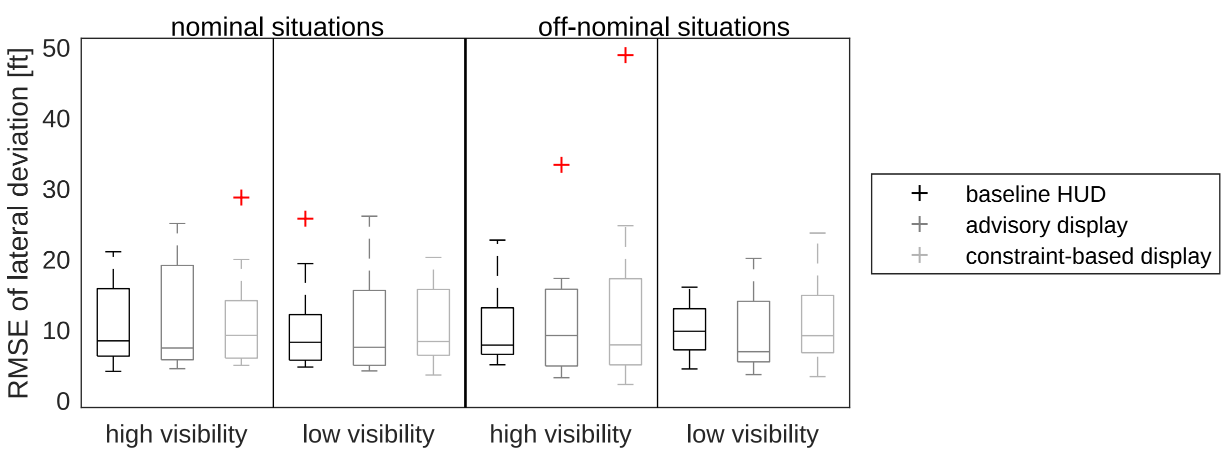

Fig. 15 Box-plots of lateral RMSE per visibility, display, and situation condition.

