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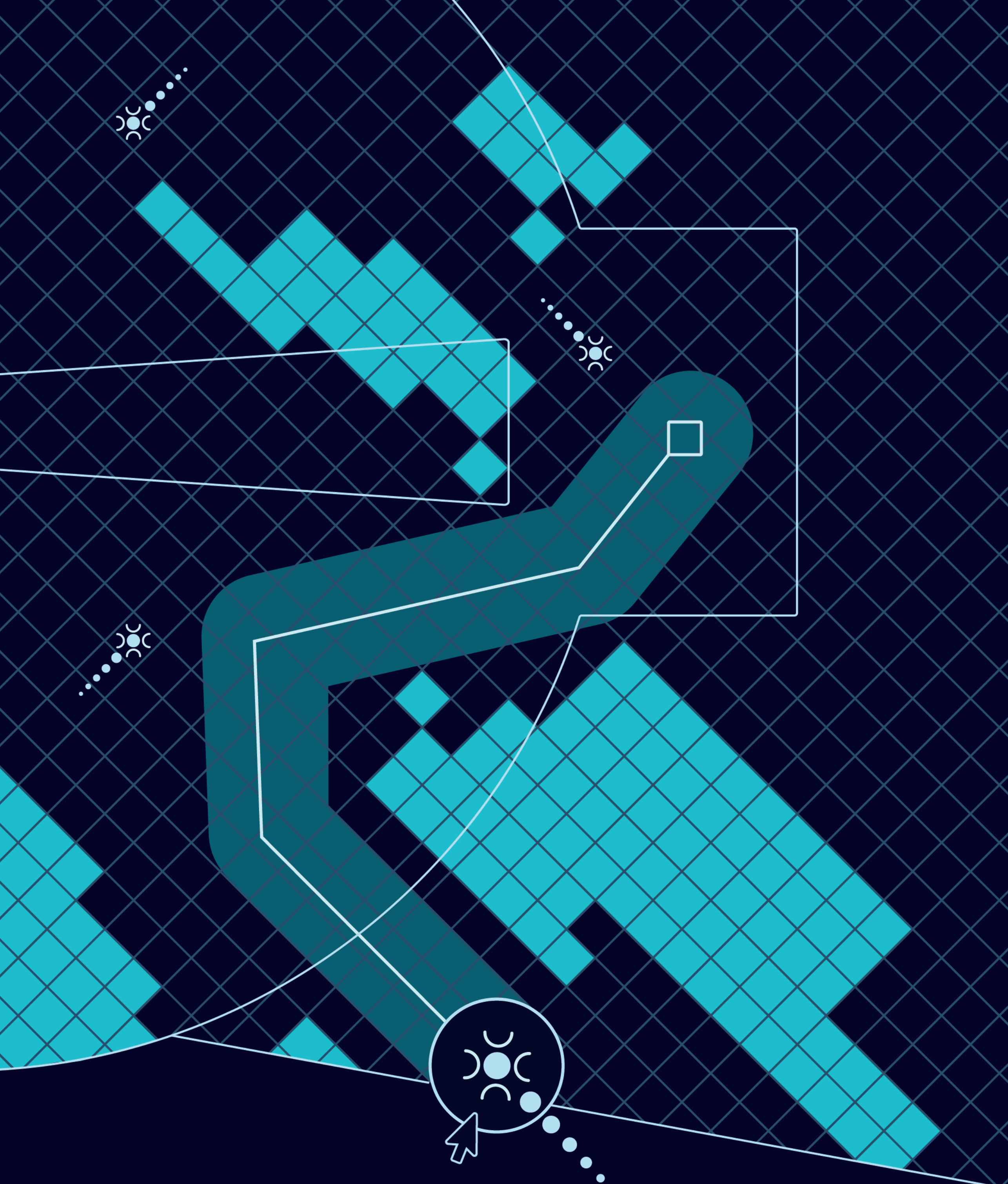

# Human Interactions with Uncrewed Air Traffic Management

Dominik Janisch

# HUMAN INTERACTIONS WITH UNCREWED AIR TRAFFIC MANAGEMENT

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## Dissertation

for the purpose of obtaining the degree of doctor
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Prof. dr. ir. H. Bijl,
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This work is dedicated to all who helped me get here.

# SUMMARY

### Human Interactions with Uncrewed Air Traffic Management

THE increasing demand for Uncrewed Aircraft Systems (UAS) will begin to strain the capacity of Air Traffic Control (ATC) in the coming years. In particular, the use of UAS to support urban delivery and infrastructure inspection missions poses the greatest opportunity for growth in the UAS sector, but also the highest risk to low-flying crewed aviation in the vicinity of towered aerodromes. Achieving a safe and orderly integration of UAS flights into existing controlled airspace structures will be crucial to prevent collisions between crewed and uncrewed aircraft. Yet, the path to achieve this is anything but straight forward. Recent disruptions and airspace closures caused by reported UAS sightings near major European airports have shown how little-prepared the current air traffic management ecosystem is to integrate UAS flights. Assuming that human Air Traffic Controllers (ATCOs) will not be able to manage the complexities of UAS missions, the aviation industry and regulators are considering the implementation of separate UAS Traffic Management (UTM) systems to guide and manage the flow of UAS and prevent collisions. Their reliance on high levels of automation and limited human intervention presents a challenge in an airspace requiring both Air Traffic Management (ATM) and UTM supervision, such as in the controlled traffic region around towered aerodromes.

The work in this thesis explored how an ecologically-inspired design of a collaborative ATC-UTM interface for tower controllers could assist them in supervising UTM decisions on UAS and achieve a safe and expeditious flow of air traffic within the control zone. The concept relies on the *segregation* of ATC and UTM areas of responsibility to avoid the issue of having multiple agents (human tower controller vs. automated UTM) manage different traffic in the same airspace. However, dynamic changes in crewed and uncrewed airspace demands may occur, making it necessary to provide flexible airspace management mechanisms. By using tools that automated UTM systems can interpret (geofences and UAS-specific commands) human controllers can temporarily turn static airspace segregation into active *separation* management of individual vehicles to maintain safety.

The research presented in this thesis attempted to answer four main questions. First, what are the underlying system goals, functions, relationships, and constraints inherent to the work domain of UTM, and how do they compare to the work domain of air traffic control? Second, in what visual form can the constraints and functions that govern the control of UAS through UTM be mapped on a decision-support interface such that it supports the work and strategies of air traffic controllers as best as possible? Third, how do air traffic controllers interact with UAS via the interface, which control strategies do they apply, and how do they perceive their role in a collaborative ATC-UTM environment? And finally, what are the safety and performance impacts of augmenting the tower control role with UTM supervision, and what role can automation play in improving them?

Answering these questions required a mapping of the differences and commonalities of the operating environments of UTM, in terms of UAS operating constraints, as well as

ATC, regarding the structures, roles, and responsibilities of aerodrome tower controllers. The resulting constraints were incorporated into an operational concept that uses Dynamic Airspace Reconfiguration (DAR) to segregate crewed aviation from UAS and assigns the tower controller as the responsible entity for imposing dynamic airspace restrictions.

A supporting tower control interface was then developed following an analysis of the work domain of the collaborative ATC-UTM environment. A constraint-based approach – inspired by Ecological Interface Design (EID) and supported by Rasmussen's Abstraction Hierarchy (AH) model – was applied in the design of the display. It reveals the system's full operational envelope that can be used by the tower controller to both monitor UTM decisions as well as perform interventions.

A series of three human-in-the-loop simulations were performed to evaluate the collaborative ATC-UTM interface with the help of ATCO participants. The design of the interface was iteratively improved with the lessons learned from each simulation experiment.

Implementations of the concept focused on the tower control task of providing a safe and expeditious flow of arriving and departing crewed aircraft which was free of conflicts with UAS. To assist the controller in this task, the first interface design provided them with geofences as tools to segregate areas from UAS flights and achieve safe separation between UAS and crewed aircraft, as well as information about UAS intentions and mission constraints which would limit their room for maneuvering. It quickly became apparent, however, that geofencing alone was insufficient in conveying the UAS re-routing intentions of ATCOs to the UTM system and increasing the predictability of UAS routing. To be more effective, the interface required additional tools for the ATCO to intervene in either individual UAS routes or more general UTM decisions that were in conflict with their own intentions for UAS traffic flows.

The second human-in-the-loop simulation incorporated these findings into a display that allowed ATCOs more options to intervene in individual UAS routes. UAS-specific commands were incorporated into the interface so that the experiment participants could instruct individual UAS to reroute, orbit around their current position, or land. The resulting simulation explored the impact of UAS automation on the strategies for UTM supervision of tower controllers within the collaborative environment. Results identified two distinct strategies: *Active* and *passive* control. The active control strategy was the most common one, as it resembled typical air traffic control actions on crewed air traffic. Interface tools, in particular UAS-specific commands, were used to vector UAS around crewed air traffic following flight rules that apply to crewed aircraft. The active strategy was considered useful in particular to support short-term conflict avoidance actions between crewed and uncrewed aircraft. The passive strategy, on the other hand, was more suitable to the proposed geofencing concept in this thesis. Rather than assessing individual conflicts between UAS and crewed aircraft, ATCOs using this strategy segregated larger volumes of airspace to achieve safety, at the expense of UAS efficiency. The passive strategy was preferred in high task load situations, yet, neither could be singled out as a suitable strategy for all types of situations. These results lead to the question of whether full segregation or full integration of ATM and UTM domains would be the optimal approach to managing the collaborative environment.

The third and final human-in-the-loop simulation explored the limitations of tactical segregation of uncrewed and crewed air traffic by tower controllers using the collaborative

ATC-UTM interface. Interface functionalities were further extended by incorporating a conflict detection tool, which highlighted areas where UAS would come into conflict with crewed aircraft, as well as improved geofence activation mechanisms which allowed multiple areas to be activated at once and thus facilitate the use of the passive control strategy. The final interface design helped ATCOs detect conflicts between UAS and crewed aircraft. However, they were not always able to adequately resolve them, which resulted in several losses of separation. Participants using the active control strategy struggled the most in this regard. It appears that the limitations of the dynamic segregation concept do not fit well with typical air traffic control strategies used by ATCOs.

Results across all three simulation experiments confirmed the utility of providing the human controller with the means to perform dynamic segregation of all UAS, as well as intervene in individual UAS routes if necessary. Making UAS route constraints salient to the ATCO was also beneficial in allowing them to understand UAS responses to geofences. Of the two control strategies observed in the experiments, the passive strategy appeared to have the highest overall safety performance, whereas the active one served best as a last-resort intervention in impending conflicts between UAS and crewed aircraft.

Yet, the interface design alone could not provide the necessary robustness to achieve high-level goals of the collaborative ATC and UTM environment in all situations. Contributing factors included a lack of predictability of UTM decisions on UAS traffic, a lack of compatibility of dynamic segregation tools with typical, current-day air traffic control strategies, and a lack of adequacy of dynamic segregation to resolve tactical conflicts.

Considering that the proposed Dynamic Airspace Reconfiguration (DAR) concept is still very new, the exploratory experiments of this thesis highlighted additional needs for further refinement beyond interface design. Incorporating stricter static segregation through a revised airspace design could minimize the risk of UAS and crewed aircraft encounters, at least on standard crewed aircraft routes. In addition, increasing the predictability of UTM decisions on UAS could alleviate the risk of conflicts with unscheduled crewed aircraft flights or non-standard flight paths (such as Helicopter Emergency Medical Service flights). This could be achieved by incorporating automation transparency, UAS flight rules with regard to crewed aircraft, and further adjustments to the interface design to support collaborative airspace management with UTM automation. Finally, separating the tower control and DAR manager roles into two separate entities could alleviate human performance concerns that arose during the experiments conducted in this thesis.

The initial design of the collaborative ATC-UTM interface for ATCOs showed potential to facilitate ATM and UTM integration. The human-in-the-loop experiments also highlighted the importance of making UTM constraints and decision-making salient for human operators within ATC. The results of this thesis lay the groundwork for a future where UAS and UTM automation will likely have a strong effect on the ATC working environment. By emphasizing the strengths of the collaborative interface and addressing the shortcomings of the operational concept identified through this research, full integration of crewed and uncrewed traffic management could be achieved if appropriate means for human operators to manage the transition between segregation and separation of UAS and crewed aircraft are provided.

# CONTENTS

# 1

# INTRODUCTION

*The background and challenges concerning the design of a supervisory control interface for air traffic controllers to collaborate with uncrewed aircraft system traffic management are introduced. The main problem statement and associated research questions to be addressed in this thesis are presented. The research approach, applied methodologies, research scope, and main assumptions are outlined at a high level, before concluding with an overview of the main chapters and their relevance to the context of this work.*

## 1.1 Background & Context

The task of Air Traffic Control (ATC) is to assure a safe and expeditious flow of crewed air traffic within controlled airspace [1]. The ATC system, which is increasingly relying on automation and digital tools to manage air traffic growth and complexity [2], is still a very human-centric concept by design. Air Traffic Controllers (ATCOs) take on the role of tactical separator between aircraft in controlled airspace and thus perform a crucial role in maintaining safety. The increasing use of airspace by uncrewed aircraft, i.e., drones, in lower airspace is beginning to challenge the capacity of the human-centric ATC system to maintain the expected level of safety performance in all airspace classes [3]. Optimistic projections expect a total fleet of 390,000 uncrewed aircraft operating in Europe by 2035 [4], which is almost eight times the global commercial aircraft fleet forecast for a similar time frame [5]. The largest share of these new airspace users comprises small Uncrewed Aircraft Systems (UAS). Uncooperative uses of UAS near aerodromes pose real threats to the safety of landing and departing crewed aircraft and can cause substantial disruptions to the air traffic flow, as a series of incidents at Gatwick [6], Heathrow [7], Frankfurt [8], Madrid [9], and more recently, Copenhagen, Oslo [10] and Munich [11] have shown. Facilitating collaborative management of small UAS and crewed aviation has been the focus of recent research and development efforts.

Air Traffic Management (ATM) research and development roadmaps around the globe [2, 12, 13] are building on the promise of UAS Traffic Management (UTM) systems to address the question of how such large numbers of new airspace users could be integrated safely alongside crewed aviation. The premise of UTM is establishing a system for managing uncrewed air traffic that does *not* rely on human decision-making in traffic management. A principal reason for this is to avoid human performance limitations imposing a bottleneck on the scalability of airspace usage by UAS. Instead, UAS access to airspace will be facilitated using scalable, automated services to provide the necessary information to allow the safe conduct of UAS flights as demand increases.

Given the European Union's large investment in research on UTM concepts, this thesis will focus predominantly on the European implementation in the representation of UTM as a whole. Research projects conducted within the framework of the Single European Sky ATM Research Joint Undertaking (SESAR-JU), an initiative of the European Union, showed means through which such scalability could be provided using modern, web-based system architectures built on micro-services and supported by cellular telecommunication infrastructure [14]. UTM services will be provided through a combination of, so-called, U-space Service Providers which themselves obtain critical information about the airspace from a Common Information Service Provider [15].

The European Concept of Operations for U-Space (CORUS) [16] outlines how UAS traffic management would be performed in practice. Rather than relying on separation requirements and flight rules as a foundation to manage UAS, as is the case for crewed aviation, the concept builds on spatial and temporal segregation of flights to avoid conflicts between UAS, as well as between UAS and crewed aviation.

At this point, it is important to clarify the definitions of "segregation" and "separation" within the context of this work. Segregation refers to the structural division of airspace to ensure that ATC-managed crewed aircraft and UTM-managed UAS do not occupy the same airspace volume at the same time. Separation refers to the tactical or procedural spacing between aircraft — whether crewed or uncrewed — to prevent collisions while they *share* the same airspace.

Applying segregation allows UAS operators much more flexibility in how they conduct their flights, which may have very differing flight profiles depending on the type of mission they aim to achieve. Moreover, segregation is currently the only means to facilitate UAS flights Beyond Visual Line-Of-Sight (BVLOS) of the remote pilot, since flight rules for crewed aircraft do not apply to them and because there is no requirement for small UAS to be certified to aviation standards [17]. This approach allows UTM and ATM systems to evolve and coexist in parallel, given that spatiotemporal segregation of flights will avoid issues in the compatibility of both systems.

UAS traffic management actions will also differ from those on crewed aircraft. Given the lack of certification of the aircraft, in the European regulatory environment, small UAS BVLOS flights are subject to a prior risk assessment before being authorized. Due to the low operating altitudes, their available room for maneuvering is just as dependent on the risk that a flight operation poses to persons on the ground, as it is to other aircraft [18]. Moreover, small UAS have much lower endurance than crewed aircraft, and mission constraints that the UAS aims to achieve further limit the available maneuvering room if traffic management actions become necessary. UTM systems must consider all these restrictions when issuing instructions to UAS traffic.

As UTM services mature, they are expected to take more and more responsibilities regarding tactical UAS traffic management away from the UAS operator [19]. This is expected to increase airspace capacity for UAS even further, due to the increase in predictability and timeliness of UAS responses to airspace restrictions. Thus, automation in UAS route decision-making will play an increasing role.

In the European context, the segregation of ATM and UTM will also allow the application of ad-hoc restrictions, which will be necessary to accommodate short-term changes in UAS or crewed aircraft airspace requirements. A concept known as Dynamic Airspace Reconfiguration (DAR) [15] was introduced into the European U-space regulation which permits ATC to dynamically change the boundaries of U-space airspace within controlled airspace and allows crewed aircraft to enter areas of airspace previously reserved to UAS flights. Applying DAR, however, does not influence the allocation of responsibilities. ATC remains responsible only for crewed aircraft within controlled airspace, while UTM is responsible for UAS within U-space. Although many technical aspects of DAR have already been addressed in dedicated research projects [20], it is not yet clear what the implications of introducing UTM into controlled airspace would be on the role of the human ATCO and to which extent human-automation coordination is required to achieve a safe and expeditious flow of crewed *and* uncrewed air traffic.

UTM will be deployed in phases, beginning with initial essential services, such as registration services of UAS operators, geo-awareness services providing information about UAS restrictions and flight plan authorization services. Examples of such UTM systems already in deployment include the United States' LAANC, Poland's PansaUTM or Austria's Dronespace UTM systems. Initial UTM will predominantly cater to the needs of VLOS missions, however unlocking the potential of BVLOS missions at scale will require more sophisticated UTM systems, such as U-space.

The UTM context presented in this thesis assumes that a mature U-space ecosystem of services and necessary infrastructures to facilitate BVLOS operations at scale are in place. These services are further assumed to have full knowledge of UAS mission constraints and are advanced enough to issue flight instructions to UAS directly. However, they are not yet mature enough to assume a fully autonomous UTM system, such that supervision and application of dynamic restrictions on UAS by ATC is required. Figure 1.1 provides an overview of the UTM context of this thesis.

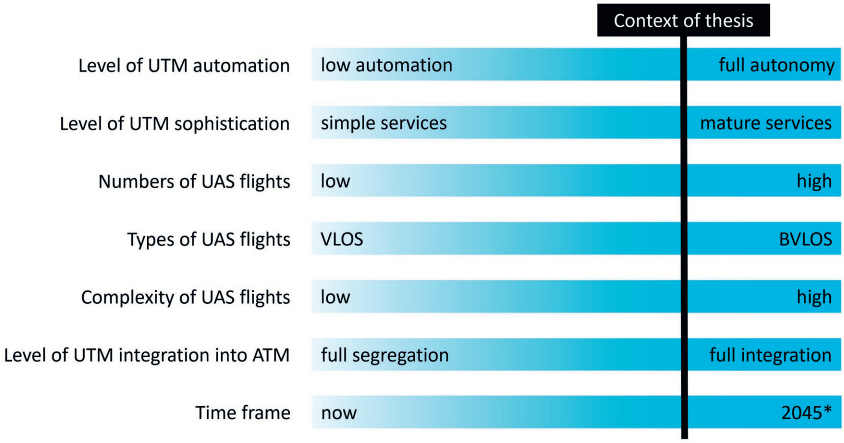

Figure 1.1: Illustration of the assumed maturity of the UTM system described in this thesis. (*) The time frame was selected in accordance with the European ATM Master Plan ed. 2025 [2].

## 1.2 Problem Definition

The envisioned collaborative coexistence of ATM and UTM will bring a significant shift in the work of the ATCO. Currently, they are tasked with preventing collisions and losses of minimum separation between aircraft in the air, coordinating air traffic, facilitating flight information and performing an alerting service [1]. Although much of the UAS traffic management tasks will be coordinated by UTM, introducing this new operational concept into controlled airspace adds the requirement of limiting airspace for UAS operations through segregation to the list of responsibilities of the air traffic control unit. This addition has implications for the way that ATCOs perform their tasks, the information about the air traffic situation that they will need to process, and which tools they will need to perform this task alongside their other commitments.

In the context of “segregation” and “separation”, this thesis adopts a conceptual framework based on the segregation of areas of responsibility between ATC and UTM. This framework assumes exclusive authority: crewed aircraft operate solely under the management of ATC, while UAS are managed exclusively by UTM. Accordingly, UAS are not permitted to enter airspace under ATC control, and vice versa.

However, at the tactical level, additional separation requirements between crewed and uncrewed aircraft may apply to maintain safety. This is due to the dynamic reconfiguration of segregated airspace boundaries in response to real-time traffic demands from both crewed and uncrewed flights. The controller delegating airspace to either ATC or UTM control must consider and ensure a minimum safe separation between UAS and crewed aircraft when flying in close proximity (both spatially and temporally).

The extent of the impact of these new requirements on ATCO safety performance is not yet clear. However, this thesis proposes that a **collaborative interface for UTM supervision and intervention by ATCOs** may provide the mechanisms to address the main ATC-relevant challenges associated with this new concept.

The first challenge is to ensure that the ATCO has enough information available to obtain a complete mental model of the air traffic situation without overloading them. Not all information about UTM, and the UAS being managed by it, may be relevant to complete the tasks at hand. At the same time, removing too much information about UAS positions, flight intentions, flight path restrictions, and UTM control actions may give the ATCO a false sense of security when UTM automation fails. Moreover, making the controller aware of UAS intentions in the control zone may benefit overall airspace efficiency as it would allow the controller to segregate airspace in a way that is optimal for both uncrewed and crewed aircraft.

This leads to the second challenge of providing the right tools to perform the new task. The proposed dynamic airspace segregation concept incorporates new, strategic airspace management requirements into tactical air traffic control. With this approach, the boundaries between airspace segregation strategies and aircraft-to-aircraft separation mechanisms begin to fade (Figure 1.2). ATCOs must be provided with the proper means to facilitate seamless switching between segregation and separation frameworks as necessary, and operate at the intersection of both simultaneously, in a way that allows them to achieve their primary goal of preventing collisions between aircraft in the air. This is not a trivial matter, as separation and segregation might require their own unique tool sets, which may be optimized for their individual domain functions, but could confuse ATCOs when switching from one context to the other. Therefore, a common mechanism for UTM supervision, segregation provision and crewed aircraft control will need to be developed. However, implementing such a new mechanism may require adopting a different control strategy than the one currently in use, potentially affecting workload, situation awareness, safety, and efficiency. For traffic management actions, ATCOs are accustomed to issuing verbal commands to the affected aircraft. In the case of UTM, they would be coordinating with an automated system, which is itself acting as “ATC for UAS traffic”. The tools must therefore be sophisticated enough to reflect ATCO intentions on where to permit UAS air traffic within the control zone, but also simple enough to not distract ATCOs from their main task of coordinating crewed air traffic.

Managing workload [21] is the third challenge that should be addressed through the interface. Although there is no agreed consensus on the exact composition and definition of the term [22], in the context of ATC, Hilburn and Jorna [23] define workload in general terms as an ATCO’s subjective experience of the demand imposed by the ATC task load. In this regard, the question of using automation to relieve the task load concerning UTM supervision arises. Automation may assist the human controller by alerting them of pending conflicts or areas that require their intervention. UTM itself, as a system relying extensively on the use of automation, may provide the necessary assistance to the ATCO via the interface. However, the challenge of collaboration with automated UTM systems may itself be a source of task load for the ATCO, in particular when UTM decision-making

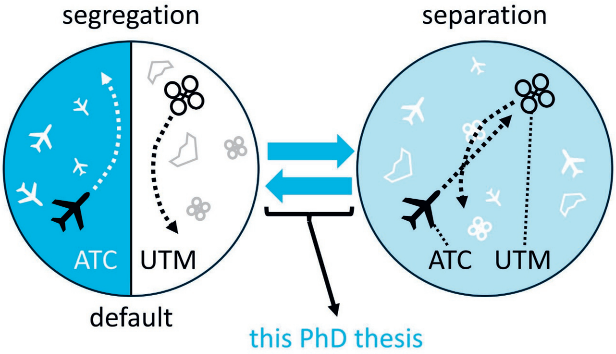

Figure 1.2: Simplified illustration of the transition between the domains of full segregation of crewed and uncrewed air traffic versus integration using separation mechanisms, which marks the main focus area of this thesis.

on UAS routes contradicts ATCO intentions for crewed air traffic.

Finally, the last challenge that could be addressed through interface design is the question of which control strategy would achieve the best possible results in terms of safety and efficiency of crewed and uncrewed air traffic. Depending on the applied design choices of the interface, ATCOs may be incentivized to use one control strategy over another. In the absence of real-world data about ATCOs' collaboration with UTM, this question has not yet been addressed.

Therefore, the development of a human-centered interface for collaborative management of ATC-guided crewed air traffic and UTM-guided uncrewed air traffic is essential to facilitate their co-existence. Based on the challenges highlighted in this section, the overarching problem statement of this thesis is formulated as follows:

**Problem statement**

Which information, tools, automation support and control strategies do ATCOs require to achieve a safe and expeditious flow of crewed and uncrewed air traffic?

## 1.3 RESEARCH APPROACH

The final aim of this research was not only to develop an interface through which air traffic controllers could interact with UTM, but also to gather some initial empirical evidence on how UTM operational concepts impacted the human performance aspects of air traffic control. At the time when this work was initiated (2019), the concept of UTM (and U-space) was still very new. Most of the research projects being conducted at that time focused on developing the operational concept and services through which the system would work within itself. This is reflected in the first half of this thesis, as the initial experiments were conducted without much guidance material on ATCO interactions with UTM available on which to base our assumptions. It was therefore necessary to analyze the concept from the ground up and make assumptions on which facets of the UTM operational environment could impact the work of the ATCO and how. From this, an initial interface was developed to assist tower controller interactions with UTM using *geofences* (volumes of airspace that can be dynamically activated to restrict UAS flights from that area).

The emergence of the COVID-19 pandemic made it necessary to reconsider how human-in-the-loop experiments would need to be conducted in this research, given the restrictions on traveling and gatherings of people that were in place at the time. These limitations, however, turned out to be a blessing in disguise. Given the strong reduction in air travel, it was *easier* to find ATCO volunteers willing to participate in research experiments. The simulation tool which would emulate the collaborative ATC-UTM interface was developed to be accessible through a web browser. This allowed participants to conduct the human-in-the-loop experiments from their own homes.

The impact of UTM on air traffic control, and what an interface could look like, became more of a focus in other UTM research projects later on, posterior to the initial research conducted for this thesis. In particular, when dedicated projects focused on ATM-UTM integration, such as PJ34 AURA [20] were funded, it became much easier to put human performance aspects of ATC with regards to UTM into perspective, given that more and more research was being conducted on the subject. The second half of this thesis is reflective of this, as one of the human-in-the-loop experiments was conducted within the scope of the PJ34 AURA project itself. The experiment and display design were matured in the context of the Dynamic Airspace Reconfiguration Manager (DAR Manager) role developed in PJ34 AURA.

The final interface design presented in this thesis is the result of an iterative design approach. Initial assumptions and design choices were updated after every experiment. Insights gained provided the basis for the next iteration of the interface design, and so on. The culmination of all design cycles would mature the interface enough to answer this thesis's four main research questions, introduced below. These are focused on the theoretical basis for the UTM operational concept in relation to ATC, the design of the interface, resulting control strategies, and finally, impacts on human and safety performance.

### 1.3.1 RESEARCH QUESTIONS

**Incorporating a new operational concept.** The first part of this research focused on understanding the novel approach applied in UAS traffic management and incorporating the resulting operational concept into the air traffic control environment. Particularly within the European regulatory framework, UAS flight authorizations are subject to risk-based assessments of each individual flight [17]. The results of these risk assessments then define the necessary mitigation measures to lower the risk to an acceptable level [18], which in turn limits the operational volume that UAS have available during their flight. The shape and size of operational volumes may also differ with each flight, depending on the use case and risk assessment. Moreover, multiple UAS may have to adhere to different flight restrictions, even if they are operating in the same geographical area. The challenge for UTM is to respect these restrictions when issuing traffic actions on UAS. Therefore, understanding how UAS constraints impact UTM decision-making is crucial for developing a collaborative interface with air traffic control.

A bottom-up analysis of UAS operational concepts, mission types, flight authorization requirements, airspace restrictions, and applicable regulations is necessary to map out the operational environment of UAS flights. This environment must also consider the tools through which UAS traffic will be managed by UTM. Similarly, the operating environment of air traffic control in its current form is mapped out with the support of regulations that govern it [1, 24–26].

The approach of this thesis is to then incorporate the UTM operational environment into that of controlled airspace, and identify discrepancies and commonalities with air traffic control. The merging of both environments will shape the operational concept of UTM within controlled airspace. Of particular interest are the means through which air traffic control and UTM will achieve their respective goals, and the degree to which they overlap. This comparison is facilitated using Ecological Interface Design (EID) [27–29] concepts, which inspired the design approach of this thesis. The term “ecological”, in this context, refers to the physical (e.g., environmental) and intentional constraints that bound safe actions (irrespective of what agent is executing those actions, human or automation). The EID philosophy builds on an understanding of how a complex system functions and provides domain transparency to the agent. A starting point for the EID framework is the top-down decomposition of the work domain using an *Abstraction Hierarchy* [30], a process which was also used in this work.

An Abstraction Hierarchy identifies the functional purposes of the system (top level), and continues down through underlying principles, processes, and function-bearing components, finishing with an overview of individual physical elements that make up the work domain (bottom level). Moreover, “means-ends” relationships indicate which elements of the layer below are used to achieve the functions of the layer above. Figure 1.3 provides a schematic representation of such a model. In this way, the whole system can be represented. Developing such a model of the collaborative ATC and UTM environment will help comprehend the functions, relationships, and constraints of both systems occupying the same space, regardless of which actor is performing control actions.

Mapping out the joint work domain of UTM and air traffic control and understanding how individual goals are achieved by either system facilitates the design of an interface. Therefore, the first research question has been formulated as follows:

**Research Question 1**

What are the underlying system goals, functions, relationships, and constraints inherent to the work domain of UTM, ATC, and how do they compare?

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**Portraying the ATC-UTM environment.** The second part of this research focused on developing an interface that allows air traffic controllers to navigate the work domain and manipulate elements of the collaborative ATC-UTM environment under their control. Inspired by the EID framework, the interface design is developed to allow the ATCO direct intervention with UTM on the display, map constraints of the work domain to visual cues on the interface, and make the Abstraction Hierarchy (i.e., “means-ends” relationships) visible in the interface to facilitate problem-solving [28].

The interface should be as functionally transparent as possible to the properties of the collaborative ATC-UTM work domain relevant to achieving ATCO objectives. The idea is to make the “deeper” structure of the work domain visually salient, such as by displaying

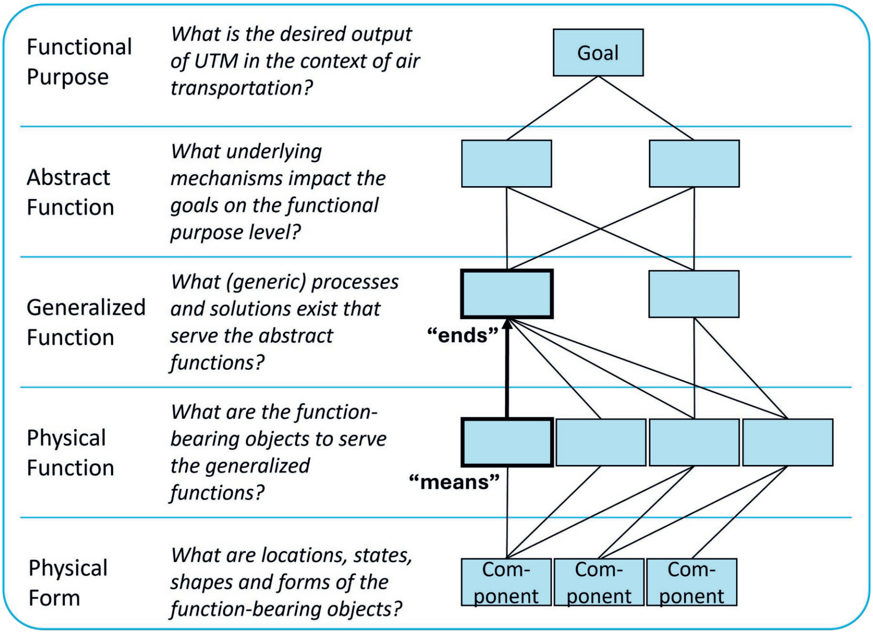

Figure 1.3: Schematic representation of an Abstraction Hierarchy.

active geofences or UAS maneuvering limitations, so as to create the perception in ATCOs that they are directly influencing UAS trajectories to facilitate their own objectives through the display, and not dealing with UTM as an intermediary.

By embedding the Abstraction Hierarchy structure into the interface, information can be portrayed at every means-ends hierarchy level, beginning at the top level (Functional Purpose), all the way down to the bottom (Physical Form) – see Figure 1.3. According to the principles of EID, this is accomplished by mapping the relational structures of the domain onto the visible properties of the objects displayed on the interface (e.g., by showing the ATCO how the activation of a UTM constraint influences the UAS under its control). The great advantage of this is that it relieves the ATCO from having to internalize how individual structures relate to each other. Finally, EID suggests that, whenever possible, commands should be communicated by directly acting on the display (e.g., clicking, dragging, sliding).

The interface design of this thesis, however, will not fully portray the entirety of the ATC-UTM work domain. Instead, the focus of the design lies on the transition between *segregation* and *separation*-relevant functions and constraints of the Abstraction Hierarchy. Making these visible to the ATCO should allow them to collaborate with UTM, whilst achieving their main objectives. These considerations lead to the second research question:

**Research Question 2**

In what visual form can the constraints on UAS, regarding airspace segregation and separation from crewed aircraft, be mapped on a decision-support interface such that it supports the work and strategies of air traffic controllers in achieving system goals?

**Collaborative control strategies.** Given the novel nature of this research, it is not possible to base assumptions on previous studies regarding the control strategies that ATCOs would need to apply to collaborate with UTM. Therefore, rather than prescribing a specific control strategy, experiment participants are given a free choice over how they use the tools at their disposal. An EID-based interface further facilitates this approach. By design, it is agnostic to the type of control strategy applied by the operator. Instead, the interface aims to support the ATCO on achieving the overarching goal of the system by allowing them to navigate the collaborative ATC-UTM work domain using the display.

It is important to note in this context that the field of Cognitive Work Analysis (CWA) builds on EID principles to incorporate control tasks and strategies into the design phases of an interface [30]. However, as these are not yet established for collaborative ATC-UTM airspace management, the research presented in this thesis did not involve a full CWA. Rather, EID principles were applied to gather initial insights into preferred strategies and control actions performed by ATC when presented with shared work domain constraints.

A total of three human-in-the-loop experiments were then conducted, which focused on testing the interface, to gather information about the utility of the proposed operational concept. Emergent control strategies can then be extracted by observing how ATCOs make use of the interface to maintain a safe and efficient flow of air traffic within the control zone. The utility of control strategies is evaluated in the context of ATCOs' achievement of the safety and efficiency of crewed aircraft as well as their workload.

All experiments are designed in such a way that uncrewed aircraft will come into conflict with crewed aircraft if no control actions are taken. It will be up to the experiment participants to find adequate control strategies to maintain a safe airspace. The final experiment also adds unpredictability to UAS flight routes by simulating UAS contingency situations. In theory, EID should allow participants to manage such situations adequately. The reason for this is that, regardless of the nature of the contingency, the set of means available for managing the fault is bound by the initial design of the system and the constraints of the work domain, both of which are represented in the Abstraction Hierarchy [28]. Thus, failures to achieve ATCO goals during unforeseen events caused by an inadequate interface representation of the work domain should become apparent.

Finally, the experiments aim to extract information about how ATCOs perceive their own role within this collaborative environment. By making the work domain of UTM salient to the human controller, there is a risk that they would be incentivized to assume responsibilities for traffic management of UAS for the sake of efficiency, or by overriding UTM decisions if it issues instructions on UAS that contradict ATCO intentions. The latter is of particular interest since flight rules for small UAS have not yet been developed. UTM will therefore always prioritize the optimal route around flight restrictions from the UAS' perspective, which may come at the expense of routing predictability from the perspective of an external human supervisor. These considerations lead to the third research question:

**Research Question 3**

How do air traffic controllers interact with UAS via the interface, which control strategies do they apply, and how do they perceive their role in a collaborative ATC-UTM environment?

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**Human performance considerations.** The fourth and final part of this research will focus on identifying human performance limitations when using the collaborative ATC-UTM interface. A minimum set of separation criteria between crewed aircraft and UAS is defined for each of the three human-in-the-loop experiments. Investigating the chain of events leading up to losses of minimum separation observed between crewed aircraft and UAS, it will be possible to gather conclusions on how well the interface assisted the ATCO in achieving safety.

Moreover, the third simulation experiment is set up in such a way that it tests the limits of the proposed operational concept for collaborative ATC-UTM airspace management. This experiment will identify areas in which the concept breaks down and therefore requires further refinement or reevaluation.

Another component that impacts the collaborative ATC-UTM interface performance as a whole is the ATCO's ability to jointly manage air traffic with an automated system. Of particular relevance is the ability of the interface to convey the control actions that the UTM automation is taking and its reasoning for doing so. This not only applies to UTM making decisions on its own UAS traffic but also its responses to restrictions imposed on UAS by the ATCO.

In the experiments conducted in this thesis, ATCOs are performing management by exception (i.e. supervisory control) [31, 32] over UAS traffic. With regards to automation, in supervisory control, the computer (in this case the UTM system) generates recommended options, selects the best one, and carries it out. The human can intervene if desired. However, in the proposed concept of this thesis, human intervention in UTM is reactionary in nature, by providing means to manipulate constraints on UAS in response to UTM-implemented decisions. With supervisory control systems, according to Endsley [31, p. 16], because of the involvement of *"automation [in] decision making [...], human engagement can be expected to be low, with reduced [situation awareness] and higher [out-of-the-loop] problems found."* Therefore, the design of the interface must be generated in such a way that ATCO situation awareness of the traffic situation remains high, and that they remain in-the-loop on UTM decision making. This leads to the fourth and final research question:

**Research Question 4**

What are the limitations, safety and performance impacts of augmenting the tower control role with UTM supervision, and what role does automation play?

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### 1.3.2 MAIN ASSUMPTIONS

Several assumptions and simplifications were necessary to conduct this research, given its exploratory nature and limited conceptual maturity. The main assumptions which apply throughout this work are presented below.

**Uncrewed traffic properties.** Uncrewed aircraft managed by UTM are assumed to fly solely BVLOS point-to-point or surveying missions. The maximum operating altitude is limited to 400 feet above ground level for all UAS flights. Moreover, it is assumed that the departure and end points differ from each other and that UAS are capable of landing on the spot. UAS flight profiles are adapted optimally to the mission requirements, and conducted by either multi-rotor or fixed-wing vehicles. The missions themselves are separated into low (e.g., package delivery, surveillance) or high priority e.g., delivery of medical supplies). Finally, all UAS flight profiles are expected to be influenced by mission constraints, environmental constraints (e.g., wind), and endurance (e.g., battery capacity).

**Air traffic control environment.** For this research, the aerodrome tower controller is selected as the responsible entity within ATC to manage the collaborative interface with UTM, as they control crewed aircraft taking off from, landing at or flying in vicinity of the aerodrome, where the risk of encounter with UAS is greatest. Therefore, the interface design and simulation environment are adapted to the working environment of the tower controller. However, the underlying operational concept and design considerations are not limited to this particular application and can be extended to other ATC domains that may be impacted by small UAS flights, such as ground control (which manages crewed aircraft movements on the tarmac) or approach control (which coordinates arriving and departing crewed aircraft).

**Crewed traffic properties.** Crewed aircraft are assumed to follow current air traffic procedures to depart and land at an airport providing ATC services, as well as adhere to their cleared arrival and departure routes. Crewed aircraft traffic load and mix of aircraft types mimic current levels. Different crewed aircraft missions are also considered, ranging from commercial operations to general aviation flights and emergency helicopter medical service missions. This thesis only considers standard crewed traffic procedures, therefore it is assumed that all crewed flight movements have been planned, optimized, and de-conflicted by other ATC units prior to contacting tower control.

**UTM environment.** In this research, the inner workings of UTM services are seen as a “black box” and are approximated by the use of a path-planning algorithm. However, it is expected that differences in the types of UTM service architectures, which can generally be divided into centralized and distributed, influence the behavior of UAS traffic in response to crewed aircraft. This thesis assumes that UTM is a centralized system, in which traffic management decisions on UAS flights are issued by a central coordinating actor, similar to crewed air traffic control. It is also assumed that UAS will react to UTM decisions without any delay, therefore simulating an environment with more sophisticated UTM automation levels and integration in UAS guidance and control systems. However, UTM is not expected to instruct proactive avoidance maneuvers on UAS if it detects conflicts with other UAS or crewed aircraft in this research, given the current lack of flight rules that prescribe how to carry them out.

**Air traffic quantities.** The quantities of crewed and uncrewed air traffic are based on the assumption that substantial increases in UAS traffic are expected with comparatively lower increases in crewed aviation traffic volumes over the next decade. This is justified in part by the lower entry barriers, broader range of use cases and lower costs associated with UAS missions when compared to crewed aviation [4]. Yet, growth in complex UAS missions, such as flights Beyond Visual Line-Of-Sight (BVLOS), which require UTM system support, is expected to be more moderate than less complex missions in Visual Line-Of-Sight (VLOS), which is reflected in the UAS traffic numbers used in this research.

**Experiment limitations.** The human-in-the-loop experiments conducted in this thesis are short-term experiments in cross-sectional studies. There is no out-of-tower view provided in any of the experiments, under the assumption that UAS cannot be tracked visually by the tower controller. Only one of the three experiments simulated voice communication with crewed air traffic and other ATCOs. Two of the three experiments were conducted remotely via a web interface. Thus, a full immersion of experiment participants into the role of the tower controller could not be provided.

## 1.4 THESIS OUTLINE

The scope of this thesis can be divided into three main parts, illustrated in Figure 1.4. The first part ① elaborates on the complexities of the UTM work domain which will need to be accommodated into the collaborative environment with ATC. The principal operating constraints of small UAS in relation to flight restrictions are mapped out and exemplified through concrete use cases in the vicinity of an aerodrome that provides ATC services. The superposition of the UTM work domain on the ATC working environment forms the basis of the collaborative ATC-UTM operational concept applied to this research. The second part ② of this research focuses on the design of an interface for tower controllers to collaborate with UTM. Application of EID principles results in an initial display design which is tested in a dedicated human-in-the-loop experiment. The final part ③ presents the outcomes of further human-in-the-loop experiments which focused on refining the interface design, adapting the operational concept, and understanding the role of automation in the collaborative environment.

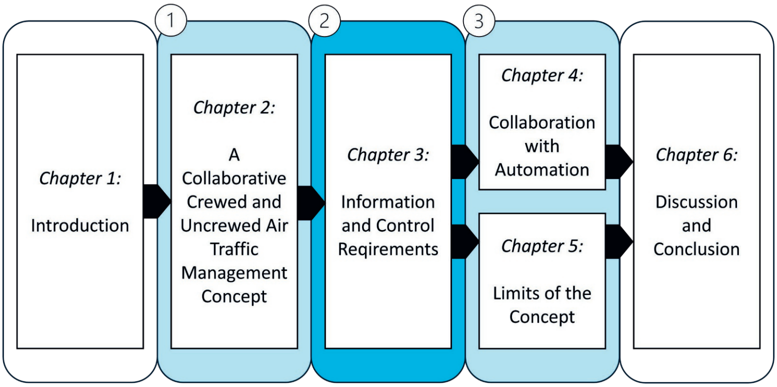


Figure 1.4: Schematic representation of the thesis structure.

This thesis is divided into six main chapters that describe the background, design, and refinement of an ecological collaborative interface between ATC and UTM, which allows tower controllers to segregate crewed and uncrewed air traffic.

Chapter 3 (*Information and Control Requirements*) is an adaptation of a published, peer-reviewed journal paper. Chapter 4 (*Collaboration with Automation*) and Chapter 5

(*Limits of the Concept*) are adaptations of peer-reviewed conference papers. Chapter 2 (*A Collaborative Crewed and Uncrewed Traffic Management Concept*) is an unpublished literature review and concept description. Each chapter states the original titles of the papers on which they are based, alongside information about co-authors and publication details, when applicable. Furthermore, sections are introduced with a brief overview of the relevance of the presented work in the context of the overall thesis.

**Chapter 2: A Collaborative Crewed and Uncrewed Air Traffic Management Concept.** In this chapter, the challenges of incorporating UAS into traditional air traffic management are introduced. The principal operating constraints of small UAS are highlighted and it is shown how these will be managed by UTM systems. By modeling UAS flights in the vicinity of towered aerodromes, the complexity of collaborative airspace management of uncrewed and crewed aviation within controlled airspace is made apparent. The resulting constraints of both domains are combined into a proposed operational concept that uses dynamic geofencing tools to segregate crewed aviation from UAS and assigns the tower controller as the responsible entity for limiting airspace for UAS operations. This chapter contains the main literature survey and theoretical foundation of this thesis.

**Chapter 3: Information and Control Requirements.** The design of the tower control interface for segregating crewed and uncrewed aircraft is presented in this chapter. First, an analysis of the work domain of the collaborative ATC-UTM environment is shown in the form of an Abstraction Hierarchy model. The implications on the interface design resulting from either the ATC or UTM domain are highlighted and explored in relation to their impact on safety and efficiency. Individual components in the Abstraction Hierarchy are discussed and it is shown how they map onto the display design of the interface. The resulting interface is then evaluated in a human-in-the-loop experiment. Results and implications on the display design are presented thereafter.

**Chapter 4: Collaboration with Automation.** The impact of UAS automation on the control strategies of tower controllers is explored within the collaborative environment. New interface elements are introduced to facilitate various levels of ATCO intervention in UAS routings. Human-in-the-loop experiment results are evaluated in terms of how the interface was used depending on the applied control strategy. The discussion of these results leads to the question of whether full segregation or full integration of ATM and UTM domains would be the optimal approach to managing the collaborative environment.

**Chapter 5: Limits of the Concept.** In this chapter the final human-in-the-loop experiment conducted for this thesis is presented, which focuses on exploring the limitations of tactical segregation of uncrewed and crewed air traffic by tower controllers. Differing vertical and horizontal segregation requirements are analyzed. The impacts of interface design and ATCO control strategies on safety performance in the collaborative environment are discussed. Finally, mitigation measures to improve safety performance are proposed.

**Chapter 6: Discussion and Conclusion.** Insights gathered from previous chapters are combined and summarized in this final chapter. An overarching discussion is presented on the ecological collaborative interface between ATC and UTM and its employment to support tower controllers in managing uncrewed and crewed aircraft. Limitations of this study, interface design improvements, and recommendations for future work in the context of real-world application of the interface are presented. Finally, conclusions are drawn concerning the main research questions.

# 2

# A Collaborative Crewed and Uncrewed Air Traffic Management Concept

*The challenges of incorporating UAS into traditional air traffic management are introduced in this chapter. By highlighting the main differences in operational constraints of small UAS and crewed aviation in the vicinity of towered aerodromes, a concept for collaborative management of crewed and uncrewed aircraft by tower controllers is developed.*

*Dramatic increases in Uncrewed Aircraft Systems (UAS) activities at low altitudes are expected over the next decade. The expected levels of air vehicle densities are not something that existing, human-centric air traffic management systems are designed to deal with. Therefore, the Air Traffic Management (ATM) sector is considering the implementation of a separate UAS Traffic Management (UTM) system to guide and manage the flow of UAS and prevent collisions. To cope with high numbers of UAS, UTM systems are designed from the ground up to rely on high levels of automation and limited human intervention. This presents a challenge in an airspace requiring both ATM and UTM supervision, such as the controlled traffic region around towered aerodromes. To address this challenge, a concept is introduced which relies on the segregation of ATM and UTM areas of responsibility to avoid the issue of having multiple agents (human air traffic controller vs. automated UTM) manage different traffic in the same airspace, whilst providing the human controller flexible airspace management mechanisms through dynamic geofencing. In this chapter the differences in UAS operating methods from traditional crewed aviation are introduced and it will be examined how UTM will manage them. An operational concept is proposed that enhances the human controller work domain with additional tools to place dynamic restrictions on UAS traffic which the UTM system would need to execute. The operational concept is exemplified through a practical use case. Finally, it is discussed how some of the challenges presented by the new operational concept could be mitigated through interface design.*

## 2.1 Introduction

In recent years there have been substantial advancements in the scale and complexity of UAS missions. For instance, the use of UAS for transporting and distributing blood samples between hospitals has become a routine sight in various locations around the world. In Rwanda, fleets of small, modular UAS are operated that can be launched at a moment's notice [33]. Even in the heart of Europe UAS delivery services are being deployed in major Swiss cities to deliver medical samples between hospitals [34]. These complex, Beyond Visual Line-Of-Sight (BVLOS) missions are supported by new, risk-based operations, as opposed to relying on full vehicle certification, which is the established means for assuring air (and ground) safety in aviation. In particular, the Specific Operations Risk Assesment (SORA) [18] is currently the most prominent risk-assessment mechanism for non-certified UAS missions to assure the safety of an individual flight. It has been adopted into European Regulation as the de facto means to assess and mitigate the flight risk of complex, non-certified UAS missions in the Specific category [17].

Foreseeing a considerable growth of risk-based UAS operations, additional concepts for managing a multitude of such operations are being developed. These concepts fall under the terminology of UAS Traffic Management (UTM). Currently, one of the most mature UTM concepts is the European Union's U-space [19] initiative, which was introduced into EU regulation in 2021 [15, 35]. This regulatory package provides the framework under which multiple non-certified UAS flights can be managed through a series of automated services that assist individual UAS operators in planning and executing their UAS missions. One of the main tasks these services perform is to convey flight restrictions to UAS operators, and once UAS missions rely on increased levels of automation, provide instructions to comply with these flight restrictions directly to the uncrewed aircraft.

To avoid conflicts with crewed aviation, regulations [17] restrict UAS flights to stay below the minimum crewed aircraft flight altitude. This vertical segregation is sufficient to avoid most potential for conflict, but not all. In this regard, UAS operations in the vicinity of aerodromes are of particular interest. The low operating altitudes of UAS in an urban environment pose a collision hazard to departing and arriving aircraft. Recent disruptions in air traffic flows caused by uncoordinated UAS operations near major aerodromes, such as Gatwick [6], Heathrow [7], Frankfurt [8] and Madrid [9] have brought the very real dangers of these vehicles around aerodromes into the public eye. However, the increase in value created by incorporating UAS technologies into existing areas of commerce must not be neglected. Airport control zones typically occupy a substantial volume of urban airspace and may become a critical bottleneck for UAS operations in cities, limiting the feasibility of UAS missions in these areas. Therefore, some mechanisms must be in place to integrate UAS operations safely into the control zone and allow UAS and crewed aircraft to operate alongside each other without risking safety in the airspace.

In this chapter, the potential impact of these new operational concepts on the established ways of managing controlled airspace around aerodromes is examined. Air Traffic Controllers (ATCOs) are given special attention in this regard, as it is necessary to ensure that they would still be capable of performing their tasks at the same level of efficiency and safety as is expected for air transportation once UAS are incorporated into controlled airspace. This is especially relevant to aerodrome tower controllers, as they will experience the effects of UAS operations directly. Since it is the role of the tower controller to ensure adequate separation of crewed aircraft, the concept will incorporate these new operating constraints into an interface for ATCOs to interact with UAS. The further aim is then to test how such an interface can support the ATCO in collaborating with the highly automated UTM system, which manages UAS flights, to maintain safe and expeditious airspace.

## 2.2 UAS Flights as Disruptors to Traditional Air Traffic Management

This section builds on the discussion points presented in the introduction by fleshing out the operational concept for UAS within the European regulatory environment, in terms of expected numbers of UAS flights, the types of missions expected to be performed by UAS, specifics of risk-based flight authorizations, the use of geozones and the role of UTM. An exemplary BVLOS delivery use case in the aerodrome environment is used to highlight points that may disrupt traditional air traffic management workflows. The findings obtained from this assessment are then projected onto the working environment of the tower controller, to see how their tasks would be impacted by introducing UAS into the control zone of towered aerodromes.

