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Ecological Collaborative Interface for Unmanned Aerial Vehicle Traffic Management and Tower Control

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The forecasted increase in unmanned aerial vehicle (UAV) traffic in lower airspace raises concerns for maintaining the safety and efficiency of flight operations near towered airports. Regulatory bodies envision a collaborative interface between UAV traffic management (UTM) and air traffic management 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 UAV priority and routing indications, as well as the utilization of a grid of geofences to dynamically segregate UAVs from manned aircraft. Surprisingly, the control strategy for geofence activation was similar to that of managing manned aircraft from a tower control perspective. Participants also mentioned that they would like more control over UAV traffic than initially expected. Performance could be improved by increasing predictability of UAV routing, adding conflict detection support as well as providing more authority over individual UAV locomotion supported by a tailored geofence structure. Further work is needed to investigate controller behavior in an environment which also requires control over manned traffic.

I. Introduction

The European Drone Outlook Study foresees an increase of up to 400,000 commercially operated unmanned aerial vehicles (UAVs) in Europe by 2035 [1]. This expected increase in UAV operations poses a threat for existing manned air traffic, in particular in proximity to airports. In order to prevent widespread disruptions to air traffic flows at airports and alleviate safety concerns due to an increased risk of collision between UAVs and manned aircraft, industry and research efforts are focusing on the development of UAV traffic management (UTM) systems. These allow UAV operators to carry out their desired missions cooperatively within the operational framework established by authorities in a safe and orderly manner [2]. Various UTM system concepts are being defined around the world, the most prominent

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of which include the European Union's U-space system [3] and the United States' Low Altitude Authorization and Notification Capability (LAANC) [4]. These systems ultimately aim to facilitate the complete and safe integration of increasingly capable UAVs 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 airports to UAV traffic [5], supported by a collaborative interface between air traffic management (ATM) and UTM to manage the information exchange required between both systems [6].

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 airport environment [7]. The low operating altitudes of UAVs pose a collision hazard to departing and arriving aircraft, low operating emergency helicopter flights, and operations within the traffic circuit. To assure adequate separation, tower controllers will therefore need to interact with the UTM system which is managing UAV flights, whilst performing their primary (mostly manual) task of coordinating manned aircraft.

To support the air traffic controller in managing this new environment, we propose to include elements which allow them to collaborate with the UTM system through a display adopting Ecological Interface Design (EID) principles ([8], [9] and [10]). This article will provide some initial interface design considerations for the development of such a collaborative display by identifying functions which would best support UAV management. In particular, it will focus on elements which allow the controller to comprehend UAV operations and guide tactical UTM traffic commands using dynamic geofences - volumes in space that prohibit UAV operations within their boundaries [6]. The assessment of a combined management of UAVs and manned aircraft was, however, not part of this study.

This paper elaborates on why it will become necessary to allow UTM operations within controlled airspace and discuss the implications on tower control which arise from introducing UTM-guided UAV operations into the airport environment (see Section II). We present an analysis of the work domain resulting from this collaborative environment in Section III and focus 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 IV 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 UAV operations from manned air traffic (see Section V). Results are presented in Section VI and discussed in Section VII. Final conclusions are presented in Section VIII.

II. Background

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

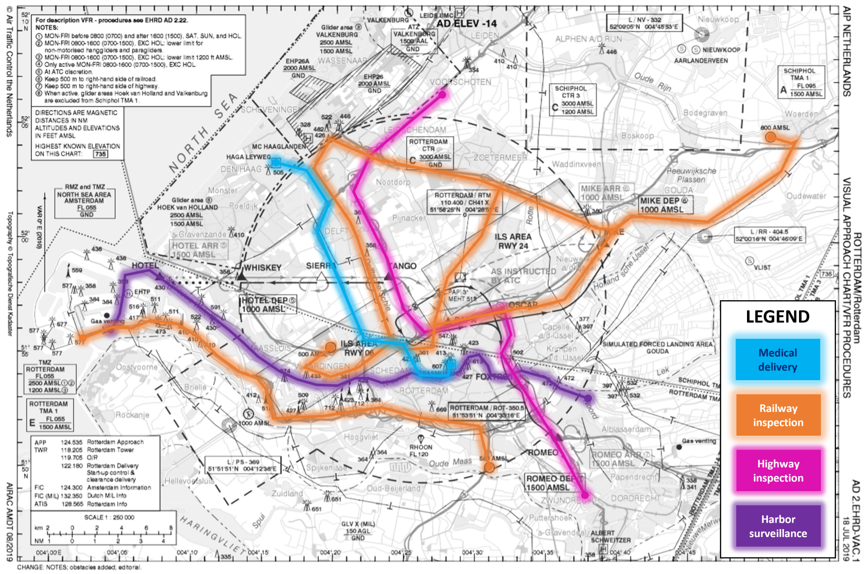


Fig. 1 Potential UAV missions within the Rotterdam The Hague Airport control zone, superimposed on a visual approach chart.