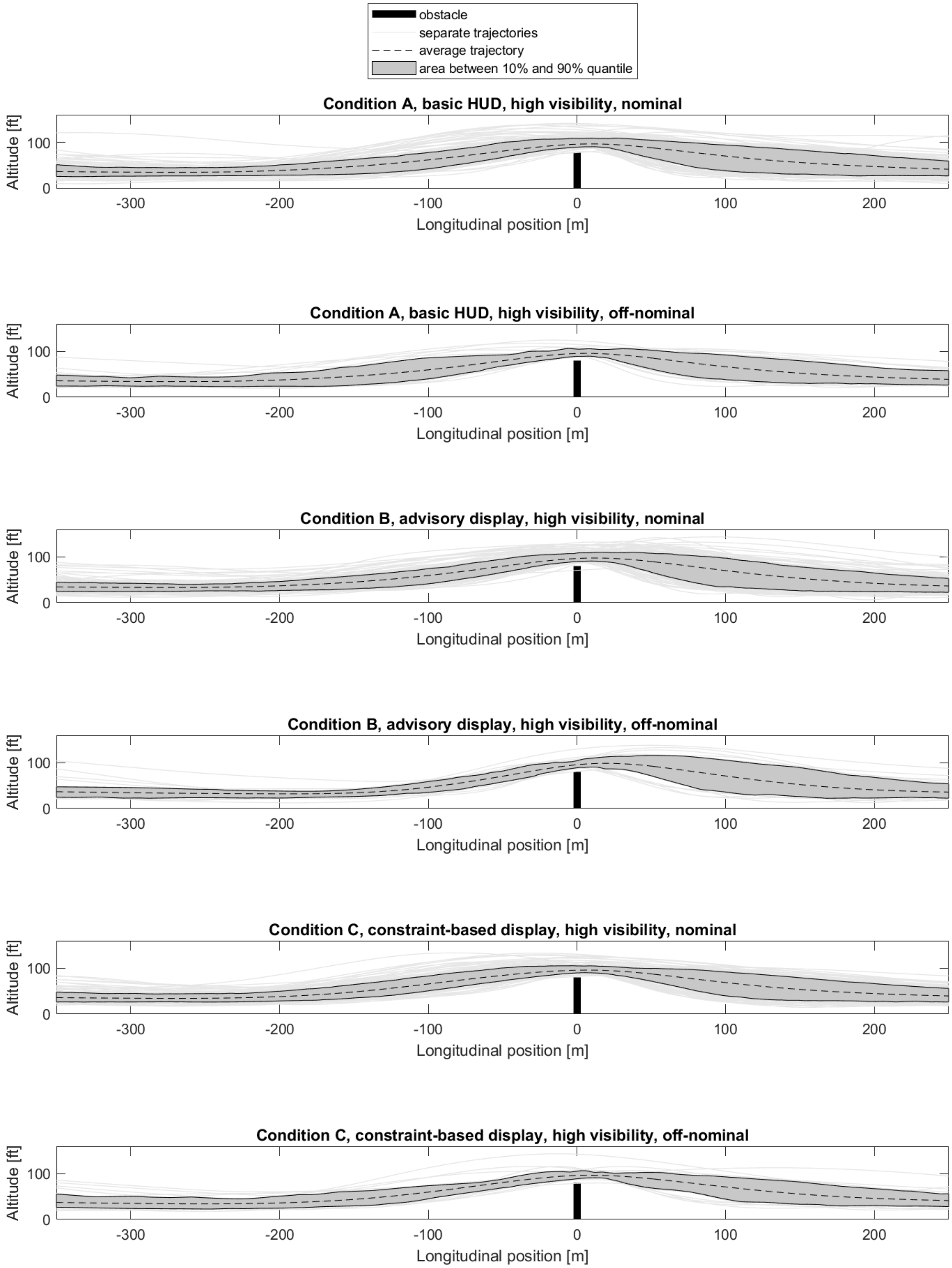

Fig. 16 Trajectories of the climb-over maneuver, all conditions with high visibility.

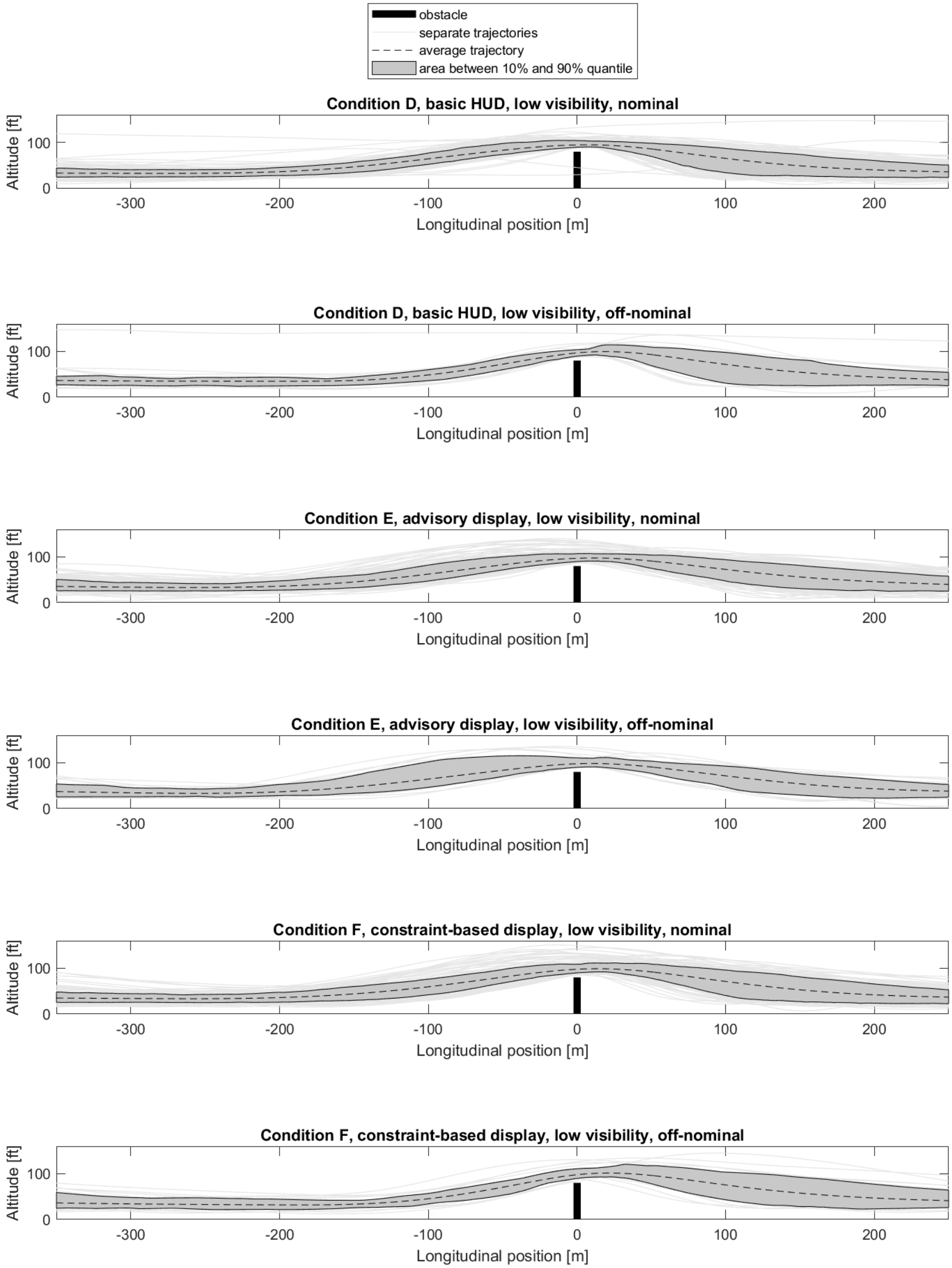

Fig. 17 Trajectories of the climb-over maneuver, all conditions with low visibility.