### 2.2.1 Projections of UAS Operation Increases

The European UAS Outlook Study [4] foresees a total of around 390,000 uncrewed air vehicles operating in Europe by 2035, an alarming number considering a forecasted fleet size of roughly 50,000 commercial aircraft for 2043 [5]. To grasp the effect that this new actor has on the airspace, it is important to break down this volume into individual domains to see where the bulk of this growth will be. The European UAS Outlook study provides an estimate of the likely distribution thereof in Europe, which has been summarized in Table

Table 2.1: Overview of forecast UAS operations per industry sector in Europe by 2035. Data are provided by the European UAS Outlook Study Annex [4].

| Sector | % of Total Fleet | UAS [in k] | Area | Primary Mission | Operation Type |
|---|---|---|---|---|---|
| Agriculture | 38 | 130 | rural | remote sensing | BVLOS |
| | | 20 | rural | spraying | VLOS |
| Delivery | 18 | 22 | rural | close proximity delivery | BVLOS |
| Public Service and Security | 15 | 22 | rural | border security | BVLOS |
| | | 37 | urban | stationary surveying | VLOS |
| Construction and Mining | 9 | 35 | rural and urban | surveying | VLOS |
| Media | 8 | 30 | rural and urban | filming | VLOS |
| Energy | 4 | 15 | rural | local site inspection | VLOS |
| | | 1 | rural | long range inspection | BVLOS |
| Real Estate | 4 | 15 | rural and urban | local surveying | VLOS |
| University | 3 | 13 | rural and urban | research | VLOS |
| Insurance | 1 | 4 | rural and urban | damage inspection | VLOS |
| Communications | 1 | 3 | rural and urban | tower inspection | VLOS |
| Mobility | 0 | 0.1 | urban and urban | personal air vehicles | BVLOS |

2.1. Although the estimation in unit values relates to the European market, the description of the individual sectors' use cases was high level enough to generalize over the total percentage of the fleet size and associated use cases. From this, it becomes evident that by far the largest portion of the total UAS fleet will be used in the agricultural sector for BVLOS remote sensing missions in rural areas. In second place, with less than half of the agricultural fleet size, UAS will be used for close proximity delivery missions in urban areas. Followed closely in third place, Public Service and Security operations are expected to employ large volumes of UAS for long-range BVLOS and local Visual Line-Of-Sight (VLOS) missions. This outlook study does not foresee a large number of urban air mobility vehicles to be operational by 2035, mostly due to reasons of lack of public acceptance of automated flying vehicles. It is also important to note that nearly all of these missions are expected to be conducted below 120 meters above ground level, in a volume of airspace classified as Very Low-Level (VLL).

From this comparison, it is now easier to map which type of UAS operations to expect in certain areas, depending on their location and the associated predominant business sectors in that region. For this study, the focus is placed on modeling the "BVLOS close proximity delivery in an urban environment" mission. This has several reasons. First, it can be reasonably expected for this type of mission to be the most likely to occur near towered aerodromes, given that such aerodromes traditionally serve large urban population centers. Furthermore, the European Drones Outlook Study expects this to be the most common type of mission to expect in an urban environment. Coincidentally, it is also expected to be one of the most challenging mission types to incorporate, given the complexity of the operation, airspace encounter risk, and risk to people or ground infrastructure, as highlighted in the use case provided in Section 2.3.

### 2.2.2 Risk-Based UAS Flight Authorizations

A major factor to consider when modeling UAS flights within the European regulatory framework is the risk-based approach to issuing UAS flight authorizations. One of the main purposes of certification of crewed aircraft is to mitigate the risk of fatalities of the humans on board the aircraft presented by critical failures through its design. For small UAS, which do not carry passengers, the risk of fatalities depends much more on the circumstances of the ground area which the UAS overflies and the risk of collision with other crewed aircraft in the area of operation. Therefore, the focus of regulations for small UAS operations has shifted from aircraft-centric to operation-centric risk assessments, and subsequently away from full certification of the vehicle. Such an approach does not apply to all types of UAS, since EASA requires certification of UAS exceeding a characteristic dimension of three meters, UAS operated over assemblies of people, transport of dangerous goods, personal air vehicles carrying passengers, or UAS of the Specific category that do not meet the risk mitigation requirements [36]. However, for low to medium-risk UAS operations performed in Very Low-Level airspace, the risk-based approach can be applied.

Within the European framework, small UAS operations can fall into either one of two categories: Open and Specific [17]. The Open category allows for relatively simple UAS flights in Visual Line-Of-Sight (VLOS) of the remote pilot up to 120 meters Above Ground Level (AGL). Depending on the maximum take-off mass of the vehicle (up to 25 kg), additional restrictions apply, such as the proximity to uninvolved persons as well as minimum distances from residential, recreational, and industrial areas. Any UAS flight beyond the limits of the Open category (e.g., BVLOS, over 120 meters AGL, close proximity to uninvolved persons) would constitute a flight in the Specific category, and thus require a SORA with associated mitigations.

The SORA concept was developed by the Joint Authorities for Rulemaking on Unmanned Systems (JARUS) and is continuously being improved based on new insights and requirements [18]. It consists of an assessment of ground and air risk posed by the UAS flight in the area of operation and prescribes measures to assure a Target Level Of Safety (TLOS). The TLOS for ground risk is one fatality for every million flight hours, for air risk under the see and avoid principle less than one mid-air collision per ten million flight hours, and for air risk in areas where separation is provided by an Air Navigation Service Provider (ANSP) one mid-air collision per billion ($10^9$) flight hours.

The SORA methodology's greatest strength comes from allowing UAS operators to operate their vehicles in a limited or restricted manner and the possibility to do so without a traditional aircraft certification. It is essentially a guideline for UAS operators and regulators to perform hazard and risk assessments of any specific-class UAS operation and their subsequent mitigation measures. The SORA process itself is performed in a twelve-step analysis which covers the following areas:

1. Description of the operation intended to be flown.
2. Determination of the operation's Specific Assurance and Integrity Level (SAIL), which incorporates the following sub-tasks:
    (a) Determination of the Ground Risk Class (GRC) which is the combination of the unmitigated risk of a person being struck by the drone and barriers in place to reduce that risk.
    (b) Determination of an Airspace Encounter Category (AEC) which is mostly dependent on the airspace in which the drone will operate and identify the associated Air Risk Class (ARC) as well as strategic mitigations that can reduce that risk.
    (c) Determination of threat barriers.
3. Feasibility check and verification of robustness of the proposed barriers.

Each of these steps will impose restrictions on the UAS missions in order to meet the required safety levels. Thus, the final flight profile is not only limited by the physical limitations of the vehicle but also by the mitigation measures defined by the SORA assessment. These mitigation measures may severely limit the room for maneuvering that an individual UAS has along its flight profile. Thus, tactical interventions on individual UAS may favor hovering in place over lateral avoidance maneuvers.

Since the focus is on assessing the impact of multiple operations in the Specific category on air traffic control procedures of towered aerodromes, additional details of the SORA assessment will not be addressed here. For further reading on the differences between SORA and traditional aircraft certification, refer to Nikodem et al. [37]. Instead, Section 2.3 presents the impact that SORA has on a UAS' flight profile and maneuvering options in the vicinity of towered aerodromes based on a BVLOS delivery use case.

The SORA concept only covers individual UAS missions. As the numbers in UAS operations increase, there is a need to manage multiple flights in a way that is coordinated, scalable, and relies on increasing levels of automation.

### 2.2.3 Managing Multiple UAS in a Given Airspace

As the number of UAS missions begins to scale, some sort of framework for the automation of permissions, management, and oversight of UAS operations must be in place; UTM systems aim to fill that niche. In essence, UTM can be summarized as the bridge linking the needs of UAS operators to provide their services to end users with those of the authorities tasked with maintaining safety and security in their area of responsibility, all the while fostering its very own service industry within the UTM ecosystem. Several examples of implementations of such eco-systems are already being developed, like the United States' [12] and Australia's [38] respective UTM systems and the European Union's U-space [19].

From their initiation, each of these systems has been designed to provide essential services and enable UAS operations at scale using automation. The European Union's

U-space initiative is currently one of the most advanced concepts and will be used as a baseline for the analysis of UTM in this research. U-space services will be rolled out in four phases, beginning with simple e-registration, e-identification and geofencing through flight planning management, weather services and aeronautical information all the way to tactical interfaces with air traffic control, capacity management and automated detect and avoid functionalities, to name a few [16, 39]. Several parallels to the existing ATM system can be drawn from this, however, U-space aims to provide these services without humans in the loop in internal decision-making processes.

At the time of this writing (2024), concepts for UTM systems such as U-space are still being matured through dedicated research projects, and are slowly being adopted into regulation. In Europe, the U-space regulation [15, 35, 40], provides a framework for an ecosystem of U-space service providers. This framework indicates which initial services shall be provided and provides basic indications on how crewed aircraft will be kept safe through dynamic segregation. However, there is little guidance within the regulatory package on how the operational processes within UTM shall be managed, or how air traffic control shall interact with UTM at a tactical level. Therefore, many of the assumptions supporting the operational concept for UTM which are not covered in regulation come from other research projects in the field of U-space. Of particular relevance to the concept proposed in this study is the PJ34 AURA project [20], which developed and tested a collaborative interface between ATM and U-space. Details on the project and its connection to this research are provided in Chapter 4.

### 2.2.4 UAS Airspace Restrictions Through Geozones

Apart from restrictions that result from the SORA process, additional airspace restrictions will also need to be considered by UAS operators before conducting their mission. The European regulatory framework for UAS allows EASA member states to define additional restrictions on UAS flights in areas where the limitations of the open and Specific category do not suffice for safety, security, privacy, or environmental reasons [17]. These restrictions are communicated through static and dynamic geographical data, which are referred to as UAS geographical zones or “geozones” for short. Restrictions may include prohibitions, particular operating conditions, additional authorization requirements, minimum environmental standards, certain UAS class requirements, or requirements on additional technical features for certain or all UAS operations. As an example, areas where U-space is established will be limited to its own geozone. It is also expected that geozones may be nested within other geozones. The operational concept for U-space also expects internal geographical zones to be established [40], which provide further structure and restrictions in particular areas if necessary, e.g., to protect critical infrastructure, such as aerodromes. Areas that block all UAS operations entirely are called prohibited geographical zones, but are commonly referred to as “no-fly zones” or “geofences”.

Initially, it is expected that geozones will be defined to cover static geographical restrictions of existing airspace structures for crewed aviation, such as civil and military control zones, restricted areas, areas around uncontrolled aerodromes, and national parks. However, it is easy to imagine static geozones being expanded beyond typical airspace restrictions to safeguard critical infrastructure, areas of national interest, as well as recreational areas. Geozones may also be implemented to support dynamic airspace restrictions.

Table 2.2: Overview of geozone categories and denominations.

| Zone denomination | Definition | Origin | Term used in this document |
|---|---|---|---|
| UAS geographical zone | Area where additional restrictions on UAS flights apply | [17] | geozone |
| Prohibited geographical zone | Geozone that blocks all UAS operations entirely (no-fly zone) | [40] | geofence |
| Internal geographical zone | Geozone within a U-space airspace | [40] | - |
| Static geographical zone | Geozone updated infrequently | [40] | static geozone |
| Dynamic geographical zone | Geozones activated for a short duration | [40] | dynamic geozone |
| - | Geofence activated for a short duration | - | dynamic geofence |

For instance, state authorities may want to issue short-term and localized restrictions on UAS in support of police or military operations. Therefore, it is likely that dynamic geofences will play a crucial role in resolving tactical conflicts between UAS and crewed aircraft, if prior strategic conflict prevention mechanisms are insufficient. Table 2.2 provides an overview of the types of geozones addressed in this document. Note that the concept proposed in this thesis utilizes dynamic geofences as a tactical UAS traffic management mechanism. More information on this will be provided in Section 2.4.

## 2.3 Modeling UAS in Proximity to Aerodromes

The use case that was elaborated in this thesis was centered around Rotterdam The Hague Airport, which was selected for multiple reasons: It is an aerodrome located at the heart of one of the largest urban centers in Europe, surrounded by densely populated housing — a prime location for several UAS business sectors outlined in Table 2.1, such as delivery, public service and security, construction, media, real estate, university, insurance and telecommunications. Similarly, its airspace boundaries are dominated by the terminal area of Amsterdam Schiphol International Airport, both horizontally and vertically, which sets important limitations on the way that arrivals and departures of crewed aircraft are structured. Moreover, with just over 50,000 flight movements of crewed aircraft per year [41], it is not a large aerodrome in terms of traffic volume, which leaves more opportunities for facilitating UAS flights than a large aerodrome, such as Schiphol.

During the high season, for example in June, Rotterdam The Hague Airport sees almost 200 aircraft movements per day, whereas during the low season, for example in December, the number of flights halves to about 100 flights per day. In general, the aerodrome sees a multitude of different flight movements throughout the year (see Figure 2.1), of which the majority of traffic movement is derived from commercial and training flights (at 28 percent each). Moreover, it can be seen that Helicopter Emergency Medical Service (HEMS) flights also form a significant portion (ten percent) of the flight movements, since the aerodrome also serves as a dispatch point for such missions [42]. HEMS flights are of particular interest for the use case, given the lower operating altitudes and less predictable scheduling and routing of such flights may pose a larger threat of collision with UAS.

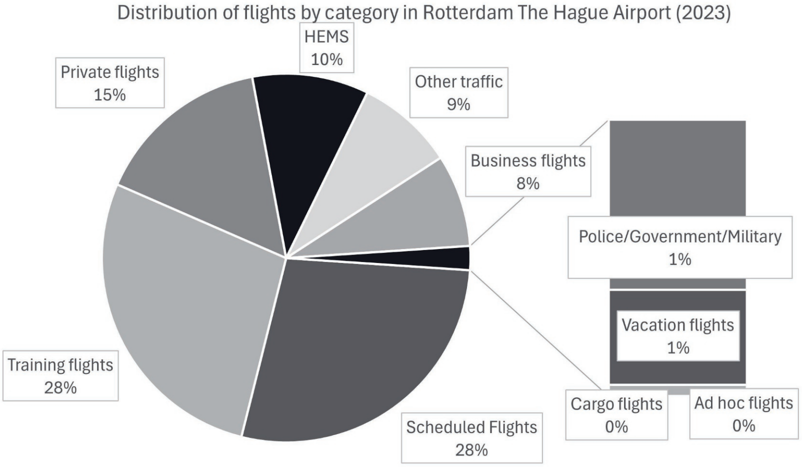


Figure 2.1: Distribution of types of flight operations in Rotterdam The Hague Airport in 2023 by percentage [42].

Rotterdam The Hague Airport has one runway of 2,200 meters, oriented at heading 060-240, which is used for take-off and landing in both directions. The departure routes of commercial flights follow along the extended runway centerline until clearing well above the 120-meter AGL maximum operating altitude of UAS. The same goes for arrivals, which limits the potential for conflict with UAS to close proximity to the runway. For training flights, which make up the same proportion of flight movements at the aerodrome, the flight patterns are quite different, since the published arrival or departure routes for Visual Flight Rule (VFR) traffic require longer durations of time at lower altitudes. Figure 2.2 shows the VFR arrival routes in red and departure routes in green. Note the altitude restrictions of 1,000 feet above mean sea level, which in this area equates to roughly 300 meters above ground level, for some of these routes. Furthermore, the Instrument Flight Rule (IFR) areas indicate roughly where commercial aircraft will descend or climb through Very Low-Level airspace, and would thus be at greatest risk of collision with UAS.

Having explored the specifics of Rotterdam The Hague Airport as a reference, a representative use case from the ones projected in Table 2.1 can be developed. For the sake of analysis, a UAS medical delivery service between the Haga Hospital Leyweg in Den Haag and Erasmus Medical Center in Rotterdam was chosen. A direct line of flight from one hospital to the other would directly overfly the aerodrome's final approach path, making for an interesting use case to examine (see Figure 2.3).

This delivery service will be conducted using a small UAS flying a BVLOS point-to-point mission under the European regulatory framework. This requires a prior SORA analysis to be performed. The result of the SORA analysis has wide-ranging implications on the flight

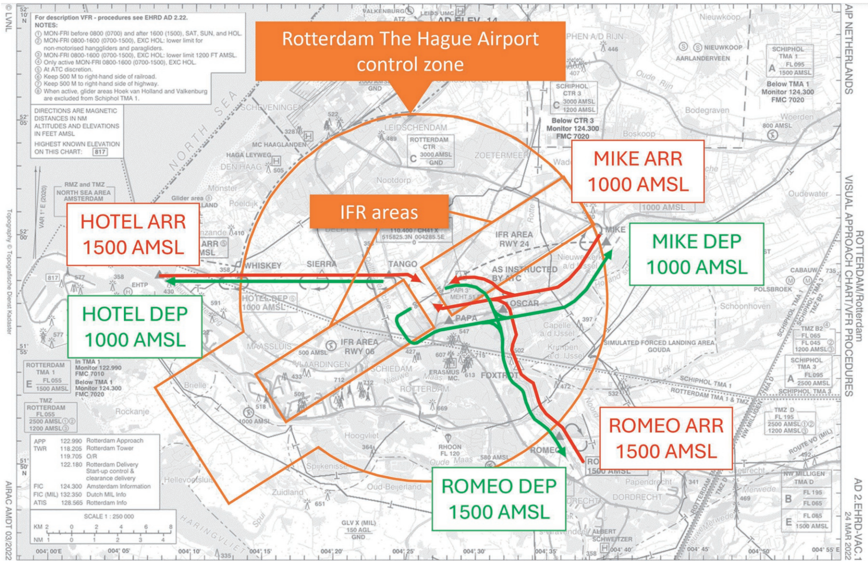


Figure 2.2: VFR and IFR approach areas of Rotterdam The Hague Airport.

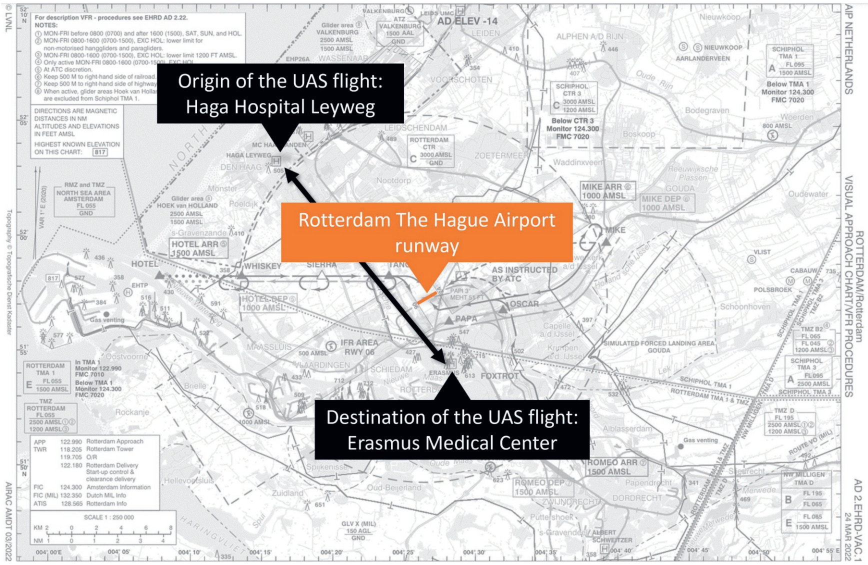


Figure 2.3: A Medical UAS mission superimposed on the visual approach chart of Rotterdam The Hague Airport.

paths that a UAS will be able to take within the control zone, since the required ground and air risk mitigation measures may severely restrict the UAS' room for maneuvering. To identify the implications of such assessments on the modeling of UAS flights in the control zone, a generic risk assessment is performed using the SORA v2.5 guidance document [18]. In the following subsections, those aspects of the assessment are highlighted that impact the UAS trajectory through the control zone.

### 2.3.1 Ground Risk Class

Since the flight will take place over large portions of urban airspace (defined in SORA as a population density lower than 25,000 people per square kilometer), the overflown geography will impose several restrictions on the planned trajectory of the UAS.

The flown trajectory must consider a combination of flight geography, contingency volume, and risk buffer to determine the ground area at risk (intrinsic GRC footprint), as depicted in Figure 2.4. Taking the proposed one-to-one principle as a reference, flying the mission at 120 meters AGL would require a buffer of at least 120 meters. Assuming the chosen UAS has a characteristic dimension of three meters, an intrinsic GRC of "7" is obtained for the area of operation as well as the adjacent area. Intrinsic GRC values are arbitrary numbers used in the SORA process to classify risk as a function of characteristic dimensions of the UAS, its maximum cruise speed, and the population density of the overflown area. The values can range from "1" to "11". However, "7" is the highest intrinsic GRC value the SORA process will support.

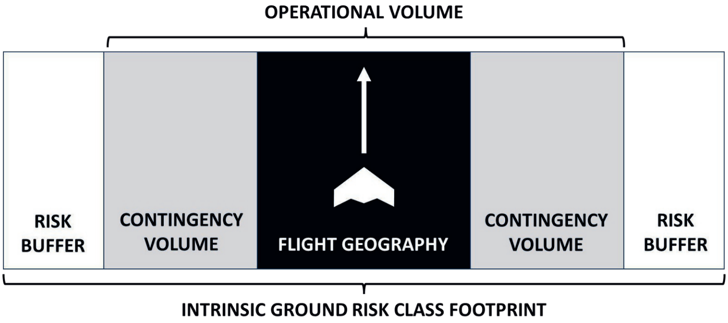


Figure 2.4: Overview of the elements that make up the intrinsic ground risk class footprint of a given UAS mission.

The SORA 2.5 process allows operators to apply additional mitigation measures to reduce the final ground risk [43]. These include strategic mitigations for ground risk M1(A), flight within Visual Line-Of-Sight M1(B), and reductions on the impact dynamics of the UAS M(2). In this case, it was chosen to apply M1(A) ground risk mitigations linked to services provided by UTM systems, namely the existence of a supplemental data service provider with static and dynamic density data about the actual number of population at risk at a given moment and provides current and forecasted weather information for the time of flight. Assuming the provision of this type of service at medium robustness [43] and service level 2 [44], applying such mitigation measures, it is possible to reduce the ground risk classification by two points, thus obtaining a final GRC of "5". To comply with this GRC, the proposed operating area and intrinsic GRC footprint will need to be continuously adjusted based on the population density values determined by the UTM system. This provides the UAS mission with more flexibility to choose alternative paths to reach its destination, albeit under the requirement of a continuous connection to UTM throughout the flight. For this use case, it is assumed that this is indeed the case.

### 2.3.2 Airspace Encounter Category and Air Risk Class

The quantification of air risk that the UAS mission imposes follows a similar approach to the GRC determination. The first step in this approach is the determination of the initial air risk class. The SORA 2.5 document provides a look-up table to facilitate this assessment. For flights in controlled airspace below 500 feet above ground level, the initial air risk class is ARC-c. Similar to the GRC process, strategic mitigations can be used to lower the overall ARC by allowing the operator to propose a residual ARC. The SORA process proposes two types of strategic mitigations [45]:

The first involves operational restrictions which the operator can impose before take-off. SORA foresees this to be a combination of geographical and time-based restrictions. For instance, a geographical restriction may confine the operating volume to areas where exposure to crewed aircraft is low. Time-based restrictions may limit the operation to flights when the aerodrome has closed or other means of limiting the exposure time. Figure 2.5 provides examples of potential mitigations through operating restrictions applied to the proposed use case. Option A shows mitigations by limiting the flight to the outer regions of the control zone below 500 feet above ground level, where an encounter with crewed aircraft may be reduced. Option B restricts the UAS flight to off peak times or times in which the aerodrome is closed as a mitigation measure. Finally, option C structures the flight route in such a way that it limits the exposure time to air risk by proposing to cross known crewed aircraft routes at right angles.

The second strategic mitigation incorporates common structures and rules [43] which cannot be controlled by the operator, such as flight rules or airspace structures which the SORA process expects to be provided by UTM. Common flight rules include the need for UAS to be electronically conspicuous to Air Traffic Control (ATC) via UTM, and the need to file a flight plan to the UTM system and obtain the necessary permission before starting the flight. Common airspace structures include the definition of corridors to allow UAS to fly through special segregated areas and the use of procedural separation provided by UTM ("*take-off windows, reporting points, assigned airways and altitudes, route clearances, etc.*", as defined in JARUS Annex C [45, p. 9]). The operator must claim to adhere to these mitigations before being eligible for an ARC reduction. In the proposed use case, a successful reduction of air risk to a residual ARC of ARC-b is assumed, which is the minimum possible in the SORA assessment [43] for operations in controlled airspace below 500 feet above ground level, under the assumptions of Table 2.3. For the sake of simplicity, the use case also assumes that all of the above-mentioned rules and airspace structures are in place and applicable. In Section 2.4 these points are explained in more detail.

Table 2.3: Overview of prerequisites to claim for an ARC reduction and compliance in the proposed use case.

| **SORA Annex C requirement** | **Justification in use case** |
|---|---|
| Equipage of the UAS with an Electronic Cooperative system and Anti-Collision Lighting | The "Electronic Cooperative system" shares telemetry data with UTM |
| A procedure has been implemented to verify the presence of other traffic during the UAS flight operation | UTM notifies the UAS operator of other traffic |
| A procedure has been implemented to notify other airspace users of the planned UAS operation | All UAS are conspicuous to other UAS through UTM flight plans and telemetry |
| Compliance with the airspace UAS Flight Rules, Regulation, and Policies | European UAS regulations [17] and U-space regulations [15, 35, 46] apply |
| A UAS airspace structure (airways, procedures, airflow management, etc.) exists in VLL airspace to help keep UAS separated from [crewed] aircraft | Lower airspace is divided into a grid of airspace blocks using geofences and UAS corridors to achieve segregation of UAS and crewed aircraft |
| A UAS airspace procedural separation service has been implemented for VLL airspace | UTM provides separation instructions to UAS (operators) depending on other UAS flights and airspace restrictions set by ATC |
| All UAS operators must be able to directly communicate with the Air Traffic Controller or Flight Information Services | Communication means are indirectly provided by UTM through the collaborative interface with ATC using geofencing restrictions |

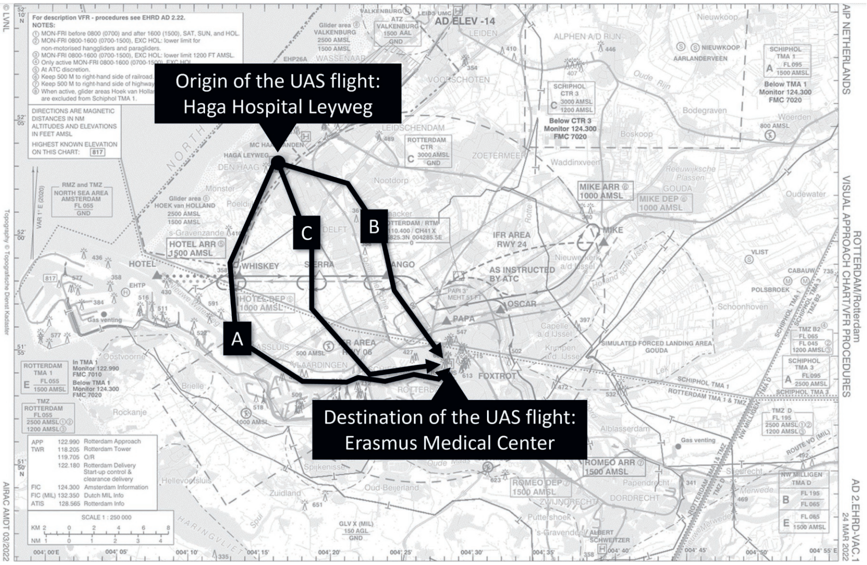


Figure 2.5: Depiction of potential restrictions to the medical UAS mission to reduce the overall ARC.

### 2.3.3 Final Specific Assurance and Integrity Level and Operational Safety Objectives

The next step in the process is the definition of the Final Specific Assurance and Integrity Level (SAIL) for the UAS flight. The SAIL is determined by combining the final GRC and residual ARC in a specific look-up table. In this specific use case, the combination of the final GRC of “5” and residual ARC-b gives a SAIL of category IV. Each SAIL category is then linked to a series of Operational Safety Objectives (OSO). The OSO are a list of requirements that the operator must adhere to at a specific level of robustness depending on the SAIL category, for the SORA to be authorized by the authority. These OSOs cover a multitude of topics, such as operator competencies, remote crew training, operational procedures for normal and contingency situations, environmental conditions, maintenance requirements, and UAS equipment.

This study will not go into individual OSO requirements but rather map the final UAS routing options based on the SORA to model the expected UAS behavior during the flight. For this mission, a combination of options B and C from Figure 2.5 was chosen. Route option B would be preferred, as it is the shortest route between both hospitals. However, a higher traffic load at Rotterdam The Hague Airport may inhibit or restrict crossing the aerodrome in such close proximity, which would make the longer route option C a more viable alternative. Thankfully, the determined GRC mitigation of using population density services allows for a more flexible definition of flight routes.

### 2.3.4 UAS Routing Behavior Influenced by SORA Mitigations

Figure 2.6 exemplifies the influence of SORA mitigations presented in the previous sections on a hypothetical situation. A day with high traffic load at Rotterdam The Hague Airport

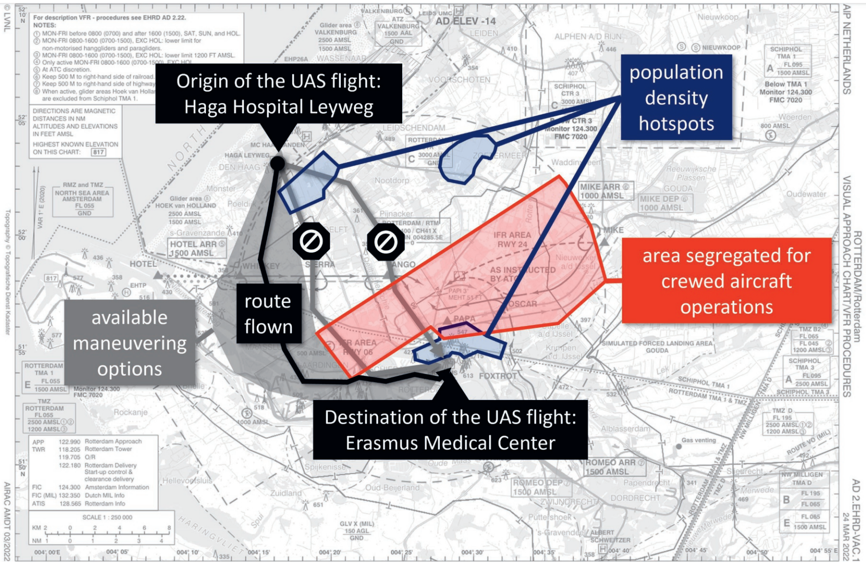


Figure 2.6: Example of the medical transport use case in the presence of airspace restrictions.

and multiple areas with high population density identified by the UTM system is used as a baseline. UTM translates these restrictions into geozones, which the UAS mission will need to avoid.

One can see that with this proposed solution, although several restrictions apply to the area of operation, the UAS still has several potential routing options to choose from. This, however, may not always be the case for all UAS missions. An alternative mission, which uses the same mitigation measures discussed for the medical use case, but for a different application, is presented to highlight this point. Figure 2.7 shows a UAS mission that aims to perform a railway line inspection from one maintenance station to another. This use case is limited to a very narrow range of operations given the need to fly in close proximity to the railway line to obtain high-quality images and cannot deviate from it to complete the inspection. In this case, the resulting geozone restrictions inhibit the UAS from completing its mission and force it to land prematurely.

These two examples show how the *same* types of airspace restrictions can have vastly different consequences on the outcome of each UAS mission. The medical mission had multiple means of avoiding restricted airspace, whereas the inspection flight needed to be completely aborted. Once UAS missions begin to scale, one can easily imagine how the unpredictability of UAS traffic responses to geozones may have important impacts on the flow of air traffic and potential knock-on effects in terms of airspace safety. Thus, it is important to develop an adequate operational concept for managing the shared airspace between UAS and crewed air traffic.

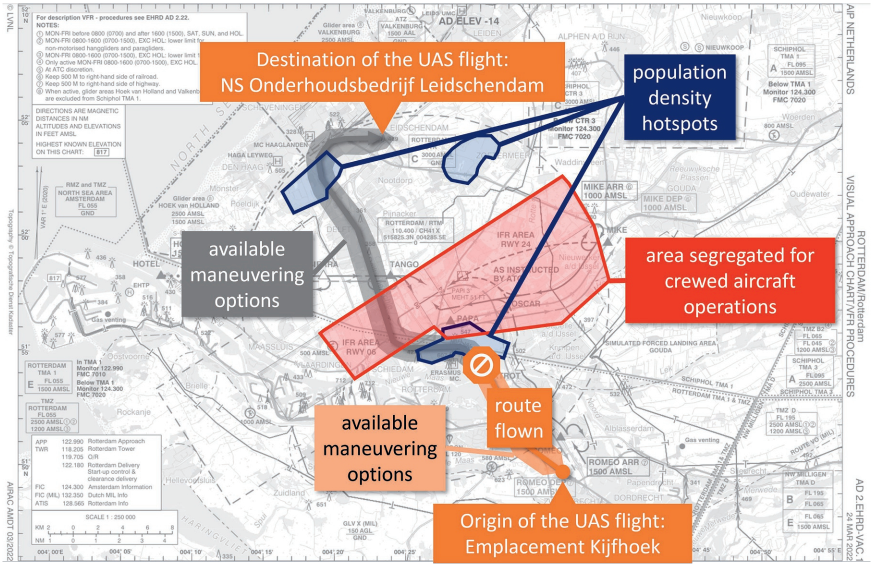


Figure 2.7: Example of an aborted railway line inspection use case due to the presence of airspace restrictions.

## 2.4 OPERATIONAL CONCEPT

The previous use cases showed how sensitive some UAS missions can be to airspace restrictions imposed on their area of operation. Although UAS flights are impacted by a multitude of potential restrictions and limitations, this research focuses on the impact that the tactical management of controlled airspace has on UAS flights. An operational concept for collaborative management of airspace shared by UAS and crewed aircraft is developed in this section which builds on the regulatory requirements for UAS which were introduced in Section 2.2 and Section 2.3.

### 2.4.1 REGULATORY FRAMEWORKS

Before going into the concept it is important to first clarify some underlying principles and fundamentals defined in regulation.

- First and foremost, the overarching goal of traditional air traffic control remains applicable, namely to establish a safe and expeditious flow of air traffic in controlled airspace [1]. It is also expected that the same principle applies to UTM.
- The regulatory framework provided by the European rules and regulations for UAS is used as a baseline for this concept. Thus, regulations regarding UAS manufacturing and equipage requirements [47] and rules and procedures for the operation of UAS [17] apply. Of particular relevance to the concept is the distinction between open, specific and certified UAS categories and associated flight restrictions.
- Moreover, the regulatory framework for U-space [15], associated requirements for air traffic management in U-space airspace designated in controlled airspace [35], as

well as requirements for crewed aviation operating in U-space airspace [46] apply. The relevant implications of these regulations on the concept are further explored in this chapter.

- The concept also considers that crewed aircraft flight operations are carried out in the same way as they currently are, with established European regulations defining common rules of the air and procedures in air navigation [24].
- Within the context of ATM procedures, standards and recommended practices defined by the International Civil Aviation Organization (ICAO) which govern how air traffic management is performed are applicable. This means that crewed air traffic will be managed in controlled airspace under existing air traffic services [26] and procedures for air navigation services [1].
- Furthermore, communication with crewed aircraft relies on established telecommunications procedures [25].
- Within the context of UAS operations in proximity to crewed aircraft, as defined in [17], all crewed aircraft will have priority over UAS. UAS must always make way for crewed aircraft, even if the UAS is performing a medical transport mission.
- Air traffic control units may place airspace restrictions on UAS within the control zone of a towered aerodrome, if such restrictions are deemed necessary maintain crewed aircraft safety, as defined in [40].

### 2.4.2 Assumptions

Some necessary fundamentals of the concept are not yet defined in regulation. Therefore, additional sets of assumptions are made to support the proposed operational concept, and to provide context in which it is applied.

- In the absence of separation rules for integrated UAS and crewed aircraft management, it is assumed that segregation of airspace reserved for UAS from the rest of controlled airspace would need to be achieved at all times. Thus, the focus of the concept is not to seamlessly integrate UAS and crewed aircraft but rather to develop a solution that provides segregation with minimal operational impact.
- In the European framework, geozones provide the primary means to communicate restrictions to UAS. To achieve segregation, the concept will use dynamic geofences (see Table 2.2 ) as the primary tool for applying restrictions on UAS related to crewed air traffic in real-time.
- Furthermore, most of the requirements to integrate UAS into controlled airspace will need to be shouldered predominantly by the UTM ecosystem, under the expectation that the existing air traffic management system cannot adapt as quickly to these new operational concepts.
- As defined in [15] all communication of UAS restrictions which derive from ATC will be relayed to UAS via UTM (U-space).

- The inner workings of U-space and information flows between U-space services and the Common Information Service will not be considered and can be seen as a black box. Although this thesis acknowledges the complexities of the service architecture that U-space aims to accomplish and the many research challenges that link to the development of such an ecosystem, it places the focus on the impact of UTM purely from an ATM perspective. From this point of view, the terms "UTM" and "U-space" services will refer to the same thing, namely "a set of digital services and infrastructure which facilitate a safe and expeditious flow of UAS".

- The term "U-space airspace" refers to a geozone designated as U-space, in which U-space services are provided.

- Finally, the proposed operational concept will only consider the tactical phase of UAS operations. Thus, the assumption is that any static geozone restrictions have already been considered and incorporated in the flight profile and maneuvering options a UAS has available once additional dynamic geofence restrictions are applied.

### 2.4.3 Overview

In this section the general concept for collaborative management of crewed and uncrewed air traffic within controlled airspace is presented. For the reasons mentioned in the introduction, the focus lies on the application of such a concept to the control zone of a towered aerodrome in which air traffic control services are provided to crewed aircraft and UTM services are provided to UAS.

Incorporating the fundamentals and assumptions of Section 2.4.1, a concept that allows air traffic control to impose restrictions on UAS using dynamic geofences was developed, in support of tactical conflict resolution with crewed aircraft. The concept focuses on dynamic geofences, as opposed to static geozones, in order to maximize the availability of lower airspace to UAS missions, and achieve the following goals:

1. Maintain the current level of safety in the control zone,
2. No disruptions to established crewed air traffic flows, and
3. Minimize the number of disruptions to UAS missions

Figure 2.8 illustrates the general idea of the concept. Air traffic control is in charge of performing its current task of coordinating crewed flights within the control zone. Additionally, it receives information about UAS flights in its area of responsibility from UTM and can impose restrictions on UAS to achieve its goal of maintaining a safe and expeditious flow of crewed air traffic. UTM relays any restrictions received from air traffic control and translates them into dynamic geofences. UTM then relays this information to all UAS affected by the restriction, which will in turn react to the new restriction.

To better explain the concept, a particular use case is considered. Figure 2.9 shows the situation in which a crewed aircraft flying is approaching Rotterdam The Hague Airport for landing using the published VFR arrival route ①. Given that information about UAS flights is provided to the air traffic control unit by UTM ②, a potential for conflicts with two UAS missions is identified.

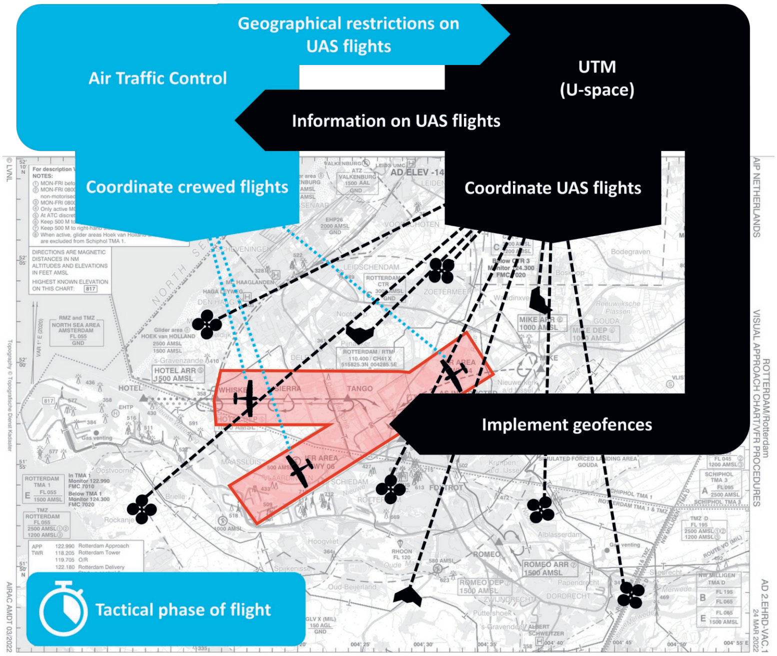


Figure 2.8: Concept for a collaborative crewed and uncrewed traffic management in the tactical phase.

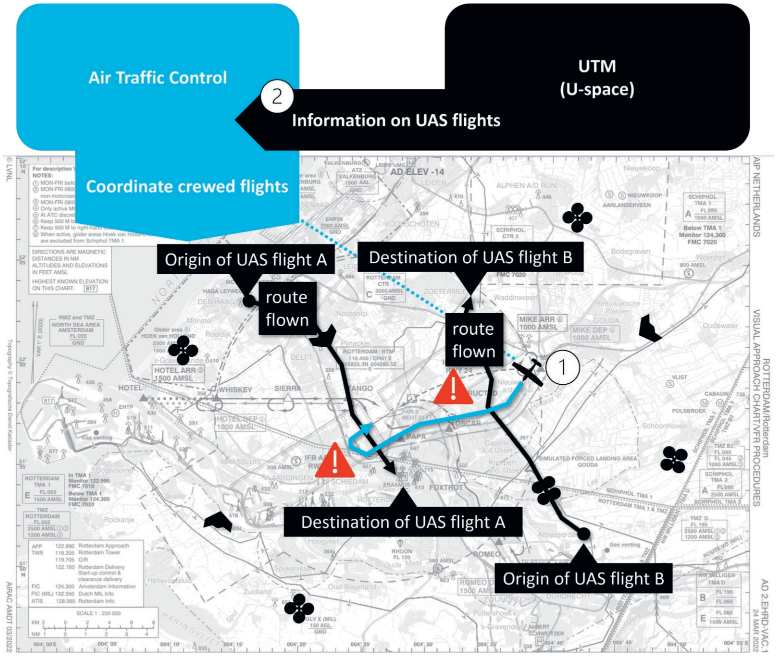


Figure 2.9: Gathering information about potential conflicts which require airspace segregation.

Figure 2.10 shows the air traffic control unit responding to this conflict using the proposed concept. The air traffic control unit assigns additional geographical restrictions to prohibit UAS from entering the VFR arrival route and visual traffic circuit, using an interface with UTM ③. The UTM system then proceeds to implement the restrictions as a dynamic geofence which is activated in real-time ④.

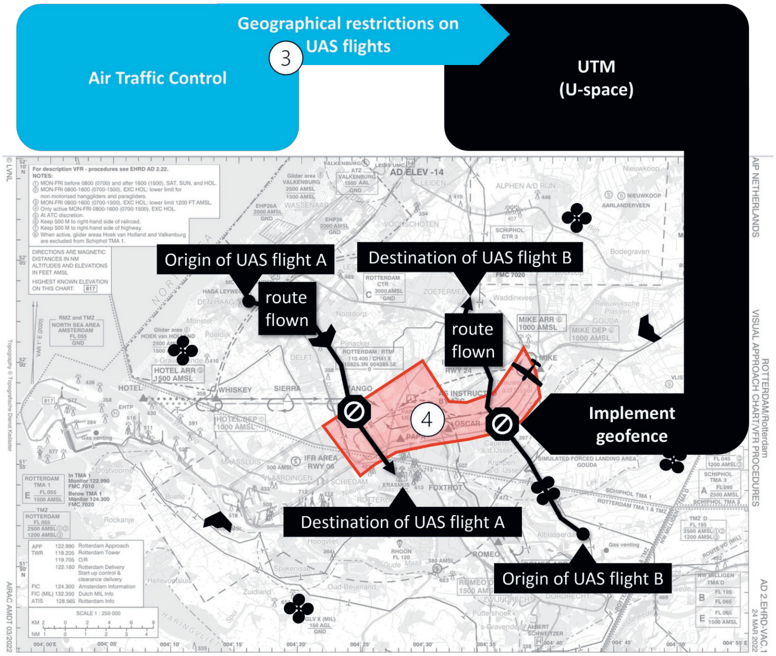


Figure 2.10: Defining a dynamic geofence and creation through the UTM system.

Figure 2.11 shows the UTM system and UAS response to the new restriction. After implementing the dynamic geofence, UTM proceeds to inform the affected UAS flights of the restriction ⑤. Both UAS have sufficient options for maneuvering available to reroute around the geofence. UTM informs the air traffic control unit of the new UAS routes ⑥.

Once the crewed aircraft has landed and the airspace is clear, the air traffic control unit may instruct UTM to remove the dynamic geofence, which allows the affected UAS to return to their original routing.

### 2.4.4 Roles and Responsibilities

As evident from the proposed concept, the two main coordinating entities are the air traffic control unit in charge of the aerodrome's control zone, and the UTM system which is coordinating restrictions on UAS. The concept assumes that the main authority for placing restrictions on UAS is the air traffic control unit, as specified in the U-space regulatory package [35, p. 3], and stating that air traffic control units shall:

- "*temporarily limit the area within the designated U-space airspace where UAS operations can take place in order to accommodate short-term changes in [crewed] traffic demand*

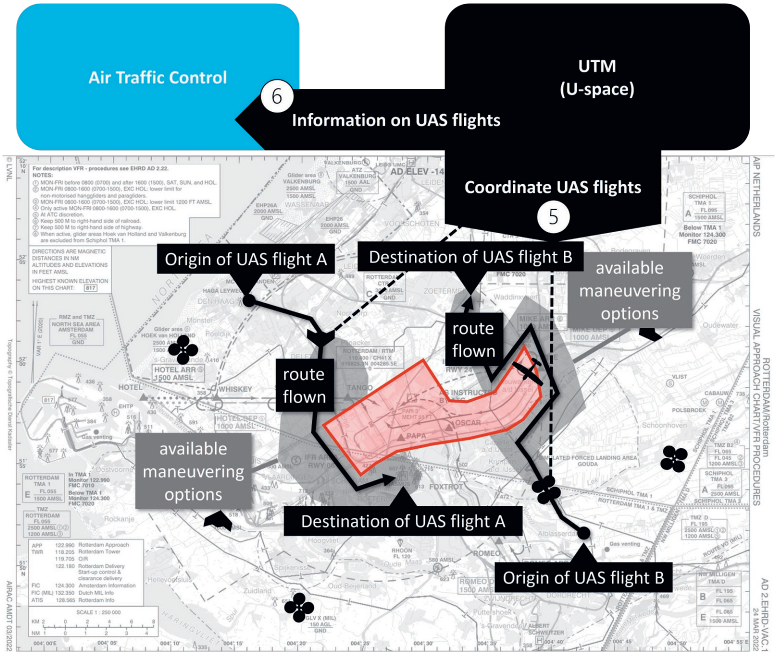


Figure 2.11: UTM implements the dynamic geofence and impacted UAS react accordingly.

*by adjusting the lateral and vertical limits of the U-space airspace;*

- *ensure that the relevant U-space service providers and, where applicable, single Common Information Service Providers are notified in a timely and effective manner of the activation, deactivation, and temporary limitations of the designated U-space airspace.*"

The regulation does not, however, specify *which* entity within air traffic control shall take charge of performing these tasks. Depending on the complexity of the airspace and the number of runways at the aerodrome, the air traffic control unit may be subdivided into individual delivery (DEL), ground movement (GND), tower (TWR), departure (DEP), and approach (APP) controllers.

Figure 2.12 provides a high-level overview of the division of responsibilities among individual air traffic control unit entities (indicated by individual blocks) in the aerodrome environment. All information presented in Figure 2.12 has been developed from [1]. Responsibilities of each unit are listed at the top of each block. Moreover, the figure maps flight progressions of crewed aircraft operating under Instrument (IFR) or Visual Flight Rules (VFR) in relation to individual ATC entities.

The flight progression is broken down into a series of aircraft *states* throughout the flight. Reading the figure from left to right follows the progression of an aircraft with an initial state "prior to start-up and push-back" to its end state when leaving the Terminal Control Area (TMA). When read from right to left, the flows of "IFR aircraft entering TMA", "VFR aircraft entering TMA" and "VFR aircraft entering CTR" can be traced back

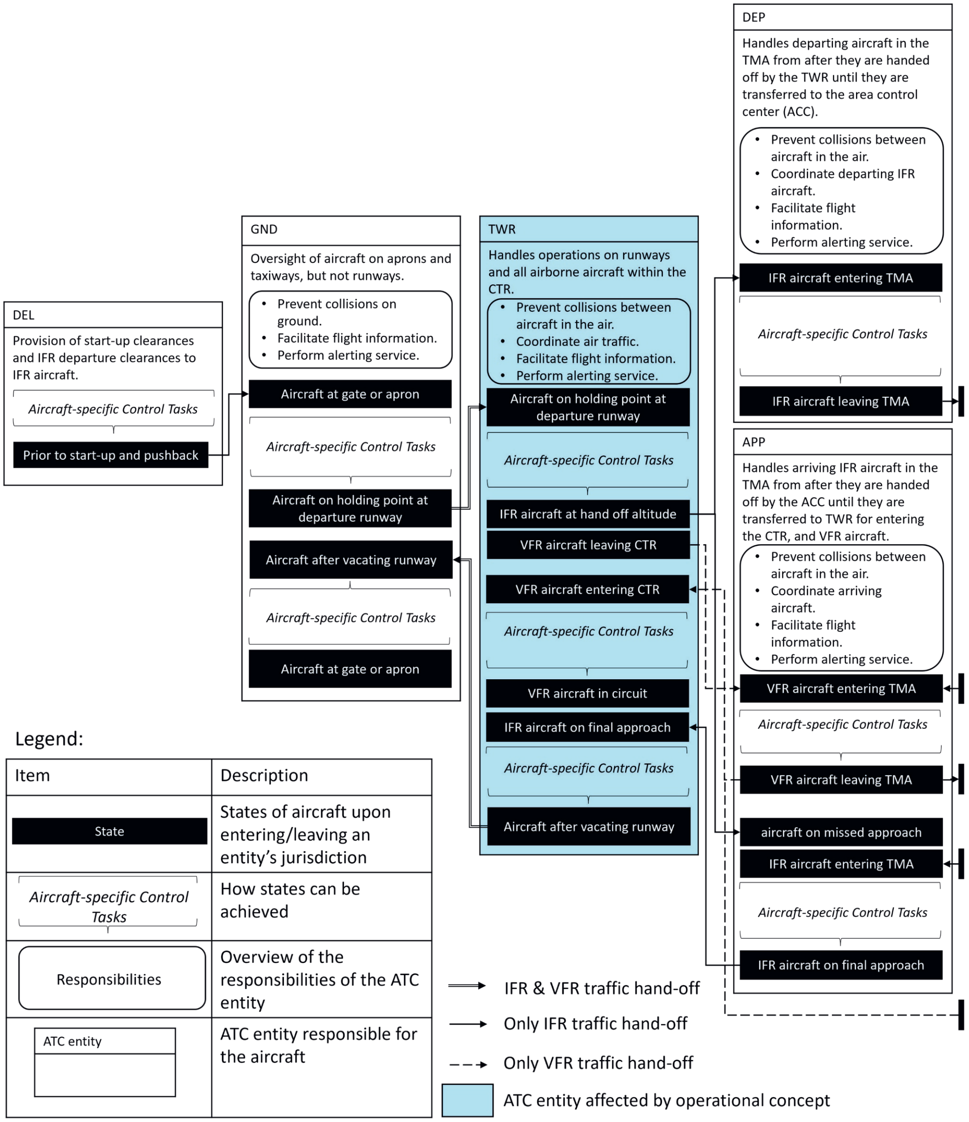


Figure 2.12: High-level overview of responsibilities of individual ATC entities in the aerodrome environment concerning crewed aircraft.

to their final state of “aircraft at gate or apron”. Apart from the initial states, the desired states of aircraft upon entering and leaving an entity’s jurisdiction are also listed. Control tasks must be executed by the ATCO to guide aircraft under their responsibility from one state to another. Arrows indicate the handover of aircraft from one ATC unit to another. Coordination among ATC units is assumed but not explicitly highlighted in the depiction.

The proposed operational concept shows that the most likely point of encounter between UAS and crewed aircraft in the vicinity of aerodromes is within the lower bounds of the control zone, in which the aerodrome control tower (TWR) is the entity responsible [48], with the tower control ATCO as the main coordinating role [49].

Therefore, the responsibility of limiting airspace for UAS operations was added to the existing responsibilities the tower controller, which can be summarized as a whole as:

- **Prevent collisions between aircraft in the air**: Defined separation minima between aircraft need to be maintained at all times, which can be can be time-based or distance-based, and depend on the maximum take-off weight of an aircraft as well as the type of propulsion used. Reduced airborne separation minima may apply, provided that each aircraft is visible to the controller or can self-separate. Moreover, under certain conditions reduced runway separation minima may also apply.
- **Coordinate air traffic**: The aerodrome control tower ATCO is responsible for controlling aircraft in the traffic circuit, departing aircraft, and arriving aircraft in line with defined procedures. Additional procedures for reduced separation minima, low visibility operations, and special VFR flights may need to be considered. The sequencing of arriving and departing aircraft shall be made in such a way that it facilitates a throughput of a maximum number of aircraft with the least average delay. Furthermore, aircraft in distress, aircraft conducting search-and-rescue operations, or aircraft carrying persons requiring medical attention are to be prioritized.
- **Facilitate flight information**: The controller is responsible for facilitating information to crewed aircraft concerning aerodrome and meteorological information, essential local traffic information (meaning traffic which may constitute a hazard to the aircraft concerned), runway incursion or obstructed runway, the uncertainty of position on the maneuvering area, wake turbulence and jet blast hazards, abnormal aircraft configuration and condition, as well as any essential information on aerodrome conditions.
- **Perform alerting service**: This concerns alerting rescue and firefighting services in case of a current or potential safety-critical event concerning one of the aircraft under the responsibility of the aerodrome control tower.
- **Limit airspace for UAS operations** – *added as a new responsibility*: In line with the proposed concept, the role of defining limits to where UAS are allowed to operate in the vicinity of the aerodrome utilizing geographical restrictions will also lie with the tower controller, as defined in Section 2.4.4.