A. The Need for Providing Access to Controlled Airspace

Control zones of towered airports commonly occupy large portions of lower airspace, as their design is centered around manned aircraft operations. Prohibiting UAV 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 UAV missions, if access to this airspace were prohibited. Figure 1 shows representative UAV missions superimposed on an aeronautical chart of Rotterdam The Hague Airport. The blue 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 UAV-based inspection flights. Such inspection missions would need to closely follow railway (orange) and highway (pink) routes within the CTR. Finally, the proximity of the airport to Rotterdam harbor, one of the most important naval trade connections in Europe, could be problematic to any potential harbor inspection and surveillance flights by UAV (purple). All of these missions would be performed almost entirely within the CTR and, in the best case, in close proximity to the airport's runway.

Further, looking at this image, several points of interaction of these missions with manned air traffic routes also become apparent. Many UAV missions cross the extended runway centerline which manned 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 potential for head-on conflicts between manned and unmanned aircraft. Subsequent discussions with Rotterdam The Hague Airport tower controllers confirm these points of encounter, and emphasized the added risk of collision with medical helicopter departures from the airport, which may depart in any given direction, commonly fly at lower altitudes and land in areas where UAVs are operating (e.g. near hospitals or highways). For an airport which regularly experiences between 80 to 170 flight movements per day [11], this potential safety risk cannot be neglected. Facilitating both UAV and manned aircraft missions within this airspace requires a coordinated management and collaboration between air traffic control and UAV traffic management, which the next section will explore in further detail.

B. Implications of a UTM-ATM 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 which helped to develop the U-space concept of operations (ConOps) [6]. During the same period of time the United States' Federal Aviation Administration (FAA) developed its own UTM ConOps [4], 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, as defined in the FAA UAM ConOps [12].

For the purposes of this study, we will now focus primarily on the European vision for a collaborative UTM-ATM environment. EASA published an opinion in early 2020 [13] on the regulatory framework through which U-space is to be implemented in Europe. This has since been adopted into regulation [14], [15], and will take effect in 2023. 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 manned aircraft while U-space service providers (USSPs) provide services to UAVs. 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, manned and unmanned vehicles.

The regulation foresees this segregation of U-space and manned operations to be facilitated through a dynamic airspace reconfiguration capability [14]. This concept facilitates the partitioning and active restructuring of controlled airspace to accommodate the needs of both U-space and ATM operations. For this study, we propose a solution to support active dynamic airspace reconfiguration in the tactical phase of operations through the use of "geofences" [6]. U-space will organize UAV operations based on operational restrictions which depend on the UAV category and operational risk classification [16]. These restrictions will be enforced using geofences – digital barriers that prevent UAVs 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 U-space and ATM will utilize geofences as a means for managing UAV traffic in controlled airspace. ATC will carry out this reconfiguration in response to manned 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 manned aircraft, such as departing emergency helicopter flights, which do not follow published departure routes.

In order to set up the airspace for dynamic restructuring, EASA promotes the definition of a pre-defined basic set of airspace blocks or a more sophisticated mathematical grid, which can be dynamically assigned to either U-space or ATM. For this study, we focus on the application of a grid structure similar to the UAV flight restriction concept applied to airports in the United States [17]. 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 [18]. It has not yet been defined how this restructuring will be enforced; however, we will assume that airspace assigned to ATC will be protected from U-space operations using geofences.

For this study we will focus in particular on the application of this dynamic airspace reconfiguration concept on the tactical phase of operations and identify how it would affect the collaborative management of controlled airspace around an airport. We envision 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 which could be incorporated into their existing working station, aimed at managing the collaborative UTM-ATM environment.

III. Analysis of the Collaborative UTM-ATM Work Domain

To understand the impact of this new concept on the work of tower controllers in a systematic way, we have developed a representation of the collaborative UTM-ATM work domain inspired by the work of Vicente [9]. In the next subsections, we will provide further detail on the work domain itself, explain the model that resulted from this analysis, and elaborate on our assumptions on the impact on safety and efficiency.

A. Work Domain Analysis

To begin, let us first consider, from an organizational point of view, how ATC operates in its current form. 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” [7]. 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 U-space, the U-space Opinion [13] and regulation [14] set specific objectives for the U-space ecosystem to achieve which appear to overlap with those of ATC in several instances.