It is expected that the inclusion of this last responsibility will have important implications on the way that information about UAS operations is transmitted to the tower controller and which tools will need to be provided for them to perform this task alongside their other responsibilities. These implications are discussed in further detail in Chapter 3.

## 2.5 Discussion

In previous sections it has been shown how new UAS operating requirements affect how uncrewed air traffic is managed. Different mission parameters restrict the types of routes UAS have available when conducting a flight. Moreover, in the absence of flight rules for UAS, airspace restrictions through geozones will be the main means of structuring UAS air traffic. Given how different the proposed operational concept is from traditional crewed aviation, the inclusion of a task to limit UAS airspace will pose a challenge for tower control ATCOs, as they will now need to:

1. Identify areas which need to be segregated from UAS,
2. Perform segregation, and
3. Understand the response of UAS towards their segregation actions.

These requirements can be supported in many different ways, such as through revised air traffic control procedures, communication, and coordination mechanisms. However, this work proposes the introduction of a collaborative interface for UTM supervision and intervention by ATCOs (see Section 1.2) in the shape of a top-down, electronic radar display as the most effective way to address the challenges associated with the new concept for collaborative crewed and uncrewed aircraft management. The rationale behind this proposal is explored in this section.

### 2.5.1 Identification of Areas Which Need to be Segregated

To identify which areas to segregate within the control zone, the tower controller needs to be supported with information about crewed and uncrewed aircraft.

Knowledge of crewed aircraft positions and planned flight profiles will be the principal means of deciding which areas to segregate. Within the control zone, crewed aircraft routes under nominal conditions are quite predictable, as they are based on predefined arrival and departure procedures for scheduled commercial flights, as well as leisure VFR flights, as provided by the example in Figure 2.2. Therefore, the controller would have a solid mental picture and understanding of which areas would be at risk of collision with UAS.

Given the UAS' low operating altitudes, a potential for collision exists with aircraft on short final or just after departure; aircraft with lower climb performance, such as single-engine piston aircraft; aircraft with a traffic circuit at lower altitude (e.g., ultralights and gliders). Nevertheless, non-standard crewed aircraft flight routes, such as those of HEMS flights, may provide additional areas of conflict that are less predictable.

In order to achieve a mental picture, tower controllers commonly track aircraft in the immediate vicinity by looking at them directly, as this is a primary requirement defined by ICAO [1]. Yet, controllers will not be able to visually identify all UAS in the vicinity of the aerodrome, due to the small size of the vehicles, low operating altitudes, flights Beyond Visual Line-Of-Sight, and numerosity of flights taking place at once. To maintain vigilance during higher workload peaks (ten to fifteen air vehicles at one time), controllers are frequently assisted by surface radar equipment in combination with flight strips [50].

Following this premise, the most effective way to assist the controller in localizing UAS is to present flight information on a digital interface, and in a format that they are used to working with, namely in the shape of a top-down, electronic radar display. By directly integrating UAS information into existing ground radar screens for crewed aircraft, the ATCO would be able to quickly obtain a mental picture of all flight movements in the control zone.

Moreover, based on the results of the analysis presented in this chapter, the interface must make restrictions set by the UAS mission transparent such that the controller can anticipate UAS routing selections and behavior in response to mission restrictions. Although this approach does not provide for a means to visually identify UAS by looking out of the control tower, it may be enough information to provide for an adequate mental picture.

### 2.5.2 Performing Air Traffic Segregation

The tower controller is tasked with separating crewed aircraft on departure, on approach to landing, and within the traffic circuit [1]. In the new concept, the controller must also segregate airspace reserved for UAS from those of crewed aircraft to avoid conflicts. In the operational concept, the tower controller will not be able to exercise direct control over UAS, which is the task of UTM, but rather impose restrictions on UAS traffic using dynamic geofences as necessary. Air traffic controllers will therefore need to understand how UAS intend to fly within their airspace and how they will respond to airspace restrictions.

As was shown in Section 2.3, the behavior of UAS will mainly depend on the mission that they aim to achieve. Each mission profile has different implications for the flow of UAS air traffic within the control zone and ultimately affects the tactical decisions that an air traffic controller must make. To activate geofences, the standard way of coordinating air traffic via voice communication will not be appropriate, since air traffic controllers will be dealing with geographical restrictions, as opposed to direct routing instructions. Rather, providing tools to define geofences directly on the same electronic display used to gather information about UAS is a much more sensible means of performing air traffic segregation. In this way, it is possible for the controller to identify areas that need to be segregated and perform the segregation action through the same interface.

### 2.5.3 Understanding UAS Responses to Segregation Measures

Although the tower controller would not be directly responsible for UTM system actions, they will need to maintain vigilance over the responses of UAS traffic towards the new restrictions to keep crewed aircraft safe. A main challenge of this task is that UAS missions will rely to a larger extent on automation to be economically viable [4]. These automated UAS flights will themselves be overseen by a fully machine-based UTM system. The human relationship with automation is therefore an important factor to consider. Thankfully, implications of automation on human performance have already been studied at length, such as through the works of Sheridan, Parasuraman, or Bainbridge (see [51] or [52]), as well as more recent studies on implications of automation based on artificial intelligence (AI), such as research performed by Endsley [53].

Current air traffic control actions demand the utilization of visual resources, comprehension, projection, decision-making, and verbal resources in a balanced way. Research performed by Cañas et. al [54] on human performance and acceptance of automated air traffic control systems found that medium and high automation air traffic control scenarios shift the human cognitive effort towards comprehension and projection. This implies that when controllers are confident in the reliability of the automatic system, they will decrease their level of activation, reducing the amount of available mental resources, according to the Malleable Attentional Resources Theory (MART) [55]. Therefore, overconfidence in automation could cause a situation of underload, due to the human being out-of-the-loop and exhibiting low situation awareness.

Furthermore, when the air traffic controller is only charged with monitoring (and not applying any action), engagement with the vigilance task may be lower. As long as the UTM system works properly, this is not an issue. However, less engagement would cause some available resources not allocated to the task to be needed in a non-nominal situation, causing an excess of mental workload when automated systems fail. It is thus imperative that issues related to the out-of-the-loop effect are addressed in the design of the interface, and indications about failures to adhere to airspace restrictions be made explicit.

## 2.6 Conclusion

Given the ever-increasing number of UAS flights, use cases, and industry growth projections, regulators are implementing standards and regulations on how UAS operations shall take place, and through which services they shall be assisted. The European risk-based approach towards UAS flight authorizations changes the way that uncrewed aircraft operate with regard to traditional crewed aviation. Moreover, in the absence of flight rules for UAS, it is shown how uncrewed air traffic is structured by implementing airspace restrictions using various types of geozones. These can be both static and dynamic, depending on whether short- or long-term restrictions are necessary. For short-term restrictions to influence UAS routes, dynamic geofences could play an important role in resolving tactical conflicts between uncrewed and crewed aircraft, supported by fully automated UAS traffic management systems.

These learnings were then applied to assess how UAS flights can be safely incorporated in proximity to controlled aerodromes. A practical use case was discussed which exemplified how mission requirements, risk assessment results, and active geofence restrictions impact the available routes that UAS have to conduct their flight around the aerodrome. The examples also showed that the same geofence restriction could have vastly different impacts on how UAS would respond to them. A UAS with a larger available maneuvering option had more possibilities to fly around a restriction, whereas a flight with a limited maneuvering option may need to abort the mission entirely.

From these observations, an operational concept was proposed that could facilitate collaborative management of airspace shared by crewed and uncrewed aircraft by accommodating the new UAS operating methods alongside traditional crewed air traffic management. To do so, the concept relies on using geofences to achieve dynamic segregation of crewed and uncrewed airspace in real-time. The responsibility of setting limits on UAS operations in this concept falls on the tower controller. As the primary authority within the airspace to achieve a safe and expeditious flow of crewed air traffic, they would also be tasked with segregating airspace in a way that minimizes disruptions to UAS missions.

To achieve this concept, a top-down, electronic radar display for tower controllers could address some of the challenges related to the new task. The most critical challenges concern the identification of areas that would need to be segregated, the means to perform air traffic segregation, and how to understand UAS responses to segregation measures. It is proposed that a radar display that shows UAS positions, highlights relevant mission restrictions, allows direct geofence activation, and indicates failures of UAS to adhere to geofence restrictions could provide the means to successfully apply the concept. However, the validity of these assumptions would need to be substantiated through evidence gathered in dedicated simulation experiments, preferably with (expert) human controllers.

# 3

# INFORMATION AND CONTROL REQUIREMENTS

*In this chapter the initial concept for a collaborative ATC-UTM display for tower controllers is introduced. It builds upon an analysis of the work domain of both operational concepts and evaluates the initial design in a remote human-in-the-loop experiment. The contents of this chapter reflect an adapted version of the following paper:*

| | |
|---|---|
| **Paper Title** | 🗎 *Ecological Collaborative Interface for Unmanned Aerial Vehicle Traffic Management and Tower Control* |
| **Authors** | D. Janisch, D. van Aken, and C. Borst |
| **Published in** | Journal of Air Transportation, Vol. 30, Issue 4, 2022, pp. 154–169. |

*The forecasted increase in Uncrewed Aircraft System (UAS) traffic in lower airspace raises concerns about maintaining the safety and efficiency of flight operations near towered aerodromes. Regulatory bodies envision a collaborative interface between UAS Traffic Management (UTM) and Air Traffic Control (ATC) to allow for coordinated operations of both systems. This study identifies the main challenges that such an environment poses for tower control. To address these challenges, an initial design for a collaborative tower control display is introduced. Remote human-in-the-loop simulations with professional air traffic controllers confirmed the usefulness of several interface elements, in particular UAS priority and routing indications, as well as the utilization of a grid of geofences to dynamically segregate UAS from crewed aircraft. Surprisingly, the control strategy for geofence activation was similar to that of managing crewed aircraft from a tower control perspective. Participants also mentioned that they would like more control over UAS traffic than initially expected. Performance could be improved by increasing the predictability of UAS routing, adding conflict detection support as well as providing more authority over individual UAS locomotion supported by a tailored geofence structure. Further work is needed to investigate controller behavior in an environment that also requires control over crewed traffic.*

## 3.1 Introduction

The European Drone Outlook Study foresees an increase of up to 400,000 commercially operated Uncrewed Aircraft Systems (UAS) in Europe by 2035 [4]. This expected increase in UAS operations poses a threat to existing crewed air traffic, in particular in proximity to aerodromes. In order to prevent widespread disruptions to air traffic flows at aerodromes and alleviate safety concerns due to an increased risk of collision between UAS and crewed aircraft, industry, and research efforts are focusing on the development of UAS Traffic Management (UTM) systems. These allow UAS operators to carry out their desired missions cooperatively within the operational framework established by authorities in a safe and orderly manner [56]. Various UTM system concepts are being defined around the world, the most prominent of which include the European Union's U-space system [19] and the United States' Low Altitude Authorization and Notification Capability (LAANC) [57]. These systems ultimately aim to facilitate the complete and safe integration of increasingly capable UAS into the existing airspace system, relying on high levels of UTM system automation to manage the forecast demand. This ambition includes the eventual opening of controlled airspace around aerodromes to UAS traffic [58], supported by a collaborative interface between Air Traffic Management (ATM) and UTM to manage the information exchange required between both systems [39].

These new developments will add an additional layer of complexity to the working environment of tower controllers, as they will need to keep track of UTM operations alongside their responsibilities for maintaining safe separation and efficient movement of aircraft within the aerodrome environment [1]. The low operating altitudes of UAS pose a collision hazard to departing and arriving aircraft, low-operating Helicopter Emergency Medical Service (HEMS) flights, and operations within the traffic circuit. To assure adequate separation, tower controllers will therefore need to interact with the UTM system which manages UAS flights, whilst performing their primary (mostly manual) task of coordinating crewed aircraft.

To support the air traffic controller in managing this new environment, elements are included which allow them to collaborate with the UTM system through a display adopting Ecological Interface Design (EID) principles [28–30]. This chapter will provide some initial interface design considerations for the development of such a collaborative display by identifying functions that would best support UAS management. In particular, it will focus on elements that allow the controller to comprehend UAS operations and guide tactical UTM traffic commands using dynamic geofences – volumes in space that prohibit UAS operations within their boundaries [39]. The assessment of combined management of UAS and crewed aircraft was, however, not part of this study.

In this chapter the necessity to allow UTM operations within controlled airspace is elaborated and the implications on tower control that arise from introducing UTM-guided UAS operations into the aerodrome environment (see Section 3.2) are discussed. An analysis of the work domain resulting from this collaborative environment is presented in Section 3.3 and focuses in particular on its effect on maintaining safety and efficiency. The insights gathered from this analysis are presented in terms of interface design requirements in Section 3.4 which were used to develop a preliminary mock-up. To gather results on the effectiveness of such a concept, a series of human-in-the-loop experiments were performed which investigated how tower controllers would use the interface to separate UAS operations from crewed air traffic (see Section 3.5). Results are presented in Section 3.6 and discussed in Section 3.7. Final conclusions are presented in Section 3.8.

## 3.2 Background

This section introduces the motivations for the analysis presented in this study. First, the need to provide access to UAS operations within controlled airspace is exemplified through a practical example. Then, ongoing industry efforts on facilitating this access to airspace and how it will affect tower controllers is explained.

### 3.2.1 The Need for Providing Access to Controlled Airspace

Control zones of towered aerodromes commonly occupy large portions of lower airspace, as their design is centered around crewed aircraft operations. Prohibiting UAS flights in this airspace, however, imposes substantial operational restrictions which could be used to service local business opportunities.

Take, for instance, the case of Rotterdam The Hague Airport in the Netherlands. Situated between two Dutch cities, its Controlled Traffic Region (CTR) occupies vast portions of urban airspace and inhibits potentially useful applications of UAS missions, if access to this airspace were prohibited. Figure 3.1 shows representative UAS missions superimposed on an aeronautical chart of Rotterdam The Hague Airport. The red line indicates potential medical delivery missions between hospitals of Rotterdam and The Hague. The Netherlands' expansive network of railway and highway infrastructure could also benefit from UAS-based inspection flights. Such inspection missions would need to closely follow railway (orange) and highway (blue) routes within the CTR. Finally, the proximity of the aerodrome to Rotterdam Harbor, one of the most important naval trade connections in Europe, could be problematic for any potential harbor inspection and surveillance flights by UAS (black). All of these missions would be performed almost entirely within the CTR and, in the best case, in close proximity to the aerodrome's runway.

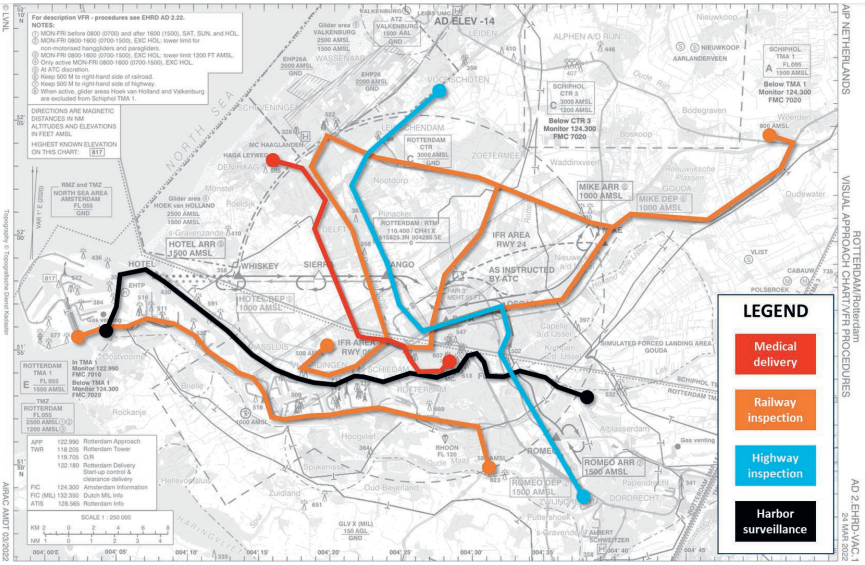


Figure 3.1: Potential UAS missions within the Rotterdam The Hague Airport control zone, superimposed on a visual approach chart.

Further, looking at this image, several points of interaction of these missions with crewed air traffic routes also become apparent. Many UAS missions cross the extended runway center line which crewed aircraft follow on landing and departure. Moreover, many of the inspection routes coincide with published departure and arrival routes of aircraft operating under Visual Flight Rules (VFR), providing the potential for head-on conflicts between crewed and uncrewed aircraft. Subsequent discussions with Rotterdam The Hague Airport tower controllers confirm these points of encounter and emphasize the added risk of collision with medical helicopter departures from the aerodrome, which may depart in any given direction, commonly fly at lower altitudes and land in areas where UAS are operating (e.g., near hospitals or highways). For an aerodrome that regularly experiences between 80 to 170 flight movements per day [59], this potential safety risk cannot be neglected. Facilitating both UAS and crewed aircraft missions within this airspace requires coordinated management and collaboration between air traffic control and UAS traffic management, which the next section will explore in further detail.

### 3.2.2 Implications of an ATC-UTM Collaborative Environment on Tower Control

The development of UTM and its inclusion into the existing air traffic system has consistently matured over the last few years. The European Union funded several exploratory research projects that helped to develop the U-space concept of operations [39]. During the same period of time the United States Federal Aviation Administration (FAA) developed its own UTM ConOps [57], which shares many similarities with its European counterpart. These concepts are continuously being updated and expanded to cover other airspace users, such as Urban Air Mobility (UAM) vehicles in the FAA UAM Concept of Operations [60].

This study focuses primarily on the European vision for a collaborative ATC-UTM environment. EASA published an opinion in early 2020 [61] on the regulatory framework through which U-space is to be implemented in Europe. This has since been adopted into regulation [15, 35]. According to these documents, U-space can be established within controlled and uncontrolled airspace, under the principle that Air Navigation Service Providers (ANSPs) provide air navigation services to crewed aircraft while U-space Service Providers (USSPs) provide services to UAS. Within controlled airspace, however, it is up to the ANSP to manage the U-space designated airspace in order to guarantee the safety of operations through dynamic segregation of Air Traffic Services (ATS) and U-space services and, thus, crewed and uncrewed vehicles.

The regulation foresees this segregation of U-space and crewed operations to be facilitated through a Dynamic Airspace Reconfiguration (DAR) capability [15]. This concept facilitates the partitioning and active restructuring of controlled airspace to accommodate the needs of both U-space and ATM operations. This study proposes a solution to support active dynamic airspace reconfiguration in the tactical phase of operations through the use of geofences [39]. U-space will organize UAS operations based on operational restrictions which depend on the UAS category and operational risk classification [18]. These restrictions will be enforced using geofences — digital barriers that prevent UAS from entering or leaving a designated volume of airspace if they are not permitted to do so. It is foreseeable that the collaborative environment between UTM (U-space) and ATC will utilize geofences as a means for managing UAS traffic in controlled airspace. ATC will carry out this reconfiguration in response to crewed traffic behavior which demands short-term U-space airspace adaptations to maintain segregated operations. This could be linked to, for instance, non-standard flight paths of crewed aircraft, such as departing HEMS flights, which do not follow published departure routes.

In order to set up the airspace for dynamic restructuring, EASA promotes the definition of a predefined basic set of airspace blocks or a more sophisticated mathematical grid, which can be dynamically assigned to either U-space or ATM. In this particular study, a grid structure similar to the UAS flight restriction concept applied to aerodromes in the United States [62] is applied. Previous studies on supervisory control of UTM by human operators have also opted for a grid structure to support operator awareness, albeit applied to airspace capacity management [63]. It has not yet been defined how this restructuring will be enforced; however, this thesis assumes that airspace assigned to ATC will be protected from UAS operations using geofences.

This study focuses in particular on the application of this dynamic airspace reconfiguration concept in the tactical phase of operations and identifies how it would affect the collaborative management of controlled airspace around an aerodrome. It envisions a future environment in which the responsibility of overseeing and managing the dynamic airspace reconfiguration process lies with the tower controller, who will need to perform this task alongside their existing ATC responsibilities. What follows is an initial interface design study assessment which provides the tower controller with an additional set of display elements that could be incorporated into their existing working station, aimed at managing the collaborative ATC-UTM environment.

## 3.3 The Collaborative ATC-UTM Work Domain

To understand the impact of this new concept on the work of tower controllers in a systematic way, a representation of the collaborative ATC-UTM work domain inspired by the work of Vicente [29] is developed. The next subsections will provide further detail on the work domain itself, explain the model that resulted from this analysis, and elaborate on the main assumptions concerning the impact on safety and efficiency.

### 3.3.1 Work Domain Analysis

To begin, let us first consider, from an organizational point of view, how ATC operates in its current form. According to ICAO [1, p. 141], the task of a tower controller is to "*achieve a safe, orderly and expeditious flow of air traffic on and in the vicinity of an aerodrome*". Safety, from an ATC point of view, primarily comes down to preventing losses of separation between aircraft and providing emergency management services. Air traffic flow expedition is linked to the number of aircraft the tower can manage within the airspace (productivity) and how efficiently (in terms of minimizing track miles) they are guided through the departure and arrival phase. Shifting now towards UTM, the U-space Opinion [61] and regulation [15] set specific objectives for the U-space ecosystem to achieve which appear to overlap with those of ATC in several instances.

An Abstraction Hierarchy model [30] of the collaborative ATC-UTM environment was developed (see Figure 3.2) to help understand the impact of having two systems with similar objectives operating within the same space. This type of model is a fundamental tool used in Ecological Interface Design (EID) to facilitate understanding of how a complex system functions, regardless of who will perform the work and how they will achieve it [30]. The main reason for opting for this type of design philosophy for the interface is because EID is fully aimed at supporting the operator in controlling complex systems, such as that of air traffic management and UTM, by providing them with domain transparency. Using such an interface, air traffic controllers would gain a deeper insight into the collaborative environment, in order to formulate goal-oriented control actions and better understand UTM control actions. EID does so by using the Abstraction Hierarchy model to guide the design of the interface and facilitate problem-solving [29]. Moreover, since its introduction roughly thirty years ago, EID has already been widely adopted to facilitate interface development in several aviation domains [64–67], as well as the management of autonomous vehicles [68, 69]. Given the iterative relationship between interface design and the work domain analysis, the Abstraction Hierarchy portrayed in Figure 3.2 serves as a starting point and is thus subject to refinements as the collaborative ATC-UTM environment concept is matured in future studies.

This section focuses predominantly on the interpretation of the proposed Abstraction Hierarchy model for a collaborative ATC-UTM environment and its role in the development of an initial display aimed at tower controllers. The Abstraction Hierarchy breakdown starts with the functional purpose of the system (top layer), continues down through underlying principles, processes and function-bearing components, and finishes with an overview of individual physical elements that make up the work domain (bottom layer). Then, in a second step, interconnecting lines are used to indicate which elements of the layer below are used to achieve the functions of the layer above (i.e., means-ends relationships). The whole system can thus be represented regardless of the actor performing the work.

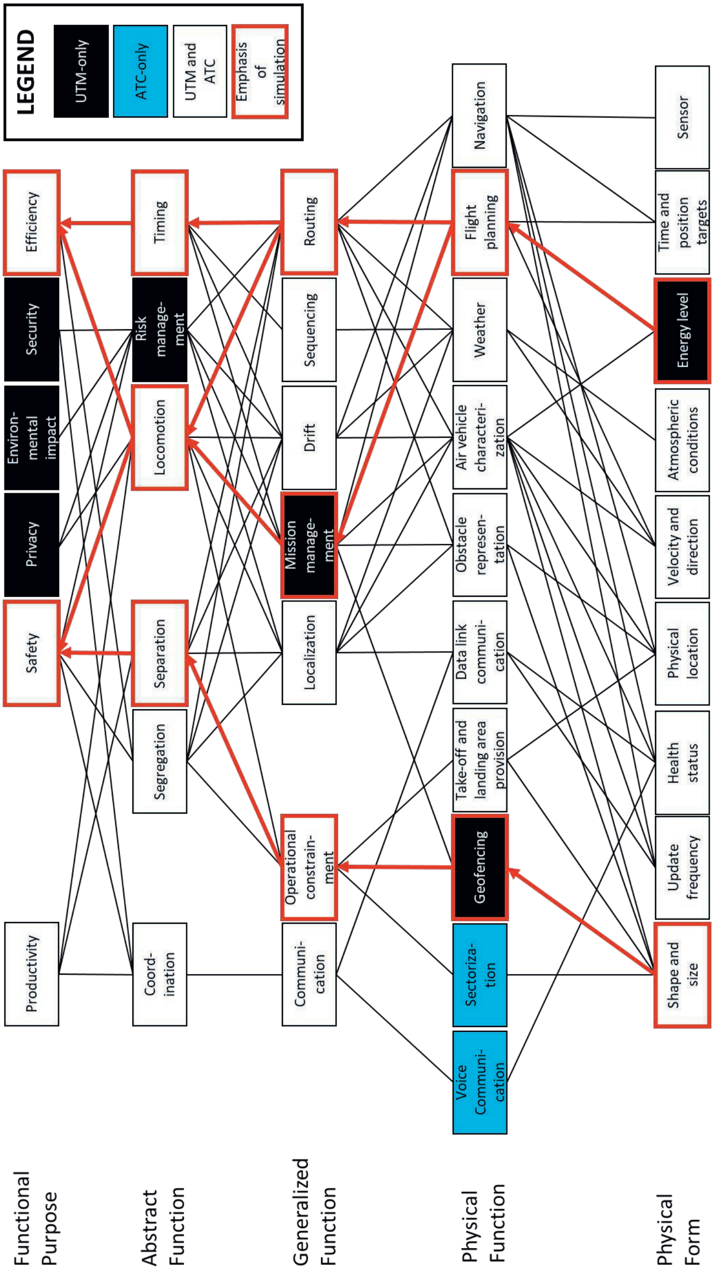


Figure 3.2: Abstraction Hierarchy model of the work domain of a collaborative environment between ATC (tower control) and UTM.

Figure 3.2 contents from the ATC point of view are based on Commission Implementing Regulation (EU) No 923/2012 [24], the ICAO Chicago Convention Annex 10 [25], Annex 11 [26] and ICAO Doc4444 [1]. Additional UTM elements are based on U-space initiatives, such as the U-space ConOps [39], EASA Opinion on U-space [61], Commission Implementing Regulation (EU) 2021/664 [15] and 665 [35], the Specific Operations Risk Assessment (SORA) [18] and the EUROCONTROL UAS Airport Concept of Operations [58].

To distinguish the functionalities of either system, an additional color coding was used. Elements highlighted in black are properties of the work domain that are only relevant to UTM, those in blue only to ATC and those in white apply to both. The results of the analysis show a striking similarity between ATC and UTM system properties, given that most of the elements of either work domain apply to both systems (white boxes). This means that, in a completely segregated ATC and UTM domain, both systems would still perform similar functions, just on different types of air traffic. The same concept holds true in the collaborative environment; however, the elements that are not the same (blue and black boxes) are of particular interest. From an air traffic control point of view, the UTM system adds some new elements to the work domain which it previously not had to deal with. This increases the complexity of the working environment of the tower controller, whose impact on the human operator would need to be investigated.

In order to get a grasp of the effect that these novel UTM elements in the Abstraction Hierarchy would have on the working environment of tower controllers, a bottom-up approach was applied to first assess the impact of lower-level elements within the hierarchy on meeting high-level objectives of their work. These include, in particular, the energy level, geofencing, and mission management UTM elements. In this initial study, the aim was to evaluate how these new elements affect the controllers' ability to meet safety and efficiency expectations at Functional Purpose-level. By working upwards from lower-level elements of the Abstraction Hierarchy (highlighted in bold red lines within Figure 3.2), it was possible to make some assumptions as to how the novel UTM elements might impact these goals, which will be elaborated on in the next subsections.

### 3.3.2 Maintaining Safety

Air traffic safety is maintained by separating aircraft on departure, on approach to landing, and within the traffic circuit [1]. The task of separating crewed aircraft from each other is usually assigned to the approach controller. The addition of UAS will add another layer of separation requirements to the mix. Given the low operating altitudes of UAS within U-space, a potential for collision exists with aircraft on short final or just after departure, aircraft within the traffic circuit, and helicopters operating at a low altitude. Crewed aircraft operating at such low altitudes in close proximity to the runway are typically managed by the tower controller. This ATC actor does not usually provide separation instructions, but within a collaborative ATC-UTM environment, enforcing separation between UAS and crewed aircraft may become necessary.

Separation standards for crewed aircraft within the terminal area require a 9.3-kilometer (five-nautical-mile) separation between aircraft operating under Instrument Flight Rules (IFR), although this can be reduced to 5.6 kilometers (three nautical miles) if the systems' capabilities permit [1]. Moreover, VFR aircraft will maintain visual separation from each other within Class D airspace, such as that of Rotterdam The Hague Airport. However, separation minima for small UAS flying Beyond Visual Line-Of-Sight of the operator and crewed aircraft have not yet been defined. Thus, lacking official guidance material, for this study, the minimum separation requirement was set to the one proposed by Weinert et al. [70] who have identified a vertical separation of 250 feet and horizontal separation of 2,000 feet (600 meters) as an acceptable well-clear limit. These values are assumed to be a much more reasonable separation criterion than the 9.3-kilometer separation specified for IFR aircraft on UAS traffic.

Since the tower controller will not be able to exercise direct control over UAS, which is the task of UTM, they must have access to mechanisms to clear areas from UAS traffic if necessary. This is where the Dynamic Airspace Reconfiguration concept comes into play, as it provides a means to segregate UAS operations in U-space from crewed operations. The size of the segregated area would need to be sufficiently large to enforce the defined separation minima. Geofences will play an essential role in this process. By providing means to dynamically activate and deactivate predefined geofences within the control zone on the collaborative interface, the tower controller would be able to influence the dynamic airspace reconfiguration process in a way that requires little effort from their side and functions as a simple means to achieve segregation from airspace designated to crewed air operations. Moreover, it alleviates the controller from having to interact with UAS operators via verbal communication, which was found to be a source of high workload on air traffic controllers in a recent NASA study on urban air mobility operations [71]. Moreover, that study suggests limiting direct human operator involvement in such missions, which the geofencing concept could address.

### 3.3.3 Maintaining Airspace Efficiency

Providing an expeditious flow of air traffic requires that air vehicles reach their desired destination as directly as possible. Standard aerodrome departure and arrival procedures ensure that the flow of operations is safe and predictable. However, if the traffic situation permits, the air traffic controller may issue vectors or permit direct routing to shorten the overall travel distance and time of an aircraft. Given that most scheduled air transport operations are point-to-point, providing the most direct routing usually assures the highest levels of efficiency possible. This paradigm changes, however with UAS operations.

Within the UTM context, the efficiency of UAS flights will predominantly depend on the mission that they aim to achieve, as evident from Figure 3.1, and previously explored in Section 2.3. Each mission profile has different implications on the flow of UAS traffic within the control zone and will ultimately affect the room for rerouting solutions within the UTM decision-making process. Moreover, UAS endurance is a substantial limiting factor for the maneuvering room it has available. The largest portion of UTM operations will be conducted via medium-sized UAS of the Specific category, which are predominantly battery-powered [4]. The battery capacity of such small vehicles is still very limited, meaning that the slightest alteration in their mission trajectory might have large consequences on their ability to complete their mission, their available energy reserves, and the behavior of the UAS flight path. Therefore, to maximize the overall efficiency of crewed and uncrewed flight operations within the collaborative controlled airspace, UAS mission constraints and flight endurance must be made transparent to the tower controller so that they can anticipate the maneuvering margins UAS will have available.

Additionally, focusing on increasing safety (see Section 3.3.2) may be detrimental to achieving efficiency, because the design choice in geofence size may affect UAS re-routing efficiency. Thus aiming for more safety (in terms of separation) can be done by increasing grid cell size, but will potentially come at the cost of more UAS track miles.

## 3.4 INTERFACE DESIGN

This section describes our assumptions on how the elements of the Abstraction Hierarchy translate into the design of the collaborative ATC-UTM interface to support tower controllers. This interface aims to portray the elements of the Abstraction Hierarchy and the means-ends links between them, while also supporting the controller in monitoring the collaborative system and manually intervening when required or desired.

The interface presented here is a preliminary design and will therefore not fully contain all elements of the Abstraction Hierarchy, nor is it sophisticated enough to simulate a fully immersive tower control environment as the emphasis was to assess the strands of the Abstraction Hierarchy highlighted in Figure 3.2. The final aim of this display is to function as a supporting tool to allow tower controllers the means to manipulate UTM operations within their working environment. The full operational domain assumes that tower controllers will continue to perform their current ATC tasks (i.e., the management of IFR and VFR runway operations and flight operations within the CTR) with the same tools that they currently have at their disposal, alongside their additional task of overseeing the ATC-UTM collaborative environment.

The interface presented here aims purely at supporting tower controllers in their new supervisory control task in which, to maintain safety, they must ensure adequate separation between uncrewed and crewed aircraft that are flying inside the CTR by reconfiguring the airspace using geofences. The resulting display shares a lot of similarities with radar displays used in approach control, but with an emphasis on flight operations within the tower controller's area of responsibility. Its functional elements should be seen as an extension of features that could be incorporated into the tower control working station (e.g., the ground radar display) once the concept has been matured.

Figures 3.4 to 3.3 show a step-by-step representation of the structure and functionality of the interface for a simple scenario. The scenario consists of an arriving IFR flight, a departing HEMS flight, and two UAS, one being a high-priority fixed wing medical UAS and the other being a regular priority multicopter delivery UAS. Relevant display elements are indicated by the letters Ⓐ through Ⓢ (see legend in Figure 3.3), which also relate to specific levels of abstraction from Figure 3.2.

The initial map view in Figure 3.4 shows the situation overview with all UAS routed directly to their destinations. First, the interface can be seen to display the physical location of all the vehicles in the area Ⓐ. Moreover, their velocity is indicated visually by means of trailing dots and numerically on the UAS information strip, flight strips, and flight labels Ⓑ. Finally, the layout of potential geofences is shown, indicating their shape and size, while highlighting the one currently selected by the mouse by a bold green border Ⓒ. Similar to tower control radar, the interface is updated every five seconds, indicated by the timer in the top left Ⓓ. Selecting a crewed air vehicle will highlight its flight strip in the flight information view and vice versa (see "KL001"). Additionally, it shows the intended flight plan of the air vehicle through a continuous line that connects all subsequent waypoints

**Physical Form**

- Ⓐ Location
- Ⓑ Velocity
- Ⓒ Shape and size
- Ⓓ Update frequency
- Ⓔ Energy level

**Physical Function**

- Ⓕ Flight planning
- Ⓖ Air vehicle char.
- Ⓗ Geofencing
- Ⓘ Navigation

**Generalized Function**

- Ⓙ Routing
- Ⓚ Mission management
- Ⓛ Operational constr.
- Ⓜ Localization
- Ⓝ Sequencing

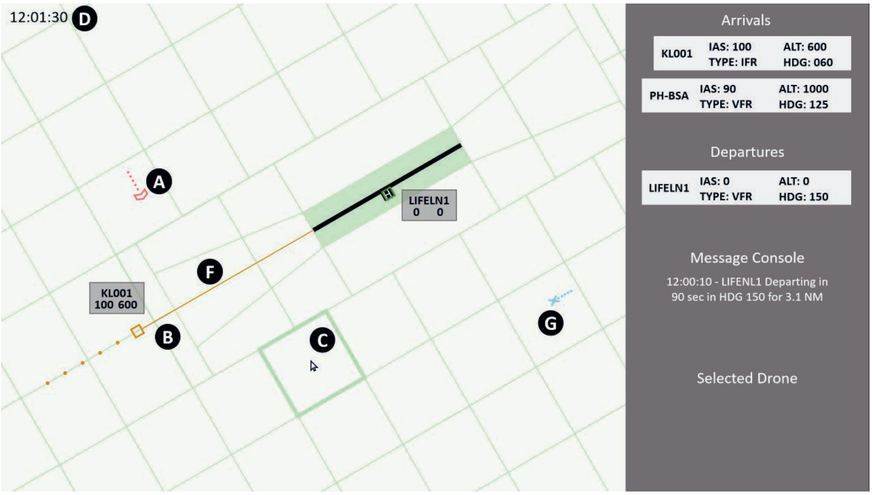
**Abstract Function**

- Ⓞ Separation
- Ⓟ Locomotion
- Ⓠ Timing

**Functional Purpose**

- Ⓡ Safety
- Ⓢ Efficiency

Figure 3.3: Index of mapped Abstraction Hierarchy elements.

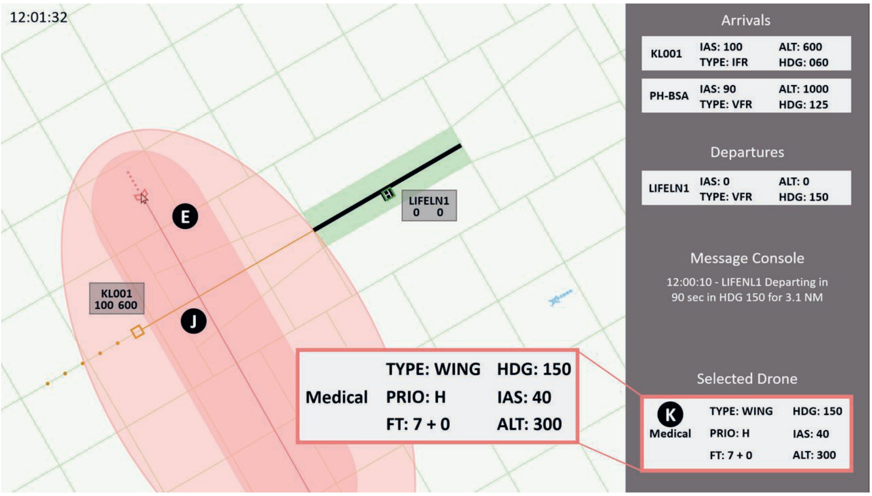


| | | |
|---|---|---|
| KL001 | IAS: 100<br>TYPE: IFR | ALT: 600<br>HDG: 060 |
| PH-BSA | IAS: 90<br>TYPE: VFR | ALT: 1000<br>HDG: 125 |
| LIFELN1 | IAS: 0<br>TYPE: VFR | ALT: 0<br>HDG: 150 |

12:00:10 - LIFENL1 Departing in 90 sec in HDG 150 for 3.1 NM

Figure 3.4: Mission overview and selecting IFR flight.

Ⓕ. It should further be noted that the vehicle icon for UAS also shows the type of air vehicle, which can either be a multicopter or fixed wing Ⓖ.



KL001 IAS: 100 ALT: 600 TYPE: IFR HDG: 060

PH-BSA IAS: 90 ALT: 1000 TYPE: VFR HDG: 125

LIFELN1 IAS: 0 ALT: 0 TYPE: VFR HDG: 150

12:00:10 - LIFENL1 Departing in 90 sec in HDG 150 for 3.1 NM

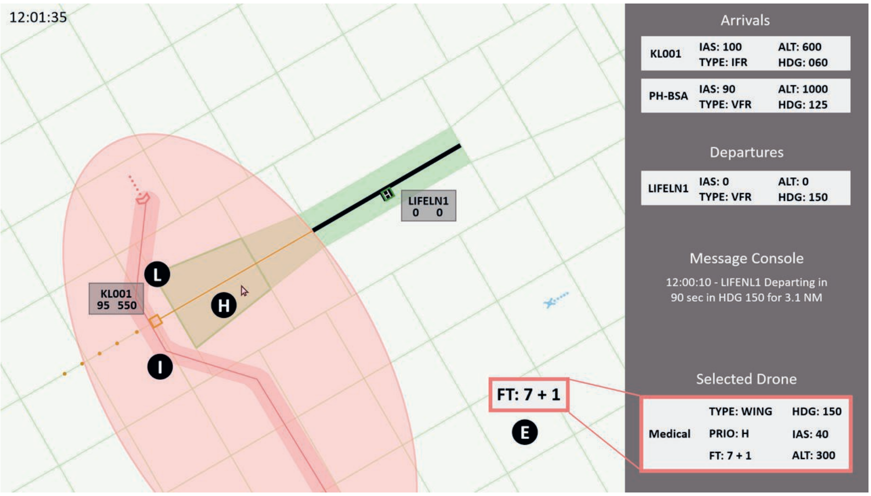
Medical TYPE: WING HDG: 150 PRIO: H IAS: 40 FT: 7 + 0 ALT: 300

Figure 3.5: Selecting a medical UAS.

Figure 3.5 shows that selecting a UAS will display two boundary regions, highlighted in red or blue depending on the color scheme applied to the UAS icon. These regions are developed as a consequence of the rationale described in Section 3.3.3. The inner region signifies the endurance the vehicle has available for re-routing Ⓔ. The outer region indicates the maximum deviation the UAS can make between its current location to its destination. Selecting the UAS also shows its flight strip, which provides the controller with additional information about the UAS, including mission type Ⓚ. Having both a crewed vehicle and UAS selected shows the routing involved Ⓙ in a potential conflict.

Two geofences are activated in Figure 3.6, restricting the UAS from accessing Ⓗ. The active geofences are marked in dark green, directly indicating which parts of the airspace are shielded from UAS travel Ⓛ. In response to this, the red medical UAS can be seen to modify its route by adding waypoints around the active geofences Ⓘ. This allows the controller to perform Dynamic Airspace Reconfiguration in order to achieve segregation, as well as manually enforce separation of UAS from crewed traffic if necessary. The impact of this re-route on the flight time can be seen on the UAS information strip Ⓔ which displays the planned flight time and additional delay in minutes.

Next, it can be seen in Figure 3.7 that the message console prompts a departure of a HEMS with callsign “LIFELN1”, as is also indicated by the flight strips. The message console was added as an element due to the lack of voice communication functionality of the interface. Selecting the flight strip highlights the corresponding air vehicle in the map view, allowing it to be used to localize the “LIFELN1” HEMS flight Ⓜ. Selecting the blue multicopter UAS shows it to be a regular priority delivery flight on its flight strip. After assessing flight priority through the flight strips, geofences can be used to influence the sequencing of UAS and crewed air traffic Ⓝ.



12:01:35

Arrivals

KL001 IAS: 100 ALT: 600
TYPE: IFR HDG: 060

PH-BSA IAS: 90 ALT: 1000
TYPE: VFR HDG: 125

Departures

LIFELN1 IAS: 0 ALT: 0
TYPE: VFR HDG: 150

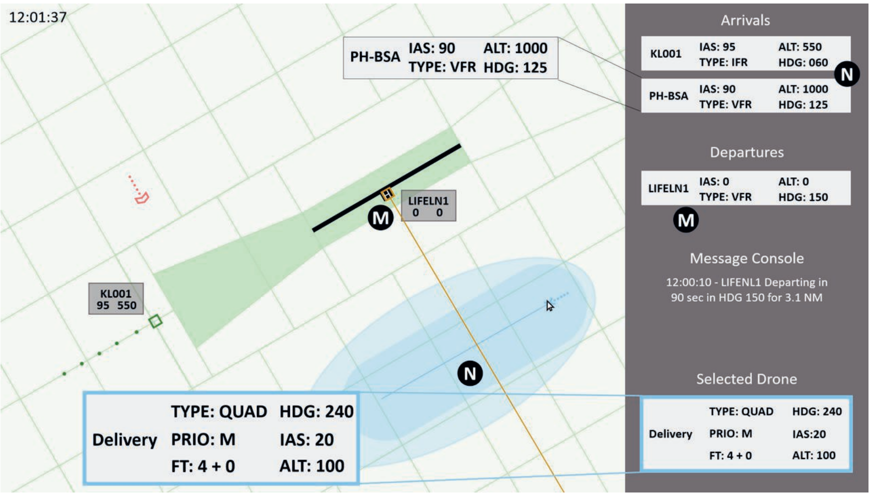
Message Console

12:00:10 - LIFENL1 Departing in 90 sec in HDG 150 for 3.1 NM

Selected Drone

Medical TYPE: WING HDG: 150
PRIO: H IAS: 40
FT: 7 + 1 ALT: 300

Figure 3.6: Activating geofences along the extended runway centerline.



12:01:37

PH-BSA IAS: 90 ALT: 1000
TYPE: VFR HDG: 125

Delivery TYPE: QUAD HDG: 240
PRIO: M IAS: 20
FT: 4 + 0 ALT: 100

Arrivals

KL001 IAS: 95 ALT: 550
TYPE: IFR HDG: 060

PH-BSA IAS: 90 ALT: 1000
TYPE: VFR HDG: 125

Departures

LIFELN1 IAS: 0 ALT: 0
TYPE: VFR HDG: 150

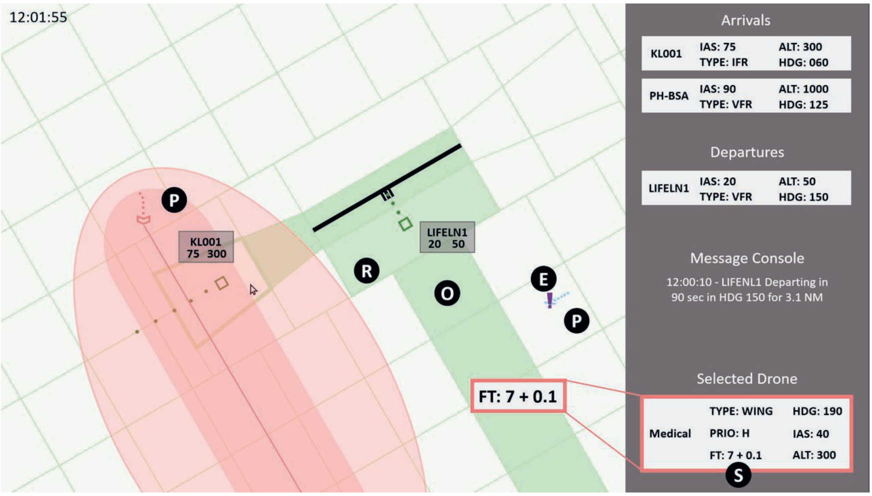
Message Console

12:00:10 - LIFENL1 Departing in 90 sec in HDG 150 for 3.1 NM

Selected Drone

Delivery TYPE: QUAD HDG: 240
PRIO: M IAS:20
FT: 4 + 0 ALT: 100

Figure 3.7: Localizing helicopter flight and selecting delivery UAS.



Arrivals

KL001 IAS: 75 TYPE: IFR ALT: 300 HDG: 060

PH-BSA IAS: 90 TYPE: VFR ALT: 1000 HDG: 125

Departures

LIFELN1 IAS: 20 TYPE: VFR ALT: 50 HDG: 150

Message Console

12:00:10 - LIFENL1 Departing in 90 sec in HDG 150 for 3.1 NM

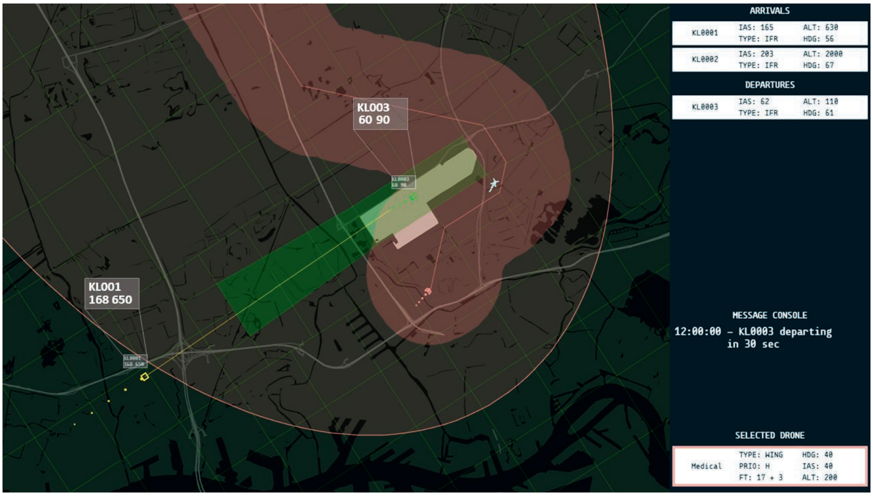
Selected Drone

Medical TYPE: WING PRIO: H FT: 7 + 0.1 HDG: 190 IAS: 40 ALT: 300

Figure 3.8: Activating geofence grid for safety and deactivating ILS geofence for optimization.

Activating the required geofences in Figure 3.8 creates a barrier beyond the outer boundary region of the blue multicopter UAS Ⓔ. This will cause it to loiter, indicated by the purple exclamation mark over the vehicle icon. Currently, all crewed traffic routes in the airspace are shielded by active geofences, signifying segregation of crewed and UAS traffic is achieved Ⓞ. The foremost top-level goal of tower control has been achieved: the safety Ⓡ of all air vehicles in the CTR. Now other top-level goals, such as efficiency, can be addressed. The boundary regions displayed upon selection of a UAS give an indication of the vehicle's locomotion constraints, such as that of the red medical UAS Ⓟ or lack of locomotion possibilities through the exclamation mark Ⓔ. By comparing UAS and crewed traffic speeds in, it can be seen that the landing crewed aircraft ("KL001") is no longer in conflict. The UAS can be allowed to proceed towards its destination by deactivating one of the geofences at the most convenient point in time Ⓠ. This action will increase the overall efficiency of the UAS operations, as indicated on the UAS information strip Ⓢ, which reduces the delay from one minute to 0.1 minutes. Monitoring UAS delays and shielding of crewed traffic routes allows the controller to balance safety and efficiency of both crewed and uncrewed aircraft within the collaborative environment.

These considerations were developed into an initial tower control display, which was used to test our assumptions on the safety and efficiency requirements of the collaborative ATC-UTM environment with professional air traffic controllers. Figure 3.9 showcases how these elements are represented in the final graphical display.



ARRIVALS

KL0001 IAS: 165 ALT: 630
TYPE: IFR HDG: 56

KL0002 IAS: 203 ALT: 2000
TYPE: IFR HDG: 67

DEPARTURES

KL0003 IAS: 62 ALT: 110
TYPE: IFR HDG: 61

MESSAGE CONSOLE

12:00:00 – KL0003 departing in 30 sec

SELECTED DRONE

Medical TYPE: WING HDG: 40
PRIO: H IAS: 40
FT: 17 + 3 ALT: 200

Figure 3.9: Screenshot of the simulation environment used during the experiment. Flight labels are highlighted for clarity.

## 3.5 Human-in-the-Loop Experiment

A human-in-the-loop simulation experiment was conducted based on the previously introduced collaborative display to investigate the utility of the design elements and to provide insights on how human controllers would use it to balance safety and efficiency. This was done by presenting experiment participants with several traffic scenarios where the use of geofences would be necessary to maintain traffic safety. Both subjective and objective experiment data was recorded and analyzed to evaluate the geofencing concept, control strategy, and interface usage.

### 3.5.1 Experiment Setup

Nine licensed air traffic controllers from two European countries volunteered to participate in the experiment, five of which were active tower controllers. However, the experiment required no in-depth knowledge of the Rotterdam The Hague Airport area and no knowledge of tower control beyond that of general air traffic control.

Due to restrictions of the COVID-19 pandemic, the experiment was performed completely remotely. This meant participants were sent a login and a web link, which they could use to enter the experiment environment from the comfort of their own homes. The simulation was then run on their own device, requiring a single screen and a mouse, which was used to give control inputs. Each participant was appointed a specific time slot and completed it in one session, which was recorded via video call. This was communicated to participants one week in advance. It should be noted that, as the experiments were conducted remotely, the experiment procedures and physical environment were more difficult to control compared to an experiment on location. However, this level of control was considered sufficient due to the exploratory nature of the experiments.

### 3.5.2 EXPERIMENT TASKS

During the experiment, participants were placed in the role of a tower controller at Rotterdam The Hague Airport, in which UAS operations have been integrated into the airspace. Within this environment, participants had to fulfill two main tasks. First, they were tasked to ensure adequate horizontal (2,000 feet / 600 meters) separation between crewed traffic and UAS traffic (vertical separation was not evaluated in this study). Second, they were tasked to minimize additional travel time for UAS, especially high-priority UAS. Both tasks were described as being of equal importance; however, the prioritization of tasks was left up to the participant.

The main tool of interaction available to the participants was a grid of geofences that could be individually activated and deactivated per grid cell, in order to shield certain areas from UAS traffic. The UAS responded only to the activation of geofences and could not be instructed individually. UAS would operate autonomously and use A* path planning [72] for tactical rerouting around geofences. Participants were given full authority over how to apply dynamic airspace reconfiguration using geofences and when to initiate it. The requirement to achieve full segregation of uncrewed flights from crewed flights was deliberately left out so that they could focus on using geofences for separation purposes. Additionally, crewed aircraft could *not* be given instructions since the experiment aimed to investigate the proposed form of interaction with UAS by using geofences. Participants did not receive feedback on their performance during the experiment run.

### 3.5.3 INDEPENDENT VARIABLES

The independent variables were the geofence size and the traffic scenario, which varied within participants, meaning all participants encountered all experiment conditions.

Geofence size had two levels, namely small (S) and large (L). The interaction between tower control and UAS traffic by means of geofences had not yet been tested using a human-in-the-loop experiment, meaning that no reference geofence size was available. It was therefore considered valuable to vary geofence size and observe how each participant responded to all experimental conditions. The size of the geofences was varied between one of two options. A 1x1 nautical-mile (1.9 x 1.9 kilometer) geofence cell was used as a baseline, as this is a common unit of reference in ATC and would provide adequate separation to UAS if the crewed aircraft passes through its center. A finer, 1x1 kilometer scale was chosen for the second geofence size option, in favor of UAS capabilities allowing a typical small UAS to clear the geofence in one minute.

A total of four traffic scenarios were considered. These contained a scenario emphasizing IFR approaches (IFR scenario) and departures, a scenario emphasizing VFR approaches and departures (VFR scenario), and a scenario including a Helicopter Emergency Medical Service (HEMS) flight with some additional mixed traffic (HEMS scenario). Finally, the fourth scenario considered a high task load use-case where all afore-mentioned scenarios were combined, and the number of UAS and crewed aircraft was doubled with respect to the first three scenarios (HTL scenario).

In total, (two x four =) eight experiment conditions were administered. All four scenarios were carried out for both geofence sizes. Therefore, the traffic scenario can be regarded as the second independent variable in a two-way repeated measures experiment. A balanced Latin square design was used to order the experiment conditions to minimize carry-over effects between the scenarios. Only the first three scenarios were shuffled in the matrix; the high task load scenario was always presented last for a given geofence size.

### 3.5.4 Scenarios

During the experiment, the participants were presented with traffic scenarios containing both crewed and UAS air traffic in the Rotterdam The Hague air traffic region. These traffic scenarios contained potential conflicts between crewed and UAS traffic which could be resolved by the controller by means of activating geofences. The crewed traffic routes in the scenarios were based on Rotterdam The Hague Airport traffic data [73], published IFR and VFR routes, and advice of Rotterdam tower controllers. The UAS traffic consisted of point-to-point delivery missions in the Rotterdam area, inspired by the missions introduced in Section 3.2.1. The number of crewed aircraft and UAS remained constant over the first three use cases and doubled for the high task load scenario. Each vehicle was scheduled to encounter one conflict during the experiment run if no geofences were activated. The traffic conditions of the experiment scenarios can be seen in Figures 3.10 to 3.13.

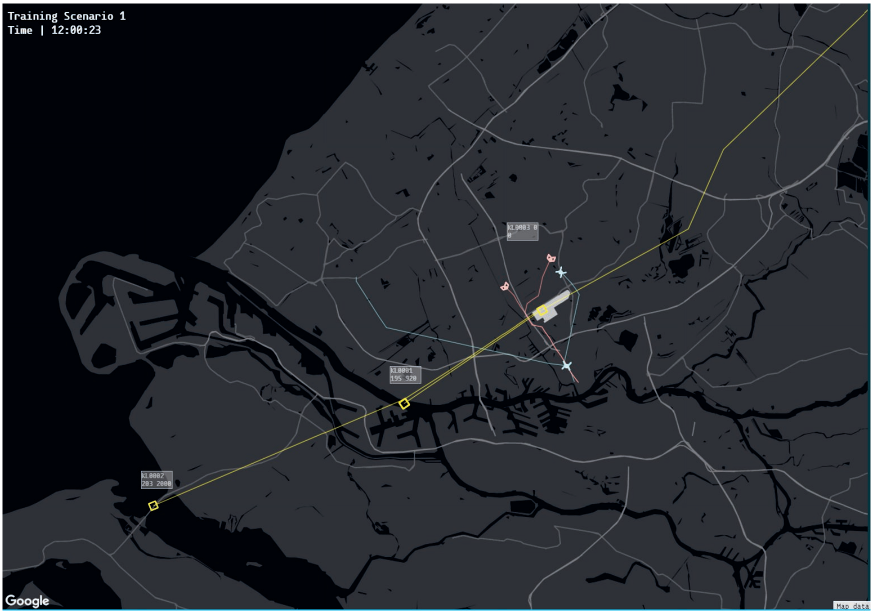


Figure 3.10: Overview of crewed and uncrewed air traffic initial route conditions in the IFR scenario.

### 3.5.5 Control Variables

Various control variables were used during the experiment. First, the interface presented to the controller was constant over all experiment runs. This implies that the controller consistently had control over the activation of geofences only, not over individual aircraft and that all interface elements were always available. Next, all the measurement scenarios had a run time of five minutes, where the display updated every five seconds. All UAS traffic was quantified as either a generic multicopter or a generic fixed-wing vehicle with

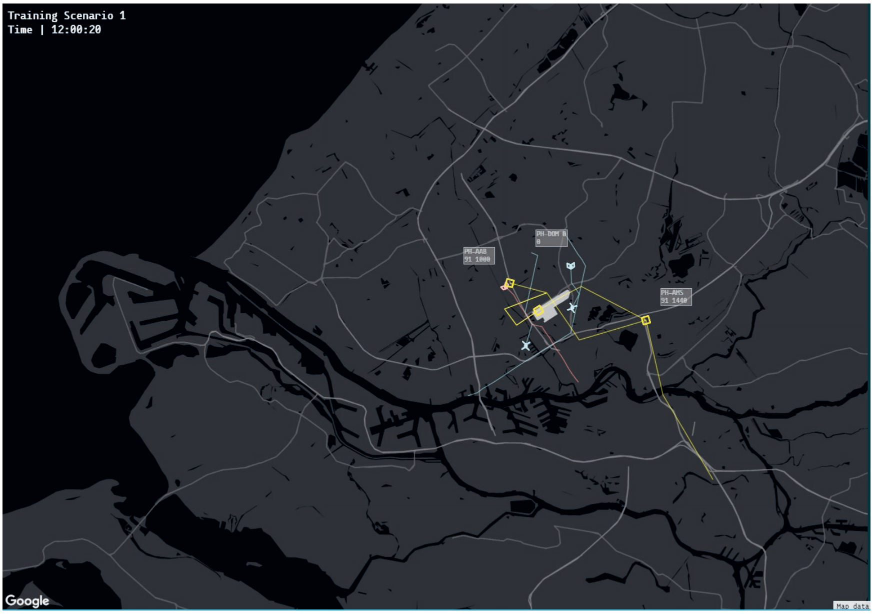


Figure 3.11: Overview of crewed and uncrewed air traffic initial route conditions in the VFR scenario.

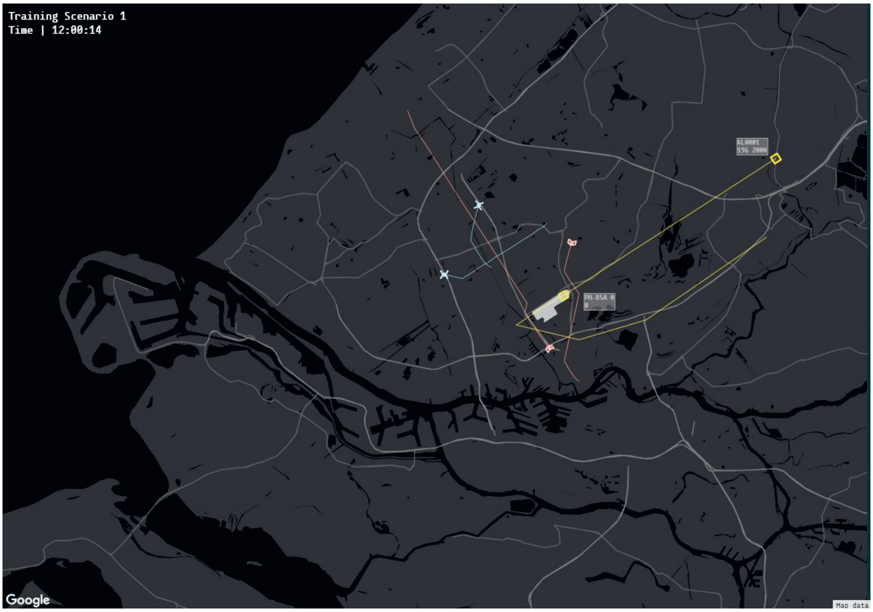


Figure 3.12: Overview of crewed and uncrewed air traffic initial route conditions in the Helicopter Emergency Medical Service (HEMS) scenario.

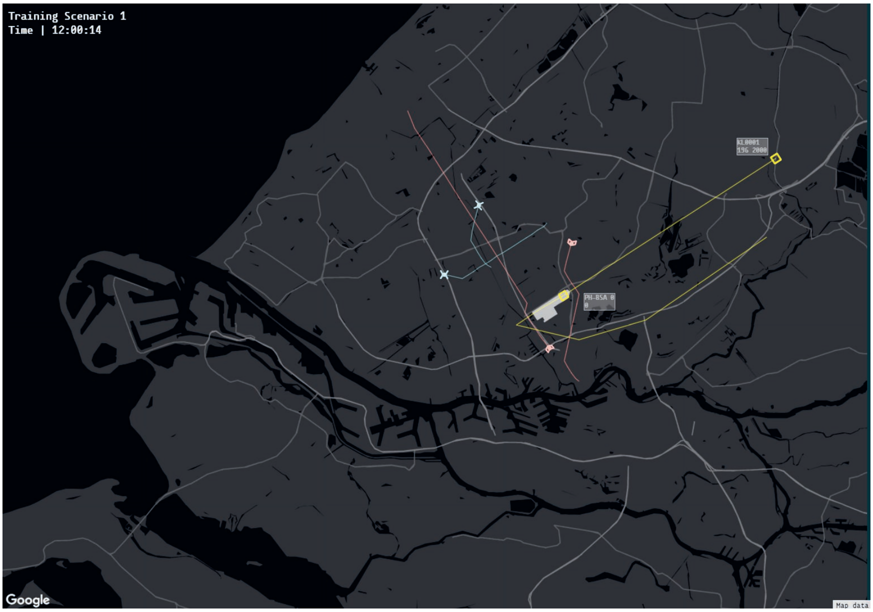


Figure 3.13: Overview of crewed and uncrewed air traffic initial route conditions in the High Task Load (HTL) scenario.

either high or regular priority. All crewed traffic was classified as a generic IFR commercial flight, a generic VFR flight, or a generic HEMS flight.

### 3.5.6 Dependent Measures

To quantify the effects of the above-described independent variables regarding the use of geofences and the interface, the participants' control strategy and control activity were recorded during the experiment. Additionally, information regarding task performance (in terms of safety and UAS efficiency) was recorded by the simulation tool to provide insight into the influence of geofence size on the task being performed by the controller. Control strategy and activity served to obtain more generic insight into how controllers perform their work.

The control strategy was quantified by measuring which geofences are activated at which point in time through time-stamped mouse clicks as well as through reviews of recorded video and audio material. Moreover, the participants were asked after each experiment run what their solution strategy was and how they used the display. This was supplemented by asking the participants which display elements they considered most useful in aiding them in this solution strategy during the experiment. Control activity was measured by recording the mouse interaction activity (clicks and scrolls) and specifying this over geofence interactions (activation and de-activation) and interface interactions (dragging and selecting for information).

### 3.5.7 PROCEDURES

Before starting the experiment, participants were requested to read the briefing documentation supplied to them. Next, a total of six training scenarios were conducted. The first three scenarios were used to familiarize participants with the Rotterdam The Hague air traffic region, the simulation environment, the interface, and the control inputs. From the fourth training scenario onward, participants were asked after each experiment run to give a short explanation of their control strategy by answering a post-scenario question. The experiment was concluded with a post-experiment survey which required participants to answer questions regarding the overall usefulness of geofences, their opinion on the traffic scenarios, simulation environment, and the interface, as well as any miscellaneous comments or suggestions with respect to the experiment. The results of this survey have been incorporated into the general conclusions and discussion section of this document.

### 3.5.8 HYPOTHESES

First, it was hypothesized that participants will prioritize crewed traffic safety over UAS efficiency (H1). This would be reflected in control behavior by the fact that participants would first apply all the required geofence restrictions based on the crewed traffic and afterward investigate if the UAS efficiency could be improved by making (small) alterations. Moreover, it was hypothesized that the high task load scenario would further emphasize the focus on traffic safety over UAS efficiency, as there was less opportunity to alter the geofence configuration for UAS efficiency (H2.1). The interface usage was hypothesized to decrease, due to interface clutter, caused by showing all UAS traffic (H2.2).

In terms of interactions with geofences, it was hypothesized that smaller geofences lead to more geofence clicks, as more geofences were required to shield a certain area from UAS traffic (H3.1). Consequently, it was hypothesized that smaller geofences would lead to more interface interactions (non-geofence), as the increased geofence interaction would more frequently change the situation (H3.2). In terms of traffic safety, it was hypothesized that smaller geofences would lead to a decrease in average separation between UAS and crewed traffic, as controlling geofences become a more tedious process, due to the increased number of mouse interactions required (H4).

In terms of UAS efficiency, smaller geofences were hypothesized to lead to a higher UAS efficiency, as participants would have more accurate control over geofence restrictions, allowing them to create the least impactful required geofence restrictions based on crewed air traffic (H5.1). Consequently, it was hypothesized that a smaller geofence size would lead to a lower average loiter time (H5.2). However, it was hypothesized that it would also lead to a higher number of reroutes, as more geofences were expected to be activated on average (H5.3).

## 3.6 RESULTS

Results of the human-in-the-loop experiment with air traffic control participants provided sufficient data to make observations on geofences as control elements within the ATC-UTM collaborative environment. A large set of performance data was collected during each experiment run. All statistical tests used a significance level of 0.05. The statistical data was found to violate the assumption of homogeneity of variance. Therefore, the within-group effects were tested using the Friedman's ANOVA, followed by Wilcoxon test with a Bonferroni correction or a Dunn-Bonferroni test to account for multiple testing. This section will focus in particular on how the interface aided controllers in achieving their control strategy and its impact on safety and efficiency.

### 3.6.1 CONTROL STRATEGY

Observations during the experiment and from the post-experiment survey showed that participants prioritized safety over UAS efficiency, resulting in a control strategy that can be divided into two parts. First, participants checked the states and intent of UAS and crewed traffic, scanning for potential conflicts. This was combined with the initial activation of geofences that resolved conflicts as quickly as possible, establishing a safe airspace. Second, participants maintained vigilance of the UAS state and intent after the geofences were activated. This was combined with the deactivation or tweaking of geofences to increase UAS efficiency. This strategy was confirmed explicitly through participants' comments when asked about their control strategy, such as the following:

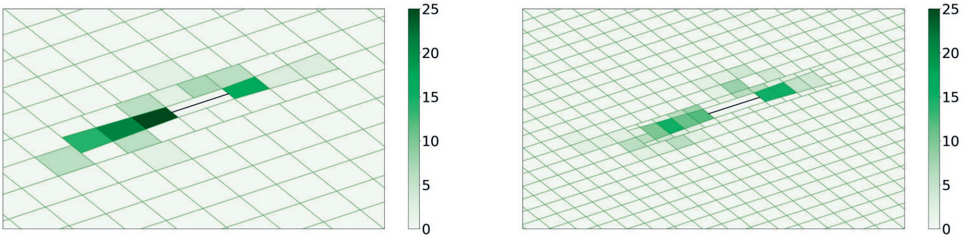
"*I activated geofences to protect both the [instrument landing system] approach, as well as the [standard instrument departure] initial miles for the traffic on departure. As soon as the arrival traffic was cleared of the fixed-wing drone, I deactivated those geofences so that the drone had a shorter path.*"

Concerning the initial assumptions on the control strategy, as hypothesized, participants were found to opt for a strategy that prioritized safety over efficiency (H1). Moreover, participants indicated they focused more on safety in the high task load scenario and had less time to focus on efficiency (H2.1).

Figure 3.14 show maps of the total geofence activation of all participants, for the four scenarios with large geofences presented on the left, and small geofences on the right. It can be observed that geofence activations were very localized and situated in areas where conflicts were likely to occur, namely near the runway, to protect approaching and departing crewed flights and low-altitude helicopter flights, as seen in Figure 3.14 (c) and Figure 3.14 (d). Geofence maps for the scenarios with small geofences do not show a significantly different control behavior in pattern or magnitude to the large geofences.

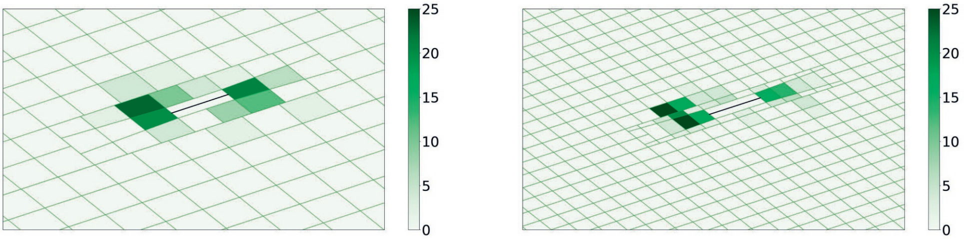
During the experiment, it was observed that most participants opted for a control technique that resembles aircraft vectoring to fulfill the above-described control strategy. They used geofences to steer a UAS along a certain route, rather than simply activating a geofence and letting the UAS find their way around it. This was mostly used to vector slower aircraft (UAS) behind the faster aircraft (crewed traffic), a common tactic in en-route air traffic control [74]. Participants indicated in the survey that this strategy is also applied in tower control if the traffic situation requires it. This meant that geofences were also used to either steer the UAS along a longer route or to add random restrictions along the route in order to enforce a longer flight time before crossing the traffic.

Figure 3.15 showcases such an example. This behavior was unexpected and caused some problems, as the geofences were not intended to be used in this way and the UAS path planning would not always reroute the vehicles in a way that the controller expected them to. On several occasions, when a particular geofence was activated for the purpose of vectoring a UAS, that activation happened to interfere with the path planning of another UAS, causing that second vehicle to reroute as well. In some cases, this would even cause



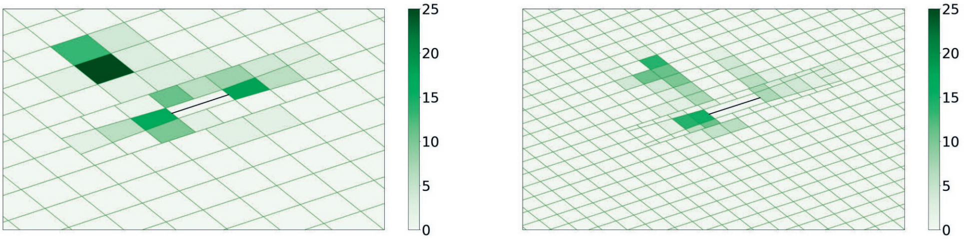
(a) IFR scenario, large geofences (IFR-L)

IFR scenario, small geofences (IFR-S)



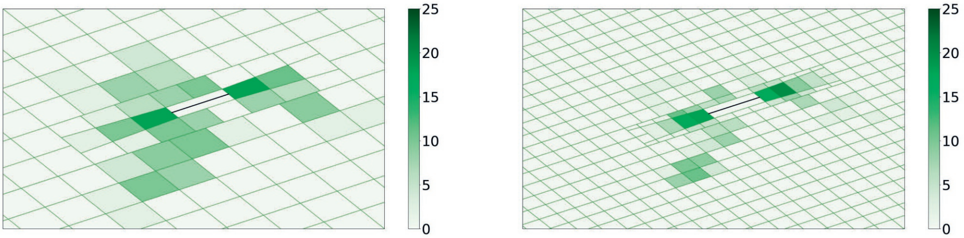
(b) VFR scenario, large geofences (VFR-L)

VFR scenario, small geofences (VFR-S)



(c) HEMS scenario, large geofences (HEMS-L)

HEMS scenario, small geofences (HEMS-S)



(d) HTL scenario, large geofences (HTL-L)

HEMS scenario, small geofences (HTL-S)

Figure 3.14: Total geofence interactions of all participants per scenario type. The runway is indicated in black.

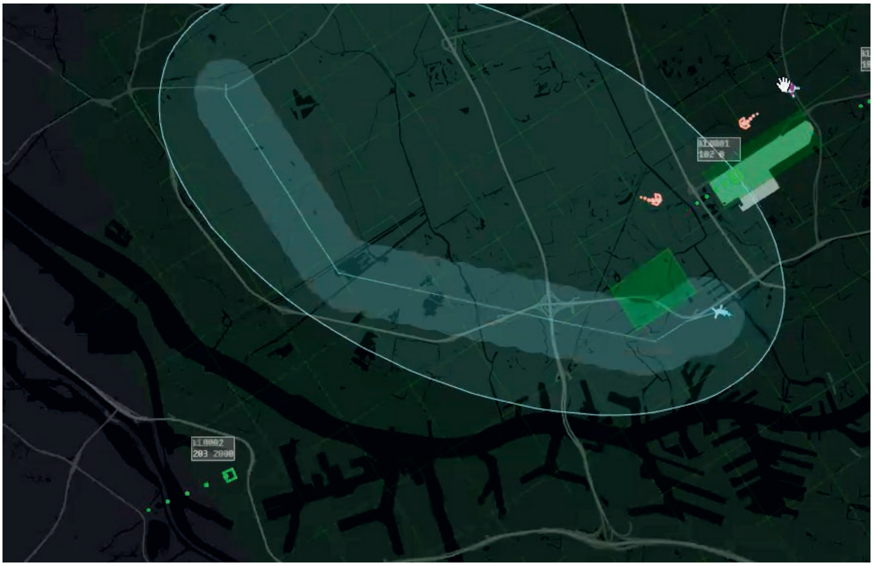


Figure 3.15: Geofence activated not to protect an area from UAS operations but to vector the selected UAS behind the landing crewed aircraft.

the second UAS to enter into another conflict with a crewed aircraft which would need to be resolved.

Another unexpected behavior observed during the execution of the simulation runs was that some participants utilized geofences to force a UAS to loiter. They did this by excessively activating geofences in a way that depletes the UAS of all maneuvering options, thus forcing the vehicle to enter loiter mode. The primary use of this was because the participants had knowledge of the length of time a geofence would be active and could estimate that loitering the drone for a short period of time would be faster than rerouting around the geofence. Figure 3.16 shows such a situation. The activation of geofences along the extended runway centerline (see Figure 3.16 above) triggers a long reroute of the highlighted blue UAS. The participant proceeded to activate several more geofences towards the north of the aerodrome (see Figure 3.16 below), so that the UAS would loiter near its current position, prepared to cross the runway centerline once the departing crewed flight had passed. This effort was made to improve the efficiency of a particular UAS, given that the controller had more knowledge about the rationale for activating geofences than the UTM system did. From the UTM perspective, any active geofence was considered to remain in this state for an undisclosed amount of time. These observations point to a shortcoming in the definition of the geofence concept for this experiment, which applies equal and time-invariant restrictions to all UAS. However, the efficiency benefit obtained from forcing UAS behavior using geofences also came at the expense of restricting freedom of movement to other UAS, which in some cases were forced to reroute substantially to reach their destination.

Figure 3.16: Utilization of geofences to force UAS loitering, rather than rerouting. The image above shows a UAS reroute due to short-term geofence restrictions. The image below shows how the UAS is forced to loiter by activating additional geofences.

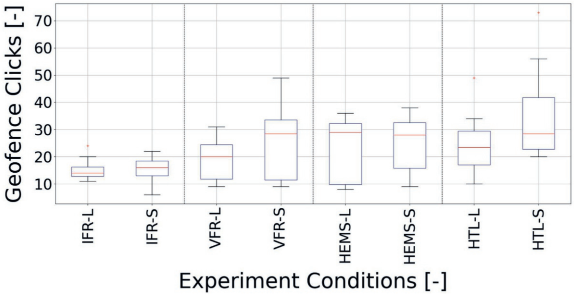


Figure 3.17: Geofence interactions per experiment condition.

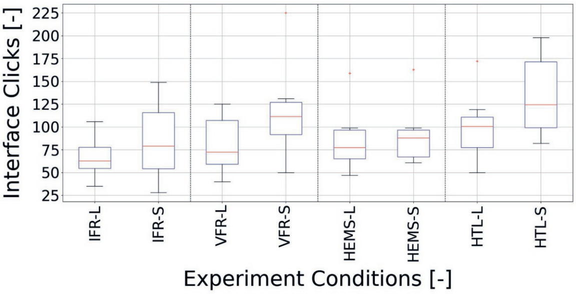


Figure 3.18: Interface interactions per experiment condition.

### 3.6.2 Interface Usage and Preferences

Figure 3.17 shows box plots of the total geofence interactions per experiment condition. At first glance, it appears as if the inclusion of VFR and HEMS traffic increased the need for activating geofences over IFR traffic. Moreover, there does not seem to be a substantial impact of the high task load scenario on geofence clicks when compared to the VFR and HEMS scenarios. Statistical analysis, however, shows that the geofence size had no significant effect on any of the differences between relevant experiment condition pairs.

Figure 3.18 covers all other clicks and drags that were not categorized as geofence interactions. This division was made because geofence clicks were considered control inputs, whereas all other clicks were interactions with the interface itself (information provision). The trend in the graph seems to indicate that the smaller geofence scenarios required more interface interactions than their large geofence counterparts.

Statistical analysis of the results shows that the total number of interface interactions was significantly influenced by the traffic scenario for the small geofence condition ($\chi^2(3) = 12.3, p = 0.006$), where a Dunn-Bonferroni post hoc test shows significant differences between the IFR and HTL scenarios ($p = 0.012$) and the HEMS and VFR scenarios ($p = 0.04$). Moreover, the number of interface interactions was significantly different between geofence sizes ($\alpha = 0.05/4 = 0.0125$) for the VFR ($Z = -2.524, p = 0.012$) and HTL ($Z = -2.524, p = 0.012$) scenarios. It can therefore be concluded from the results that the traffic scenario influenced the total interface interaction and that smaller geofences generally lead to a larger number of interface interactions. Looking at these observations as a whole, it seems that the scenarios in isolation result in certain trends, but the combination of all scenarios (HTL) is not necessarily the “sum of its parts”. In HTL-L, geofence click quantities are pretty similar to VFR and HEMS. However, only in HTL-S, interface clicks are significantly increased compared to HTL-L, meaning that smaller geofence sizes increase the information provision effort when the task load is high.

Concerning the initial hypotheses, although there were some significant differences between individual experiment conditions in small geofence sizes, overall there was no significant trend in interface interactions between lower and higher task load scenarios (H2.2). After the completion of the experiment, most participants indicated that they did not notice the change in geofence size. When asked about this, participants indicated that they preferred larger geofences, as this reduced the amount of interaction required for obtaining and maintaining safety. Although the results do not show the hypothesized influence of geofence size on geofence interactions (H3.1), they do show the expected significant increase in interface interactions for smaller geofences (H3.2).

Figure 4.6 shows the scores participants gave to the individual interface elements on a scale from 1 (not useful) to 10 (very useful). It can be seen that interface elements regarding crewed traffic were consistently scored lower than those concerning UAS traffic. It was recorded during the post-experiment survey that participants scored these interface elements lower due to their inability to interact with crewed traffic. It can further be observed from the data that UAS priority was found more useful than UAS vehicle type. The interface elements regarded as most useful were UAS route, UAS priority color, and geofence state.

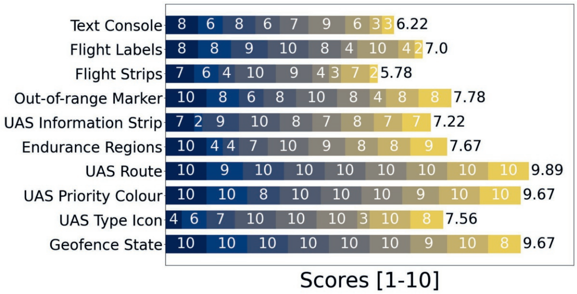


Figure 3.19: Subjective scores of interface elements from all nine participants, displaying the average score at the end of the bar.

Special attention was given to the endurance regions, as these were non-standard interface elements in ATC and were designed to aid in geofence selection. Participants with a control strategy focusing on safety generally indicated they did not extensively use the endurance regions. Some of these participants indicated that it helped them understand UAS routing intentions. As the endurance regions were only displayed upon selecting a vehicle, they were never deemed intrusive. Participants with a control strategy that focused more on UAS efficiency indicated that they did consider the endurance region in their decision-making. They commented that it helped them in predicting UAS behavior and in making choices regarding geofence selection.

The grid layout of geofences was generally well received, but the additional structure, such as designated UAS transfer corridors to cross the runway midfield and extended runway centerline at 90-degree angles was preferred. The use of distinct markers to distinguish UAS from crewed aircraft was considered useful, however the UAS vehicle type distinction was not relevant unless the aim was to physically see and identify the vehicle by looking out of the tower (which was not the case). The use of a distinct color to highlight UAS priority was considered useful to identify priority vehicles, although it was suggested not to use red given that in typical radar screens, it indicates an emergency or conflict.

### 3.6.3 Achievement of Safety

Figure 3.20 shows box blots of the average horizontal separation between UAS traffic and crewed traffic per experiment condition. This considers the average separation between a crewed aircraft in airspace and all other UAS. Statistical analysis of the results shows that the average separation distance between UAS and crewed traffic was significantly influenced by the traffic scenario for both geofence sizes ($\chi^2(3) = 19.5, p < 0.01$). The effect of geofence size on average separation was found to be significant for all traffic scenarios ($\alpha = 0.05/4 = 0.0125, Z = -2.521, p = 0.012$). It can therefore be concluded that the traffic scenario influenced the average separation and that smaller geofences lead to a lower average separation between UAS and crewed traffic, as was initially expected (H4). Losses of separation (less than 600 meters) between crewed aircraft and UAS occurred nine times during the experiment runs. They predominantly occurred with participants with a less conservative control strategy. Moreover, results show that over half of the losses of separation (LOS) involved HEMS flights, as depicted in Figure 3.21. This can likely be explained due to the less predictable nature of such flights and the fact that the interface did not provide any conflict detection assistance.

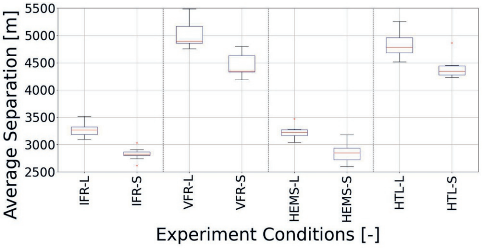


Figure 3.20: Average separation between UAS and crewed traffic per experiment condition.

### 3.6.4 Achievement of Efficiency

Figure 3.22 shows box plots of the average UAS flight time efficiency (the difference between the flight time at the beginning and the end of the scenario) per experiment condition. Statistical analysis of the results shows that the average UAS efficiency was significantly influenced by traffic scenario for both large ($\chi^2(3) = 10.05, p = 0.018$) and small geofences ($\chi^2(3) = 13.65, p = 0.003$). The effect of geofence size on UAS efficiency can be seen to have differed per scenario, while it was only found to be significant for the HEMS scenario ($\alpha = 0.05/4 = 0.0125, Z = -2.521, p = 0.012$). It can be concluded from the results that the

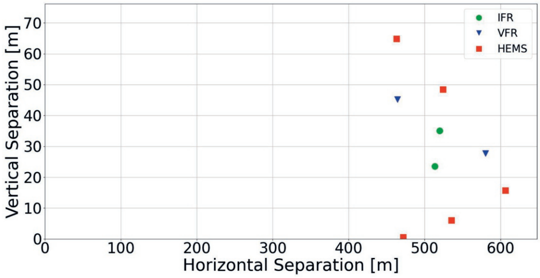


Figure 3.21: Overview of losses of separation with UAS per crewed vehicle type across all experiment conditions and scenarios.

combination of traffic scenario and geofence size influenced the UAS efficiency. However, rather than increasing efficiency, the effect of geofence size on UAS efficiency was found to be negative, positive, or negligible, depending on the traffic scenario (H5.1). This emphasizes the importance of tailoring geofences towards common traffic behaviors. The statistical analysis of the average UAS loiter time shows that only the traffic scenario had a significant influence on the average loiter time for large geofences ($\chi^2(3) = 13.65, p = 0.003$) and are therefore not shown. Similarly, results for the average reroutes per UAS do not yield significant effects. As such, geofence size was not found to have a significant effect on loiter time or number of reroutes (H5.2 and H5.3).

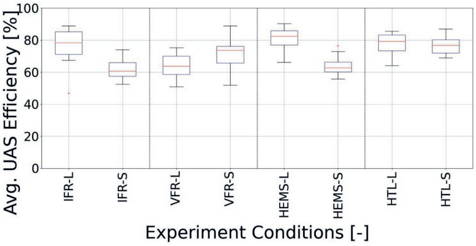


Figure 3.22: Average UAS flight-time efficiency per experiment condition.

## 3.7 Discussion

Geofences were generally considered a useful tool by the participants to maintain separation between UAS and crewed air traffic. Given the lack of having to instruct crewed aircraft and that UTM did not provide any separation actions on UAS, most participants used geofences to actively influence UAS routings and vector them behind crewed aircraft. This type of control style differs from the original intent of using geofences as a means to protect crewed aircraft, and caused some complications, as the UAS's path finding did not always select the route that the participant intended it to. A higher transparency in UAS (re)routing decisions, supported by a more sophisticated path planning algorithm, such as that proposed by Xue and Wei [75] or Jung and Kartik [76] should therefore be considered as part of the display components. Moreover, a geofence structure that would allow UAS to use midfield crossings from one side of the runway to the other should be incorporated, as this is a common tactic in ATC to structure air traffic.

As a consequence of these limitations, participants expressed the desire to be able to instruct UAS to briefly loiter until a geofence restriction was lifted, as this would lead to a more predictable UAS routing behavior. This strategy is at odds with the concept proposed by the U-space regulation [15], which does not foresee an air traffic controller exercising direct control over UAS. Future studies would therefore need to assess the implications of allowing the controller to instruct individual UAS if necessary and assess how prevalent this control strategy would be with increasing workload and task saturation.

The “knock-on” effects experienced by participants when activating a geofence for a particular UAS, but affecting multiple UAS routes through the same area, also merit further investigation. Such situations require the controller to activate additional geofences to resolve new conflicts, which could lead to instability in terms of the control task when more UAS are introduced. This may be avoided by implementing geofences that can be assigned to individual UAS, rather than those used in this study which apply to all UAS at once. Moreover, results highlight the need to incorporate the notion of geofence activation time into the dynamic airspace reconfiguration concept so that UAS are not unnecessarily penalized by short-term airspace reconfigurations. This may also alleviate the need for issuing individual loiter commands and improve human operator awareness in an environment with higher amounts of UAS traffic. Surprisingly, most participants indicated they would have prioritized high-priority UAS over VFR flights had they had the opportunity to control VFR traffic. This indicates that the allocation of flight priorities among crewed and uncrewed aircraft may not be as trivial as first thought.

The observed active UAS control approach to using geofences is a limitation of the study conducted with regards to the current U-space regulation [15], which mandates segregation of ATC and U-space operations. In this study, however, participants were specifically asked to enforce a predefined minimum separation of UAS from crewed aircraft when segregating airspace using geofences. In practice this concept should be incorporated into the dynamic airspace reconfiguration process itself, for instance by adding sufficiently large buffer zones around geofences to ensure by design that separation minima are met. Future studies should therefore compare an environment that simulates the stricter limits set by the U-space regulation (which would alleviate their responsibility to separate crewed aircraft from individual UAS) with one that allows for a much higher level of air traffic controller involvement, to see which of the two extremes provide more merit to safety, efficiency and human performance.

These results have shown that the experiment interface set-up was insufficient in supporting all types of participant control styles, in particular those who prefer active involvement in UTM decision-making. The use of geofences as the only means to achieve this end was problematic, given their greater utility in achieving segregation between ATC and UTM rather than guiding UTM decisions on UAS routings. Future interface designs should therefore consider some of the additional features proposed in this study to support controllers preferring a more active control style and investigate other means for them to guide UTM routing decisions. Moreover, the issuing of vectoring instructions is commonly used in en-route and approach control, but hardly used in tower control, as was elaborated on in Section 3.3.2. Given that experiment participants opted for this type of control strategy means that the control responsibilities of the tower controller may need to be augmented to fully support all types of control styles, beyond the use of geofences.

The fact that participants were not required to take active control over crewed air traffic is a noteworthy constraint in the interpretation of the results of this study. Participants were able to give their full attention to UAS traffic displayed on the interface, and thus micro-managed UAS routings by using geofences to issue "vectoring" instructions. In a real-life scenario, participants remarked that this active strategy may not be sustainable alongside their normal tower control tasks, especially if the number of crewed aircraft is high. This, however, would need to be validated in another human-in-the-loop experiment which also allows for control of crewed aircraft in order to assess how these new segregation tasks would impact existing ATC responsibilities concerning traffic management.

These findings indicate that future research should consider a simulation environment where participants must assume control of crewed traffic as they currently do, supported by an immersive tower control simulation whilst managing the dynamic airspace reconfiguration process using geofences. The combination of high UAS traffic density, a full segregation requirement, and control over crewed traffic is expected to shift the operators' control strategy away from the currently observed active control (vectoring). This could result in a more conservative use of geofences around the runway, with a focus on letting UAS traffic pass safely, rather than minimizing individual UAS delays. The implementation of a fully immersive UTM and ATC simulation will likely impact how the interface will be used, given that the controller will have less time available to interact with the display alongside their typical tower control activities such as scanning the horizon to visually identify crewed aircraft on the tarmac or on final approach, as well as managing runway operations. It is assumed that this will likely reduce the frequency of participants actively controlling UAS routings, although the interface should still incorporate elements to allow for this type of strategy. Results indicate that, in more complex scenarios, the controller would be better supported by providing them with larger geofences, as the HTL scenario indicated, and incorporating conflict detection functionalities into the display, to avoid losses of separation such as those experienced in the HEMS scenarios. The latter could be achieved by predicting where a crewed aircraft and a drone would meet and highlighting that grid cell so that a controller would know which geofence to activate to prevent separation loss.

It is also important to mention that, given the limitations of this preliminary design study, it was not possible to present sufficient proof that the defined separation minima are mature enough to be implemented in practice nor that individually activated geofence areas are adequate for this purpose. The results should rather be seen as a set of potential mechanisms for the use of geofences to support the implementation of collaborative airspace management for UTM and ATC traffic from the perspective of the tower controller.

Finally, the results also highlight some relevant nuances of the Abstraction Hierarchy which will need to be further elaborated on in future studies. The most relevant of which relates to the abstract functions "separation" vs. "segregation". The fact that geofences (which serve the function of achieving segregation) were used to actively vector UAS in order to achieve separation means that the lines between the two concepts were not as clear as initially assumed. To achieve this strategy, geofences were used as a means to achieve “sequencing”, which represents a novel connection within the presented Abstraction Hierarchy. Further elements that affect sequencing were also identified, namely “vehicle priority” and “geofence activation time”, which are currently not included in the hierarchy. Moreover, the participants’ recommendation to have a higher level of control over UAS traffic points to a need to assess whether additional functional U-space elements apart from geofencing should be incorporated into the Abstraction Hierarchy, and subsequently into the interface design, as previously discussed. The updated Abstraction Hierarchy is presented in Figure 3.23. Finally, the “energy level” of UAS, which determined vehicle endurance, seemed to have a much lower impact on the participants’ goal of maintaining safety than initially thought, given the low consideration that this element received in the evaluation of the interface. These insights warrant a review and subsequent assessment of both the Abstraction Hierarchy and the associated interface in future studies.

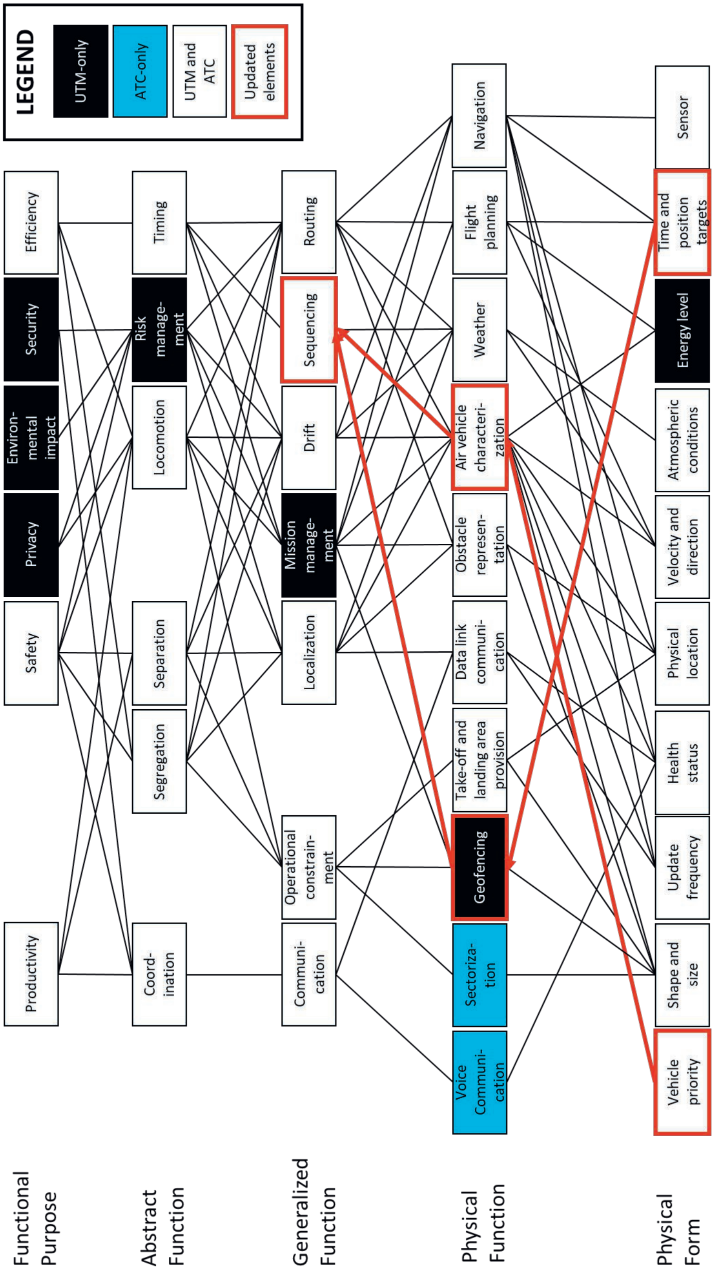


Figure 3.23: Updated Abstraction Hierarchy model of the work domain of a collaborative environment between ATC (tower control) and UTM.

## 3.8 Conclusion

The goal of this study was to establish a preliminary tactical interface for aerodrome tower controllers to interact with UTM systems in a collaborative environment. The interface was developed and based on reference material from the European U-space implementation and was modeled onto an Abstraction Hierarchy. The emphasis of the proposed interface was placed on supervising and adjusting UAS traffic within the CTR of Rotterdam The Hague Airport, surrounded by crewed aircraft that could not be controlled, by dynamically activating and deactivating geofence areas. The aim of this approach was to identify its impact on achieving safe and efficient UAS operations within the collaborative environment.

Results of a small-scale human-in-the-loop experiment with nine professional tower and en-route controllers indicated that various interface elements (e.g., UAS priority, UAS routes and geofence state) were deemed useful in both supervising and controlling UAS behavior in relation to crewed aircraft trajectories. Surprisingly, participants opted to use geofences for a more active, vectoring-style approach to re-route UAS, rather than passively protecting crewed aircraft as the current U-space regulation indicates. This suggests that controllers may want to have more control over UAS traffic than initially expected.

This result, however, could be partially explained by participants not needing to control crewed aircraft. Further work is therefore needed to investigate control behavior and human performance in a more realistic tower control environment. This would require updating the simulation to allow participants to have control over crewed traffic and adding situations that would require tower controllers to look away from the interface (to simulate "head-up time") alongside supervising UTM traffic using geofences. The UTM environment realism could be improved as well with a more sophisticated path-planning algorithm for UAS, the simulation of environmental factors such as wind drift, and the incorporation of UAS contingency scenarios. The geofencing concept would also need to be updated to avoid "knock-on" effects on several UAS missions. Such effects could be mitigated by assigning geofences to individual UAS and specifying how long a geofence will be active. Tailoring the geofence grid to better fit established crewed air traffic routes as well as providing fixed transfer corridors for UAS would also improve the interface. Finally, the interface could be further improved by incorporating conflict detection and alerting functionalities.

# 4

# COLLABORATION WITH AUTOMATION

*The findings of the initial experiment of using geofences to segregate ATC and UTM control, Chapter 3, were incorporated. A human-in-the-loop experiment was conducted to study human collaboration with automation. By allowing experiment participants control over both crewed and uncrewed air traffic, two types of collaborative control strategies were identified. The contents of this chapter reflect an adapted version of the following paper:*

| | |
|---|---|
| **Paper Title** | 🗎 *Exploring Tower Control Strategies for Concurrent crewed and Uncrewed Aircraft Management* |
| **Authors** | D. Janisch, P. Sánchez-Escalonilla, J. M. Cervero, A. Vidaller and C. Borst |
| **Published in** | Proceedings of the 2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC), 2023, pp. 1-10. |

*Ongoing efforts to establish Uncrewed Aircraft Systems Traffic Management (UTM) alongside Air Traffic Management (ATM) point towards the segregation of both domains. However, strict segregation around smaller airports near urban areas may not be possible at all times due to variable crewed traffic patterns, demanding human supervision and intervention. This study explored potential control strategies for tower controllers to dynamically re-configure UTM airspace in the vicinity of aerodromes to support crewed air traffic operations. A human-machine interface prototype was developed to assist the human controller to allow overseeing Uncrewed Aircraft Systems (UAS) missions, controlling individual UAS when needed, and reconfiguring airspace by using geofences. Results from an exploratory experiment identified an "active" and "passive" control strategy, which was applied by both licensed tower controller participants. Yet, neither could be singled out as a suitable strategy for all types of situations. Future research should look into the implications of segregation vs. integration of ATM and UTM domains, in particular with regards to operational procedures, responsibilities, and assignment of roles within the collaborative environment. Findings should then be substantiated by a larger sample size and an in-depth statistical analysis.*

## 4.1 Introduction

In the near future, it is expected that large numbers of Uncrewed Aircraft System (UAS) flight operations will co-exist alongside crewed air traffic. This is especially problematic around smaller aerodromes near urban areas where the expected increase in UAS missions, such as for surveillance and delivery purposes [4] require access to the control zone, thereby increasing the risk of collisions between UAS and arriving or departing crewed air traffic. To mitigate this risk, aviation regulatory bodies, industry, and research organizations in Europe and the United States are developing concepts integrating UAS Traffic Management (UTM) systems into the current Air Traffic Management (ATM) environment.

One possible way, as proposed by the European Aviation Safety Agency (EASA), uses geographical segregation of airspace delegated to UTM and ATM, which can be adjusted using Dynamic Airspace Reconfiguration (DAR). This reconfiguration of airspace shall be carried out by an Air Traffic Control (ATC) unit in response to variable crewed traffic patterns, which demand mid- or short-term UTM airspace adaptations. The concept, explained at high-level in the European U-space regulation [15] and accompanying guidance material [40], consists of basic airspace blocks, that could either be activated or deactivated by ATC to reshape the boundary between ATM and UTM. However, little is described about *how* ATC should perform this new DAR task alongside their normal ATC tasks, *who* in ATC will be tasked to perform it, and how exactly the interaction with the UTM system will take place. This situation is complicated even further by the fact that both systems rely on different underlying operational concepts. Whereas ATM is a human-centric concept built on long-established flight rules and procedures, UTM is expected to be a fully digitalized and automated system developed around airspace reservations for individual missions [39].

Previous work by van Aken, Janisch, and Borst [77, 78], as presented in Chapter 3, explored the use of dynamic geofences (UTM airspace blocks that restrict UAS flights within them) that allowed tower controllers to either temporarily or permanently shield predefined portions of the aerodrome control zone (CTR) by selecting those areas on an enhanced radar display. The results and methods of that study formed the basis of the DAR operational concept and interface designs developed within the SESAR PJ34 AURA project

[20], which received funding from the SESAR3 Joint Undertaking under grant agreement No 101017521. Differing from the study conducted by van Aken, Janisch and Borst, in which tower controllers could not interact with crewed traffic, the AURA project explored the possibility of a tower controller assuming the role of a DAR manager alongside performing their traditional ATC tasks.

In this chapter, first more details are provided about the proposed AURA operational concept describing the DAR role, where it is assumed that the added complexity of performing concurrent tasks can be mitigated by relying on decision-making automation and interface design. A preliminary human-in-the-loop experiment with two recently licensed tower controllers was performed within the PJ34 AURA project to identify potential control strategies to support the proposed concept, which is presented in Section 4.3. After presenting the results, a discussion and initial conclusions are presented about the feasibility of the AURA concept of operations with regard to the observed strategies and subsequent merging of tower control and DAR manager roles.

## 4.2 AURA Concept of Operations

The most important aspects of the concept of operations for DAR defined in the AURA project are highlighted. Emphasis is placed on the roles and responsibilities of ATC within this concept and the proposed interface and automation requirements to support these.

### 4.2.1 Dynamic Airspace Reconfiguration Management

The regulatory framework for U-space [15, 35], which is the European UTM concept, defines DAR as a means for air traffic service providers to temporarily adjust the vertical and/or horizontal boundaries of airspace managed by UTM within controlled airspace. They will do so by activating or deactivating airspace blocks within the control zone to either expand or limit the airspace assigned to UTM control. The ambition is to allow flexibility in accommodating short-term changes in crewed air traffic demands, such as in response to (unscheduled) priority flights or contingency situations, whilst maintaining segregation from uncrewed air traffic. Any UAS already flying in unavailable airspace should be requested to either exit it or land. To ensure that segregation can be achieved in an orderly manner, the guidance material proposes an anticipation time of two minutes and an advisory time prior to activation of the change to an airspace configuration of five times the anticipation time (e.g., ten minutes). The regulatory framework, however, does not provide concrete indications on how the proposed operational concept for DAR shall be implemented or which tools or interfaces.

In an effort to materialize and mature the DAR concept and regulatory framework, the AURA project developed a DAR Manager as an additional role within ATC. The DAR Manager is responsible for dynamically re-configuring UTM-managed airspace boundaries according to crewed and uncrewed air traffic demands, in a way that considers safety, air vehicle prioritization, balancing traffic demand and capacity, and fair and equitable access of all airspace users. This is done by using DAR to maximize the amount of airspace available to uncrewed flight operations in lower airspace when crewed air traffic density is low. Areas with higher densities in crewed air traffic, such as those in close proximity to the airport runway(s), can be permanently assigned to ATM, although the incorporation of corridors to transfer high-priority UAS from one side of the runway to another can be a possibility. The DAR Manager must also respond to emergency situations that affect airspace segregation and react to possible airspace violations of crewed aircraft or uncrewed vehicles quickly and efficiently.

When applied to the aerodrome control zone, the AURA concept of operations [20], which builds on the foundations of the concept defined in Section 2.4, proposes the idea of the aerodrome tower controller performing the DAR Manager role alongside their traditional ATC tasks. The assumption made within the AURA concept is that the high levels of UTM system automation could be used to provide support to the human controller in this role and, together with an integrated collaborative display, allow them to complete this task whilst maintaining a safe and expeditious flow of air traffic.

### 4.2.2 AURA Interface and Automation

To fulfill the DAR Manager role, the tower controller will be supported via a radar display utilizing decision-support tools to collaborate with a highly automated UTM system, inspired by the interface designs introduced in Chapter 3, using dynamic geofences as a means to achieve DAR. There is, however, a notable difference in operational usage of the interface. The results of the study by van Aken, Janisch, and Borst [77, 78] showed that controllers used geofences to actively separate UAS from crewed aircraft in the control zone. The AURA interface, however, specifically emphasizes segregating UTM and ATM operations, in line with the U-space regulation. This is because geofences as an airspace block, are not designed for *tactical* separation purposes.

By shifting the focus to segregation, geofences are used to support the more strategic reconfiguration of airspace managed by UTM. An active geofence blocks the UTM system from routing UAS into that area and requires any UAS already inside to exit it, subsequently allowing crewed aircraft to fly unhindered. For this to work, geofences need to overlap with airspace commonly traversed by crewed aircraft, such as the traffic circuit or final approach to landing. The same concept is also applied to open/close specific geofences defined as “UAS transfer corridors” which allow high-priority UAS to cross the runway approach areas near the airport.