We developed an Abstraction Hierarchy model [10] of the collaborative ATC and UTM environment (see Figure 2) to help us understand the impact of having two systems with similar objectives operating within the same space. This type

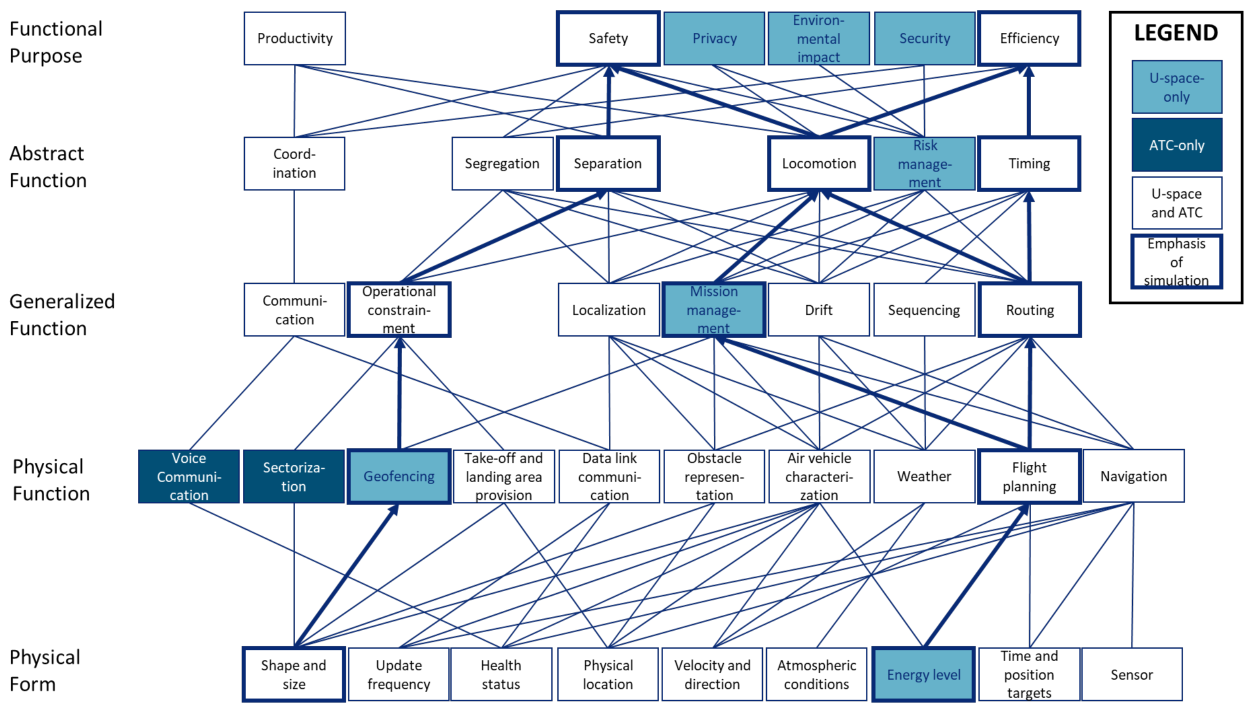


Fig. 2 Abstraction Hierarchy model of the work domain of a collaborative environment between ATC (tower control) and UTM.

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 [10]. 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 [9]. Moreover, since its introduction roughly thirty years ago, EID has already been widely adopted to facilitate interface development in several aviation domains ([19], [20], [21] and [22]), as well as the management of autonomous vehicles ([23] and [24]). Given the iterative relationship between interface design and the work domain analysis, the Abstraction Hierarchy portrayed in Figure 2 serves as a starting point and is thus subject to refinements as the collaborative UTM-ATM environment concept is matured in future studies.

In this particular publication we will focus predominately on the interpretation of our proposed Abstraction Hierarchy model for a collaborative UTM-ATM 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 2 contents from the ATC point of view are based on Commission Implementing Regulation (EU) No 923/2012 [25], the ICAO Chicago Convention Annex 10 [26], Annex 11 [27] and ICAO Doc4444 [7]. The additional UTM elements are based on U-space initiatives, such as the U-space ConOps [6], EASA Opinion on U-space [13], Commission Implementing Regulation (EU) 2021/664 [14] and 665 [15], the Specific Operations Risk Assessment (SORA) [16] and the Eurocontrol UAS Airport ConOps [5].