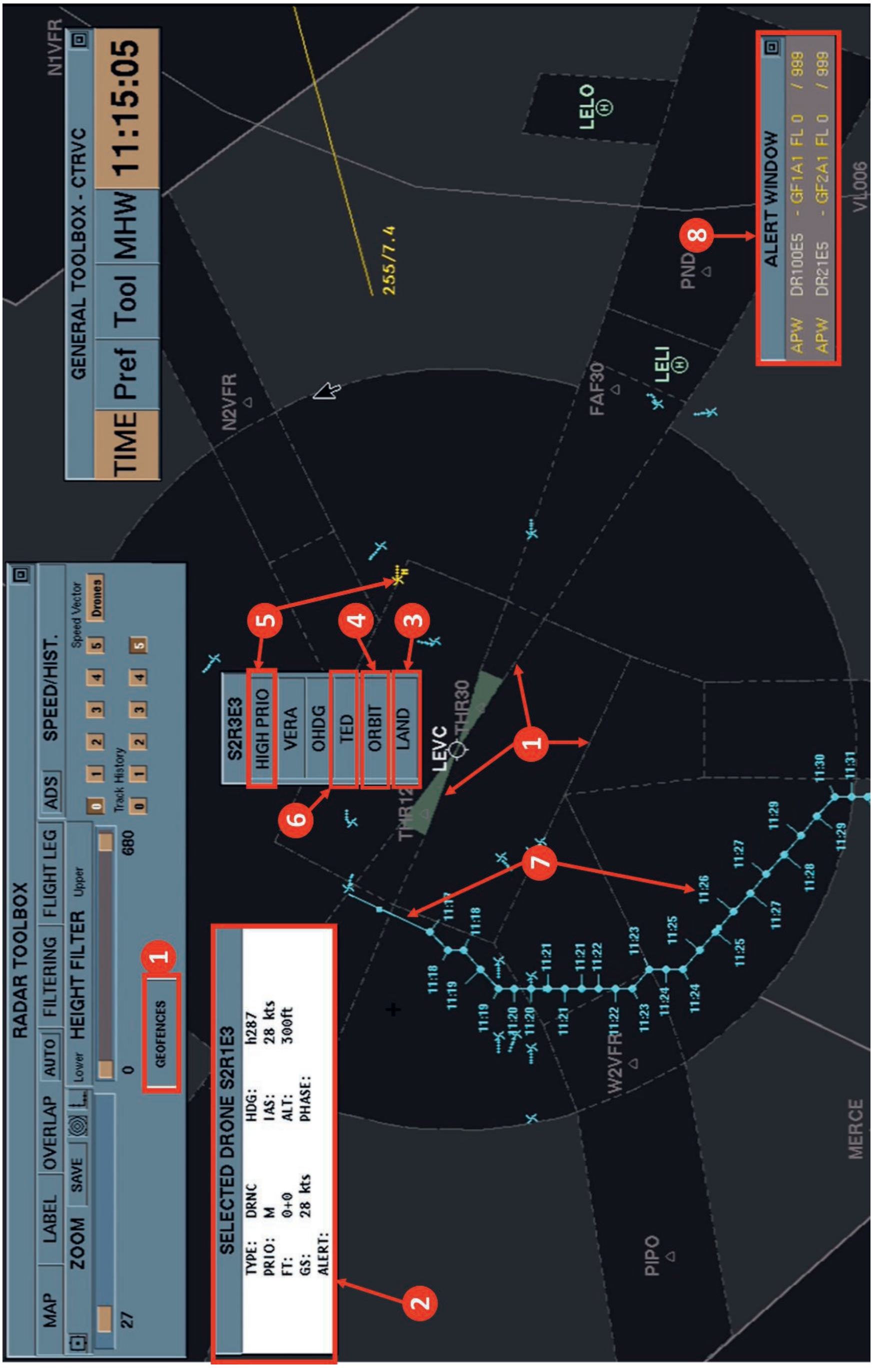
AURA also considered additional interface tools that allow tower controllers to override UTM traffic commands and thus implement specific instructions to individual UAS. The functionality of having more direct control over UAS is at odds, however, with the DAR concept proposed in the U-space regulation, which does not foresee direct controller intervention in UTM decisions. For the purpose of maintaining safety and efficiency of crewed air traffic flows, as well as reacting to unforeseen UAS traffic behavior, the possibility of allowing controllers more direct control over UAS was explored here.

The relevant AURA interface elements and their functions are summarized in the list below and shown in Figure 4.1:

① *Geofence indication*: (De-)activating geofence elements allows the DAR Manager to segregate UTM and ATM airspaces.

② *UAS flight label*: Depicts a UAS’s callsign, altitude, speed, priority, and mission parameters.

③ *UAS “land” command*: Instructs the selected UAS to descend and land immediately.



SELECTED DRONE S2R1E3

TYPE: DRNC
PRIO: M
FT: 0+0
GS: 28 kts
ALERT:
HDG: h287
IAS: 28 kts
ALT: 300ft
PHASE:

ALERT WINDOW

APW DR100E5 - GF1A1 FL 0 / 999
APW DR21E5 - GF2A1 FL 0 / 999

Figure 4.1: Overview of the integrated tower control and DAR Manager interface functionalities. Numbered elements are explained in-text.

④ *UAS "orbit" command*: Instructs the UAS to orbit or loiter around its current location.

⑤ *UAS priority indication*: Depicts the UAS priority (e.g., high priority in case of medical delivery) by highlighting it in a different color directly on the radar display.

⑥ *UAS rerouting button*: Issues a direct instruction to the UAS to change the initial route.

⑦ *UAS route indication*: Shows the planned route and estimated arrival time over subsequent waypoints.

⑧ *Alert window*: Alerts are shown for those UAS whose time to enter into ATC-controlled airspace is lower than two minutes, taking as reference its projected location based on the vehicle's current heading. It shows the geofence that could be infringed as well as the altitude of incursion.

The functioning of geofence elements is based on a grid-like structure, adjusted to assimilate to the most common flight routes of crewed aircraft within the control zone, as recommended in the U-space guidance material.

The use of color coding for emphasizing priority was chosen so that the DAR Manager had the possibility to identify at a glance those UAS which were performing priority missions or eligible for particular routes, such as crossing transfer corridors.

The "land", "orbit", and "rerouting" command elements have been included in this display following the recommendations of van Aken, Janisch, and Borst [77, 78], to allow controllers the possibility to directly interact with individual UAS if necessary.

## 4.3 HUMAN-IN-THE-LOOP EXPERIMENT

An exploratory study supported by a human-in-the-loop experiment with two licensed, but inactive, tower controllers was conducted to gather initial insight into potential control strategies to support the proposed new concept. Details on the conducted experiment are provided in the following subsections.

### 4.3.1 EXPERIMENT SETUP

The experiment scenario focused on flight operations within the control zone of Valencia Airport. This airport was selected for three reasons. First, because it is situated right between the city of Valencia to the northeast and a large industrial area to the southwest, requiring UAS delivery flights between the two areas to cross the airport premises. Second, the runway orientation requires landing or departing aircraft to overfly the city, thus creating potential areas of conflict with urban UAS missions. Third, the smaller airport size and lower traffic complexity due to single-runway operations made it easier to simulate with a limited number of participants.

Crewed commercial aircraft were simulated to follow published standard instrument arrival and departure routes of Valencia airport. Crewed aircraft flying under Visual Flight Rules (VFR) followed the established visual flight corridors. Finally, emergency helicopter operations were simulated to fly to their designated landing site, such as hospitals or accident locations, in the most direct manner. The number of crewed aircraft flight operations was based on a traffic sample of a day with a high number of flights occurring in the summer of 2019.

UAS flight operations and routes were developed from the ground up for this experiment, given that no such flights yet exist within the city of Valencia. Routes were designed according to potential future UAS missions and built around a hypothetical network of vertiports (aerodromes exclusive to the operation of aircraft capable of vertical take-off and landing [79]) at key locations within the city:

- Surveillance/maintenance missions of the train tracks in the city of Valencia.
- Surveillance missions on the main highways of Valencia.
- Surveillance missions of Valencia's beaches.
- Parcel delivery missions to and from warehouses in the vicinity of Valencia.
- Medical delivery missions between hospitals of Valencia.

In order to accommodate a high number of UAS missions, most of the airspace under 500 feet above ground level (known as Very-Low Level (VLL) airspace) was segregated to allow UAS flight operations, the only exception being the airspace in close proximity to the runway. The existing design of the Valencia control zone was subdivided into additional airspace blocks which could be dynamically assigned to either ATC or UTM control by the tower controller (who is acting as DAR Manager). These blocks were tailored towards safeguarding areas within the control zone commonly traversed by crewed aircraft, such as the extended runway centerline, final approach area, VFR corridors and hospital heliports (landing areas designated to crewed helicopter flights). Two corridors were incorporated just upwind and downwind of the runway, which could be opened to allow high-priority UAS missions to pass more directly, using the geofence activation tool of the interface. An overview of the geofence layout is provided in Figure 4.2.

### 4.3.2 Experiment Platform

The experiment was conducted at CRIDA premises in Madrid, Spain, using a version of the "EUROCONTROL ESCAPE Light" simulation platform, which was tailored to meet the needs of this experiment. The platform consisted of several control positions; one for tower control, one for approach control, one for the pseudo-pilot as well as one supervisory position used for the UAS fleet supervisor, for launching the experiment run, and for monitoring the UTM simulation module. Each platform position consisted of two non-tactile screens for displaying the simulation environment and interface, a keyboard and mouse for interacting with the screen and manipulating the interface, and a headset for communicating with other test participants.

An overview of the simulation platform setup is provided for clarity in Figure 4.3. Bounding boxes indicate the control screens of the pseudo-pilot ①, UAS fleet supervisor ②, approach control ③ and integrated tower control and DAR Manager ④ positions.

From a technical perspective, the simulation platform was updated to incorporate an integrated Human-Machine Interface (HMI) providing the necessary DAR Manager functions presented in Section 4.2.2 and in Figure 4.1. Particular care was taken to develop

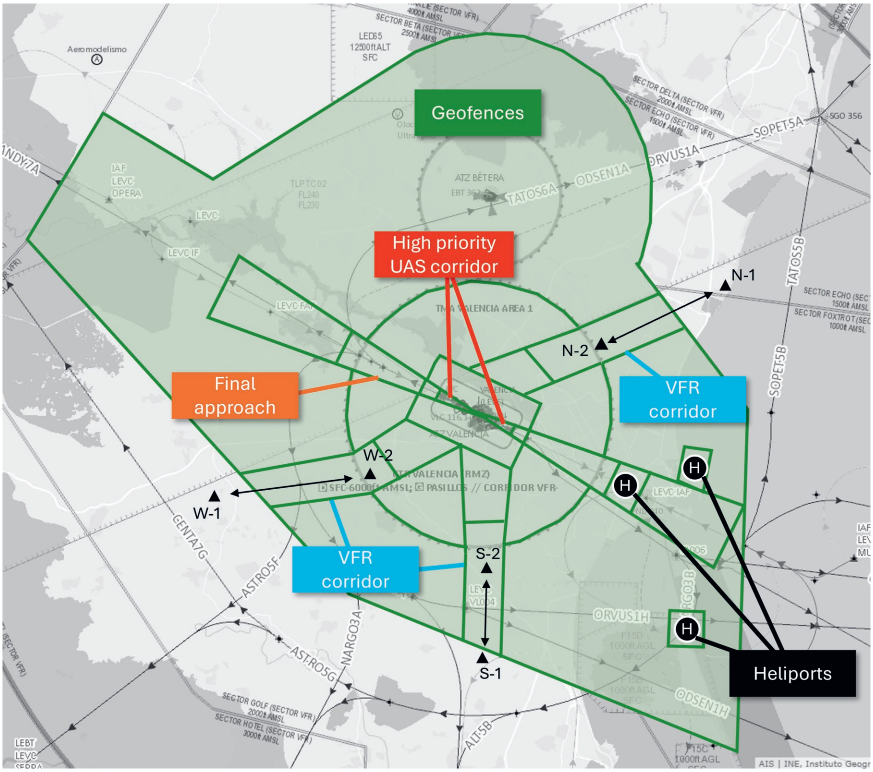


Figure 4.2: Schematic representation of the geofence layout used in the simulation experiment, superimposed on a visual approach chart of Valencia airport.

Figure 4.3: Technical set-up of the simulation experiment.

the experiment which simulates the experience of dealing with human-supervised UAS missions, which are themselves guided by an automated UTM system. Complex UAS missions within UTM airspace are expected to rely on UAS pilots overseeing multiple, highly automated UAS at once, rather than having a single pilot per vehicle [20]. A UAS fleet supervisor position was developed for the experiment where a pseudo-pilot could manage multiple UAS routes simultaneously. A UTM simulation module was also incorporated into the simulator to automatically re-route UAS traffic based on changes to the airspace configuration and ATC commands, and as such simulate the automated UTM system overseeing all UAS flights, including those managed by the UAS fleet supervisor. An A* (A-star) search algorithm was used for this purpose, based on the UAS simulation concept developed by van Aken, Janisch, and Borst [77].

### 4.3.3 Use Cases

In this study, two use cases for traffic situations that warrant the initiation of an airspace reconfiguration by the DAR Manager were explored:

**Use case 1) Reconfigure in favor of ATM to accommodate low-flying crewed aircraft**: This use case in particular serves to accommodate VFR aircraft entering or departing the aerodrome traffic circuit and low-flying emergency helicopter missions.

**Use case 2) Reconfigure in favor of UTM to accommodate high-priority UAS missions**: Following the recommendations of van Aken, Janisch and Borst [78], two UAS corridor areas for crossing upwind and downwind of the runway were incorporated into the airspace design. These areas could be opened to UTM traffic during situations with low crewed air traffic, to allow high-priority UAS missions to cross from one side of the airport to another on a more direct route.

### 4.3.4 Experiment Tasks

The focus of the experiment lay in the tasks of the tower controller. With regard to crewed aircraft, the tower controller was tasked with managing airport arrivals and departures of commercial Instrument Flight Rule, Visual Flight Rule, and Helicopter Emergency Medical Service flights, by issuing verbal clearances. An emphasis was to be placed on providing a safe and expeditious flow of crewed air traffic within the control zone. This included issuing separation instructions to other crewed aircraft, should the need arise (e.g., for conflicts within the arrival sequence among commercial and VFR traffic). Handovers of crewed aircraft leaving or entering the control zone were coordinated verbally with the participant performing approach control. No ground controller was available for these experiments, so handovers were performed automatically within the simulation; Departing aircraft would appear on the holding point at their scheduled departure time, whereas arriving aircraft would disappear from the runway once they had touched down.

Additionally, the tower controller would perform the role of the DAR Manager, which required them to segregate airspace for crewed aircraft from those areas where uncrewed aircraft were flying, in coordination with the automated UTM system overseeing them. In order to assume this role, the participant would be able to make use of all of the information acquisition and control elements about UAS traffic provided to them on the display.

Should the need arise, the tower controller had the possibility to change the configuration of the airspace in response to fluctuations in crewed aircraft demand and flight routes, as well as to assist crewed aircraft operating in Very Low-Level airspace or landing at uncontrolled heliports. Configuration changes, however, would need to be performed in such a way that segregation of both environments was always assured. The controller would achieve segregation by activating the dynamic airspace management function of the HMI and selecting the airspace blocks to be either assigned to or removed from UTM control. The UTM system module would then automatically reroute UAS in response to the configuration changes. Participants were not given any indication of how much lead time would be required before performing DAR, in order to gather information on their own preferences in timing. Furthermore, tower control participants were given the liberty of deciding if and when to reconfigure the airspace and open dedicated UAS transfer corridors.

If segregation assurance was not possible, the controller was given the choice to resolve any resulting conflicts by providing traffic deconfliction instructions to either crewed aircraft via verbal communication with the pseudo-pilot or UAS via the collaborative interface. In the latter case, the options presented to the participant were “rerouting”, the issuing of “heading” or “loitering” instructions, as well as the means to instruct a UAS to “land” (essentially terminating the flight). Should the need to resolve conflicts between crewed and uncrewed aircraft arise, the controller was instructed to prioritize any crewed aircraft under their control over UAS.

The UAS fleet supervisor would monitor the conduct of high-priority UAS missions in response to UTM and tower controller traffic management decisions. They would act as the UAS pilot in command, reroute UAS through open transfer corridors, and react in case either actor implements traffic actions that exceed UAS mission limitations. The concept, however, did not provide any means for verbal communication between the UAS fleet supervisor and the tower controller, under the assumption that the coordinating instance between both entities is the UTM system.

The controller was also instructed to conduct a secondary control task alongside their primary tasks, which revolved around putting a series of flight strips corresponding to the flights simulated in the experiment into the correct sequential order, as well as filling out the correct time of arrival/departure and aircraft type. This secondary task was used to incentivize the participant to look away from the radar screen and simulate the visual scanning procedure that tower controllers perform when identifying an aircraft.

All other experiment participant roles served to immerse the tower control participant in the simulation environment by implementing the control actions requested by the tower controller and increasing the level of realism by doing so. Table 4.1 shows the main tasks of each actor involved in the simulations.

### 4.3.5 SCENARIOS

A total of four simulation scenarios were developed. Each scenario incorporated point-to-point UAS surveillance and delivery missions, high-priority medical delivery UAS missions within UTM-managed airspace, and a mix of commercial flights, VFR training flights, and high-priority medical helicopter flights in crewed aviation. Table 4.2 shows the main characteristics of each traffic sample, including commercial and VFR traffic, UAS operations, and Helicopter Emergency Medical Service (HEMS) flights.

The scenarios themselves varied in terms of levels of complexity and task load. Scenarios EXE1 and EXE4 had a more even distribution of crewed flight movements throughout

Table 4.1: Overview of experiment tasks per participating actor.

| **Actor** | **Role** |
|---|---|
| Tower Controller[a] | Coordinate arrivals and departures<br>Manage UAS transfer corridors<br>Segregate UAS flights |
| Approach Controller | Prepare arriving traffic |
| Pseudo-pilot | Control all crewed aircraft |
| UAS Fleet Supervisor | UAS rerouting for corridor crossings |
| UTM System | UAS rerouting around geofences |

[a] Evaluated in study.

Table 4.2: Overview of experiment traffic samples.

| **Traffic Sample** ID | **Number of Flights Simulated** | | | | **Duration** |
|---|---|---|---|---|---|
| | Crewed Aircraft | | | | |
| | *Commercial* | *VFR* | *HEMS* | *UAS* | |
| EXE1 | 13 | 5 | 2 | 184 | 1.25h |
| EXE2 | 19 | 5 | 2 | 184 | 1.25h |
| EXE3 | 27 | 5 | 2 | 186 | 1.25h |
| EXE4 | 21 | 5 | 2 | 184 | 1.25h |

their run time. Scenarios EXE2 and EXE3 had higher crewed traffic peaks with higher numbers of movements in the case of EXE3. For this reason, Scenarios EXE1 and EXE4 were considered low task load exercises and Scenarios EXE2 and EXE3 were considered high task load exercises. Moreover, the high ratio of UAS to crewed aircraft added additional complexity to the scenarios, as depicted in Figure 4.4.

### 4.3.6 PROCEDURES

Two licensed tower controllers participated as the primary test subjects and alternated their roles as tower controller and approach controller. Additionally, two experienced pilot participants assumed the roles of pseudo-pilot for crewed aircraft and UAS fleet manager during the experiments. The experiment was conducted over a five-day period. The first day was used to introduce the participants to the proposed concept through a series of short training sessions. The rest of the days were focused purely on performing simulations. The order of experiment scenarios was randomized to mitigate learning effects. After conducting an experiment run, participants were asked to fill out a post-experiment questionnaire in private. Afterwards, a general debriefing session was held to collect qualitative data within a group session.

### 4.3.7 DATA RECORDING AND PROCESSING

During each experiment run a large set of system data as well as video and audio data was collected. System data was recovered via data logs provided by the simulation tool, and video and audio recordings were obtained through recording software installed on the tower control position. Data logs were used to analyze control performance, and the video and audio recordings were used to support the assessment of control strategies.

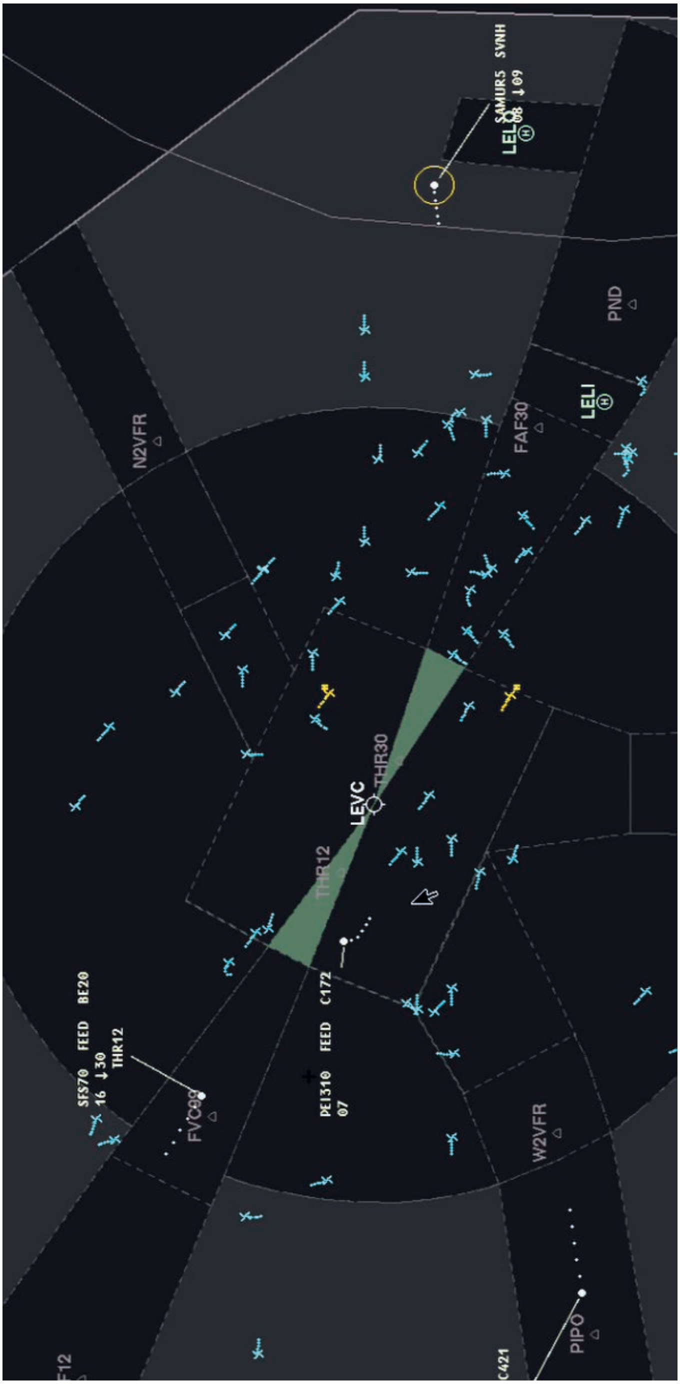


Figure 4.4: Snapshot of UAS and crewed air traffic movements during peak traffic load situations.

## 4.4 RESULTS

In this section experimental results are discussed. An in-depth statistical analysis could not be performed, given that only two tower control participants were available. Instead, the analysis focuses on the control strategies observed during the experiment to identify the desired means of interacting with the UTM system.

### 4.4.1 OBSERVED CONTROL STRATEGIES

Participants actively made use of UAS-specific commands, frequently in combination with geofence activations. For instance, it was observed during the first runs that controllers tended to accompany closures of UAS transfer corridors with orbit instructions or manually rerouting the UAS that were about to enter them. Controllers mentioned that they preferred to intervene and issue direct instructions to the UAS to avoid the UTM system unnecessarily replanning a longer route around a corridor that they knew would only be closed for a short period of time. The UAS fleet supervisor understood that this command meant that UAS would receive further clearance to continue crossing the corridor at a later time, and thus did not intervene.

In some cases, the “orbit” command was used to hold UAS in a specific area to allow crewed aircraft to pass, without having to activate the transfer corridor geofences as an additional step. Controllers, however, shifted to a more passive activate and forget approach to corridors and other geofences in later runs. This control strategy was also utilized more during crewed traffic peaks. One participant mentioned that it was easy to forget about the existence of UAS when the traffic load for crewed aircraft was higher, so they preferred to simply close an airspace or corridor in advance of arriving traffic without paying special attention to the UAS flying in proximity.

UAS-specific commands were still used, albeit more to force UAS to expedite reroutes out of activated geofences. In such situations, the controllers considered that the lead time required to issue UAS-specific commands in real life should be from a few seconds up to one minute, depending on the situation and closing speed of a potential conflict.

These observations can be summarized through defining two types of control strategies.

- **Active control strategy**: ATCOs manually intervene in UAS routings to influence their flight paths using the tools provided in the interface, rather than rely on DAR. UAS would often be instructed to orbit or be rerouted by the ATCO following a geofence activation. This approach allowed them more control over how UAS traffic behaved in proximity to the airport or in response to short-term DAR. This strategy was observed frequently during times of low crewed traffic load, in support of transfer corridor activations, as well as during situations where the UTM system would fail to reroute UAS out of an active geofence around helicopter landing sites. Figure 4.5 shows the application of this strategy, where the tower controller manually reroutes a UAS, indicated by a bright yellow line ①, following a failure of the UAS to clear an active geofence, as indicated by the red UAS icon ②, ahead of a landing helicopter (“SAMUR10”) ③. This strategy is invasive to UTM decision-making and at odds with the proposed DAR concept, which assumes the segregation of ATM and UTM domains and, subsequently, air traffic management responsibilities.

- **Passive control strategy**: ATCOs only use geofences as a means to restrict UAS movements, trusting that the UTM system would make the necessary traffic actions around segregated airspace. This activate and forget approach requires less supervision of UAS flights in the short term but at the expense of greater foresight into potential future conflicts with departing and arriving crewed aircraft. In this strategy, ATCOs used UAS route and timing indications on their display to estimate when to activate a geofence prior to an aircraft crossing. This strategy was used more frequently during times of high crewed traffic load, in preparation for transfer corridor activations or geofencing areas around helicopter landing sites prior to their arrival. Although conforming to the proposed DAR concept, participants were actively supervising UAS flights to identify potential future conflicts with crewed aircraft, even if the end goal was to achieve segregation.

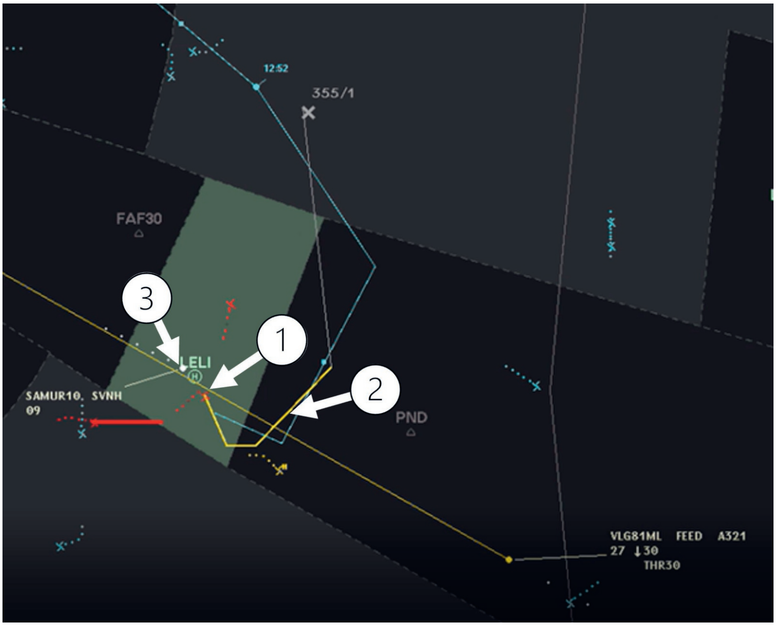


Figure 4.5: Application of the active control strategy applied by a tower controller through manually rerouting a UAS to clear an active geofence ahead of a landing helicopter.

When asked about their preference over the two types of control strategy, participants mentioned that they felt more comfortable with the passive control strategy, given that it requires the least amount of effort from the ATCO.

### 4.4.2 Use of Dynamic Airspace Reconfiguration

Controllers exhibited a very scarce use of DAR throughout the experiment, as most of the predefined geofence elements were not activated at all. In general, a permanently closed geofence covering the runway and airport area was established. The transfer corridor geofences situated just upwind of the active runway as well as that covering the final approach area were used the most often. The geofences surrounding heliports were also frequently used to support crewed helicopter arrivals.

The reason for this control behavior was that participants did not consider it necessary to activate more geofences. And this was because UAS operating on VLL airspace and crewed traffic were simulated to be already properly segregated in altitude. Even geofences within the VFR traffic circuit or along a helicopter flight route were not used, given that crewed air traffic was still flying slightly above VLL airspace in those areas.

Regarding the use of corridors, participants preferred to allow them to be open to all high-priority UAS as standard, and only be closed when crewed aircraft were approaching. This was done to facilitate high-priority UAS the most direct routing to their destination. Given the generally high numbers of UAS flights in the simulations, corridor crossings of high-priority flights occurred every few minutes.

### 4.4.3 USE OF UAS-SPECIFIC COMMANDS

The “orbit” command was issued extensively on UAS aiming to cross the extended runway center line, usually whenever there were crewed aircraft arriving and departing.

The UAS “reroute” command was also used extensively, as it allowed ATCOs to influence UAS routing to cross the final approach area directly. Participants mentioned that in some cases it was more intuitive to reroute a UAS directly than activate a geofence and wait to see what the UTM system would do. A downside of this approach is that on several occasions, controllers were observed to micromanage specific UAS missions using these interface functionalities, essentially overriding UTM traffic commands.

Surprisingly, the “land” function, which essentially terminates the flight, was never used, not even in emergency situations.

### 4.4.4 INTERFACE DESIGN

Participants were asked to rate the interface functionalities in terms of their utility on a four-point Likert scale of “useless” (1) to “very useful” (4), see Figure 4.6. The interface tools for airspace reconfigurations and individual UAS commands received the highest utility ratings, in particular, the UAS rerouting functionality, the displayed UAS route and estimated waypoint overflight indications and geofence activity indications. The UAS priority indication was considered relevant, as it assisted the participants in understanding which UAS were eligible to cross the transfer corridors. The “orbit” command was considered useful, as it was used frequently during the experiments in combination with corridor closures. The “land” command scored low on this list, as it was never used during the scenarios. The UAS flight label information and alert window scored low, as they were not given any attention during the experiments.

Participants stated that, although having these tools available, they felt that they had not carried out their tasks in the most effective way. It was also commented that the tools available to the ATCO would need to be limited to only the bare minimum necessary, to reduce the incentive to involve themselves in the UTM decision-making process. Controllers were not fully comfortable with the minimum lead times for implementing DAR changes and commented that they would have preferred to have a better understanding of the impact of DAR changes on the fulfillment of the UAS missions or on the overall UTM system efficiency.

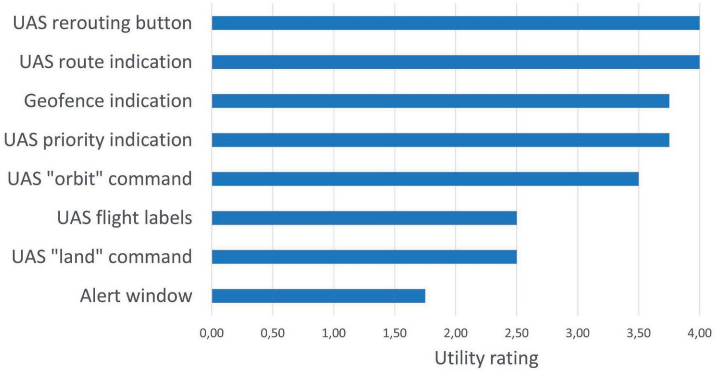


Figure 4.6: Utility ratings of interface functionalities.

### 4.4.5 LIMITATIONS

The most important limitation to the realism of the simulations was the lack of an "out of tower" view. This forced participants to focus more on their radar display than they would in a real environment. It was also not possible to simulate aircraft ground movements, in particular regarding the departure line-up of aircraft waiting at the holding point. To make up for this, a departure management tool was incorporated to provide some situation awareness of the upcoming departures. Finally, the low number of runs and having only two participants mean that all findings need to be considered within the current context and not generalized.

## 4.5 DISCUSSION

The results obtained provide insight into the operational preferences of tower controllers concerning the proposed DAR concept and interface functionalities, as well as its limitations when applied to current air traffic control practices. Although only two controllers participated, some important observations were made which could guide further research and mature the DAR concept.

The observed active control strategy appears to be in line with the observations of van Aken, Janisch, and Borst [77, 78] in their initial concept study for a collaborative interface between a UTM system and tower control, as presented in Chapter 3. In their study with nine licensed air traffic controllers, participants expressed their wish to actively influence UTM routing decisions to resolve conflicts between UAS and crewed aircraft, as opposed to applying the proposed method of using geofences to segregate UTM airspace in a way that would inhibit any kind of conflict altogether. A similar outcome was observed in a follow-up study by Zou and Borst [80], in which a majority of the twelve ATCO and twelve UAS expert participants preferred active control over UAS rather than passive control via geofences. This behavior was also observed in the current study, as individual UAS commands were used in favor of geofences to resolve potential conflicts in a predictable manner. UTM traffic actions were not given much thought, or overridden entirely.

In contrast, the passive control strategy was generally preferred by ATCO participants during situations with high crewed traffic load, as it simplified the interaction with UTM at the expense of a less predictable UAS traffic behavior in response to airspace reconfigurations. This strategy, however, required controllers to pay much greater attention to the *timing* of DAR actions such as closing UAS transfer corridors or airspace around helicopter landing sites in advance of approaching aircraft. This strategy, denoted by participants as activate and forget, could still lead to conflicts of UAS with crewed aircraft, however. In situations where the ATCO is dealing with a high crewed traffic load, it was easy to forget about having to segregate airspace around critical areas for UAS, which then prompted the ATCOs to intervene to reroute UAS out of the area in time for the crewed aircraft to arrive, the active control strategy.

From these observations alone it is difficult to rule out one control strategy over another, as both types appear to have their merits, depending on the situation at hand. Participants mentioned that they would prefer the passive control strategy to be used as standard, which would also adhere to the segregation concept for DAR as proposed by the AURA project. However, this strategy did not suffice when short-term traffic actions needed to be performed, such as the need to clear UAS from a segregated area on short notice ahead of an unplanned crewed aircraft arrival. For such situations, the active control strategy, which allows the ATCO direct intervention in UAS routings and overrides UTM traffic decisions, seems to provide the necessary fidelity for the controller to assist in avoiding collisions.

Surprisingly, the use of DAR to segregate airspace was hardly used at all in most of the control zone. As UAS flights were conducted in Very Low-Level (VLL) airspace, that is, airspace up to 120 meters above ground level, participants did not find it necessary to reconfigure the airspace, as long as crewed aircraft were flying above VLL airspace limits and were thus segregated in altitude. The reconfiguration of the airspace was predominantly limited to areas in close proximity to the runway, where arriving and departing aircraft would descend below VLL airspace limits. Hence, airspace design has a substantial impact on how the DAR concept could be used, and which control strategy could be applied.

Both participants proposed, for example, that the airspace could be configured in favor of UAS flights during off-peak hours, allowing them to operate much closer to the airport premises. This airspace could then be reassigned to ATM as part of a procedural reconfiguration strategy for the airport, as soon as the scheduled traffic load increases. This strategic use of DAR could alleviate controllers from having to decide when to activate and deactivate geofences in proximity to the airport, thus allowing them to focus on identifying potential collisions with off-nominal air traffic, such as emergency helicopters. In such cases, the passive control strategy could be applied as standard, assuming that the DAR Manager has the capacity to supervise both crewed and UTM flight operations and predict potential points of conflict or segregation infringements. The active control strategy could then be used as a last means of collision avoidance, by influencing UAS reactions to short-term airspace reconfigurations.

These findings are at odds, however, with the idea of full segregation of UTM and ATM traffic management actions. Even if the controller would be denied any kind of direct intervention on UAS routings, the act of performing DAR requires some sort of conflict detection capability between UAS and crewed aircraft. This was particularly evident during the runs including crewed air traffic which did not adhere to predictable flight paths, such as helicopters. These situations required the ATCO to identify potential conflicts in real time and apply DAR on short notice. In several cases, these DAR changes were accompanied by manual intervention in UAS routings to avoid conflicts.

The observed control strategies also raise the question of responsibility when DAR is being performed. In the experiment, the initial division of responsibilities was such that ATCOs were in charge of coordinating crewed air traffic and acting as DAR Manager, UAS were managed by the UTM module and supervised by the UAS fleet supervisor. However, when applying the active control strategy, the ATCO intervened in UTM routing decisions on UAS traffic.

To a certain degree, this type of behavior can be attributed to the limitations and setup of the current study. For instance, the UTM simulation module would take a few seconds before calculating a new route and implementing traffic management actions on UAS in response to DAR changes. The ATCO participants were much quicker in reacting to conflicts caused by short-term DAR changes. The ATCOs initiated the DAR process as they had a clear understanding of the aim they were trying to achieve when reconfiguring the airspace. Thus, the incentive was greater to simply manually intervene in UAS routings to achieve a predictable outcome to the conflict situation, rather than waiting for the UTM system to respond, possibly in a manner that contradicts the expected behavior of UAS from the ATCO's point of view (as also observed in the study of Chapter 3).

This effect is exacerbated even further when considering that only part of the tower control environment was simulated. In a fully immersive simulation, the tower controller would have also had to scan out of the tower to visually identify aircraft on approach. This makes up most of their working time, meaning that the time to monitor and track UAS on the radar display is greatly reduced. The secondary task performed by the participants was meant to make up for the missing head-up time to a certain extent, but it was still observed that the majority of their time was spent scanning the radar display. The availability of UAS traffic management tools in their radar display could have further incentivized their intervention in UTM system decisions, given that it was very easy to reroute UAS using just a few clicks. This may have influenced the active control strategy to such a degree that UAS traffic interventions using the display functionality were preferred to issuing voice commands to crewed aircraft when resolving conflicts, as was observed in the experiment.

Bearing these limitations in mind, the observed active control strategy indicates a tendency for the ATCO to want to manage UTM traffic in a similar manner as they would manage crewed air traffic. This behavior could be linked to the current role of ATCOs as the single manager of the airspace they are assigned to, and therefore wanting to make use of the tools provided to them to maintain a safe and expeditious flow of air traffic within their airspace, even if this means going beyond their assigned area of responsibility. Achieving full segregation of ATM and UTM domains would require not only operational segregation of crewed aircraft and UAS, but also a clear limitation of ATCO responsibilities from airspace which has no longer been assigned to them through DAR. Dynamic segregation concepts are also being explored in the ATM domain concerning civil-military coordination, particularly through SESAR projects such as PJ07 [81, 82] and PJ09 [83, 84]. These projects focused on the flexible use of airspace, enabling dynamic airspace management throughout all ATM operations. Introducing a similar solution to DAR in the UTM domain, civil-military coordination integrates dynamic mobile areas to optimize the organization and management of airspace. However, the design of configurations requires careful attention to mitigate risks associated with a high number of configurations, a fact to take into account also regarding DAR. Future studies on the implementation of DAR for UTM and ATM segregation could benefit from the lessons learned in these concepts.

Full segregation would also require the removal of all UAS command tools from the ATCO interface entirely, other than the DAR tool itself, thus severely limiting the means for the DAR Manager role to interact with UTM. The ATCO would then only have the means to intervene in tactical conflicts of crewed aircraft with UAS (or airspace segregated for UTM flight operations) by issuing instructions to crewed aircraft to avoid collisions. Such traffic control situations were, however, already tested in the experiment of van Aken, Janisch, and Borst [78], in which ATCOs expressed their wish for further means of interacting with UAS other than geofences. This approach would build on the active control strategy by further developing the additional UAS management tools provided in the ATCO display. This concept, however, would require the definition of separation standards for UAS and crewed aircraft, as well as flight rules for UAS. The idea of having multiple traffic management actors in the same airspace is explored by the SESAR Flight Centric ATC (FCA) concept [85], where a controller is no longer in charge of managing the entire traffic within a given sector. In FCA, multiple ATCOs are responsible for a specific number of aircraft within the same airspace. The FCA concept was proven operationally feasible through several real-time simulations, especially with low to medium traffic demands. However, ATCOs requested higher levels of automation in supporting tools for conflict detection and resolution, as well as clear procedures for coordination and communication between controllers in the FCA area [86]. These procedures should determine which of the ATCOs involved in a potential conflict is in charge of the resolution of the conflict. Therefore, addressing challenges associated with human-automation teaming will be one of the key aspects to be solved in scenarios with full integration of ATM and UTM domains, requiring more insights into human performance impacts due to shifts in teamwork dynamics, human-automation communication (e.g., automation transparency) and trust in automation [53].

The concept which was explored in this study is essentially a hybrid version of both, relying on segregation for managing the airspace during nominal situations but overriding segregation to allow the ATCO to intervene in UTM decisions on short notice. The tools provided to the ATCO participants helped them to understand their preferred control strategies regarding active vs. passive management of the airspace, but also failed to address the shortcomings of either option, given the current maturity level of the concept. Future studies should therefore explore the implications of separation vs. segregation in further depth, in particular with regard to operational procedures, responsibilities, and assignment of roles within the collaborative environment. An increased focus should also be placed on how to manage transitions between segregation and separation modes in the interface. Only once the implications of either option on the work domain of the ATCO have been sufficiently explored, tested, and understood would it make sense to conclude on a potential candidate for implementation, and whether or not a hybrid option is still the best approach.

## 4.6 Conclusion

The aim of this preliminary study was to explore the tactical control implications of incorporating dynamically segregated, UTM system-controlled airspace into the existing air traffic management domain. The starting point for this study was the Dynamic Airspace Reconfiguration (DAR) concept for dynamically assigning predefined airspace blocks within the control zone of an airport to either ATM or UTM control in response to changing crewed and uncrewed air traffic situations. An exploratory human-in-the-loop experiment with two licensed tower controllers was conducted to test whether this task could be conducted by tower controllers as an additional task within their area of responsibility and which control strategies would be preferred by the human operators.

The experiment provided insights into the control preferences of the controllers regarding this new environment and highlighted limitations regarding the proposed DAR concept and interface functionalities. Two types of control strategy were observed: An active control strategy in which participants influenced UTM routing decisions directly rather than relying solely on geofences for airspace segregation was a common tactic to support short-term conflict avoidance between UAS and crewed aircraft. However, a passive control strategy was favored in busy crewed traffic situations as it simplified interactions with UTM, albeit with less predictable UAS traffic behavior.

The study also highlighted the impact of airspace design on DAR implementation and raised questions about the responsibility and division of tasks during DAR, and whether full segregation or integration of ATM and UTM domains should be preferred. All are qualitative, however, because of the small sample size. Future research should flesh out the proposed control strategies in a more comprehensive and dedicated study, in order to determine the most suitable concept for facilitating collaborative ATM and UTM management.

# 5

# LIMITS OF THE CONCEPT

*In this chapter the limitations of the collaborative ATC-UTM interface developed in Chapter 3 of this thesis for tactical dynamic segregation of UAS using geofences will be investigated. The contents of this chapter reflect an adapted version of the following paper:*

| | |
|---|---|
| **Paper Title** | 🗎 *Exploring the Limits of Uncrewed and Crewed Air Traffic Segregation by Tower Controllers* |
| **Authors** | D. Janisch, S. Wen, Y. Zou, and C. Borst |
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*As concepts for incorporating Uncrewed Aircraft Systems (UAS) into controlled airspace are being developed, the need for automated UAS Traffic Management (UTM) systems to guide UAS and maintain safety is becoming more apparent. A major point of concern for the implementation of UTM is how such systems could coexist alongside the human-centric air traffic management system that is already in place. The European Union's U-space concept proposes the use of dynamic segregation of airspace reserved for UAS within the control zone. A simulation experiment with ten Air Traffic Controller (ATCO) volunteers was conducted to gather insights into the feasibility of aerodrome tower controllers performing the dynamic segregation task. An interface prototype that supports dynamic geofencing and low-level UAS control was developed for this purpose. The proposed interface design helped ATCOs detect potential conflicts between UAS and crewed aircraft. However, they were not always able to adequately resolve them, which resulted in several losses of separation. It appears that the limitations of the dynamic segregation concept do not fit well with typical air traffic control strategies used by ATCOs. To substantiate the findings, future research should investigate how to overcome the limitations of dynamic segregation to resolve tactical conflicts by revising ATCO control strategies, reevaluating their role in dynamic segregation, as well as considering the definition of flight rules and separation minima for UAS.*

## 5.1 INTRODUCTION

CONCEPTS for safely incorporating Uncrewed Aircraft System (UAS) flights into controlled and uncontrolled airspace are being developed around the globe. Initial regulations concerning the certification of UAS [87] and operational prerequisites for UAS operators [17] are being implemented. However, as the demand in UAS flights with ever-increasing range and autonomy increases, the need for UAS Traffic Management (UTM) systems has become apparent. These systems provide services to support UAS operators in conducting safe and efficient flight operations, including traffic management to avoid conflicts between individual UAS as well as between UAS and crewed aircraft. In this regard, UTM can be likened to the current Air Traffic Management (ATM) system, since it tries to achieve many of the same underlying goals, as shown in a previous assessment [78] (Chapter 3 of this thesis). Examples of concepts for UTM systems include the European Union's U-space [16, 19] and the United States' [12] and Australia's [38] respective UTM initiatives. This research focuses particularly on addressing one of the main human-performance challenges of UTM, namely how such systems can coexist with ATM.

Current UTM concepts rely on segregated airspace reserved only for UAS, to avoid issues in compatibility with the existing ATM ecosystem. According to the International Civil Aviation Organization (ICAO), the term 'segregated airspace' refers to an "*airspace of specified dimensions allocated for exclusive use to a specific user(s)*" [88, p. 4], essentially blocking out any unauthorized users during the time frame that the segregated airspace is active. Using a static segregation of airspace reserved for UAS flights, UTM can be implemented separately from the existing ATM environment. However, static segregation itself becomes a liability as soon as a legitimate need for the use of segregated airspace by crewed aircraft arises. This is particularly relevant when implemented in an already capacity-constrained environment, such as the control zone of towered aerodromes.

Previous research evaluated the utility of providing a collaborative ATM-UTM interface with dynamic airspace segregation tools for tower control ATCOs [78]. The initial assumption was that they would be suited to perform this task given their role as the main tactical airspace manager. However, experiment results raised doubts about the utility of assigning an ATCO to perform dynamic segregation to resolve tactical conflicts between UAS and crewed aircraft, as highlighted in the next section. The experiment presented in this chapter was developed to explore the limits of the concept and also to substantiate the observations of Chapter 4 using a larger number of participants.

## 5.2 Challenges of Dynamic Segregation of UAS and Crewed Air Traffic

Using a Work Domain Analysis (WDA) of the dynamic segregation concept, Chapter 3 identified information and control needs of aerodrome tower controllers to help them, respectively, to understand and place restrictions on UAS traffic in their airspace [77], and formulated interface design requirements to support them [78]. ATCO participants were tasked to perform a series of simulations where they could use a radar-like control display to restrict UAS flights within a control zone using geofences (volumes of segregated airspace which an ATCO could dynamically activate or deactivate using the interface). It was the task of the UTM system to reroute UAS flights around or instruct any UAS captured within geofences to exit them. ATCO participants were instructed to use these tools to maintain safety within the control zone. Results showed that, rather than simply blocking airspace, participants used geofences as tools to influence individual UAS flight routings, similar to how they would issue instructions to crewed aircraft.

These findings prompted a follow-up experiment to investigate the control strategies of air traffic controllers whilst collaborating with UTM automation, which was presented in Chapter 4. The experiment was conducted under the umbrella of the PJ34 AURA project [89], in which tower control participants were tasked with performing their normal air traffic control tasks whilst applying Dynamic Airspace Reconfiguration (DAR). DAR is part of the European Union’s U-space concept and is outlined in the Commission Implementing Regulation 2021/664 [15] and accompanying guidance material [40]. Using DAR, air traffic control units can dynamically adjust the boundaries of U-space airspace to impose limits on UAS air traffic, similar to the geofencing concept of the first experiment in Chapter 3. UAS-specific commands were incorporated into the interface, allowing participants to influence UAS routes directly if necessary. A post-experiment evaluation identified *active* and *passive* control strategies for DAR. In the active control strategy, participants influenced UAS traffic directly using UAS-specific commands to support short-term conflict avoidance between UAS and crewed aircraft. In the a passive control strategy, participants focused on using geofences to segregate a large portion of the airspace was favored in situations with a high crewed traffic load. This strategy simplified interactions with UTM at the expense of less predictable UAS traffic behavior. Results were inconclusive, however, due to the low number of subjects. It was impossible to single out a suitable strategy for all types of situations. The passive strategy was generally favored but seemed insufficient to resolve short-term conflicts between crewed aircraft and UAS.

The findings of Chapters 3 and 4 exposed important limitations of applying dynamic segregation to manage tactical conflicts from an ATCO perspective. There appear to be certain situations where traditional ATC strategies based on separation minima and flight rules may be preferable. Moreover, the impact of vertical separation requirements in the operational concept became apparent, due to their relevance when UAS need to cross crewed aircraft arrival and departure routes, or come into conflict with low-flying crewed aircraft, such as Helicopter Emergency Medical Service (HEMS) flights, whose vertical profiles are often difficult to predict.

UAS are also sensitive to vertical gradients in wind speed and direction, as well as to sudden changes in wind conditions (gusts) [90]. Interactions between wind and urban structures can generate complex flow patterns and vortices, leading to severe and unpredictable gusts at lower altitudes [91]. Simulations by Krawczyk et al. [92], and Mohamed et al. [91], demonstrate that UAS may experience abrupt deviations in trajectory, angle of attack, and aerodynamic loads when exposed to urban gusts. These disturbances can exceed the response capabilities of UAS flight control systems, particularly during low-speed operations near buildings.

The additional ATCO task load of considering uncertainties of crewed aircraft vertical profiles as well as UAS behavior in response to local wind conditions when applying geofences may be detrimental to safety performance.

These observations led to the development of the follow-up experiment presented in this chapter. The aim was to investigate the interface in terms of adequacy to resolve tactical conflicts, whether removing vertical separation requirements would improve performance, and whether the placement of the tower controller as the central coordinator was adequate.

## 5.3 Interface Design Improvements

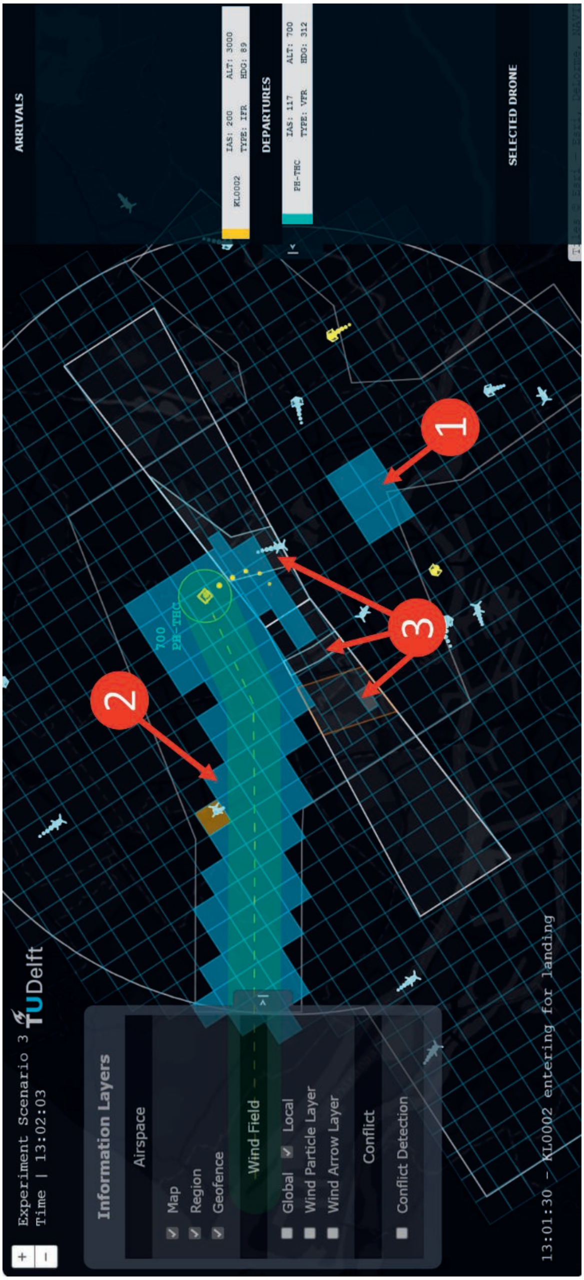
Following the outcomes of previous experiments, the interface design underwent an additional iteration which emphasized increasing operational realism. This was done by including wind effects, higher fidelity mission boundaries, UAS contingency scenarios, improved UTM simulation behavior and improved ATCO manipulation tools for geofences as well as UAS interactions.

### 5.3.1 Means of Control

Given that the final responsibility of assuring segregation lies with the air traffic control unit [15], the interface was designed to be similar to ground radar displays that tower controllers were already used to working with. Previous experiments showed the utility of providing such a display design [78, 89]. In this section the novel elements added to the interface are introduced. Details on the original interface elements are provided in Chapters 3 and 4.

Figure 5.1 shows the adaptations of the geofencing tools, which were improved in three different ways. Apart from simply activating and deactivating individual geofences, participants could also use a multiselect tool ① to “paint” areas on the interface that they wished to activate. The interface also allowed participants to activate geofences along the entire projected flight path ahead of individual crewed aircraft with a single click ②. Finally, predefined “UAS corridors” near the runway could be activated and deactivated with a single click ③.

Figure 5.2 shows the additional tools for ATCOs to instruct individual UAS ④ that were incorporated into the interface. Should the need arise, the ATCO could issue: a loiter



Experiment Scenario 3
Time | 13:02:03

KL0002 IAS: 200 ALT: 3000
TYPE: IFR HDG: 89

PH-THC IAS: 117 ALT: 700
TYPE: VFR HDG: 312

☑ Map
☑ Region
☑ Geofence
☐ Global ☑ Local
☐ Wind Particle Layer
☐ Wind Arrow Layer
☐ Conflict Detection

13:01:30 - KL0002 entering for landing

Figure 5.1: Overview of geofence tool improvements on the collaborative ATM-UTM interface for tower controllers. Online demo: `http://dronectr.tudelft.nl/`, Participant ID: `demo`. Training material for the interface is provided in Appendix B.

instruction, which would instruct a UAS to orbit in-place until instructed to resume flying; a “contingency” instruction, where UAS would head towards the nearest predetermined landing site; and a “land immediately” instruction, where UAS would abort their mission and land immediately.

Figure 5.2: Overview of new UAS intervention tools incorporated into the collaborative ATM-UTM interface for tower controllers.

## 5.3.2 Simulated UTM Behavior

Rather than applying the A* algorithm used in the experiments of Chapter 3 and Chapter 4, a Theta* algorithm was used in this experiment as it produces straighter paths that are better aligned with typical flight trajectories (see also the work by Zou and Borst on algorithmic transparency in path planning [93] for further reading).

In addition to Theta*, a Safe Interval algorithm was used to detect imminent horizontal conflicts between UAS and crewed aircraft and to alert the ATCO in advance. This involved detecting time interval overlaps between vehicles within geofence grid cells.

To assist the ATCOs in identifying conflicts between crewed aircraft and UAS, a conflict detection tool (see Figure 5.2, item ⑤) was developed, which would highlight grid cells having an overlap in predicted arrival times between UAS and crewed flights in “red” to mark the problematic areas. Vertical separation minima were, however, not considered by this tool, which participants were made aware of before the simulations. Clicking on a red grid cell would highlight the vehicles involved in the conflict. Although Safe Interval Path Planning (SIPP) algorithms exist that can also automatically resolve such conflicts, here the algorithm only detected and highlighted conflicts. Resolving conflicts was purposefully left to the human ATCO to focus on how they would apply geofences to structure air traffic and avoid conflicts.

### 5.3.3 OPERATIONAL REALISM

To increase the realism of the simulation, a “mission boundary” (see Figure 5.2, item ⑥) was added to each surveillance UAS flight. It is a corridor of a preset width which the UAS is not allowed to exit and thus constrains the trajectories that the Theta* algorithm can produce. This feature depicted the operational limitations imposed by ground risk mitigation requirements of the “specific” category [17], which are expected to be the most common category of UAS missions [4]. If an activated geofence blocked the mission boundary of a UAS, it would continue along its planned trajectory and loiter at a location just outside the geofence boundary until removed.

In addition, a 2D variable wind field was included that could impact the UAS endurance (see Figure 5.3). Real wind data at 100 feet above ground level on February 12th, 2021 between 13:00 and 14:00 local time was sourced from *Wins50* (see `https://www.wins50.nl/`) for this purpose. As UAS would fly at a fixed airspeed, wind caused their groundspeed to vary which impacted their arrival times at trajectory waypoints. Wind speeds ranged from 5 meters per second (10 knots) to a maximum of 12 meters per second (23 knots). For the simulations, 12 meters per second was considered excessive, given the average speed of UAS was set to around 24 knots. The wind field was portrayed using colored arrows relative to average drone speed, ranging from red (23 knots) to green (10 knots). When a UAS encountered a large head wind, it would reduce the UAS endurance and possibly its capability to complete its mission.

Should the UAS reach the limits of its flight endurance, or pass through an area of excessive wind speeds, it would automatically enter a contingency mode and head towards the nearest alternate landing site, as shown in Figure 5.4, item ⑦.

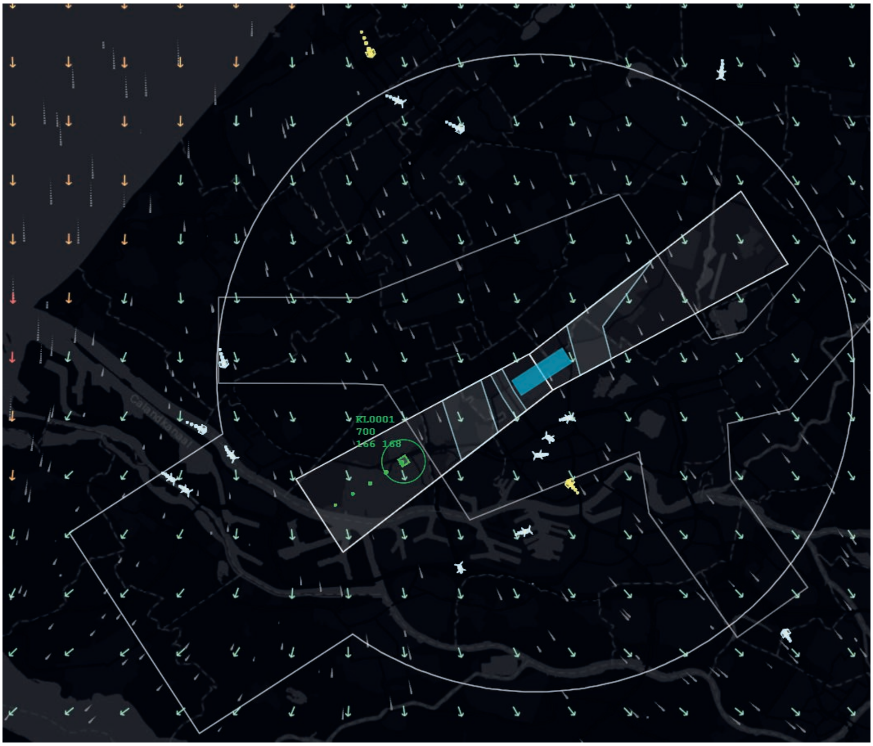


Figure 5.3: Depiction of the 2D variable wind field included in the simulation tool.

Figure 5.4: Depiction of a UAS in a contingency situation and indication of the minimum horizontal separation required around crewed aircraft.

## 5.4 HUMAN-IN-THE-LOOP EXPERIMENT

The findings of these previous experiments were incorporated into an updated interface design and tested using ten licensed ATCO volunteers in a series of simulation scenarios.

### 5.4.1 PARTICIPANTS AND TASKS

Ten licensed ATCO volunteers participated in the simulation. All had varying degrees of experience in working in a tower control environment (six active tower controllers, two former tower controllers and two ATCOs without a tower control rating) and stemmed from different cultural backgrounds (nationalities from four European countries).

Participants were tasked to segregate UAS traffic in Very Low-Level airspace from crewed air traffic around Rotterdam - The Hague Airport. They could achieve this by reconfiguring the airspace boundaries between UTM- and ATM-controlled airspace using dynamic geofences, similar to the DAR concept developed for U-space, but supported by minimum separation criteria between UAS and crewed aircraft which were used in the experiment of Chapter 4, namely 1,000 meters horizontal separation and 500 feet vertical separation. The interface provided indications about the minimum horizontal separation distance required in the form of a circle around the crewed aircraft blips (see Figure 5.4, item ⑧).

### 5.4.2 INDEPENDENT VARIABLES

The experiment featured a mixed design with the traffic scenario as the within-participants manipulation (having three levels) and the participant group as the between-participant manipulation (having two levels).

Participants were divided into two groups of five. The first group, referred to as the "horizontal group" (H), would be tasked with conducting dynamic segregation by only considering horizontal separation requirements (i.e. 1,000 meters) between crewed traffic and UAS. The second group, the "vertical group" (V), would have to consider both horizontal and vertical (i.e. 500 feet) separation requirements. The two groups were defined under the assumption that vertical separation would play a smaller role in close proximity to the aerodrome since the difference in altitudes between UAS and crewed aircraft would be very low, as well as the uncertainties in vertical trajectories of UAS makes vertical separation difficult and potentially risky.

All participants performed the same three traffic scenarios in a quasi-randomized order (to counterbalance presentation order), but were required to maintain different separation minima, depending on whether they were assigned to the horizontal or vertical group. They were tasked to minimize disruptions to the original UAS traffic routes as much as possible in all scenarios. This led to a total of fifteen data points (five participants × three scenarios) per group.

### 5.4.3 TRAFFIC SCENARIOS

UAS traffic was based on potential point-to-point and surveillance missions in proximity to the airport. Use cases similar to the ones presented in Chapter 3, Figure 3.1 were used as a baseline for UAS flight profiles, which included medical delivery between hospitals, railway or highway infrastructure inspections, and harbor patrol flights. These types of missions

Table 5.1: Traffic scenario details.

| | Crewed aircraft | | | UAS | | | Events | |
|---|---|---|---|---|---|---|---|---|
| **Scenario** | Commercial | VFR | HEMS | Medical | Surveillance | Delivery | Conflicts | Contingencies |
| E1 | 3 | 2 | 0 | 2 | 15 | 3 | 2 | 2 |
| E2 | 2 | 2 | 1 | 2 | 15 | 3 | 2 | 1 |
| E3 | 2 | 2 | 1 | 3 | 17 | 2 | 4 | 0 |

were expected to be the most common ones for commercial Beyond Visual Line-Of-Sight UAS flights, according to UAS industry growth projections [4]. Moreover, UAS missions could either have a "high" or "medium" priority and a maximum flight altitude of 120 meters above ground level (a value commonly referenced in European regulations). Crewed aircraft included a mix of commercial flights arriving and departing under Instrument Flight Rules (IFR), single-engine piston aircraft utilizing designated Visual Flight Rule (VFR) corridors and traffic circuits, and Helicopter Emergency Medical Service (HEMS) flights departing the aerodrome directly in the direction of their destination at low altitude. An overview of the simulation scenarios is provided in Table 5.1. Examples of the flight paths of crewed aircraft (continuous lines), UAS (dash-dotted lines), UAS contingencies and predetermined conflicts are provided in the map view depictions of Figure 5.5 and timeline depictions of Figure 5.6. Of the crewed aircraft, those with a callsign beginning with "KL" are commercial, "PH-" are VFR, and "LIFELN" are HEMS flights. Of the UAS, those with a callsign beginning with "MED" are high-priority medical delivery, "DEL" are non-priority delivery, and "SRV" are non-priority surveillance flights.

UAS would automatically respond to the imposed geofence constraints under the guidance of an automated, centralized UTM system simulation module, which relayed the airspace configuration changes and subsequent routing instructions to UAS in real time. The UTM system, however, would not by itself impose any traffic actions on impending conflicts with crewed aircraft. Therefore, if necessary, participants could intervene in individual UAS routings and override UTM instructions through direct commands.

Finally, UAS contingency events were also added to the experiments to increase the realism of the simulation and to analyze how participants would use the interface to manage them. These events were triggered by preprogrammed UAS failures and flights into areas of excessive wind speed (i.e. greater than 12 meters per second). The interface would update every five seconds, a common update rate in air traffic control. Geofence restrictions could be activated and deactivated by the ATCO at any time. UAS routes would respond to airspace changes and ATCO commands instantly, allowing the concept to be simulated at a completely tactical level.

### 5.4.4 Control Variables

Various control variables were used during the experiment. The interface and its functionalities were constant over all experiment runs. Participants could not issue instructions to crewed aircraft, since the aim was to evaluate interactions with UTM, and were therefore presented with a traffic flow that had already been deconflicted with other crewed aircraft.

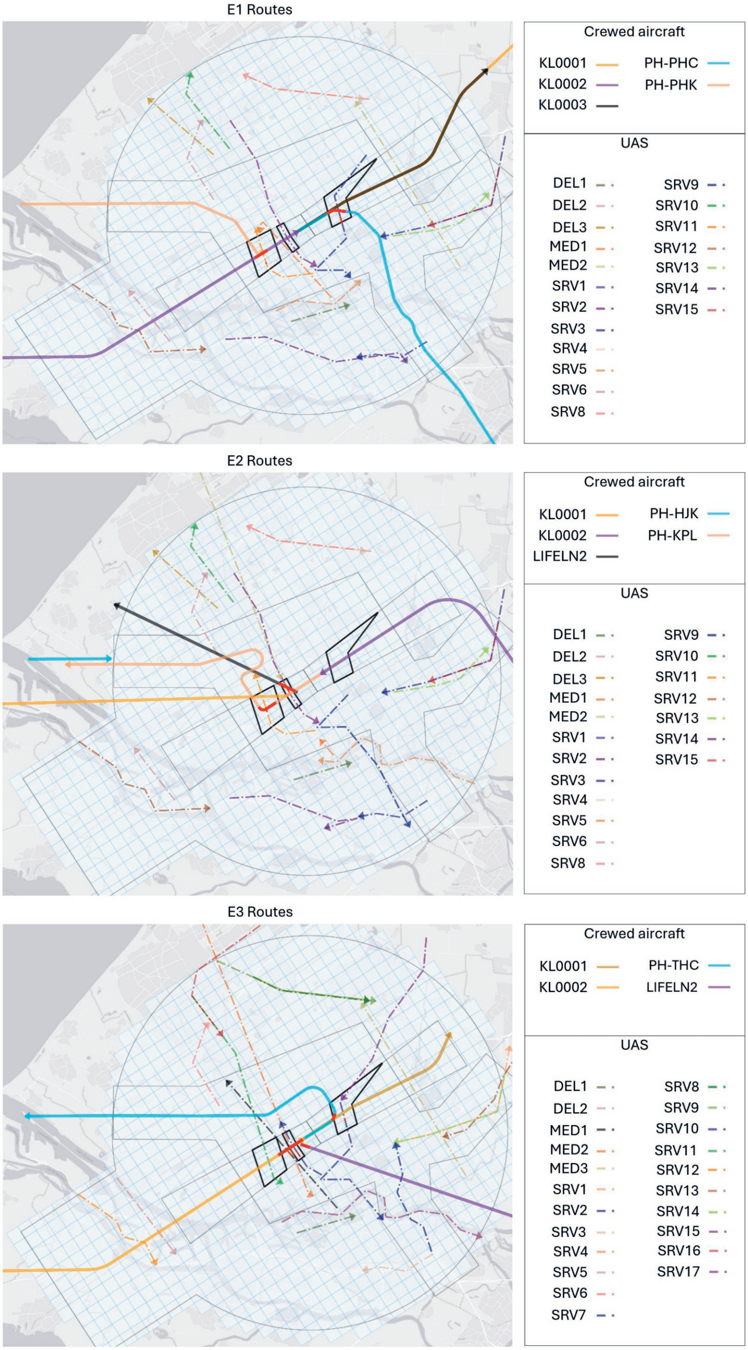


Figure 5.5: Illustration of crewed aircraft and UAS routes in scenarios E1 (top), E2 (center) and E3 (bottom).

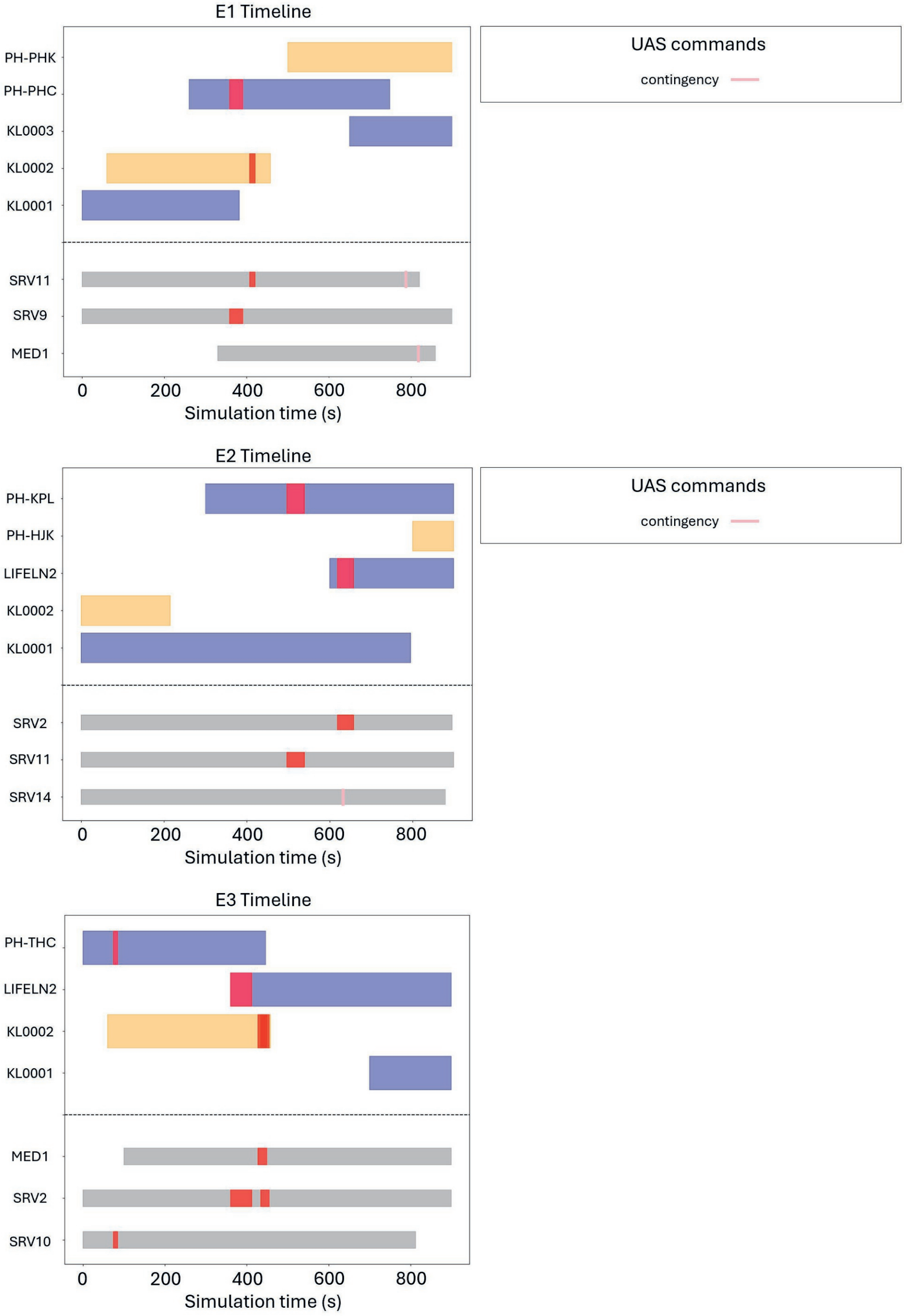


Figure 5.6: Timeline of planned crewed aircraft and UAS conflicts in scenarios E1 (top), E2 (center) and E3 (bottom).

```
13:00:00 - KL0001 entering for landing
13:01:20 - KL0002 departing in 120 sec
13:03:30 - PH-PHK entering for landing
13:06:20 - LIFELN2 departing in 120 sec
```

Figure 5.7: Examples of messages provided in the simulation to indicate whether crewed aircraft were entering to land or when they would depart.

There are also other limitations of the simulation. No “out-of-tower” view was provided and the fact that crewed aircraft could not be controlled meant that participants could dedicate their full attention to UAS traffic and the interface. Moreover, no voice communication with crewed aircraft was available. Instead, text messages (see Figure 5.7) provided information about the departure or landing intentions of crewed aircraft.

### 5.4.5 Dependent Measures

A series of qualitative and quantitative metrics were measured in the experiment to support the assessment of results. System data recordings (i.e., UAS and crewed aircraft positions, speeds, altitudes, and routes) provided the necessary information needed to assess the achieved level of safety and efficiency in each experiment run. Safety performance was measured in terms of the number of losses of minimum horizontal and vertical separation (LOS) between crewed aircraft and UAS (in meters) and the total duration of each occurrence (in seconds). Efficiency was determined by the average delay (in seconds) on UAS missions which resulted from geofence activations requiring them to reroute from their optimum flightpath, as well as the total number of UAS impacted by geofence activations. Conclusions concerning the participants’ control strategies were obtained by measuring which interface elements (geofences, UAS-specific commands and general interactions) were activated at which point in time through time-stamped mouse clicks, through reviews of video and audio recordings made during the experiment, as well as through post-experiment questionnaires. These questionnaires also provided information about the participants’ perceived task performance and other subjective data.

### 5.4.6 Experiment Procedure

The experiment was set up in a way that participants could connect to the simulation sessions remotely from their own homes using a web browser. They were asked to perform the experiment at a time and place where they would not be disturbed and could connect to the experimenter through a video call.

Each participant, regardless of their assigned group, would complete seven training scenarios of five minutes each to familiarize themselves with the interface and its functionalities, before conducting three simulation sessions, each lasting fifteen minutes. After each simulation run, participants would complete a subjective assessment survey with specific questions about the traffic scenario. Moreover, a dedicated post-experiment survey was presented to participants with more general questions regarding the concept as a whole.

### 5.4.7 Hypothesis

It was hypothesized that participants in the horizontal group would have a better safety performance than participants in the vertical group, assuming that vertical separation would play a lesser role in close proximity to the aerodrome and increased risk due to uncertainties in vertical profiles. It was therefore expected that total number (H1.1) and duration (H1.2) of LOS would be lower in the horizontal than the vertical group. In contrast, it was expected that overall UAS efficiency would be higher in the vertical group due to a reduced need for rerouting UAS when vertical separation minima are achieved, meaning a lower average delay of all UAS (H2.1), lower average delay of medical UAS (H2.2) and fewer number of UAS impacted by geofence activations (H2.3). Following the same rationale, concerning interface interactions, the total number of UAS-specific commands (H3.1), geofence activations (H3.2) and general interactions (H3.3) with the interface were expected to be lower in the vertical group. The hypotheses were tested by aggregating experiment data in terms of safety, efficiency, and the number of interface interactions of ATCOs to judge their performance. Finally, no significant differences were expected between the three simulation scenarios.

## 5.5 Results

To facilitate data analysis and to allow for a better comparison between participants, interface and UAS traffic interactions were plotted on a timeline. Figures 5.8 and 5.9 show an example of a timeline for participant P01 of the horizontal group, who experienced several conflicts between UAS and crewed aircraft in experiment scenario E3. The map (Figure 5.8) depicts the routes of crewed aircraft in continuous lines and UAS in dash-dotted lines. The intensity of the blue shading highlights the frequency of geofence activations.

The timeline graph of Figure 5.9 depicts the duration when crewed aircraft (top bars) and UAS (bottom bars) were flying in the simulation. The continuous vertical lines across all UAS bars highlight when geofences were activated (in green) and deactivated (in black). Moreover, the smaller vertical lines within each UAS bar highlight UAS-specific commands that were issued. The red colors in both crewed aircraft and UAS bars depict the duration that both aircraft were experiencing a loss of separation.

Based on the raw data, aggregate metrics for performing statistical analyses are extracted. Given the small sample size and presence of outliers, a normal distribution of the underlying data could not be assumed. Therefore, the non-parametric Mann-Whitney U Test was used to compare metrics and identify if there was a difference between the horizontal and vertical groups. None of the tests showed any statistically significant differences between samples on any of the metrics depicted in Figure 5.10. However, further investigation of the box-plot data on the total number of interactions with the interface hints at a proclivity for greater numbers of interface interactions in the horizontal group

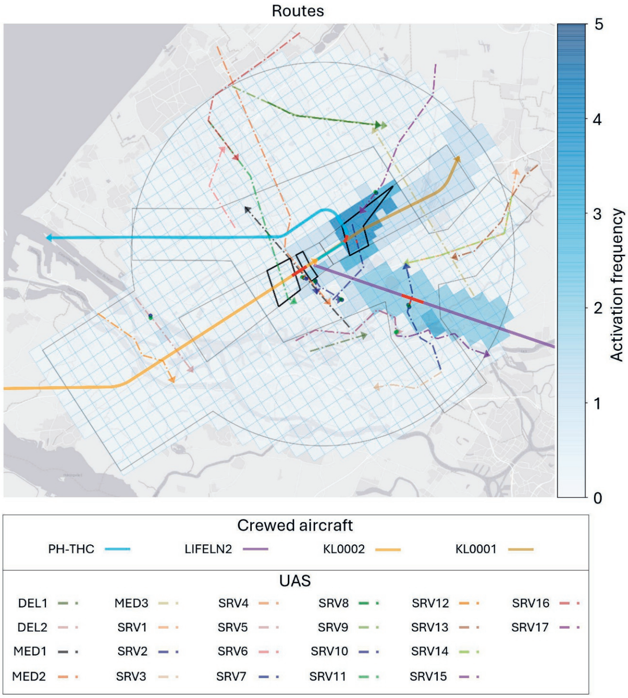


Figure 5.8: Exemplary route illustration of crewed aircraft and UAS for participant P01 in scenario E3.

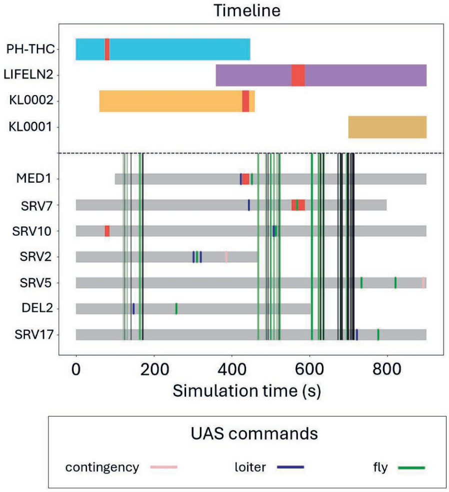


Figure 5.9: Exemplary timeline illustration of participant P01 in scenario E3.

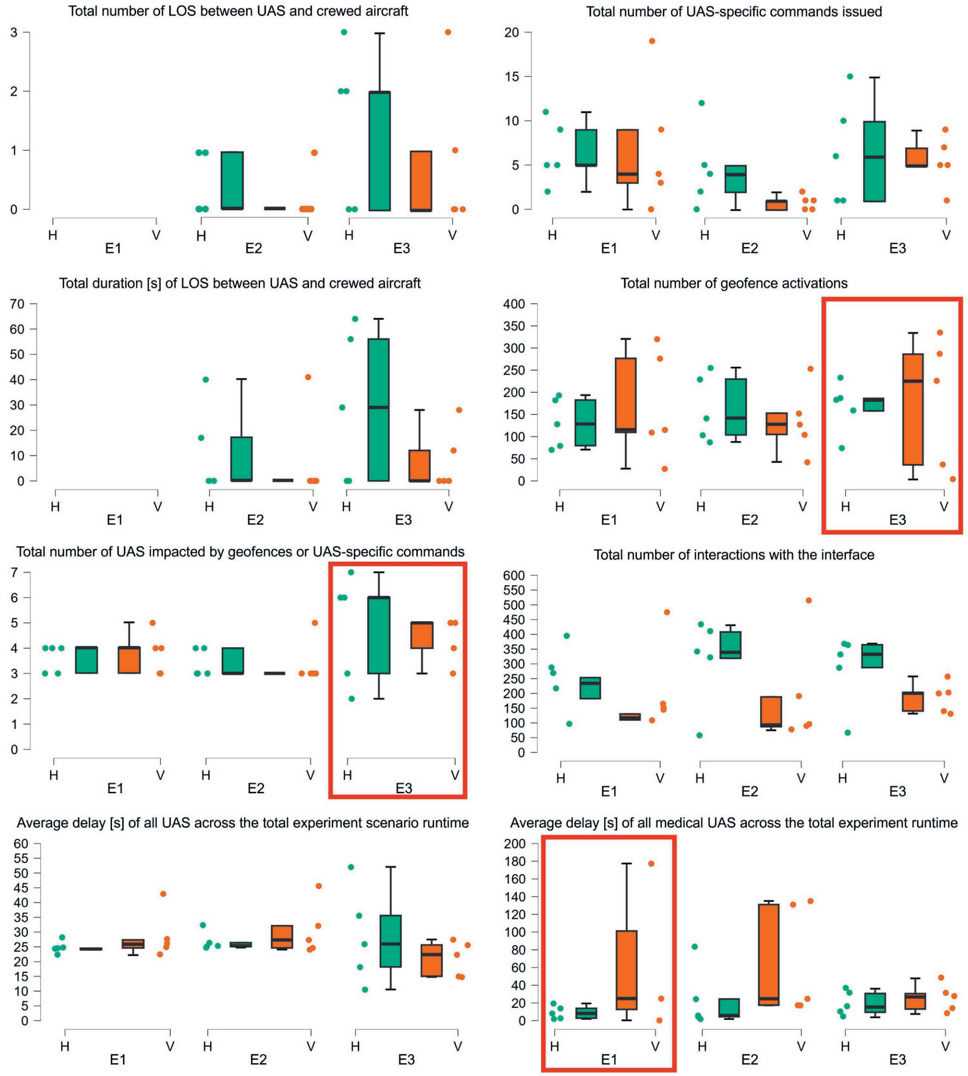


Figure 5.10: A box-plot overview of aggregate samples of each dependent measure, separated by group (H - V) and simulation scenario (E1 - E2 - E3). Dot-plots are also provided given the small sample size per group. No significant differences were found except in the spread of datapoints between the samples marked with red boxes.

over the vertical group, as hypothesized in H3.3.

In addition, a non-parametric Ansari-Bradley Test was conducted for each metric to compare the dispersion in the data between the two groups. None of the tests showed any significant differences between the spread of samples except on three occasions. A significant difference was found in the spread of the number of geofence activations ($W = 20, p = 0.048$) of simulation scenario E3, in the total number of UAS impacted by geofences or UAS-specific commands ($W = 9.5, p = 0.049$) of simulation scenario E3 and in the average delay of all medical UAS across the total experiment runtime ($W = 21, p = 0.016$) of simulation scenario E1. Areas where a significant difference in the data spread was found are marked in red boxes in Figure 5.10. This hints at the potential for greater dispersion in the number of geofence activations and medical UAS delay if the participant is part of the vertical group. On the contrary, the spread of the total number of UAS impacted may be larger in the horizontal group. This would indicate that the number of geofence activations under only horizontal separation requirements would be more consistent, given the lower spread, whereas the number of UAS impacted by ATCO actions would be more predictable when vertical separation minima are applied, although efficiency of high priority UAS would benefit from horizontal separation minima only. Yet, these results cannot be generalized to either group, since significant differences were always limited to one of the three simulation scenarios. Therefore, the hypothesis that the type of separation requirement would impact ATCO performance is rejected. Although manipulations regarding horizontal and vertical separation minima were not significant, several loss-of-separation events were identified that merit further discussion.

Every participant managed to reduce the number of conflicts between crewed aircraft and UAS compared to the baseline in every scenario except in one instance, where the overall number of conflicts remained the same. However, when conflicts occurred, the impact of the loss of separation (LOS) could be considered severe, as in every case both horizontal and vertical limits were infringed. Most of the LOS situations involved VFR aircraft, followed by HEMS flights and then commercial aircraft. Moreover, most LOS incidents occurred in close proximity to the runway threshold, where crewed aircraft were at their lowest altitudes. Subjective feedback from participants confirmed that situations involving conflicts with HEMS, VFR aircraft or UAS crossing near the runway presented the largest challenge in the simulation.

Table 5.2 summarizes the instances where a loss of separation (with respect to the minimum LOS criteria) occurred. Contrary to the hypothesis (H1.1), there were slightly more LOS situations in the horizontal group (nine) than in the vertical group (eight). Most of the LOS situations involved VFR aircraft (nine), followed by HEMS flights (five), and then commercial aircraft (three). Out of all seventeen LOS occurrences, three involved the high-priority medical UAS.

Participants rated the utility of interface elements provided to them, which were then accumulated and ranked in descending order (see Figure 5.11). Interface functions providing information about UAS flight paths and allowed them to be manipulated (geofences and commands) scored highest. Participants also reported their mental effort, situation awareness and perceived level of safety. Mental effort observations were collected on a Borg CR100 Scale (see Figure 5.12), which could range from 0 (“absolutely no effort”) to 150 (“extreme effort”). High levels of perceived situation awareness were reported throughout the experiment runs via ten-point Likert scale (see Figure 5.13). Contrary to expectations due to the severe LOS events which occurred during the experiment runs, participants also reported a high level of perceived safety performance on a five-point Likert scale (see Figure 5.14). Non-parametric Mann-Whitney U Tests were conducted on the reported mental effort, perceived situation awareness and perceived safety performance ratings. No statistically significant differences were found between horizontal and vertical groups.

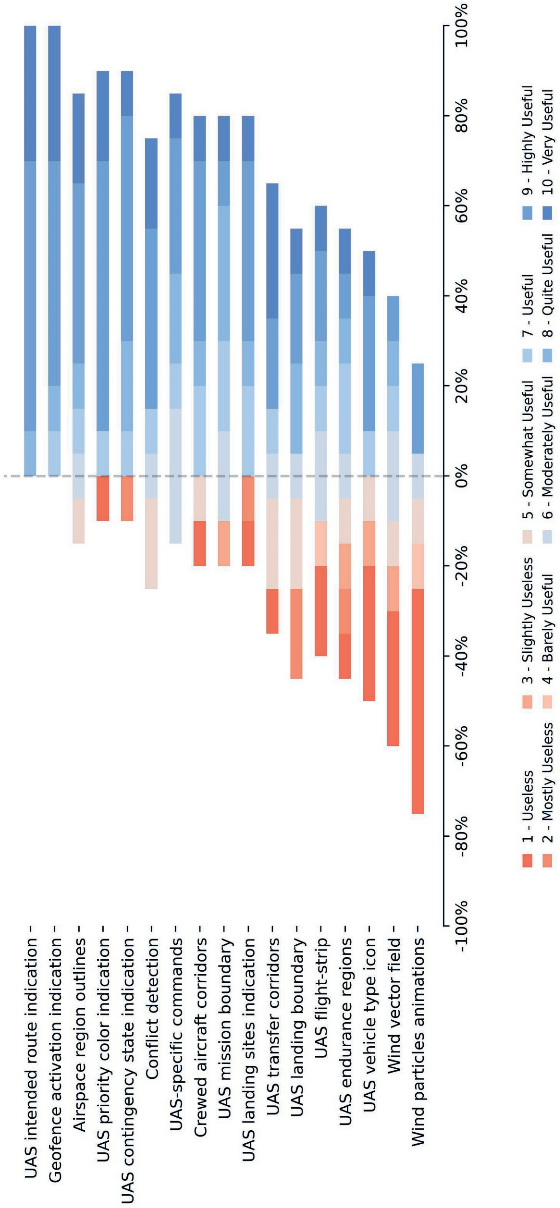


Figure 5.11: Overview of interface element utility subjective ratings by participant.

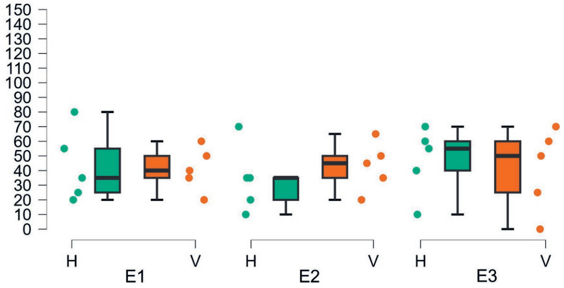


Figure 5.12: Subjective mental effort ratings on a Borg CR100 Scale, separated by group (horizontal group on the left and vertical group on the right) and simulation scenario (E1 - E2 - E3).

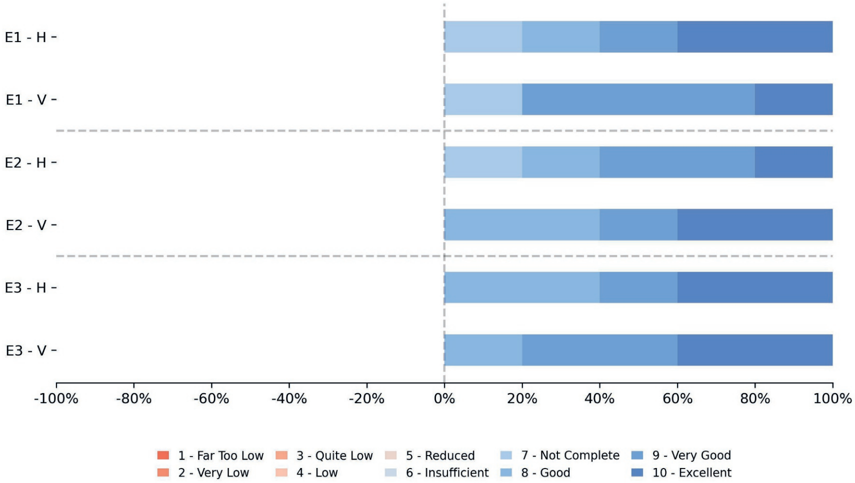


Figure 5.13: Subjective situation awareness ratings on a ten-point Likert scale, separated by group (horizontal group on the top and vertical group at the bottom) for each simulation scenario (E1 - E2 - E3).

Table 5.2: Overview of the severity of loss of separation events between crewed aircraft and UAS.

| Participant | Group | Scenario | Horizontal dist. [m] | Vertical dist. [ft] | Crewed aircraft | UAS |
|---|---|---|---|---|---|---|
| P01 | H | E3 | 526,32 | 16,59 | Commercial | Medical |
| | | E3 | 460,64 | 32,73 | HEMS | Surveillance |
| | | E3 | 852,17 | 46,53 | VFR | Surveillance |
| | | E2 | 887,55 | 151,44 | VFR | Surveillance |
| P03 | H | E2 | 657,63 | 149,45 | VFR | Surveillance |
| P04 | H | E3 | 942,97 | 16,88 | HEMS | Surveillance |
| | | E3 | 811,09 | 46,53 | VFR | Surveillance |
| P10 | H | E3 | 865,75 | 20,95 | HEMS | Surveillance |
| | | E3 | 852,17 | 46,53 | VFR | Surveillance |
| P05 | V | E3 | 852,17 | 46,53 | VFR | Surveillance |
| | | E2 | 45,53 | 19,16 | HEMS | Surveillance |
| | | E1 | 982,78 | 125,54 | VFR | Medical |
| P07 | V | E3 | 434,76 | 19,05 | Commercial | Medical |
| | | E3 | 937,74 | 32,98 | HEMS | Surveillance |
| | | E3 | 852,17 | 46,53 | VFR | Surveillance |
| | | E1 | 946,39 | 4,42 | Commercial | Surveillance |
| | | E1 | 859,67 | 29,90 | VFR | Surveillance |

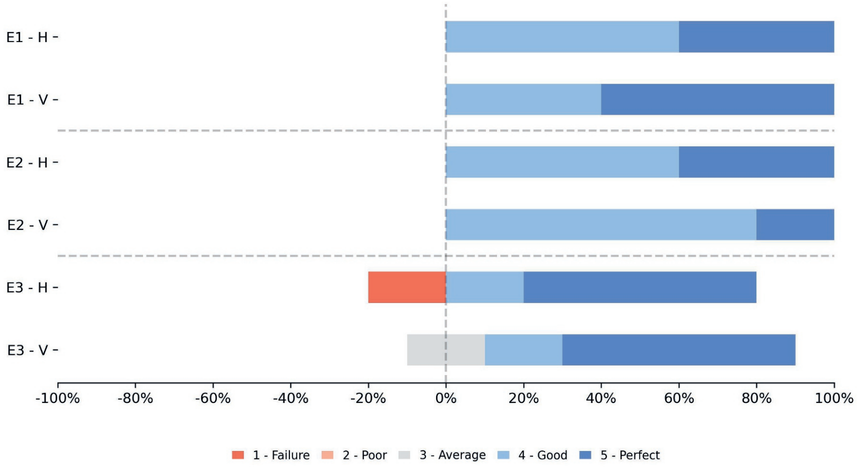


Figure 5.14: Subjective safety ratings on a five-point Likert scale, separated by group (horizontal group on the top and vertical group at the bottom) for each simulation scenario (E1 - E2 - E3).

## 5.6 Discussion

The assessment of results could not identify any significant differences between horizontal and vertical groups in terms of safety, efficiency, or in the number of interface interactions, thus rejecting all hypotheses (H1.1-2, H2.1-3 and H3.1-3). There were also no significant differences across experiment scenarios (E1, E2 and E3). However, the number of (severe) losses of separation in the experiment was surprising. The scenarios were designed in a way that excessive workload or task saturation could be ruled out when analyzing performance results. Traffic load was average and, since participants were not performing any other ATC tasks, they could focus their attention entirely on the display. This was also confirmed by participants in their responses to workload and situation awareness questionnaires. Moreover, dedicated questions showed that participants understood the interface functions provided to them to resolve conflicts and a generally high understanding of what each of the functions do. Surprisingly, ATCOs reported a high level of perceived safety performance in these questionnaires, which was not reflected in the data. It was therefore re-evaluated whether the interface design and tools were adequate in highlighting and resolving conflicts, as well as whether unforeseen ATCO control strategies influenced the results.

### 5.6.1 Contributing Factors to Losses of Separation

Several contributing factors to the LOS that occurred in the simulations were found, which are summarized in Table 5.3. In seven LOS events, results indicate that participants could not properly judge what the minimum horizontal separation distance was on the interface. It was not possible to confirm whether participants considered the minimum horizontal separation indication (see Figure 5.4 ⑧) when resolving conflicts. It appears that they were more focused on making sure that the actual trajectories between UAS and crewed aircraft would not overlap.

The strong reliance on the conflict detection tool indications may have caused false confidence in ATCOs that a conflict was indeed resolved, directly contributing to four LOS events. Since the conflict detection tool could only detect areas where horizontal separation minima would be infringed, it made it harder for ATCOs to judge vertical separation at the point of conflict. Vertical separation could therefore only be assessed through comparison of altitude indications on the flight strips of each conflicting UAS and crewed aircraft, which required more effort from the participants.

In one incident a participant was tracking a particular UAS which they believed caused a conflict with a crewed aircraft, when it was in fact another UAS. Even though the conflict detection tool had been indicating the correct UAS, the ATCO was initially too focused on

Table 5.3: Main contributions to losses of separation.

| **Main contributor to LOS incident** | **Number of occurrences** |
|---|---:|
| Inability to properly judge separation | 7 |
| Reliance on conflict detection functionality | 4 |
| Preoccupation with other conflict | 2 |
| Uncertainty of crewed aircraft departure timing | 1 |
| *Not possible to verify* | *3* |

the other aircraft. When they realized their mistake, they only had a few seconds remaining to resolve the conflict and, failed to do so.

Participants also had difficulty judging when crewed aircraft departures would take place since they are used to hearing that information through the audio, rather than having to read the transcript provided in the interface. This limitation was the main contributor to one LOS incident. Additionally, the large speed differences between UAS (slow) and crewed aircraft (fast) may have made it difficult to perceive the urgency of conflicts and when to take action, since ATCOs are not familiar with such large differences in velocity and vehicle performance.

The combination of HEMS or VFR with surveillance UAS flights was by far the most common (see Table 5.2). Although the type of aircraft was not found to be directly attributable to the LOS incident upon further analysis, it does appear to confirm the initial notion that low-flying crewed aircraft with less predictable routes would be the most difficult for ATCOs to manage.

### 5.6.2 Interface Effectiveness in Managing Conflicts

In general, participants quickly identified conflicts between UAS and crewed aircraft using the interface. Of the conflicts that resulted in a loss of separation, the average lead time between the initial conflict detection (measured from the time that the ATCO used interface functionalities to gather information) and the LOS occurring was over two minutes.

The most common functionalities used to identify conflicts were the conflict detection tool, the UAS and crewed aircraft route indications and finally, when applicable, the altitude indications of UAS and crewed aircraft. Participants actively selected individual UAS and conflict areas to highlight the routes of the affected aircraft and gather situation awareness.

Overall, the tools provided by the interface were considered sufficient to reliably detect conflicts between UAS and crewed aircraft early on, even in situations where the conflict was not resolved by the ATCO. However, as the previous discussion surrounding Table 5.3 showed, the most prominent shortcoming of the interface in this regard was a failure to prominently convey the minimum separation distance between UAS and crewed aircraft on the interface, and to effectively and reliably alert the ATCO of pending infringements in both horizontal and vertical separation minima through the conflict detection tool.

Shortcomings in interface functionalities can only partially explain why they failed to resolve conflicts in time. Results also indicate that the control strategies applied by ATCOs contributed to the observed LOS events.

### 5.6.3 ATCO Control Strategies Used to Resolve Conflicts

For most participants, geofence activations were the primary means of structuring UAS traffic. On average, participants would change the number of active geofences 37 times over the fifteen-minute duration of each experiment scenario. This is a high rate by typical ATM standards. In comparison, the dynamic airspace configuration concept developed for en-route crewed aviation defines a twenty-minute minimum time interval between airspace configuration changes [94]. When UAS-specific commands were used, it was often the combination of “loiter” and “fly” commands to support geofence activations and create a predictable UAS traffic behavior when crossing the final approach and departure areas upwind and downwind of the runway.

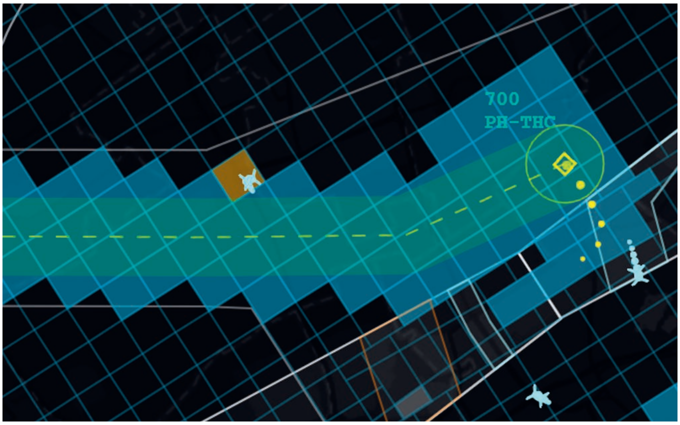


Figure 5.15: Activation of geofences (light blue grid cells) to block larger areas in the passive control strategy.

The intended use of the interface would have been primarily to segregate the airspace using geofences in such a way that crewed aircraft would not come into conflict with UAS, and then trust the UTM system managing the UAS to reroute them around the airspace restrictions, as depicted in Figure 5.15. UAS-specific commands were meant to serve only as a last means for intervention to resolve a pending loss of separation. This was termed as the “passive strategy” in previous experiments.

Instead, a majority of ATCOs (seven out of ten) used the interface tools to force a particular UAS trajectory following control strategies they typically apply when issuing instructions to crewed aircraft – which was referred to as the “active strategy” in the previous experiment of Chapter 4. Participants indicated in their comments that the type of control strategy could have been influenced by the time they had available to dedicate to UAS routes. The lower the task load, the more time to actively manage UAS. These observations could, however, not be validated from the results obtained. One controller using the active strategy also mentioned that they would have preferred the passive strategy, but chose the active one for the sake of UAS efficiency.

Figure 5.16 shows a situation where an ATCO applied this active strategy. Two geofences were activated along the route of a UAS (highlighted in orange) which conflicts with a departing crewed aircraft (PH-KPL), with the purpose of forcing the UAS to divert from its original route. Since the UTM system would search for reroutes around segregated airspace, UAS would sometimes go in unwanted directions and cause additional conflicts with traffic which the ATCOs had not foreseen. This was particularly problematic when participants opted to activate smaller, more local geofences, as they provided more room for UTM to reroute UAS around them.

Additionally, knock-on effects would occur, as new geofence restrictions affected all UAS routes passing through that area, not just the specific UAS the ATCO was attempting to reroute. Therefore, some participants opted to manually intervene using UAS commands to maintain a high level of predictability by overriding UTM decisions, as depicted in Figure 5.16 through the UAS command selection tool, and in some cases even foregoing the use of geofences altogether.

Figure 5.16: Use of UAS-specific commands to manage conflicts in the active control strategy.

Table 5.4: Overview of interface interactions per participant, group and observed control strategy.

| Participant | Group | Observed Strategy | LOS | Interface Interactions E1 | E2 | E3 | Average |
|---|---|---|---|---|---|---|---|
| P01 | H | Active | 4 | 217 | 322 | 368 | 302,3 |
| P03 | H | Passive | 1 | 97 | 58 | 67 | 74,0 |
| P04 | H | Active | 2 | 269 | 342 | 332 | 314,3 |
| P06 | H | Active | 0 | 395 | 411 | 364 | 390,0 |
| P10 | H | Active | 2 | 288 | 434 | 287 | 336,3 |
| P02 | V | Passive | 0 | 152 | 78 | 131 | 120,3 |
| P05 | V | Active | 3 | 475 | 515 | 203 | 397,7 |
| P07 | V | Active | 5 | 165 | 191 | 257 | 204,3 |
| P08 | V | Active | 0 | 145 | 90 | 200 | 145,0 |
| P09 | V | Passive | 0 | 109 | 96 | 140 | 115,0 |

The active strategy seems to be the most “natural” to how ATCOs manage air traffic today. However, since the interface did not allow them to issue routing instructions to UAS, it was difficult for them to apply it. The discrepancy between the intended active control strategy and the limitations of the operational concept to support it was a major contributor to the LOS that occurred.

Although no significant differences between samples were found, further analysis of the collected data points identified a bimodal distribution in the total number of interface interactions. A subsequent data analysis was conducted to see if there was a pattern with regards to the amount of interface interactions and those participants who we identified as following a passive or active strategy. Table 5.4 compares each participant with the number of interactions per experiment run, the number of LOS and the type of control strategy.

Looking at these results there appears to be an overlap in the number of interface interactions and the observed control strategy. Averaged across all three experiments, every participant following a passive control strategy had a lower number of interface interactions than their active control strategy counterparts. Although not verifiable through statistical analysis, it does seem to indicate that an active control strategy requires participants to interact more with the interface than the passive control strategy. Moreover, a majority of participants applying the active control strategy showed higher numbers of LOS than those using the passive control strategy. This is an important finding. Had all participants opted for (or been instructed to use) the passive strategy, the results in terms of safety and the number of interface interactions might have been better across the board. Following these insights, the next section proposes to incorporate several mitigation measures to the interface and operational concept in order to improve safety performance.

### 5.6.4 Potential Mitigations

One option to reduce the active control tendency exhibited by ATCOs may be to provide more transparency into the UTM decision-making process on UAS routings. By revealing more information that helps ATCOs understand the rationale behind UTM decision-making, both their engagement and situation awareness could be improved. Promising concepts for this are being explored by Zou and Borst [95], who reported means to portray automation decision-making to human UAS supervisors.

Another option may be to approximate UTM traffic management decisions on UAS towards air traffic control strategies for crewed aircraft to increase predictability. Thus, UAS would behave in a similar manner to crewed aircraft, both in regards to conflict avoidance with other aircraft as well as routings around geofences. The former would require the definition of flight rules for UAS similar to those of crewed aircraft. Potential candidates to be explored include the Digital Flight Rule [96], Enhanced Flight Rule [97] and U-space Flight Rule [98] concepts. The latter could be supported by a more capable path-finding algorithm for UAS that also considers dynamic obstacles, such as Zeta*-SIPP [99].

The segregation concept could also be revised based on findings in these and similar simulations. For instance, a majority of participants (six in total) favored vertical separation requirements over horizontal ones, citing that horizontal separation minima would only be necessary if crewed aircraft were operating at low altitudes. This comment essentially inverts the original assumption that achieving horizontal separation between UAS and crewed aircraft would be the main criteria for airspace reconfiguration. The enforcement of these separation criteria would also need to be supported using more sophisticated conflict detection tools and depictions on the interface, as previously discussed.

Dedicated ATCO training towards a more passive strategy concerning UAS may be beneficial, supported by interface updates which limit the use of UAS-specific commands to very concrete situations. Schwoch et al. [100] provide some suggestions on how UAS-specific ATC commands could be used for instructing UAS to hold position before implementing a DAR change or ahead of low-flying crewed aircraft, as well as guidance on how to manage crewed and uncrewed aircraft contingency situations supported by automated system messages.

Finally, it is important to consider that in the post-experiment survey, all but one participant agreed that an additional airspace manager position would be required to perform the tasks in the experiment. Considering that geofencing and dynamic segregation of airspace are tools more akin to strategic airspace management, which ATCOs are not typically trained for, this might explain the tendency to actively manage UAS traffic. The assignment of a separate role within ATC to manage DAR was explored in experiments conducted by Teutsch et al. [101, 102]. This would remove a substantial task load from the tower controller in times when UAS or crewed aircraft operations are high, as results from their study confirm. However, the interplay between the tower controller and the, now delegated, DAR Manager would need to be supported by clear procedures on how tactical interventions on UAS traffic conflicts with crewed aircraft would need to be managed. The addition of another human actor in the decision-making process incorporates additional human performance challenges which would also need to be addressed in future studies.

Perhaps this role could also be assigned to UTM using automation, where the UTM system is tasked with activating geofences to resolve conflicts with crewed aircraft, rather than the ATCO. Sharing crewed traffic information with UTM, or making crewed aircraft electronically conspicuous will allow UTM to proactively take corrective actions ahead of conflicting air traffic, and therefore assisting the ATCO in maintaining a safe airspace. Considering the low safety performance in the experiment even with active ATCO involvement, automatic conflict resolution between UAS and crewed aircraft using a more capable UTM algorithm (like Zeta*-SIPP) might even be more effective at improving safety than increasing the level of transparency. Insights gained from work on UAS fleet supervision within the field of Human Autonomy Teaming could provide valuable guidance in this matter, such as in the studies by Smith et al. [103] and Sadler et al. [104].

## 5.7 CONCLUSIONS

Although significant differences between experiment groups were not found, the detailed analysis of loss of separation incidents showed important limitations of a collaborative interface for ATCOs to interact with UTM through dynamic segregation.

The interface provided sufficient indications to alert ATCOs to potential conflicts and allow them enough time to deal with them. However, the tools provided were inadequate to meet the demands of the control style applied to resolving conflicts.

Most ATCO participants tended to actively influence UAS routing in the control zone. Instead of simply opting to segregate sufficient airspace and allowing the UTM system to reroute UAS by itself, participants were more likely to attempt to accommodate UAS routings among their crewed air traffic by themselves. However, geofences and UAS instructions alone would not always resolve the conflicts in a way that they expected. This took away time for ATCOs to focus on other conflicts and maintain an overview of the airspace situation.

This experiment showed the limitations of using strategic airspace management tools to resolve tactical conflicts between UAS and crewed aircraft using typical air traffic control strategies. It appears that applying the dynamic segregation concept to such a short-term time horizon breached the limits of how such a concept could be successfully used.

A majority of participants (nine out of ten) therefore mentioned that the role of reconfiguring UTM airspace should be a *separate entity* from the ATCO performing tower control. Perhaps letting the UTM system automatically detect and resolve conflicts using geofencing would yield better results. Otherwise, to resolve tactical conflicts between crewed traffic and UAS, perhaps the definition of UAS flight rules, separation minima and accompanying ATCO control strategies could support dynamic segregation.

# 6

# DISCUSSION AND CONCLUSION

*In this chapter the main conclusions of the thesis, in response to the defined research questions are summarized. Supported by insights gained through simulation experiments, their implications on continued research in this domain are discussed.*

One of the major challenges posed by the incorporation of UAS flights in the vicinity of towered aerodromes is the need to coordinate Uncrewed Aircraft Systems (UAS) traffic managed by UAS Traffic Management (UTM) and crewed air traffic managed by Air Traffic Control (ATC). The current operational concept for U-space, the European approach to UTM assumes the need to segregate airspace for crewed and uncrewed aircraft to avoid conflicts. However, different use cases and mission requirements for crewed and uncrewed flights add an additional layer of complexity which makes static airspace segregation unreasonable. As the analysis of use cases presented in this thesis showed, simply segregating the airspace below 120 meters above ground level to UAS traffic is insufficient to meet the demands on airspace availability of crewed aircraft, such as Helicopter Emergency Medical Service (HEMS) or other low-level air traffic. Similarly, large-scale segregation of airspace in favor of crewed air traffic blocks crucial segments of airspace for UAS missions.

The operational concept proposed in this thesis builds on the principles for dynamic airspace reconfiguration defined in U-space, and explores the use of dynamic geofences to re-draw static airspace segregation to support dynamic changes to airspace needs by crewed aircraft and UAS. Moreover, in the best interest of safety, the role of performing airspace segregation was assigned to the Air Traffic Control (ATC) unit in charge of the controlled airspace around the airport, in line with the European U-space concept. Specifically, the role of the tower controller was augmented to include the responsibility of limiting airspace where UAS are operating, alongside their other control tasks. It was assumed that the additional task load could be mitigated through geofencing tools provided in a collaborative interface. Subsequently, three real-time simulation experiments involving air traffic controllers were performed to test the operational concept, investigating control strategies, interface design, and task performance.

The findings obtained from these experiments, in relation to the four research questions defined in Chapter 1, are explored in this chapter, as well as how the operating concept can be improved to maintain safe airspace and facilitate the collaboration of Air Traffic Controllers (ATCOs) with UTM.

## 6.1 Incorporating a New Operational Concept (RQ1)

The first part of this research focused on understanding the novel approach applied in UAS traffic management and incorporating the resulting operational concept into the air traffic control work domain. In Chapter 2, the main differences in operating constraints of small UAS and crewed aviation were highlighted, focusing on the vicinity of towered aerodromes. It was shown how the combination of geozone restrictions and results of Specific Operations Risk Assessments (SORA) affect the UAS routing options for a given UAS flight. In Chapter 3, an Abstraction Hierarchy of the new operating environment was developed. The groundwork presented in these two chapters aimed to answer the first research question:

**Research Question 1**

What are the underlying system goals, functions, relationships, and constraints inherent to the work domain of UTM, ATC, and how do they compare?

**Modeling the UTM environment.** A major factor to consider when modeling UAS flights within the European regulatory framework is the risk-based approach to issuing UAS flight authorizations. Therefore, the focus of regulations for small UAS operations has shifted from aircraft-centric to *operation-centric* risk assessments. Analyses of air and ground risk caused by a UAS flight define the area for maneuvering that a vehicle will have. Moreover, additional geographical restrictions to UAS air traffic are defined through geozones. Static geozones are established to communicate airspace restrictions to UAS, as well as safeguard critical infrastructure, population centers, wildlife reserves, and other areas. Dynamic geozones will also be applied for short-term UAS traffic restrictions, such as police and emergency responses. While UAS flight rules are absent, dynamic geofences are crucial to resolve tactical conflicts between UAS and crewed aircraft.

These characteristics of the proposed UAS operational concept were mapped onto the work domain of air traffic control using an Abstraction Hierarchy. The Abstraction Hierarchy was used to discover the functional constraints that bound opportunities for action in the work domain, which itself is governed by procedural and physical constraints. Using this tool the collaborative ATC-UTM work domain that tower controllers will navigate was mapped out, as depicted in Figure 6.1. For each experiment the realism of the simulations were increased incrementally by including more of these constraints, like mission boundaries (procedural), mission priorities (procedural), flight types (physical) and environmental constraints (physical), such as wind effects. The resulting functional map confirms a substantial overlap of ATC and UTM purposes, functions, and forms, showing that both systems aim to achieve similar objectives within the same airspace. The Abstraction Hierarchy also provides insights on new elements (“black boxes”) which UTM adds to the current-day ATC work environment, increasing complexity from an air traffic control perspective.

The insights provided by the work domain analysis highlight the advantages of applying such a framework to the collaborative ATC-UTM environment. It shows a holistic view of the common and individual constraints limiting action by ATC and UTM, which would not have been made salient through the SORA or review of ATC requirements alone.

It is important to highlight that the Abstraction Hierarchy presented in this work is not a final and complete depiction of the UTM and ATC working environment. Rather, it serves as a tool to model the relevant aspects of the work domain of both entities, from the perspective of the current state of the art and regulatory frameworks applicable at the time of this writing. In this thesis, the emphasis was not on developing a comprehensive Abstraction Hierarchy as the final product, but rather to use it, and if necessary change it, as an important component of iterative design. Therefore, as research progresses on UTM and ATC integration, just like the interface between both domains, the Abstraction Hierarchy will surely be subjected to further refinement.

**Collaborative traffic management.** A new operational concept for the collaborative management of crewed and uncrewed air traffic within controlled airspace was proposed in Chapter 2. This concept places the air traffic control unit as the main coordinating entity between ATM and UTM, in line with current regulations. Specifically, it is proposed that the tower controller assumes the tasks of coordinating crewed flights within the control zone and imposing geographical restrictions on UAS. ATCOs are provided with an interface that allows them to identify UAS in the control zone and apply geographical restrictions in

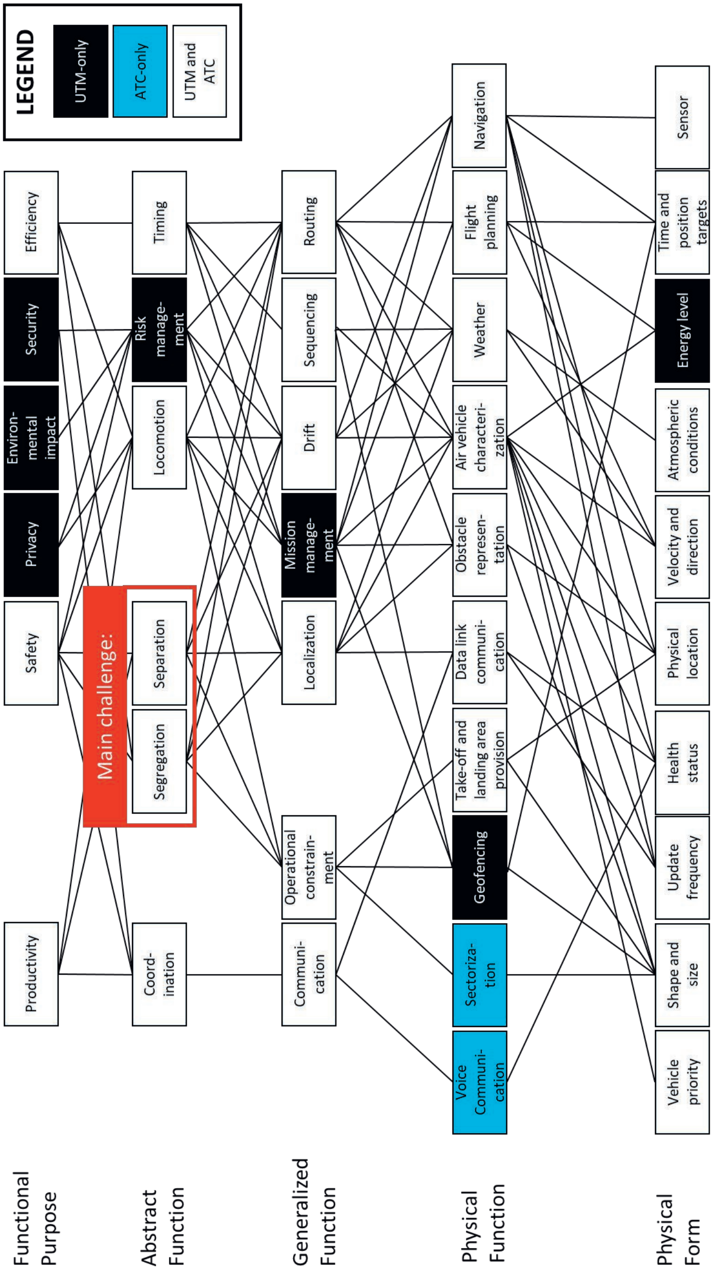


Figure 6.1: Abstraction Hierarchy model of the work domain of a collaborative environment between ATC (tower control) and UTM.

areas where crewed aircraft intended to operate. By activating dynamic geofences, tower controllers can restrict UAS flights from entering specific areas without controlling them individually. UTM would then take care of routing UAS around these new restrictions, whilst considering their operational constraints.

However, results of all three experiments showed that, out of all novel elements in the Abstraction Hierarchy, the most relevant challenge presented by the work domain relates to the abstract functions *separation* vs. *segregation*, as highlighted in Figure 6.1. Air traffic controllers are currently trained to achieve safe separation between aircraft. However, the additional need to segregate two different domains was a challenge to ATCO participants in all experiments.

In particular, the interplay between mission restrictions of individual UAS and geofencing (which affect all UAS intending to pass through an area) was a considerable source of confusion for ATCOs. This is because geofences reshape the boundaries of where UAS are allowed to operate, and thus impact all UAS flights in an affected area, rather than specific ones. Activating geofences in areas with dense UAS traffic generated knock-on effects which impacted UAS routing predictability and UAS traffic frequently responded to geofences in a way that was not immediately clear to the air traffic controller.

Rather than using geofences as segregation tools, experiment participants applied these as mechanisms to indirectly control individual UAS and achieve separation through sequencing relevant UAS behind crewed air traffic. Due to uncertainty about UAS routing responses to geofence activations, ATCOs requested additional tools to intervene in individual UAS routes to increase the predictability of air traffic. These tools were introduced in the experiments of Chapters 4 and 5 that allowed tower controllers to instruct individual UAS to loiter, land, or change their route. This gave controllers more opportunities to interact with UAS traffic within their airspace. However, this level of active involvement by ATCOs did not improve safety. On the contrary, ATCOs which applied passive segregation strategies had better safety performance overall, albeit at the expense of lower UAS predictability. A balance between full segregation of ATC- and UTM-controlled traffic and pairwise interventions in UAS and crewed aircraft conflicts would need to be found and supported by the interface.

**Architectural considerations.** The operational concept and simulations of this thesis assume a UTM system architecture in which a central coordinating service orchestrates all UAS responses to geofences. However, the U-space regulation [15] also assumes the possibility of more distributed UTM system architectures. Multiple U-space Service Providers may issue traffic instructions within the same U-space airspace, and will coordinate with each other to avoid conflicts among the UAS to which they provide services.

Going one step further, another approach to UTM may be to delegate the conflict detection and execution of avoidance responsibilities to individual UAS (operators) entirely, as is the case in the Federal Aviation Administration's approach to *Normalizing Unmanned Aircraft Systems Beyond Visual Line of Sight Operations* [105]. In this scenario, individual UAS could respond to conflicts or other airspace restrictions in a way which best suits their performance limitations and mission requirements. In such a fully distributed UTM system, every UAS would need to be intelligent enough to take care of its own separation from any other aircraft (either visually, through the operator's own UTM services or using sense-and-avoid technologies).

However, such architectures increase the complexity of human-automation coordination mechanisms, since one controller would need to interact with multiple agents simultaneously. Each service provider or UAS operator may impose their own sets of rules and procedures in response to geofence restrictions and ATC instructions, which could be detrimental to the human controller's performance and situation awareness.

All three experiments incorporated a centralized UTM system to allow UAS traffic to follow predictable patterns. Yet, results showed that ATCOs struggled with unpredictable UAS behavior, prompting them to actively intervene to increase predictability. This observation hints at the possibility that the issue of UAS predictability could be decoupled from the underlying UTM architecture altogether. Rather, it might be an issue of properly defining common rules for UAS and agreed procedures for UAS traffic management actions within a given airspace, regardless of the UTM architecture applied.

## 6.2 Portraying the UTM Environment (RQ2)

A human-machine interface that allowed tower controllers to navigate the work domain and manipulate elements of the collaborative ATM and UTM environment under their control was developed. Chapter 2 and Chapter 3 elaborated on how the crucial elements of the Abstraction Hierarchy were incorporated in the interface. This part of the research attempted to answer the following research question:

**Research Question 2**

In what visual form can the constraints on UAS, regarding airspace segregation and separation from crewed aircraft, be mapped on a decision-support interface such that it supports the work and strategies of air traffic controllers in achieving system goals?

**Objectives of the interface.** It was not the intention to map the entire work domain of the collaborative ATC-UTM environment onto the display, but rather to facilitate the achievement of overarching objectives through a collaborative interface. High-level tower control objectives (achieving a safe, orderly, and expeditious flow of air traffic on and in the vicinity of an aerodrome) had not changed in this new operational concept. Rather, ways to achieve these goals had to be augmented with additional functions to allow the introduction of UAS and UTM in the same airspace. Analysis of the work domain showed that the most complex element of the collaborative ATC-UTM work domain from a tower control perspective involves the dynamic segregation of airspace in coordination with an automated UAS traffic management system, over which controllers have limited control. The interface was therefore designed in a way that:

1. *Allows ATCOs to identify areas that need to be segregated.* This was achieved by designing the interface in the shape of a radar display and incorporating UAS alongside crewed flight information. This was supported by making UAS and crewed aircraft flight intentions visible on the interface.

2. *Provides ATCOs with the means to perform segregation.* In the initial interface design of Chapter 3, tower controllers were not able to exercise direct control over UAS,

but rather impose restrictions on UAS traffic using dynamic geofencing. Tools for activating and deactivating geofences were incorporated right into the interface itself. In this way, the controller could identify areas that need to be segregated and perform the segregation action through the same interface.

3. *Allows ATCOs to understand UAS flight restrictions.* The interface made maneuvering restrictions set by the UAS mission transparent such that the controller can anticipate UAS routing selections and behavior in response to mission and geofence restrictions. Moreover, alerts to failures of UAS to be able to adhere to imposed restrictions were also incorporated.

4. *Allows ATCOs to intervene in individual UAS routes.* A feature which allowed tower controllers to issue specific commands to particular UAS was incorporated in later design iterations of the interface (Chapters 4 and 5), to accommodate control strategies with higher ATCO involvement in UTM decision-making. This feature also allowed greater flexibility to resolve unexpected conflicts and increase UAS routing predictability.

**Design of interface elements and components.** To support the identification of areas to segregate, it was important to make UAS positions and flight intentions visible to the tower controller. In that way, they could identify which UAS missions may conflict with crewed traffic in their area of responsibility. To make these assessments, knowledge about crewed aircraft positions and flight intentions concerning UAS was just as important. Furthermore, providing this information in the shape of a plan view radar display in combination with flight strips was considered the most appropriate way to present information in a way that ATCOs are familiar with.

Portraying UAS mission constraints was another important component of the interface. In particular, the limitations defined by SORA assessments and the limited range of UAS made evading large areas of airspace impractical. ATCOs would therefore need to be made aware of the implications of their segregation actions on the UAS missions that they affected. Showing the room for maneuvering that UAS had available allowed ATCOs to better understand the impact that a geofence had on their flight profile, and which response they would likely take. The display incorporated a graphical indication of the maximum deviation from the flight plan which the mission parameters allowed in combination with an indication of the maximum flight endurance that a vehicle had remaining.

The final crucial component of the collaborative interface is the design of the geofencing tool. Several iterations and refinements of this interface element were tested in our experiments. The main questions regarding this tool concerned the size, shape, and layout of the geofencing function; how geofences would be activated and deactivated; and how they would be portrayed to the ATCO. Regarding the latter, the use of predefined geofence structures which ATCOs could quickly activate or deactivate was preferred, rather than allowing them to draw individual geofences by themselves. The aim was not to create a geofence design tool, but rather a tool that can be quickly and tactically applied to restrict areas from UAS operations. This allowed for a more standardized approach to how the tool can be used and did not require the ATCO to invest too much time in deciding where to draw the boundaries of each geofence. Several layouts were tested, ranging from a very fine-grained grid of 1x1 kilometer geofences (see Section 3.5), to very large areas that were shaped around common crewed aircraft flight paths (see Section 4.3). The final version of the geofencing tool incorporated findings from both experiments and allowed the ATCO to activate individual geofences on a fine-grained grid, as well as activate multiple geofences along typical crewed aircraft routes at once with a single click. Moreover, tools for automatically segregating airspace in proximity to the active runway were incorporated.

**Interface adaptations in support of unforeseen control strategies.** The interface was well received and provided ATCOs flexibility to resolve conflicts using several control strategies. The initial interface design (Chapter 3) was adequate to support ATCOs using a more conservative passive control strategy focused on safety. However, the use of geofences as the only means to interact with UAS was insufficient in supporting the control styles of ATCOs who prefer active involvement in UTM decision-making for the sake of increasing efficiency, as shown in Chapter 4. For instance, the original interface did not explicitly provide the controller with tools to "vector UAS behind crewed aircraft", but implicitly via segregation tools, such as geofences. This is because the proposed operational concept expects ATC to adopt a more passive, supervisory role. Observing ATCOs adopting an active strategy to interact with individual UAS in the experiments was surprising. Therefore, additional tools were included in the experiments of Chapters 4 and 5, which allowed ATCOs the possibility to instruct individual UAS to land, orbit/loiter, reroute, or execute their contingency plan.

Out of all the tools and information provided by the interface, UAS route indications generally scored the highest. Information about UAS contingency responses on the display was considered valuable, as well as the means to force UAS to land immediately. However, across all experiments, participants wished for greater clarity about how UAS would respond to geofence activations. Incorporating greater transparency about the impact of ATCO decisions on UAS traffic before acting on them would have been beneficial. Moreover, results highlight the need to incorporate the notion of geofence activation time to the geofencing tool so that UAS are not unnecessarily penalized by short-term airspace reconfigurations. Since no means for transmitting geofence activity time was provided, UTM could not consider this metric in the planning of UAS routes beforehand. ATCOs frequently kept geofences active only for the duration it took to resolve a particular conflict, which caused some UAS which were not affected by a conflict to be rerouted unnecessarily whenever an ATCO manipulated a geofence. This may also alleviate the need for issuing individual "loiter" commands and improve human operator awareness in an environment with higher amounts of UAS traffic.

Overall the interface developed in this thesis provided a useful tool for ATCOs to gain situation awareness on UAS traffic within the control zone and provide means to interact with UAS. However, the interface could not properly support them in managing conflicts between UAS and crewed aircraft. This is not simply a limitation of the interface, but rather a general shortcoming of the operational concept based on dynamic segregation. If combined with refined procedures, rules and responsibilities for collaborative management of controlled airspace with UTM, safety performance could be improved. This will be explored in the next sections.

## 6.3 Collaborative Control Strategies (RQ3)

A total of three human-in-the-loop simulation experiments with licensed ATCO participants were conducted to test the effectiveness of the provided interface elements in supporting ATCO control tasks. By allowing experiment participants free choice over how they used the tools at their disposal, it was possible to observe how they would use the interface to maintain a safe and efficient flow of air traffic within the control zone and answer the following research question:

**Research Question 3**

How do air traffic controllers interact with UAS via the interface, which control strategies do they apply, and how do they perceive their role in a collaborative ATC-UTM environment?

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**Active and passive control styles.** Two general types of control strategy were observed during the experiment of Chapter 4, which can be summarized at a high level into *passive* and *active*.

In the passive strategy, ATCOs used the interface as a *segregation* tool to reserve large portions of airspace around areas where crewed aircraft would descend below the maximum operating altitude of UAS flights. Coming from a “safety first” mindset, these segregations were made regardless of whether a crewed aircraft was flying there or not. ATCOs would geofence portions of controlled airspace where they would not be comfortable having UAS flights due to the potential for conflict with crewed aircraft. Commonly segregated areas included the runway final approach and initial departure areas, VFR traffic circuits, and known helicopter landing sites. This strategy would often come at the expense of UAS mission efficiency, and in many cases required UAS flights near the aerodrome to abort their mission altogether.

On the other hand, for the active strategy, ATCOs used the interface as a *separation* tool, initially via geofence activations to vector specific UAS around conflicting crewed aircraft. Vectoring is a common control technique applied in air traffic control and appeared to be the most natural and efficient approach to collaborative management of UAS and crewed aircraft from an ATCO perspective. This however caused unpredictable UAS routing behavior in response to geofence activations, given that geofences were unfit to be used as vectoring tools. This resulted in situations of severe loss of separation between UAS and crewed aircraft. When additional UAS-specific commands were incorporated in Chapters 4 and 5, ATCOs used them to increase the predictability of UAS responses to geofences as well as to avoid the UTM system unnecessarily re-planning longer routes around temporary geofence restrictions. The active strategy also came at the expense of a higher workload and incentivized ATCO interventions in UTM decisions, going against the intended collaborative ATC-UTM operational concept.

**Prioritizing safety over efficiency.** The passive control strategy seemed more suited for ATCOs with a supervisory mindset, whereas the active control strategy was reminiscent of a typical air traffic control mindset. ATCO workload also had an impact on the type of strategy being used: In the combined experiment of Chapter 4, in which ATCOs were tasked to control crewed aircraft and segregate airspace using geofences, both participants applied the passive control strategy at times when workload was high, and the active one when workload was low.

When specifically asked about their preference of control strategy in the experiment of Chapter 5, ATCOs proposed to use the passive strategy as standard, and the active one as either a last resort intervention in UAS and crewed aircraft conflicts or as a means to increase UAS efficiency during times with low crewed traffic load. However, the feasibility of the active control strategy in a real environment was questionable, due to the observed low safety performance, as well as its potential to drastically increase workload and complexity concerning current ATCO tasks. The strategy also tends to work against UTM decisions in some cases. The active strategy appeared to be the most intuitive to the ATCO control style but should be disregarded in favor of a passive control strategy to decrease the potential for UAS conflicts with crewed aircraft.

**Managing unforeseen traffic conflicts.** As results showed, the potential for unforeseen conflicts between UAS and crewed aircraft exists in either strategy. This is particularly relevant for crewed traffic with low predictability. Conflicts between UAS and HEMS or Visual Flight Rule (VFR) flights posed the greatest challenge to ATCOs since such flights would depart on short notice, do not always follow standard arrival or departure routes, and fly at lower altitudes than is common. This, coupled with the issue of low predictability of UAS responses to geozone activations, made it difficult for ATCOs to resolve conflicts. From the experiments it was not possible to conclude how either control strategy could have been applied to resolve such conflicts adequately.

**Reevaluating roles and responsibilities in the collaborative ATC-UTM environment.** From these experiences, it also became evident that the Abstraction Hierarchy (see Figure 6.1) did not provide sufficient insights on how the interface would be used or what impact the design of the interaction functionalities would have on the ATCOs' preferred control styles.

The extent to which the interface supported collaboration with the automated UTM system can also be put into question from these experiences. It appears that the interface failed to invoke true collaboration between the human ATCO and automated UTM system, and merely facilitated basic interaction between the two systems using the tools provided. Both the passive and active control strategies were more reflective of one-way interactions of tower controllers with automation, which then needed to restructure UAS traffic around the imposed restrictions. True collaboration would have also allowed the UTM system to communicate and to propose alternatives means of action to allow it to achieve its own goals for UAS traffic.

The experiments also showed how the ATCOs' own perception of their role within the collaborative ATC-UTM environment differed from the intended one. The initial interface design of Chapter 3 was centered around a passive supervisory control role for ATCOs to restrict UAS movements so that they would not be disturbed when managing crewed aircraft. The control over UAS routes was intended to be completely left to the UTM system. However, actual evaluations in Chapters 3, 4 and 5 showed that this is not how participants perceived their role. ATCOs frequently extended their actions beyond their official responsibilities, often actively managing UAS traffic to maintain situation awareness and ensure safety. This behavior seems to originate from their established role as sole managers of controlled airspace and was likely reinforced by the incentive to simply manually intervene in UAS routings and achieve a predictable outcome to the conflict situation, which the UTM system would sometimes solve in another manner. Consequently, ATCOs requested additional integrated control tools to be incorporated into the interface.

This behavior could have also been amplified by the nature of the experiments themselves. Stress and consequences of the participants' actions on crewed air traffic were not as prominent, since the simulations were not as sophisticated as a full tower control environment, nor did they simulate the full complexity of an operational UTM system (only simple A*/Theta* path planning automation was used to simulate UAS management). Therefore, rather than focusing mostly on crewed traffic, these limitations could have prompted participants to "play around with the interface" more than they would have in a fully immersive simulation.

## 6.4 Human Performance Considerations (RQ4)

Experiment results in Chapters 3, 4 and 5 showed that the type of control strategy applied to the interface could have important impacts on human performance, in particular concerning achieving safety and efficiency. Chapter 5 explored the limits of where the dynamic geofencing concept could be applied at a tactical level. Through dedicated experiments of Chapters 4 and 5, it was possible to highlight the shortcomings of the operational concept and address the following research question:

**Research Question 4**

What are the limitations, safety and performance impacts of augmenting the tower control role with UTM supervision, and what role does automation play?

**Addressing safety concerns.** Several Loss-of-Separation (LOS) events between UAS and crewed aircraft were recorded in the experiments of Chapters 3, 4 and 5. Many of the LOS that occurred in Chapter 5 were so severe that they could be considered near misses. Further investigation showed that the likely cause for these events was a combination of control strategy, aircraft types, interface limitations, and uncertainty of UTM decision-making. Participants using an active control strategy showed a lower safety performance than those who applied a passive strategy. This was in part facilitated by the design of the interface and the control mechanisms provided to the tower controller, which supported the intended operational concept focused on segregation of all UAS from crewed aircraft using geofences, favoring the passive control style. Applying geofences to influence individual UAS routes was not the correct strategy to maintain safety.

When losses of separation between crewed aircraft and UAS occurred, HEMS flights were the ones most frequently involved, followed by VFR and commercial flights. Results also showed that the interface allowed ATCOs to identify conflicting crewed and uncrewed aircraft routes early on. However, it was difficult for ATCOs to apply typical traffic management strategies to resolve conflicts, because geofencing tools were not suited to perform this task.

**Human performance impacts.** The analyses of LOS events also highlight an important limitation of the operational concept from a human performance perspective: A lack of predictability. The combination of crewed air traffic flying non-standard flight routes at low altitudes in conflicting paths with one or several UAS was a particularly difficult scenario in this regard. ATCOs found it difficult to resolve such conflicts using dynamic segregation alone because UTM could freely decide how it wished to reroute UAS around restrictions. The slow UAS speeds in relation to crewed aircraft contributed to the overall poor judgment of separation distances observed in the studies.

Even after the introduction of tools specifically designed to help ATCOs manage conflicts, such as UAS-specific commands and conflict detection alerts, in Chapters 4 and 5 ATCOs found it difficult to resolve conflicts adequately. This indicates that their mental model and expectations of UAS behavior were not aligned with actual system behaviors, and raises the question of whether the display adequately conveyed this information to the ATCO. In addition, more extensive training may have been necessary to familiarize ATCOs with UAS behavior and how it differs from crewed aircraft. Moreover, these findings put into question whether ATCOs should take on this additional responsibility at all.

**Understanding automation.** Results point towards a gap in the interface design concerning the comprehension of automated UTM decision-making in response to ATCO control inputs. The interface designed in this thesis was built around the concept of ATCOs performing supervisory control (aka. management by exception) over UAS traffic.

To get an understanding of how well the interface design supported supervisory control tasks, an analysis using the *Guidelines for the Design of Human–Autonomy Systems* developed by Endsley et al. [31, 32] was conducted. Results from this analysis are summarized in Table 6.1 and explained in further detail in Appendix A. The analysis showed that the system design was compliant with a majority of the design criteria, particularly in supporting human understanding of autonomous systems and minimizing their complexity. Where the interface was lacking was in the provision of what-if functionalities, automation transparency, as well as information about confidence levels in the information provided and performance of the task at hand. The incorporation of such elements in the interface design could improve human performance regarding collaboration with the UTM system.

**The question of segregation vs. integration.** Throughout the research on collaborative ATC-UTM airspace management presented in this work, the common recurring theme was the question of where the boundaries between dynamic segregation were, before an integrated traffic management approach needed to be considered. The last experiment (Chapter 5) concluded that the boundary was breached once tactical intervention in conflicts between UAS and crewed aircraft was necessary to maintain safety.

In Chapter 4, the notion of establishing a concept focused on full segregation of ATM and UTM domains, removing short-term dynamic segregation tools in favor of much longer segregation change time-frames (e.g., upwards of 10 minutes for any reconfiguration change) was explored. This approach could benefit from research into dynamic airspace management from other ATM domains, such as the SESAR PJ07 [81, 82] and PJ09 projects [83, 84] focused on civil-military collaboration. Another option was to increase the focus on full integration of ATM and UTM domains, building on the active control strategy insights gained in the experiments. To avoid safety issues, a clear definition of roles and responsibilities of the ATCO and the UTM system would need to be defined; an adjustment of interface design and ATCO training to support human-machine teaming would be required; and the definition of flight rules for UAS in relation to crewed aircraft would be necessary to increase traffic predictability.

Table 6.1: Overview of the level of compliance of the collaborative ATC-UTM interface with guidelines for the design of human-autonomy systems by Endsley [31].

| **Guideline** | **Verdict** |
|---|---|
| **Support human understanding of autonomous systems** | |
| (1) Automate only if necessary—avoid out-of-the-loop problems if possible | Partially compliant |
| (2) Use automated assistance for carrying out routine tasks rather than higher-level cognitive functions | Partially compliant |
| (3) Provide situation awareness support rather than decisions | Fully compliant |
| (4) Keep the operator in control and in the loop | Fully compliant |
| (5) Avoid the proliferation of automated modes | Fully compliant |
| (6) Make modes and system states salient | Fully compliant |
| (7) Enforce automation consistency | Fully compliant |
| (8) Avoid advanced queuing of tasks | Fully compliant |
| (9) Avoid the use of information cuing | Partially compliant |
| (10) Use methods of decision support that create human/system symbiosis, such as contingency planning and critiquing systems | Non-compliant |
| (11) Provide automation transparency | Non-compliant |
| **Minimize the complexity of autonomous systems** | |
| (12) Ensure logical consistency across features and modes | Partially compliant |
| (13) Minimize logic branches | Fully compliant |
| (14) Map system functions to the goals and mental models of users | Fully compliant |
| (15) Minimize task complexity | Partially compliant |
| **Support situation awareness** | |
| (16) Integrate information to support comprehension of information (Level 2 SA) | Fully compliant |
| (17) Provide assistance for SA projections (Level 3 SA) | Fully compliant |
| (18) Use information filtering carefully | Fully compliant |
| (19) Support assessments of confidence in composite data | Non-compliant |
| (20) Support system reliability assessments | Non-compliant |

However, neither option is fully adequate to resolve all types of traffic situations. Therefore, this research proposes a *unified* approach to UTM and ATM integration, which supports dynamic segregation through the definition of improved UAS traffic intervention tools, incorporation of airspace structures, and adaptations of ATC responsibilities (such as the separation of ATCO and DAR Manager roles), supported by human-automation collaboration concepts.

## 6.5 CONCLUSIONS

In this thesis, the assumption was explored that the incorporation of uncrewed air traffic management systems into the work domain of air traffic control could be facilitated by the development of a human-centered, supervisory control interface for aerodrome tower controllers. Results showed that the proposed operational concept which placed the aerodrome tower controller at the center of UTM supervision and guidance using dynamic geofences suffered in practice from a lack of predictability of UTM decisions on UAS traffic, a lack of compatibility of dynamic segregation tools with control styles typically applied by air traffic controllers as well as a lack of adequacy of dynamic segregation to resolve tactical conflicts. Insights gathered from this research can therefore be summarized into the following main conclusions:

- Results revealed the need for UTM to consider the intentions of ATC in its decision-making to make UAS routes more predictable, and for the display to make UTM automation more transparent to the human supervisor. Only making the routing constraints of UAS salient on the display, as was the case in the experiments conducted, was insufficient to achieve this transparency.
- A majority of experiment participants applied common, separation-based air traffic control actions to achieve dynamic segregation between uncrewed and crewed air traffic. This approach, in combination with the limitations defined in the operational concept built around airspace segregation, was a primary cause of poor safety and human performance in the simulation experiments.
- A full reliance on dynamic segregation using geofencing tools was found to be insufficient to properly resolve short-term conflicts between crewed and uncrewed aircraft. The incorporation of interface elements which allowed ATCOs to influence individual UAS helped them to mitigate these issues, but not resolve them completely.
- Issues in the compatibility of dynamic segregation concepts with active ATCO control styles, and resulting safety concerns, hinted that aerodrome tower controllers might not be the right entity to perform this task, but rather a separate human operator trained to employ a more conservative, passive style of UTM interaction.
- For the reasons mentioned above, full segregation of ATC and UTM domains cannot be safely achieved using segregation tools alone.
- On the other hand, full integration of ATC and UTM domains will also not be possible unless clearer role definitions and improved human-machine coordination mechanisms are in place for managing the transition between segregation and separation of UAS and crewed aircraft.

These results do not discredit the dynamic segregation approach to ATC-UTM integration, but highlight areas where it can be improved from a human supervisory-control perspective. Abandoning the concept entirely until full UTM autonomy is feasible would be premature and counterproductive, as it may be years or decades away. Delaying integration efforts could hinder the development of scalable, safe UAS operations. Rather, the concept should be iteratively refined, supported by more immersive simulation environments.

## 6.6 Recommendations

Across all experiments, it was possible to identify ATCOs' preferred way of working in a collaborative ATC-UTM environment, and which interface elements they would wish to use. However, improving safety performance and increasing situation awareness in collaboration with UTM are of greatest concern.

Initially, full segregation of ATC and UTM domains will need to be applied until air traffic management at the boundaries of segregation and separation are properly understood. A logical next step would be structuring the airspace in such a way that limits the need for dynamically reconfiguring the airspace to occasions that involve non-standard crewed and uncrewed air traffic.

Assigning this additional task to an active tower controller has the potential to exceed their ability to maintain a safe and expeditious flow of crewed and uncrewed air traffic. Feedback gathered from participants of the experiment conducted of Section 5.6.4 confirm a desire to allocate the dynamic segregation task to a human DAR Manager who is not conducting active control on crewed air traffic. This recommendation is supported by work performed by Teutsch [106] as well as Teutsch and Petersen [101], who propose a distribution of responsibilities where a DAR Manager is assigned as a separate coordinating role between UTM, tower and approach controllers. This operator should apply a passive control strategy by default and be trained in supervisory control of UTM, intervening individual UAS routes in situations where additional intervention is required, such as to avoid conflicts with crewed aircraft.

By placing a greater focus on the "sequencing" and "timing" components of the Abstraction Hierarchy (Figure 6.1), interface elements could be improved to facilitate ATCOs' preferred control styles to manage such conflicts. The interface could therefore be improved by incorporating ability to adjust geofence activation times and vertical boundaries.

The definition of flight rules for UAS when avoiding crewed aircraft could assist ATCOs in understanding UAS behavior, even if they are not in charge of performing the separation maneuvers. Some initial proposals for additional flight rules already exist, and are briefly mentioned, which should be further investigated in relation to the ATC-UTM collaborative interface. The National Aeronautics and Space Administration's (NASA) proposes Digital Flight Rules (DFR) as an addition to existing IFR and VFR concepts [96]. The Joint Authorities for Rulemaking on Unmanned Systems [97] propose the introduction of Enhanced Flight Rules (EFR) to support aircraft with increasing levels of automation, and augment, but not replace VFR and IFR. EFR could be likened to a digitalized version of VFR, in which the UAS operator will make use of a digital view of the entire operational environment to make separation decisions. More recently, Sievers et al. of the DLR Institute of Flight Guidance published a concept of operations for U-space Flight Rules (UFR) [98]. These flight rules will be implemented in support of the current U-space regulatory framework, and as such provide additional rules alongside dynamic segregation, rather than replacing it. The premise for this concept is that U-space will remain segregated airspace within which all aircraft (crewed and uncrewed) must operate under UFR.

The poor safety performance experienced during the experiments also highlights that the responsibility of resolving imminent conflicts between UAS and crewed aircraft should not lie with the ATCO (or DAR manager) alone. Rather, authority and responsibility to execute conflict resolution actions on UAS should be placed on UTM, the UAS operator, or a combination of both. Direct intervention tools in UAS routes may still be necessary, but in this way the ATCO can focus on safely guiding crewed aircraft out of conflict situations, and allowing UTM to manage UAS.

These considerations have important ramifications on existing regulations. Namely, the DAR concept proposed in the U-space regulation [15] will need to be explicitly removed as a control option for managing pairwise conflicts between crewed aircraft and UAS in favor of direct UAS commands. Instructions issued to UAS should be limited, clear and concise, in combination with clear procedures for UAS to respond to each type of ATC intervention. Results of the experiments showed that it is crucial to define *how* UAS shall avoid crewed aircraft, so that remote pilots can be trained to conduct predictable avoidance procedures, and that UTM systems can instruct UAS to follow them. Applying these rules will facilitate predictable UAS behavior in controlled airspace. Thus, the second necessary update to the regulatory framework, namely that of rules and procedures for the operation of UAS [17], as well as the common rules of the air [24]. And finally, from an organizational perspective within ATC, the role of the DAR Manager, as well as the distribution of responsibilities within the organization as a separate entity from tactical tower control shall be made explicit in regulation [35].

Once the operating procedures for segregated ATC and UTM are mature and flight rules for UAS in relation to crewed aircraft are established, the unified approach to UTM and ATM integration, as proposed in this thesis, can be attempted.

In this regard, continued refinement of the interface would benefit from applying novel concepts from human-automation research, such as by applying the Joint Control Framework developed by Lundberg and Johansson [107] to map further critical processes in the collaborative ATC-UTM environment, such as the detection of conflicts or application of UAS-specific commands by the ATCO. This framework uses the Abstraction Hierarchy to describe the fundamental structure of the work domain, but expands on it by modeling how control shifts between the human and automation over time and how they work together in complex scenarios. It can also be used to discover competing tasks and potential deadlocks in decision-making flows when control authority and responsibilities are shared between human supervisors and automated UTM systems.

Confusion about how UTM automation would instruct UAS to respond to geofences was one of the main incentives for ATCOs to get involved in UAS routes. In their study on *Investigating Transparency Needs for Supervising Unmanned Air Traffic Management Systems* [95], Zou and Borst propose a unified taxonomy for algorithmic transparency [80] that incorporates operational transparency (i.e., helping the operator understand what the current situation is) and engineering transparency (i.e., helping the operator understand how the system works). Increasing UTM engineering transparency (i.e., helping the operator understand how the automated system works) could improve safety performance in conflict situations. For nominal situations, increasing information acquisition automation whilst at the same time increasing human involvement in UTM control actions appears to be a promising way forward for collaborative ATC-UTM airspace management.

Incorporating these concepts into a revised design of the interface could provide the ATCO with sufficient information about the current traffic situation and their potential avenues of action to take an adequate decision. Thus, bridging the gap between crewed and uncrewed air traffic *segregation* and *separation*.

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# A

# Human–Autonomy System Design Assessment

*This appendix contains an assessment of the collaborative ATC-UTM interface using the Guidelines for the Design of Human–Autonomy Systems developed by Endsley et al., which identifies where the interface is compliant and where it is lacking.*

## A.1 INTRODUCTION

The collaborative ATC-UTM interface design elements were reviewed using the *Guidelines for the Design of Human–Autonomy Systems* developed by Endsley et al. in their work on *Designing for Situation Awareness: An Approach to User-Centered Design* [32] and *From Here to Autonomy: Lessons Learned From Human–Automation Research* [31].

The guidelines and explanations thereof are cited directly from the work of Endsley [31]. Presented below is an analysis of how well the collaborative ATC-UTM interface developed in this thesis adheres to each of these design guidelines. Considering the background of these guidelines, the main focus of the assessment revolves around the interface's ability to provide the ATCO with the necessary Situation Awareness (SA) of the status of UAS flights concerning crewed aircraft and airspace restrictions. Table 6.1 summarizes the verdict for each guideline. The assessments which led to each verdict are presented thereafter.

## A.2 SUPPORT HUMAN UNDERSTANDING OF AUTONOMOUS SYSTEMS

### (1) Automate only if necessary—avoid out-of-the-loop problems if possible.

> "*As autonomy can lead to such significant difficulties in lack of understanding, system complexity, decision biasing, and out-of-the-loop performance problems, it should be avoided except in those situations where its assistance is really needed.*" (Endsley [31, p. 18])

**Assessment:** The interface used automation in several areas. In some cases, incorporating automation was necessary to simulate automated UTM system decisions on UAS traffic. Movements of crewed traffic were also completely automated for the sake of realism. Other automation used in the interface was incorporated to assist the ATCO, such as conflict detection and tools to activate multiple geofences at once. In all, the following interface elements were automated:

1. A*/Theta* path planning for UAS around active geofences
2. Movements of crewed aircraft
3. Conflict detection between crewed aircraft and UAS
4. Contingency procedures of UAS
5. Activation of multiple geofences based on trajectory projections of crewed aircraft
6. Activation of multiple geofences based on transfer corridor placement

**Verdict:** Partially compliant

### (2) Use automated assistance for carrying out routine tasks rather than higher-level cognitive functions.

> "*Reliable autonomy that carries out the action portion of routine tasks is highly beneficial for reducing manual workload and error. Autonomy that carries out the decision portion of tasks should be avoided, unless highly reliable due to decision biasing problems and [out-of-the-loop].*" (Endsley [31, p. 18])

**Assessment:** Some system components violated this rule, as they carried out decisions on behalf of the ATCO, for routine tasks and higher-level cognitive functions:

1. Movements of crewed aircraft (higher-level cognitive function)
2. Conflict detection between crewed aircraft and UAS (higher-level cognitive function)
3. Contingency procedures of UAS (routine-task)
4. Activation of multiple geofences based on transfer corridor placement (routine task)

**Verdict:** Partially compliant

**(3) Provide SA support rather than decisions.**

> "*Significant performance improvements and more robust decision making can be found with systems that enhance SA through improved information presentation to operators, integration, and projections.*" (Endsley [31, p. 18])

**Assessment:** The interface provided several SA supporting components, such as displaying UAS mission and system constraints, as well as projections of future positions of UAS.
**Verdict:** Fully compliant

**(4) Keep the operator in control and in the loop.**

> "*To minimize the out-of-the-loop effect, increase operator involvement and control, improving engagement in task performance. Ensure that the operator maintains control over the automation and devise strategies that incorporate the human decision maker as an active ongoing participant, such as lower levels of automation and periods of manual control via adaptive automation.*" (Endsley [31, p. 18])

**Assessment:** The simulator facilitated keeping the ATCO in the loop by involving them in reconfiguring the airspace so that UTM could reroute UAS around constraints. Multiple tools allowed them to intervene in UTM automation directly or indirectly.
**Verdict:** Fully compliant

**(5) Avoid the proliferation of automated modes.**

> "*Autonomy modes increase system complexity and the ability of operators to develop a good mental model of how the system works. They also make it harder to keep up with which mode the automation is in at the present time, increasing SA errors and increasing training requirements.*" (Endsley [31, p. 18])

**Assessment:** Two modes of autonomy were used in this simulator, namely the nominal and contingency mode UAS simulation. A UAS could only adopt one of the two modes at any given time.
**Verdict:** Fully compliant

### (6) Make modes and system states salient.

> "*When modes are present, the current mode should be made highly salient to the operator (including mode transitions back to manual operations). The current state of the system autonomy should be salient so that any violations of operator expectations will be readily apparent.*" (Endsley [31, p. 18])

**Assessment:** A UAS switching from nominal to contingency mode was made apparent through a clear change in color of the blip and display of mission parameters.
**Verdict:** Fully compliant

### (7) Enforce automation consistency.

> "*Consistency in the terminology, information placement, and functionality of the system between modes should be enforced to minimize errors in working with system autonomy.*" (Endsley [31, p. 18])

**Assessment:** System functionality and information placement remained the same when a UAS switched from nominal mode to contingency mode.
**Verdict:** Fully compliant

### (8) Avoid advanced queuing of tasks.

> "*Systems that allow the operator to set up in advance a number of different tasks for the autonomy to perform are most likely to leave that operator slow to realize there is a problem that needs intervention. Approaches that maintain operator involvement in the decisions associated with execution of tasks should be considered.*" (Endsley [31, p. 18])

**Assessment:** All functionalities of the simulator would take immediate effect upon activation. There were no components that allowed for advanced queuing of tasks.
**Verdict:** Fully compliant

### (9) Avoid the use of information cuing.

> "*Unless there is very high reliability, information cuing (automatic highlighting of information) should be avoided in favor of approaches that allow people to use their own senses more effectively. For example, systems for systematically decluttering unwanted information or improving picture clarity are preferable.*" (Endsley [31, p. 19])

**Assessment:** The conflict detection tool would automatically highlight an area of conflict and the conflicting crewed traffic and UAS.

**Verdict:** Partially compliant

**(10) Use methods of decision support that create human/system symbiosis, such as contingency planning and critiquing systems.**

> "*Decision support systems that avoid decision biasing include "what-if" analysis, encouraging people to consider multiple possibilities and perform contingency planning that can help people formulate Level 3 SA, as well as systems that help people consider alternate interpretations of data, helping to avoid representational errors in their SA.*" (Endsley [31, p. 19])

**Assessment:** No "what-if" functionalities were used in the interface.
**Verdict:** Non-compliant

**(11) Provide automation transparency.**

> "*A high degree of transparency and observability of system behavior and functioning is needed, making it clearly apparent not only what the system is currently doing but also why it is doing it and what it will do next.*" (Endsley [31, p. 19])

**Assessment:** There was no indication of how a UAS would respond to airspace changes using the A*/Theta* algorithm. Many ATCOs were surprised by the action performed by the UAS in light of geofence activations.
**Verdict:** Non-compliant

## A.3 MINIMIZE THE COMPLEXITY OF AUTONOMOUS SYSTEMS

**(12) Ensure logical consistency across features and modes.**

> "*Inconsistencies in the logical functioning of the system dramatically increase complexity. Differences in operational logic, display of information, and different sequences of inputs that are not directly necessary for the operation of that mode or feature should be reduced or eliminated.*" (Endsley [31, p. 19])

**Assessment:** The functionality of individual UAS commands and the way that UAS would navigate were different between the nominal and contingency mode of operations.
**Verdict:** Partially compliant

**(13) Minimize logic branches.**

> "*Minimize complexity by reducing the linkages and conditional operations contained in the autonomy, avoiding modes with their multiple-branch logic as much as possible.*" (Endsley [31, p. 19])

**Assessment:** Multiple-branch logic was not used in the interface.
**Verdict:** Fully compliant

**(14) Map system functions to the goals and mental models of users.**

> "*A clear mapping between user goals and system functions should be present, minimizing the degree to which operators need to understand the underlying software or hardware linkages in order to operate or oversee the autonomy.*" (Endsley [31, p. 19])

**Assessment:** Functions and goals were mapped clearly. A*/Theta* path planning objectives and boundaries for UAS flight were visually displayed. Changes in states were clearly distinguishable. The effect of UAS intervention tools and subsequent traffic behavior were mapped directly.
**Verdict:** Fully compliant

**(15) Minimize task complexity.**

> "*Task complexity (the number of actions needed to perform desired tasks and the complexity of those actions) should be minimized, reducing sequence errors and cognitive load in interacting with the autonomy.*" (Endsley [31, p. 19])

**Assessment:** The complexity of actions required to complete a task was kept to a minimum, however, the tools provided to achieve the desired goal required a high number of actions in the active control strategy.
**Verdict:** Partially compliant

## A.4 SUPPORT SITUATION AWARENESS

**(16) Integrate information to support comprehension of information (Level 2 SA).**

> "*As attention and working memory are limited, autonomy that displays information that is processed and integrated to support operator understanding of data in relation to key goals will be beneficial.*" (Endsley [31, p. 19])

**Assessment:** The information displayed about the current state of the autonomous system was sufficient in facilitating understanding of the goals of the system.
**Verdict:** Fully compliant

**(17) Provide assistance for SA projections (Level 3 SA).**

> "*Autonomy support for projecting possible and likely future events and states of the system should directly benefit SA, particularly for less experienced operators.*" (Endsley [31, p. 19])

**Assessment:** The information displayed provided some clues about the potential future state of the UAS guided by the autonomous system, such as indications of remaining fuel, areas with high wind, conflict areas, and planned routing of the UAS and crewed aircraft.
**Verdict:** Fully compliant

**(18) Use information filtering carefully.**

> "*While extraneous information should not be shown to operators, autonomy should refrain from filtering information needed for prioritizing across operator goals or for forming projections of possible upcoming events or problems.*" (Endsley [31, p. 20])

**Assessment:** The ATCO was able to decide which information to see and which not and could apply filters as they desired.
**Verdict:** Fully compliant

**(19) Support assessments of confidence in composite data.**

> "*Autonomy should explicitly represent its confidence level when data are fused to form higher levels of SA or decisions to include the effects of underlying data and fusion algorithms.*" (Endsley [31, p. 20])

**Assessment:** No such functionality was included in the system.
**Verdict:** Non-compliant

**(20) Support system reliability assessments.**

> "*In that trust and effective judgments on when to intervene in the performance of system autonomy depend on an accurate assessment of its reliability for performing the task at hand, interfaces should make explicit how well the autonomy is currently performing and its ability to handle upcoming or contemplated tasks.*" (Endsley [31, p. 20])

**Assessment:** No such functionality was included in the system.
**Verdict:** Non-compliant

# B

# INTERACTIVE TRAINING SCRIPT

*This appendix contains the experiment briefing and interactive training script for the human-in-the-loop experiments performed in Chapter 5 to evaluate the last version of the interface design. The experiment consisted of a total of seven training scenarios, in which participants were asked to follow the instructions closely, and three experiment scenarios, which are not included in this appendix. A screenshot of each of the scenarios is provided after the instructions.*

## B.1 INTRODUCTION

Thank you for participating in this experiment! The experiment aims to investigate the influence of Uncrewed Aircraft Systems (UAS) traffic on the work behavior of tower control. The experiment consists of four parts. First, you will be provided with a background to the experiment, an explanation of the tasks you have to fulfill during the experiment, and an overview of the experiment setup. Secondly, you will be presented with a few pre-experiment questions regarding your participant ID and work position. Thirdly, you will be provided step-by-step instructions on the training scenarios, and the experiment runs, and after the completion of each scenario, including the training scenarios, you will be asked to answer some questions. After completing all seven training scenarios and three experiment scenarios, you will be asked to submit your experiment data. Finally, you will fill in a post-experiment survey. If you have any questions during the experiment preparation and training, feel free to ask the experimenter(s).

## B.2 PROBLEM BACKGROUND

UAS operations in urban areas are expected to significantly increase in number in the near future due to their large potential in medical deliveries, infrastructural inspections, and surveillance missions. However, as indicated by several incidents, the increase in UAS traffic could threaten crewed air traffic operating at low altitudes, such as emergency helicopter flights and crewed aircraft during landing and take-off.

The SESAR Joint Undertaking initiated the U-space concept in 2017 to safely manage increased UAS traffic in Very Low-Level airspace (below 500 feet above ground level), which relies on a set of services based on a high level of digitalization and automation. It is envisioned that some if not most of the Very Low-Level airspace will be assigned to U-space to manage UAS traffic.

A critical tool that allows ATC to reclaim airspace from U-space back to ATM temporarily is a concept called Dynamic Airspace Reconfiguration (DAR). Dynamic geofences are used to pose temporary restrictions on UAS traffic in specific U-space volumes to ensure segregation between crewed and uncrewed traffic. However, UAS are vulnerable to adverse environmental conditions such as wind and more prone to failures than crewed aircraft, which might result in their incapability to respond to the imposed geofence constraints in a timely and safe manner.

This research investigates the impact of UAS on tower controllers and addresses potential procedures that could reduce the workload controllers experience during a contingency event. This concept will be applied to a hypothetical use case of Rotterdam The Hague Airport, which has recently opened up its lower airspace (below 500 feet above ground level) to UAS flight operations managed by U-space. Most of the airspace has been assigned to U-space to maximize the number of UAS missions that can be conducted within the cities of Rotterdam and The Hague.

## B.3 EXPERIMENT TASKS AND GOALS

In this experiment, it is your task to separate UAS traffic in Very Low-Level airspace (below 500 feet or 150 meters) from crewed traffic around Rotterdam The Hague Airport. You will be presented with various traffic scenarios that are important to the interaction of tower control with UAS traffic. During the experiment, you are responsible for activating and deactivating geofences to shield certain areas from UAS traffic mainly as a tactical segregation tool rather than a separation tool. The UAS traffic will respond dynamically to the imposed geofence constraints. Moreover, additional functionalities allow you to direct individual UAS, such as loiter commands. Note that the activation/deactivation of geofences and the aforementioned commands are the only means to manage UAS traffic.

In this experiment, you will not be able to take control over crewed aircraft, as the traffic flow has already been optimized and deconflicted from other crewed aircraft. UAS traffic is fully managed by an automated U-space system, which relays the DAR changes to UAS pilots in real time. In this scenario, the responsibility to adapt the flow of air traffic to DAR rests entirely on the U-space system. Therefore, crewed aircraft will not change their routing due to DAR changes, only UAS.

Please consider the following two goals during the execution of your control tasks:

1. Ensure a **horizontal separation of 1,000 meters or a vertical separation of 500 feet (150 meters)** between **crewed and UAS traffic** at all time;
2. **Minimize disruptions** to UAS traffic, including **additional travel time and mission failures**, especially high-priority UAS.

## B.4 EXPERIMENT SETUP

The experiment involves using an online interface simulator which you can access online, preferably on Google Chrome or Mozilla Firefox as a browser, via:

- Link: `http://dronectr.tudelft.nl/sw-exp-v1.1/`
- Participant ID: `610001`.

After you open the simulator page, please do not close it unless instructed to do so, which will be after completing all scenarios. You can switch tabs in your browser between the experiment page and this survey. Please note that a full screen for the experiment with high screen brightness is required, as well as that you use a computer mouse.

Before the actual experiment starts, you will first be guided through seven training scenarios to familiarize yourself with the display. The training scenarios will build up in task complexity and have more features. The last training scenarios present you with mixed traffic scenarios similar to the experiment scenarios with a full set of the aforementioned elements. Afterward, three experiment runs will be conducted, taking fifteen minutes each.

At the end of each simulation run (including training runs), a ZIP file consisting of simulation data will be directly downloaded to your local computer.

## B.5 TRAINING SCENARIO 1

This training scenario demonstrates crewed traffic and does not yet contain any geofences or UAS traffic. The scenario takes four minutes. Notice that crewed traffic routes cannot be influenced during the simulation runs and aircraft are assumed to remain properly separated from each other. The interface provided to you is made up of several components, which are explained below.

### B.5.1 Map View

This view depicts air traffic movements in the form of blips. Each crewed aircraft blip shows trailing dots, flight labels, and separation rings. The flight label specifies the

- Aircraft call sign;
- Altitude in feet;
- Indicated airspeed (left); and
- True airspeed (right) in knots.

Note the difference in the green tone of the color of IFR and VFR icons. The separation ring is 1,000 meters. Pressing the left mouse button on the aircraft blip shows the intended flight plan and the green minimum separation indication, which extends 1,000 meters perpendicular to the flight plan. Messages regarding new flights will be prompted at the bottom left corner of the map view as early as 120 seconds before the flight.

### B.5.2 Flight Information View

This view contains information about crewed aircraft in the form of flight strips which list:

- The flight callsign;
- The indicated airspeed in knots (IAS);
- The flight rule (TYPE);
- The altitude in feet (ALT); and
- The heading in degrees (HDG) of an aircraft.

The flight strips of arriving traffic are placed at the top half of the panel (yellow), with the earliest arrival stacked at the bottom. The flight strips of departing traffic are at the bottom (blue) with the earliest departure stacked on the top. The flight strips of Helicopter Emergency Medical Services (HEMS) flights are indicated as red, have a call sign beginning with “LIFELN”, and fly at Very Low-Level altitude.

### B.5.3 Information Layers Panel

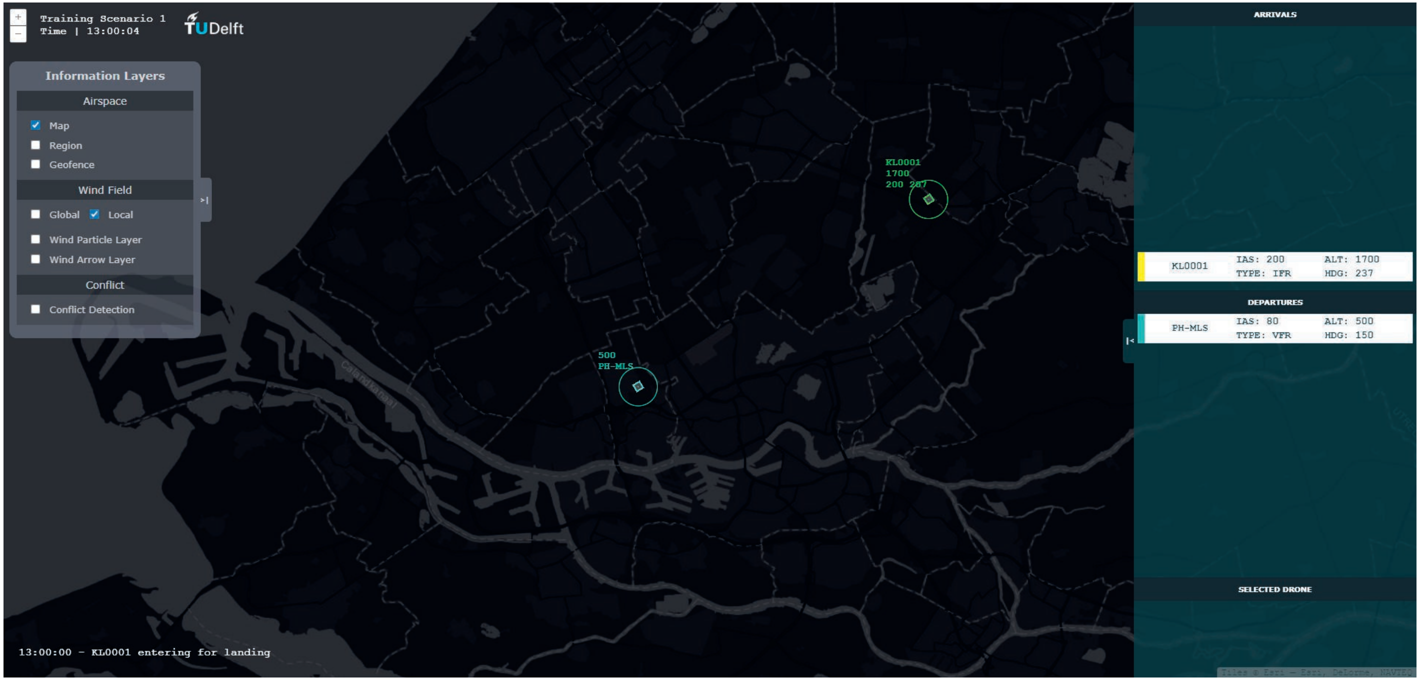
This tool allows you to show more information about the airspace, the wind situation and highlight conflicts. In this training scenario, note that the Map checkbox shows/hides a background map of the Rotterdam Area.

### B.5.4 Tasks

Please make sure to test all interactions with the crewed traffic information provision during the first training scenario:

1. Drag the map view using your left mouse button and then zoom it with the scroll wheel.

2. Observe the differences in flight labels and color of aircraft icons of IFR and VFR flights.
3. Observe the messages at the bottom left of the map view.
4. Hovering over a crewed aircraft icon will highlight its corresponding flight strip in the flight information view, and vice versa; hovering over a flight strip will highlight the matching aircraft in the map view.
5. Click on the crewed aircraft icon to show its intended route (a yellow solid line for IFR flights and a dashed line for VFR and medical helicopter flights) and the corridor of the corresponding aircraft (the green area around the intended route) in the map view. It can be deselected by either clicking the icon again, the background map, or selecting a different vehicle.
6. Clicking on an individual flight strip in the flight information view is another way to check the intended route of the corresponding aircraft.
7. Click the Map checkbox to hide the map of the Rotterdam area in the background and click again to display it.
8. Click the flight label on the marker of crewed aircraft with the left mouse button and drag it around on the map view.
9. Collapse both the flight information panel and the information layers panel by left-clicking the triangle-like icon with the mouse and then reopening the panels by clicking the vertical line icon.



Training Scenario 1
Time | 13:00:04

**Information Layers**

Airspace
☑ Map
☐ Region
☐ Geofence

Wind Field
☐ Global ☑ Local
☐ Wind Particle Layer
☐ Wind Arrow Layer

Conflict
☐ Conflict Detection

ARRIVALS

KL0001 IAS: 200 ALT: 1700
TYPE: IFR HDG: 237

DEPARTURES

PH-MLS IAS: 80 ALT: 500
TYPE: VFR HDG: 150

SELECTED DRONE

13:00:00 - KL0001 entering for landing

Figure B.1: Training scenario 1 at initialization.

## B.6 TRAINING SCENARIO 2

This training scenario demonstrates only UAS traffic. UAS are assumed to maintain sufficient separation among each other through UTM system actions. The scenario takes five minutes.

### B.6.1 UAS INFORMATION

The icon of a UAS symbolizes its vehicle type (“quadcopter” or “fixed wing”). Concerning the color of the UAS:

- A yellow icon means a high-priority mission, such as medical delivery. High-priority UAS should be diverted to a minimal extent.
- A light blue icon means a low-priority mission, such as package delivery.

UAS can be selected using the left mouse button, which loads the UAS flight strip. The UAS flight strip contains information about:

- UAS mission type (delivery, medical delivery, surveillance);
- UAS vehicle type;
- Heading in degrees (HDG);
- Priority state (high or low);
- Indicated airspeed in knots (IAS);
- Ground speed (GSms) in knots;
- Altitude (ALT) in feet;
- Remaining flight time in minutes (FT); and the
- Potential delay in flight time (DT) in minutes.

Moreover, upon selecting a UAS blip with the left mouse button, two boundaries appear:

- *Mission boundary*: Indicates the area where the UAS is allowed to operate due to its mission constraints.
- *Endurance region*: Indicates how far the UAS can divert from the current position given its endurance.

Note that the flight route of surveillance UAS missions is defined by several waypoints that must be visited to complete its mission. And that package delivery and medical delivery missions are not constrained by a mission boundary.

When a UAS endurance runs out, it will go into a contingency state. In this mode, the UAS icon turns red and the UAS will automatically find the closest reachable landing site. The interface will display a red boundary area that defines the maximum distance the UAS can reach. Reachable landing sites are indicated as orange dots.

### B.6.2 UAS-SPECIFIC COMMANDS

A right-click on a UAS icon with your mouse will present four options for issuing commands:

- *Loiter*: The UAS will stop or orbit around its current position, depending on the vehicle type. A red exclamation mark on the UAS icon indicates the loiter status.
- *Resume flying*: To stop loitering, you need to select the resume flying command.
- *Contingency*: With this command, the UAS enters its contingency state. In this state, an additional "direct to" command is available for you to select another UAS landing site.
- *Land immediately*: Selecting this command will make the UAS perform an emergency landing at its current location.

### B.6.3 TASKS

Please make sure to test all interactions with UAS traffic during this training scenario:

1. Hover your cursor on different UAS icons to observe the highlighting state.
2. Select a high-priority UAS by clicking it with your left mouse button.
3. Observe its endurance regions and its flight plans.
4. Observe the UAS flight information strip at the bottom of the flight information view.
5. De-select the UAS by clicking the icon again, on a different UAS icon, or on the background map. Repeat the steps for the low-priority delivery UAS.
6. Select a surveillance UAS by clicking with your left mouse button.
7. Observe its mission boundary and inner endurance region.
8. Select any UAS and right-click the icon with your mouse to view the command options.
9. Left-click the loiter option and observe the shrinking of the endurance region as the UAS is loitering.
10. Select any UAS and select the "resume flying" command by repeating the same step for selecting the "loiter" command. Observe the change in the icon display.
11. Select any UAS and select the "contingency" command for that UAS.
12. For the UAS in step 11, observe the change in the icon color, the transition from its nominal mission boundary/endurance region(s) to the landing boundary, the orange landing site dots, and the intended route to the closest landing site.
13. Select any UAS, repeat step 11, and then select another landing site by right-clicking with your mouse. Observe the change in the intended route.
14. Select any UAS and select the "land immediately" command. Observe the UAS icon disappearing from the map view and the flight strip from the flight information panel.

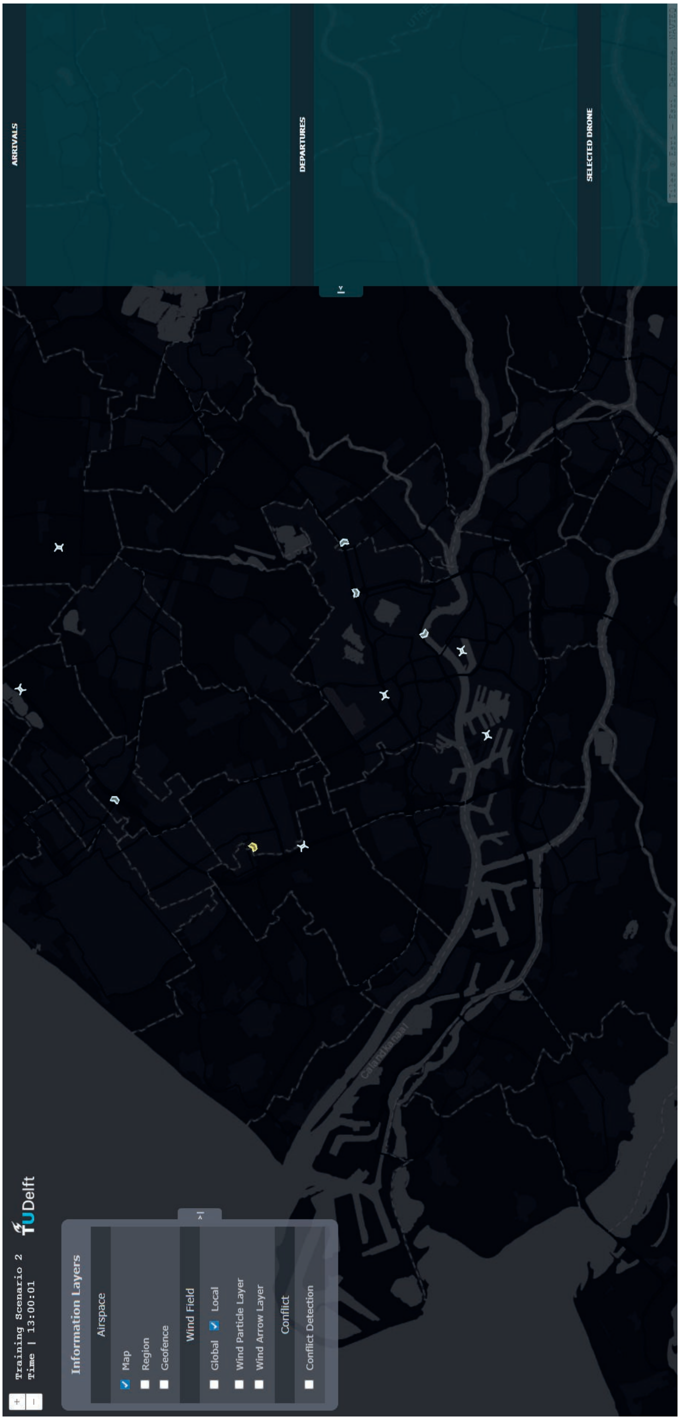


Figure B.2: Training scenario 2 at initialization.

## B.7 Training Scenario 3

This training scenario demonstrates the interaction of geofences with UAS traffic in the simulation. These geofences are your main interaction tool during the experiment to restrict certain regions from UAS traffic. The scenario takes five minutes.

### B.7.1 Geofences

The geofences are organized in a grid of squares aligned with the orientation of the runway. The blue area at the center of the map view is the runway area, which is permanently geofenced. Extending upwind and downwind of the runway are, so called, ILS geofences. These are shaped to cover the part of the Instrument Landing System (ILS) obstacle clearance area that is in Very Low-Level airspace (below 500 feet above ground life). Finally, transfer corridor geofences, which can be opened and closed using a simple activation command, are situated in areas near the runway to allow UAS to pass.

Geofences can be activated and deactivated using several keyboard and mouse-click combinations:

- Control key and hovering your cursor with your mouse over the geofences will highlight them.
- Individual geofences are activated by left-clicking on it with your mouse and pressing the control key on your keyboard simultaneously.
- To activate multiple geofences at once, you can click with the left mouse button while pressing down the control key and hover your mouse over the geofences.
- Individual geofences are deactivated by clicking it with the right mouse button and hitting the control key.
- To deactivate multiple geofences at once, you can click with the right mouse button while pressing down the control key and hover your mouse over the geofences.

### B.7.2 UAS Responses to Geofences

Active geofences that contain UAS traffic within will be marked orange. UAS traffic will leave the activated geofence by the fastest point of exit which lies within the smaller of the two: the endurance region or mission boundary. The applied exit strategy depends on the mission type of the UAS.

Depending on the number of active geofences, UAS may be unable to replan a route around them. In this case, UAS will:

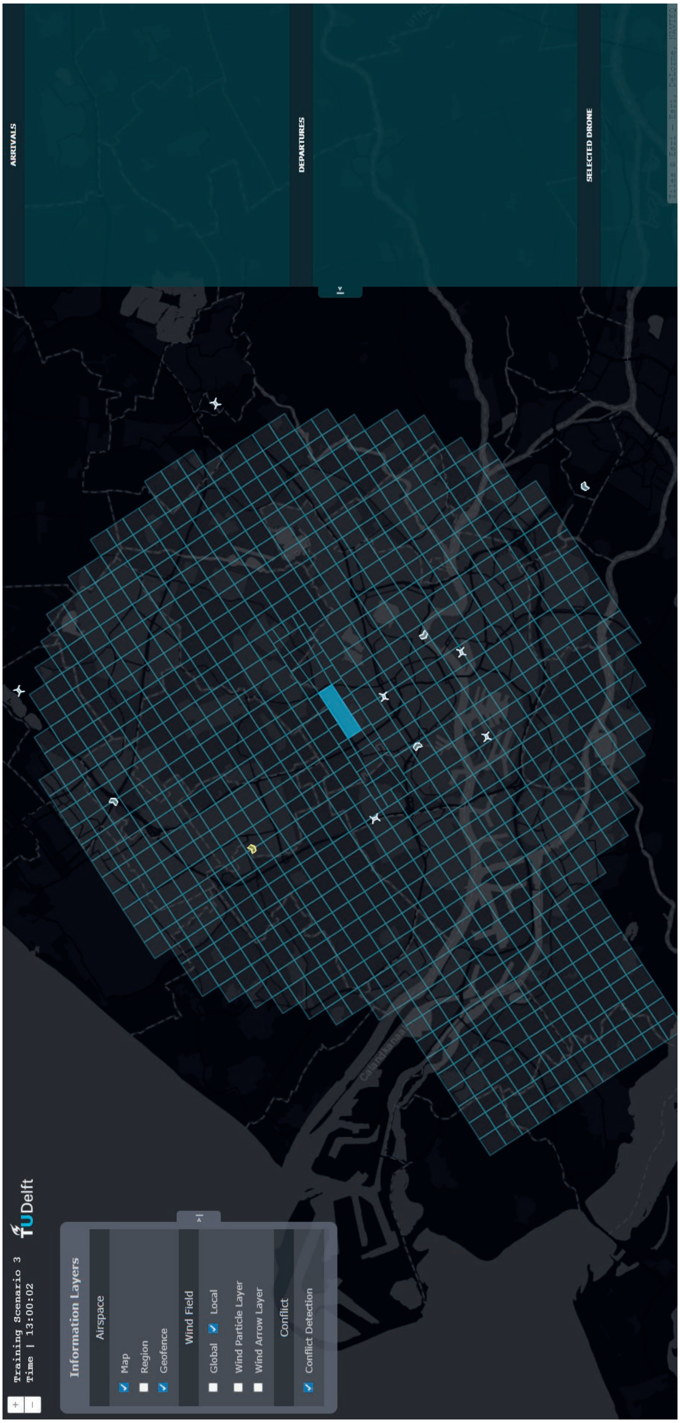
1. Fly to the closest non-geofenced point to the next waypoint on their mission, and
2. Start loitering until one or more of the geofences are deactivated.

If a geofence that contains one of the waypoints is activated, the UAS will fly to the closest point of entrance and loiter until the geofence is deactivated. Moreover, UAS will not respond to any geofence constraints when they are in a contingency state.

### B.7.3 TASKS

Please make sure to observe the geofence configuration around the runway and test all interactions with the geofence during the second training scenario:

1. Press the control key and move your mouse to hover the paintbrush over the geofence to highlight them.
2. Press the control key and left-click with your mouse on a non-active geofence that will activate it.
3. Press the control key and right-click with your mouse on an active geofence to deactivate it.
4. To activate/deactivate multiple geofences, you can drag your mouse while pressing the control and left/right mouse buttons.
5. Please draw the permanent geofences that you prefer to shield UAS traffic from crewed operations.
6. For a delivery UAS, activate one or more geofence(s) along its current route.
7. Observe the updated flight plan of the delivery UAS in step 5, and the endurance region decreases as less endurance is available for re-routing. Also, observe the expected travel time and delay on the information strip change. Deactivate to observe what happens.
8. Activate the geofence a delivery UAS is currently in. Notice the fastest exit point and the orange geofence indicating the pending state. Notice the geofence turning blue (active) when the UAS leaves the geofence.
9. Repeat steps 5-6 for a surveillance UAS.
10. For a surveillance UAS, activate a row of geofences along the entire width of the mission boundary region (short axis) right ahead of the UAS.
11. Activate the geofence a surveillance UAS is currently in. Notice the fastest exit point and the orange geofence indicating the pending state. Notice the geofence turning blue (active) when the UAS leaves the geofence.
12. Keep activating geofences around the same surveillance UAS as step 13 and observe what happens.
13. Activate the geofences the waypoints of a surveillance UAS are in.
14. Initiate a UAS contingency command for a UAS of your choice and then activate some geofences between its current location and the selected landing site. Notice that the UAS will fly through the geofences.



Training Scenario 3
Time | 13:00:02

Information Layers

Airspace
☑ Map
☐ Region
☑ Geofence

Wind Field
☐ Global ☑ Local
☐ Wind Particle Layer
☐ Wind Arrow Layer

Conflict
☑ Conflict Detection

Figure B.3: Training scenario 3 at initialization.

## B.8 TRAINING SCENARIO 4

This training scenario demonstrates the wind field affecting UAS traffic in the simulation.

### B.8.1 WIND FIELD

The simulation uses a two-dimensional wind field which affects all traffic in the simulations. The Wind Field overview of the Information Layers panel provides multiple selection tools for portraying wind parameters in the simulation:

- *Global and local toggle*: Selecting Global shows the wind field across the entire simulation area, whereas selecting Local shows a local wind field in relation to a UAS mission, and is only visible when a UAS is selected.
- *Wind Particle Layer*: Depicts wind direction and strength via moving particles.
- *Wind Arrow Layer*: Depicts wind direction and strength in the form of an arrow with distinct colors. Orange and Red arrows indicate high and excessive wind speeds, respectively.

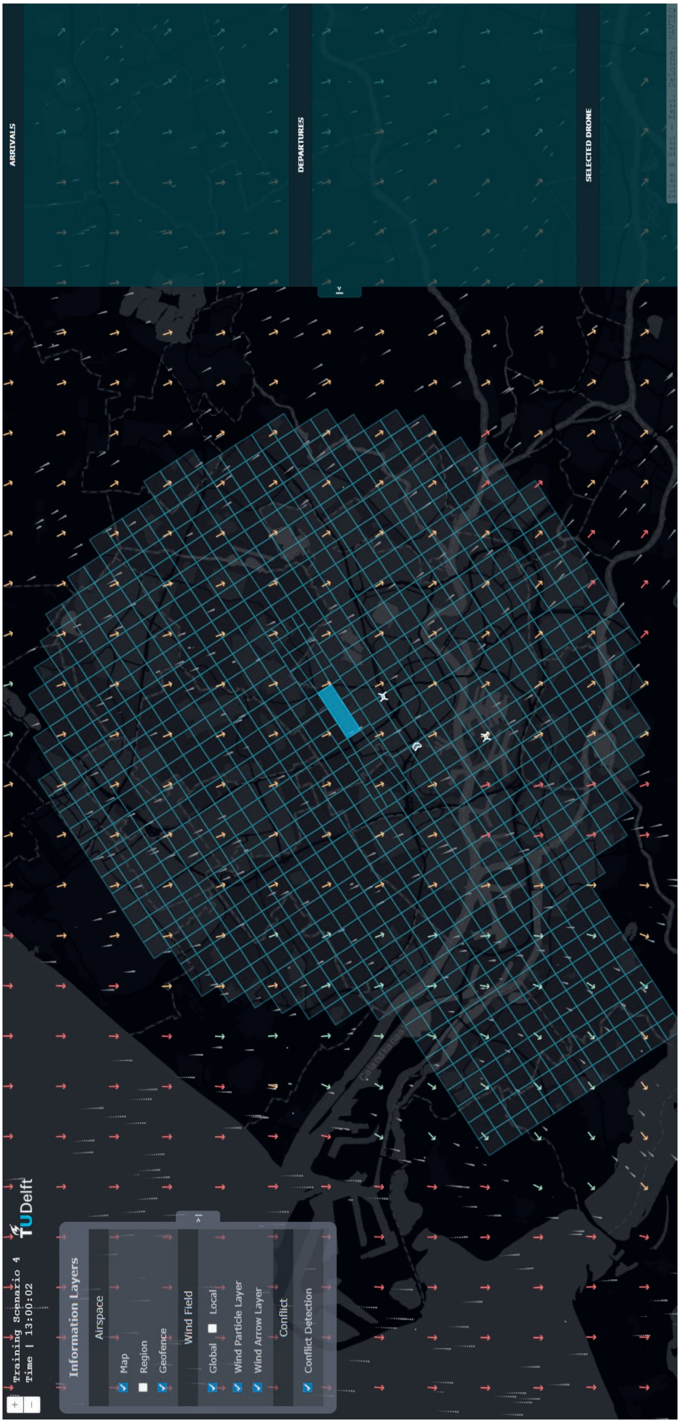
### B.8.2 UAS INTERACTIONS WITH THE WIND FIELD

When a UAS passes an area of excessive wind (indicated by a red arrow in the Wind Arrow Layer), it will not be able to withstand the high wind and automatically initiate its contingency mode. Moreover, a UAS will experience significant delays to its route when passing an area of high wind (indicated by an orange arrow in the Wind Arrow Layer).

### B.8.3 TASKS

Please make sure to test all interactions with the wind depictions:

1. Observe the global wind field.
2. Hide the wind particles by left-clicking the Wind Particle Layer checkbox under the wind field tab in the information layers panel.
3. Hide the wind arrows by left-clicking the Wind Arrow Layer checkbox under the wind field tab in the information layers panel.
4. Select the local wind field option by left-clicking the local checkbox on local under the wind field tab in the information layers panel.
5. Select the wind arrows and wind particles checkboxes.
6. Select each of the UAS on display and check if its flight plan will fly over a high-speed region (red arrows).
7. If you find a UAS, especially a high-priority medical delivery UAS, that will fly over a high-speed region, try to use geofences to reroute the UAS away from those regions.
8. Hide the wind particles and select a UAS again to observe only the wind arrows.
9. Now hide the wind arrows and select the wind particles layer again. Select a UAS to view the wind particles.



Training Scenario 4
Time | 13:00:02

**Information Layers**

Airspace
- ☑ Map
- ☐ Region
- ☑ Geofence

Wind Field
- ☑ Global ☐ Local
- ☑ Wind Particle Layer
- ☑ Wind Arrow Layer

Conflict
- ☑ Conflict Detection

Figure B.4: Training scenario 4 at initialization.

## B.9 TRAINING SCENARIO 5

This training scenario combines all elements of previous training scenarios and involves one IFR flight, one VFR flight, and one HEMS flight along with 20 UAS flights. The scenario takes six minutes.

### B.9.1 CONFLICT DETECTION

The Conflict Detection tool is a geofence-based method for detecting possible conflicts between UAS and crewed aircraft at the horizontal level. The tool is activated by selecting the conflict detection checkbox on the information layers panel. Potential conflicts between UAS and crewed aircraft are highlighted in:

- Orange, when the lateral separation is larger than 2,000 meters or
- Red, when the lateral separation is lower than 2,000 meters as an alert.

Hovering over the alerted geofence will highlight conflicted aircraft and UAS. Left-clicking the geofence will display the intended route and boundaries of the crewed aircraft and UAS. Right-clicking the geofence will display information about the estimated separation level and time of impact

### B.9.2 AIR CORRIDOR

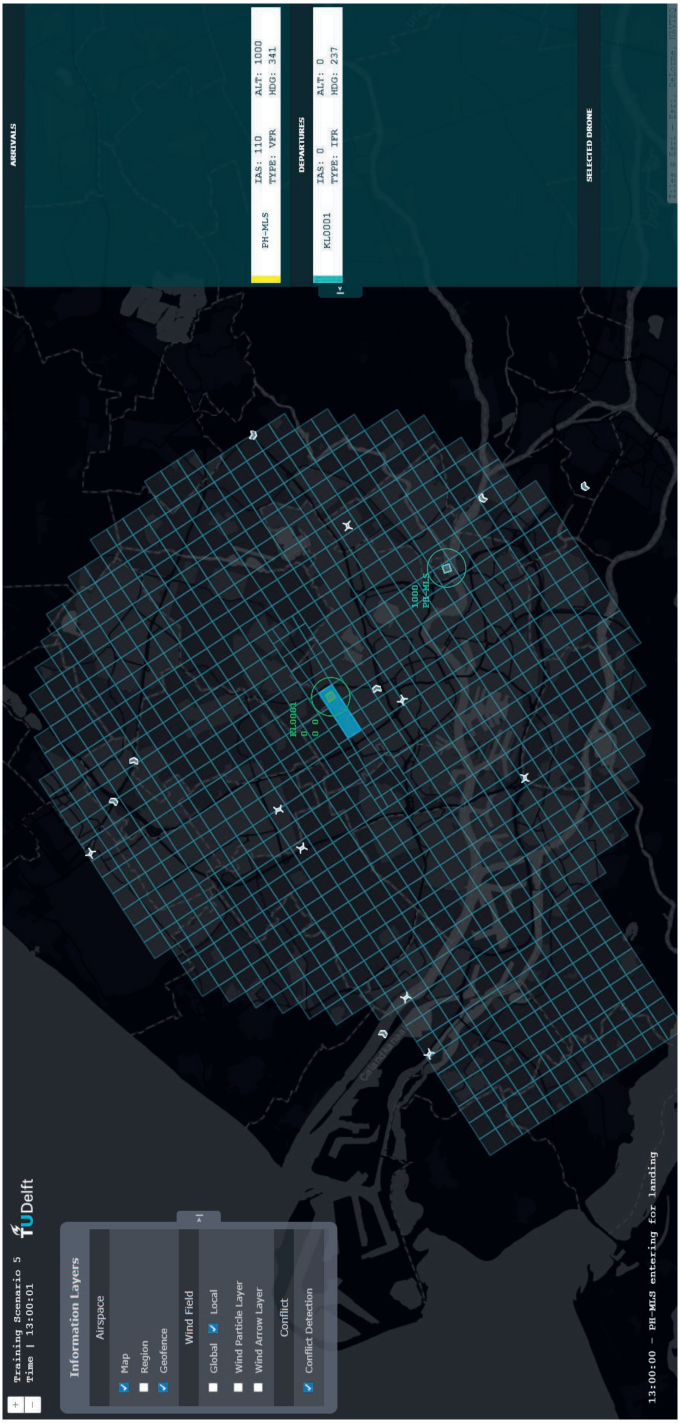
Air Corridors are simple means to activate an area of geofence grids along the path of a selected crewed aircraft. They are activated by pressing the control key and clicking the left mouse button, and deactivated by pressing the control key and clicking the right mouse button.

### B.9.3 TASKS

Please make sure to test all interactions with the conflict detection tool and the air corridor:

1. Hide the alerts by unchecking the Conflict Detection box in the information layers panel.
2. Show the alerts by checking the box in the panel.
3. Hover your mouse over any alerted (red or orange) geofence and then observe the highlighted crewed aircraft and UAS.
4. Select the alerted geofence by clicking the left mouse button and view the intended route and boundaries of both the crewed aircraft and UAS.
5. View the estimated separation level and time of impact info by clicking the right mouse button.
6. Activate the alerted geofence and notice the geofence turns red/orange to blue.
7. Observe what happens to the corresponding UAS in conflict.
8. Observe if there are any new alerts after activation of the alerted geofence.

9. Deactivate the geofences and observe what happens next.
10. You can now continue to resolve any conflicts using this tool.
11. Select a crewed aircraft that has been alerted to be possibly in conflict with UAS and activate its corridor. Observe what happens to the corresponding conflicted UAS.
12. Deactivate some of the activated geofences resulting from the corridor activation.
13. Deactivate the corridor and observe what happens to the alerts and associated UAS.



Training Scenario 5
Time | 13:00:01

Information Layers

Airspace
☑ Map
☐ Region
☑ Geofence

Wind Field
☐ Global ☑ Local
☐ Wind Particle Layer
☐ Wind Arrow Layer

Conflict
☑ Conflict Detection

ARRIVALS

PH-MLS IAS: 110 ALT: 1000
TYPE: VFR HDG: 341

DEPARTURES

KL0001 IAS: 0 ALT: 0
TYPE: IFR HDG: 237

SELECTED DRONE

13:00:00 - PH-MLS entering for landing

Figure B.5: Training scenario 5 at initialization.

## B.10 Training Scenario 6

This scenario demonstrates the airspace regions and UAS transfer corridors involving crewed and uncrewed traffic. The scenario takes eight minutes. The airspace regions (circle with a rectangle) outline the control zone boundaries, final approach areas for IFR traffic, and visual approach areas for VFR traffic. Moreover, at around four minutes, two UAS scheduled to use the corridors will appear.

### B.10.1 UAS Transfer Corridors

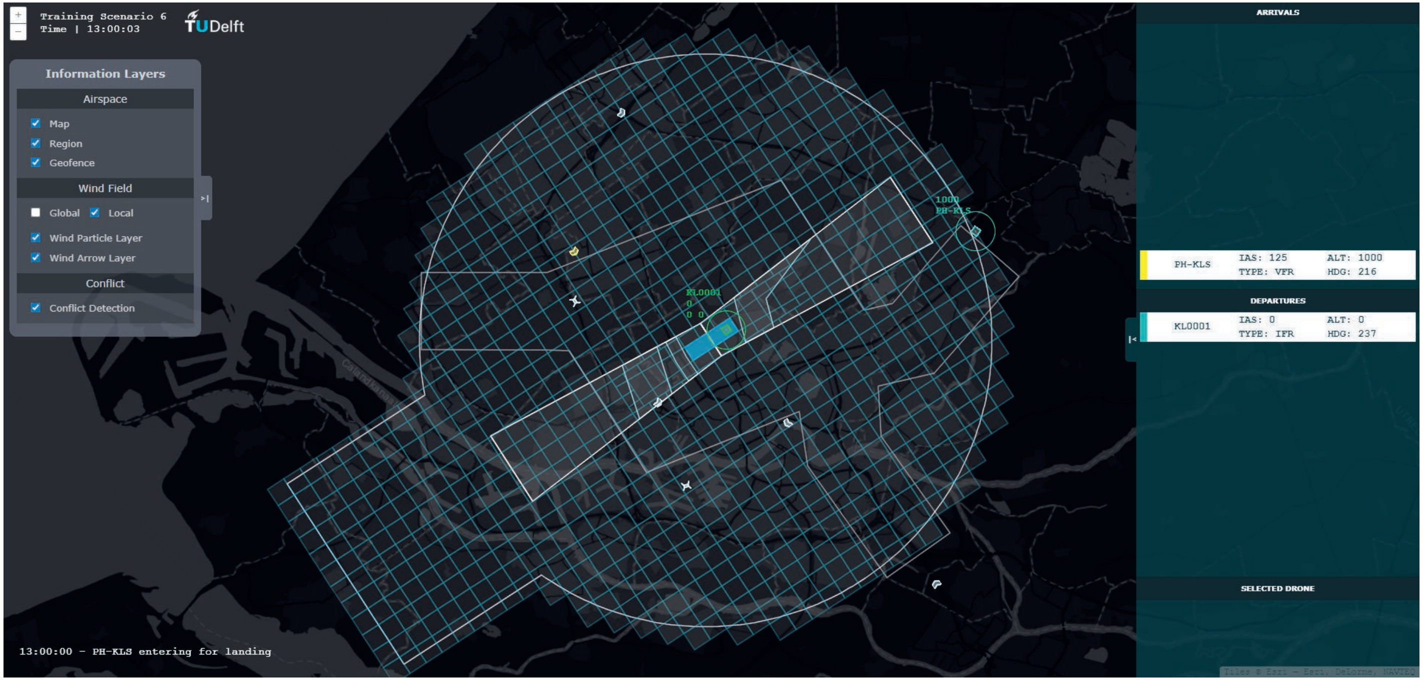
UAS transfer corridors are included to quickly activate or deactivate geofences near the runway to allow highway and railway UAS surveillance operations to pass. Activating a UAS transfer corridor will activate all of the intersecting geofences at once. Interactions with the UAS transfer corridors can be done as follows:

- Hovering over the UAS transfer corridor with your mouse will highlight the UAS that are scheduled to pass through the corridor.
- To activate the corridor, press the control key while clicking the left mouse button on the corridor.
- To deactivate it, you need to use the right mouse button on the corridor with the control key pressed as well.

### B.10.2 Tasks

Please make sure to test all interactions with the UAS transfer corridors and airspace regions:

1. Hide or show the airspace regions and the UAS transfer corridors by checking and unchecking the Region checkbox under the Airspace tab in the information layers panel.
2. Hover your cursor over the UAS transfer corridors and observe the highlighted UAS if there are any.
3. Activate the corridor to observe what happens to the UAS traffic.
4. Deactivate the corridor.



Training Scenario 6
Time | 13:00:03

**Information Layers**

Airspace
- ☑ Map
- ☑ Region
- ☑ Geofence

Wind Field
- ☐ Global ☑ Local
- ☑ Wind Particle Layer
- ☑ Wind Arrow Layer

Conflict
- ☑ Conflict Detection

13:00:00 - PH-KLS entering for landing

ARRIVALS

| | | |
|---|---|---|
| PH-KLS | IAS: 125<br>TYPE: VFR | ALT: 1000<br>HDG: 216 |

DEPARTURES

| | | |
|---|---|---|
| KL0001 | IAS: 0<br>TYPE: IFR | ALT: 0<br>HDG: 237 |

SELECTED DRONE

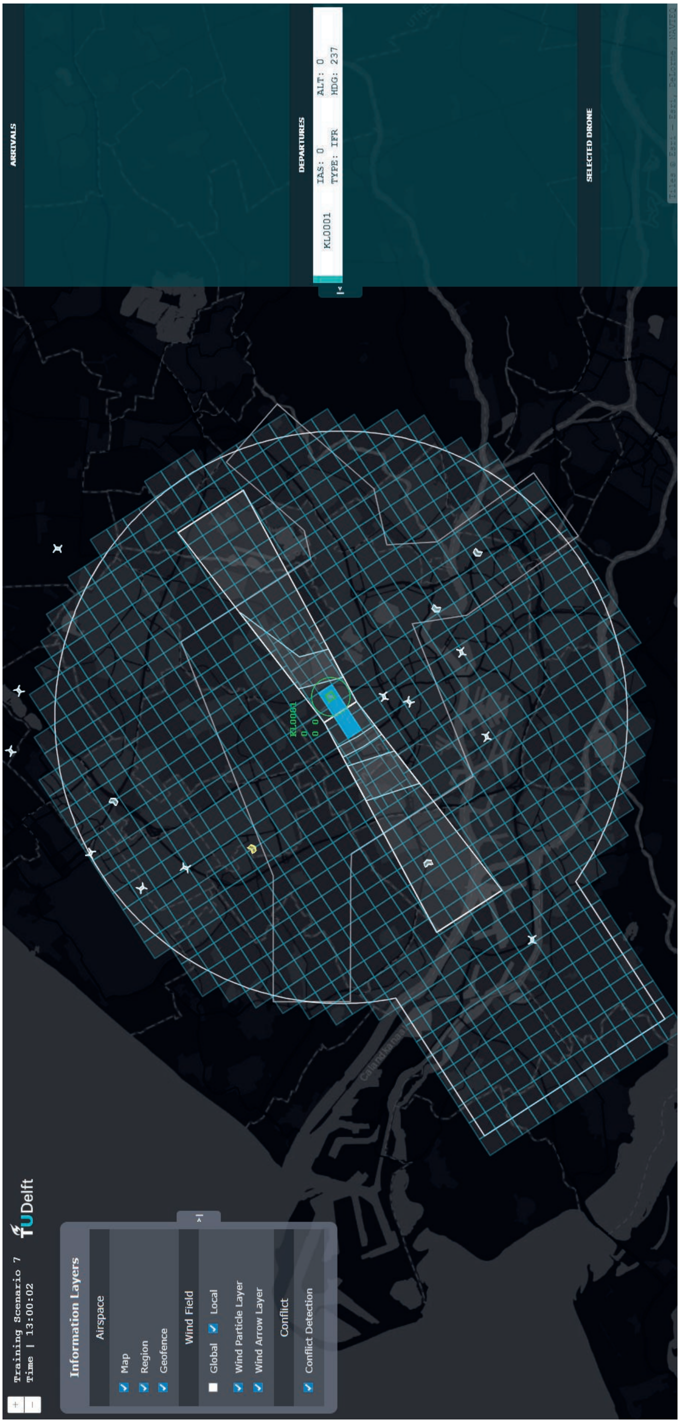
Figure B.6: Training scenario 6 at initialization.

## B.11 Training Scenario 7

You have completed the first six training scenarios, aimed at interacting with different interface features. The final training scenario allows you to practice performing your experiment tasks in a scenario similar to the experiment scenarios. From this point on, you will not get any instructions per scenario. To remind you of your control tasks, your goals are to:

1. Ensure a horizontal separation of 1,000 meters horizontally and 150 meters / 500 feet vertically between crewed traffic and UAS traffic;
2. Minimize disruption to UAS traffic, including additional travel time and mission failures, especially high-priority UAS.

This scenario takes ten minutes involving two IFR flights, a VFR flight, a HEMS flight, and twenty UAS flights.



Training Scenario 7
Time | 13:00:02

**Information Layers**

Airspace
- ☑ Map
- ☑ Region
- ☑ Geofence

Wind Field
- ☐ Global ☑ Local
- ☑ Wind Particle Layer
- ☑ Wind Arrow Layer

Conflict
- ☑ Conflict Detection

ARRIVALS

DEPARTURES

KL0001 IAS: 0 ALT: 0
TYPE: IFR HDG: 237

SELECTED DRONE

Figure B.7: Training scenario 7 at initialization.

# Acknowledgments

It still feels surreal to be in the position to write these words at the finish line of a long journey toward obtaining my Ph.D. Out of all the content provided in this book, I believe this section is the most important one, as I would not be here without the contributions of all the people mentioned here, who deserve special recognition.

First and foremost, I would like to thank Max and Clark, my promotors, who have shown incredible trust and flexibility throughout my journey. I know that my situation as an external Ph.D. candidate working completely remotely was not easy to administer, which is why I am all the more grateful to both of you for being proactive in finding ways to fit my situation. Max, your encouraging attitude always left me motivated and empowered to keep pushing, even when I had difficult obstacles to face. And Clark, without your continued support and guidance I would not have been able to complete my doctoral journey. I remember us discussing ways to incorporate my frankly a bit too ambitious ideas into a research proposal. It took me a long time to understand the concept of *less is more* when it comes to research, but I think I got it now. Thank you for being there every step of the way and knowing just what was needed next for me to continue.

My gratitude also goes out to the Master's and Ph.D. students at the Control and Simulation department who supported this research. Daan, your tremendous skill and ingenuity in turning a generic idea into a full simulation tool in a matter of weeks was truly inspiring. Moreover, your ability to adapt to the challenges presented by the COVID-19 pandemic and develop a fully remote experiment is what made the first part of this research so successful. It was thanks to you that we won Best Paper in Human Factors in 2021! Yiyuan, you fully convinced me of your programming genius. The quality and dedication you put into developing the simulator to conduct the follow-up experiments rivals that of commercial simulation systems. Wherever your career path ends up taking you, rest assured that your future employer is lucky to have you. Suyi, it was an absolute pleasure to work with you. I admired your steadfastness and willingness to carry on with the remote simulations, even though I was only available to help you out half of the time. Although I am not sure where you are now and how well you are recovering, I sincerely hope that same spirit guides you back to health.

Next, I would like to acknowledge my former colleagues at CRIDA who directly contributed to this research. Pablo, you have been a mentor to me since the very beginning of my work. Thank you for taking me under your wing and allowing me to grow as an independent researcher. Without your continued support I would not have been able to develop my ideas and lead the PJ34 AURA simulations. José María, thank you for sacrificing so much time in setting up the simulator and for being so insistent with the supplier to provide us with the necessary adaptations. Otherwise, I don't think we would have made the experiments in time. Ana and Daniel, you were invaluable in getting the simulation experiments up and running and preparing the scenarios. A special praise is also warranted for EUROCONTROL for their continued support in developing the ESCAPE Light simulator functionalities and interface, Universidad Politécnica de Madrid for providing the controller participants, and SENASA for their provision of professional pseudo-pilot participants.

I would also like to thank my former employer, CRIDA, for being so flexible in providing me the time and resources needed to work on my dissertation. I would like to extend my gratitude to Jose Miguel and Fernando, who somehow believed in my potential enough to hire me and set up an Erasmus internship after my initial interview with a horrendously broken Spanish. Thank you also to my former colleagues whom I had the pleasure of working with and learning from, many of which I am humbled to call friends: Marta, Ángel, Adrián, Fernando, Javier G., Enrique, Iciar, Guillermo, Gonzalo, Rubén G., Alejandro, Christian, Chen, Diego, Eva, Amalia, Elena, Gianfranco, Manuel, Erica, Natividad, Raquel, Leticia, Damián, Alan, Rebeca, Faustino, Andrés, Jonathan, Lorena, Mayte, Danlin, Oscar, Sara, Patricia L., Jose Manuel, Lidia, Florencia, Juan Antonio, Rubén R., Javier P., Nicolas, Patricia T., Steve, and Alba.

Similarly, I would like to thank my employer, Austro Control, for providing me with the support I need at the end of my doctoral journey, and for allowing me to apply the knowledge I have acquired in this field into practice. I would particularly like to mention Christian, Andra, and Robert, who I am honored to have (had) on my team to battle giants with every day, as well as Nina, for entrusting me with the task of coordinating the UTM ecosystem. I am also grateful to count on the help and experience of Martina, Raphaela, Johannes, Lukas, Joy, Lisa, Susanna and Tara.

Moreover, there are particular individuals who deserve a special mention. Brian, it was thanks to your initiative that got me into contact with TU Delft and began my journey as a Ph.D. candidate. If it hadn't been for our long discussions on human factors research, I wouldn't have thought I could be someone to consider this path. Markus, you have been my closest friend since university. We've gone through *hell and high water* together. I can't thank you enough for being my partner in crime and support through all these years. And to all my friends (you know who you are), I am truly blessed to have such a wonderful and diverse group of individuals around me. Although we are spread out across the globe, you make life more interesting every time we meet.

It goes without saying that I owe a special thanks to my parents, Josef and Theresia, for being there every step of the way and encouraging me to follow my crazy dreams since birth, and to my siblings Bettina and Tobias, who teach me every day the beauty of companionship that a family can offer. All of you provide me with the foundation on which I can be who I am. This is as much your achievement, as it is mine. I also want to extend the same gratitude to my new family in law: Jose, Begoña, and Marta, for accepting me into their family and for giving me a second place to call home.

There is no person I am more grateful for than Virginia for entering my life. I wouldn't have been able to complete this journey without the encouragement, patience, and love you have given me every day. Over the course of our time together, we have gone through amazing but also difficult moments and come out stronger every time.

And finally, to my daughter Olivia, for reminding me on a daily basis that life is more than just work. To you, I wish to dedicate more effort than any Ph.D. thesis could require and can't wait to see the wondrous places your curiosity will end up taking you.

*Dominik*
*June 2026*

# Curriculum Vitæ

## Dominik Janisch

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| 28-05-1993 | Date of birth in Feldbach, Austria |

### Education

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| 1999-2011 | Primary School: Volkschule Ilz, Ilz (AT)<br>Primary School: York Elementary School, Raleigh, NC (USA)<br>Secondary School: BG/BRG Gleisdorf, Gleisdorf (AT) |
| 2012-2015 | Bachelor of Science in Engineering<br>Fachochschule Joanneum University of Applied Sciences, Graz (AT)<br>Inholland University of Applied Sciences, Delft (NL) |
| 2015-2017 | Master of Science in Engineering<br>Fachochschule Joanneum University of Applied Sciences, Graz (AT)<br>Universidad Politécnica de Madrid, Madrid (ES) |
| 2019-2026 | Doctor of Philosophy in Aerospace Engineering<br>Delft University of Technology, Delft (NL) |

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| Thesis: | Human Interactions with Uncrewed Air Traffic Management |
| Promotor: | Prof. dr. ir. M. Mulder |
| Promotor: | Dr. ir. C. Borst |

### Work Experience

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| 2015-2015 | Mechanical engineering intern<br>AMES Aerospace and Mechanical Engineering Services, Peggau (AT) |
| 2016-2017 | Human factors engineering intern<br>Airbus Defence and Space, Manching (DE) |
| 2017-2022 | R&D and innovation engineer in air traffic management<br>CRIDA A.I.E, Madrid (ES) |
| 2022-now | UTM coordinator<br>Austro Control GmbH, Vienna (AT) |

Dominik Janisch was born in Feldbach (AT) on May 28th, 1993. Growing up in Ilz (AT) and Raleigh, NC (USA), his frequent air travels during this time sparked a lifelong interest in aviation. He obtained his private pilot license at an airfield in Fürstenfeld (AT) at the age of 17 and graduated BG/BRG Gleisdorf in 2011, with an elective track specialized in natural sciences. Considering his passion for aviation, enrolling in the faculty of Luftfahrt/Aviation at Fachochschule Joanneum University of Applied Sciences (FHJ) in Graz (AT) was a logical next step.

During his studies at FHJ, he participated in an ERASMUS exchange semester at InHolland University of Applied Sciences in Delft (NL), which marked his first connection to the city. He completed his bachelor's degree in aeronautical engineering in 2015 and continued his academic pursuits to complete his master's degree in aeronautical engineering at FHJ. Prior to graduating in 2017, he completed two internships which would define the path for his career in aviation. The first was a human factors engineering internship at Airbus Defence and Space in Manching (DE), which inspired him to focus on human performance and interface development in aviation. Thereafter, he attended a second ERASMUS exchange semester at Universidad Politécnica de Madrid, which allowed him to work as an intern in Air Traffic Management (ATM) research at Centro de Referencia de Investigación, Desarrollo e Innovación en ATM (CRIDA) in Madrid (ES).

After his graduation, he was not only allowed to continue his work in ATM research as an employee of CRIDA, but also embarked on a completely new field of research known as Uncrewed Aircraft Systems Traffic Management (UTM). This exciting new field allowed him to shape the concept of U-space, the European Union's own UTM initiative, by participating in a series of Single European Sky ATM Research (SESAR) projects, such as IMPETUS, TERRA, SAFEDRONE, and DACUS. By chance, Dominik was made aware of a potential opening for an external Ph.D. at the department of Control and Simulation (C&S) at Delft University of Technology, following a lengthy conversation about human-factors research experiences with a colleague from the TERRA project.

What followed were several exchanges of ideas with the C&S department on how a potential Ph.D. could be set up in parallel to his work in CRIDA, which ultimately led to the initiation of the research presented in this thesis in 2019. Despite the difficulties of conducting human-in-the-loop experiments during the COVID-19 pandemic, his first publication was awarded Best Paper in Human Factors at the 14th ATM R&D Seminar (online). Conducting research for this thesis was further facilitated when the PJ34 AURA project was funded, allowing him to develop the collaborative ATC-UTM concept through his involvement in PJ34 AURA Solution 2 as leader of a simulation exercise. The results of these experiments culminated in a research paper awarded Best of Session UAV/UAS/UTM at the 42nd AIAA/IEEE Digital Avionics Systems Conference of 2023 in Barcelona (ES).

In 2022, Dominik accepted a once-in-a-lifetime opportunity to apply his research in his current role as UTM coordinator for Austro Control in Vienna (AT). His main contribution was the coordination of stakeholders and facilitating the successful deployment of the Dronespace UTM system in 2023. Since then, he has been working to mature the UTM ecosystem in Austria and realize the concepts presented in this thesis.

# List of Publications

1. J. A. Pérez-Castán, F. Gómez Comendador, A. B. Cardenas-Soria, *D. Janisch*, R. M. Arnaldo Valdés. Identification, Categorisation and Gaps of Safety Indicators for U-space. *Energies*, 13(3):608, 2020.
2. V. Alarcón, M. García, F. Alarcón, A. Viguria, A. Martínez, *D. Janisch*, J. J. Acevedo, I. Maza, and A. Ollero. Procedures for the Integration of Drones Into the Airspace Based on U-space Services. *Aerospace*, 7(9):128, 2021.
3. P. S. Escalonilla, *D. Janisch*, C. Forster, M. Büddefeld, and H. E. Teomitzi, Towards a Continuous Demand and Capacity Balancing Process for U-space. In *Proceedings of the 10th SESAR Innovation Days*, Online, pages 1-9, December, 2020.
4. 🏆 D. van Aken, *D. Janisch*, and C. Borst. Development and Testing of a Collaborative Display for UAV Traffic Management and Tower Control. In *Proceedings of the Fourteenth USA/Europe Air Traffic Management Research and Development Seminar*, Online, pages 1–10, September, 2021.
5. *D. Janisch*, P. Sánchez-Escalonilla, V. Gordo, and M. Jiménez. UAV Collision Risk as Part of U-space Demand and Capacity Balancing. In *Proceedings of the 11th SESAR Innovation Days*, Online, pages 7-9, December, 2021.
6. 📄 *D. Janisch*, D. van Aken, and C. Borst. Ecological Collaborative Interface for Unmanned Aerial Vehicle Traffic Management and Tower Control. *Journal of Air Transportation*, 30(4):154–169, 2022.
7. 🏆 📄 *D. Janisch*, P. Sánchez-Escalonilla, J. M. Cervero, A. Vidaller, and C. Borst. Exploring Tower Control Strategies for Concurrent Manned and Unmanned Aircraft Management. In *Proceedings of the 2023 IEEE/AIAA 42nd Digital Avionics Systems Conference (DASC)*, Barcelona, Spain, pages 1–10. IEEE, 2023.
8. 📄 *D. Janisch*, S. Wen, Y. Zou and C. Borst. Exploring the Limits of Uncrewed and Crewed Air Traffic Segregation by Tower Controllers. In *Proceedings of the SESAR Innovation Days 2024*, Rome, Italy, pages 1–9, November 2024.

📄 Included in this thesis.
🏆 Won best paper in session.