To distinguish functionalities of either system, an additional color-coding was used. Elements highlighted in light blue are properties of the work domain that are only relevant to UTM, those in dark blue only to ATC and those in white apply to both. The results of the analysis show a striking similarity of 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 (dark and light blue 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 U-space 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" U-space elements. In this initial study, we wanted 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 lines within Figure 2), we were able to make some assumptions as to how the novel U-space elements might impact these goals. The reasoning behind this approach is briefly elaborated on in the next subsections.

B. Maintaining Safety

Air traffic safety is maintained by separating aircraft on departure, on approach to landing and within the traffic circuit [7]. The task of separating manned aircraft from each other is usually assigned to the approach controller. The addition of UAVs will add another layer of separation requirements to the mix. Given the low operating altitudes of UAVs 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. Manned 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 UTM-ATM environment, enforcing separation between UAVs and manned aircraft may become necessary.

Separation standards for manned aircraft within the terminal area require a 9.3km (5 nautical-mile) separation between aircraft operating under instrument flight rules (IFR), although this can be reduced to 5.6 km (3 nautical miles) if the systems' capabilities permit [7]. Moreover, VFR aircraft will maintain visual separation among each-other within class "D" airspace, such as that of Rotterdam The Hague Airport. However, separation minima for small UAVs flying beyond visual line-of-sight of the operator and manned aircraft have not yet been defined. For this study, we have chosen to set the minimum separation requirement to the one proposed by Weinert et al. [28] who have identified a vertical separation of 250 feet and horizontal separation 2000 ft (600 m) as an acceptable "well-clear" limit. We believed this to be a much more reasonable separation criteria than enforcing the 9.3km separation specified for IFR aircraft on UAV traffic.

Since the tower controller will not be able to exercise direct control over UAVs – that is the task of UTM – they must have access to mechanisms to clear areas from UAV traffic if necessary. This is where the dynamic airspace reconfiguration concept comes into play, as it provides a means to segregate UAV operations in U-space from manned 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 pre-defined geofences within the control zone on their radar display, 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 manned air operations. Moreover, it alleviates the controller from having to interact with UAV 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 [29]. Moreover, that study suggests limiting direct human operator involvement in such missions, which the geofencing concept could address.

C. Maintaining Airspace Efficiency

Providing an expeditious flow of air traffic requires that air vehicles reach their desired destination as directly as possible. Standard airport departure and arrival procedures assure that the flow of operations is safe and predictable. However, if the traffic situation permits, the 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 UAV-operations.

Within the U-space context, the efficiency of UAV flights will be predominately depend on the mission that they aim to achieve, as evident from Figure 1. Each mission profile has different implications on the flow of UAV traffic within the control zone and will ultimately affect the room for rerouting solutions within the UTM decision-making process. Moreover, UAV endurance is a substantial limiting factor for the maneuvering room it has available. The largest portion of U-space operations will be conducted via medium-sized UAVs of the "specific" category, which are predominantly battery-powered [1]. 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 UAV flight path. Therefore, to maximize overall efficiency of manned and unmanned flight operations within the collaborative controlled airspace, UAV mission constraints and flight endurance must be made transparent to the controller so that they can anticipate the maneuvering margins UAVs will have available.

Additionally, focusing on increasing safety (see Section III.B) may be detrimental to achieving efficiency, because the design choice in geofence size may affect UAV 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 UAV track miles.

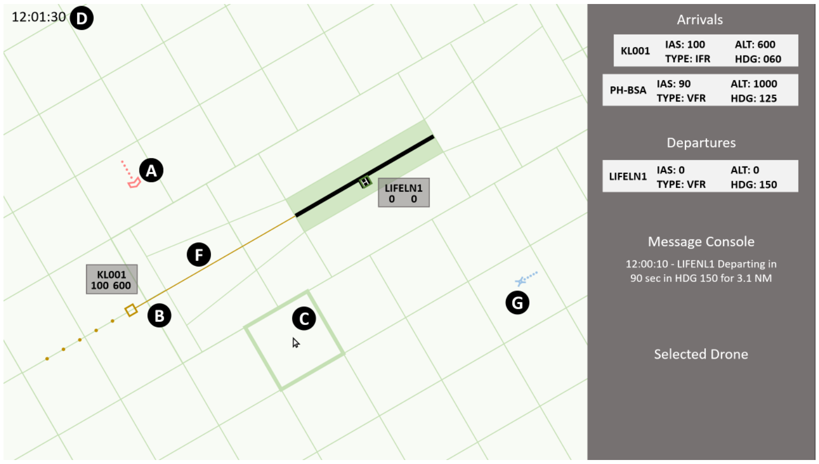
IV. Interface Design

This section describes our assumptions on how the elements of the Abstraction Hierarchy translate into the design of the collaborative UTM-ATM interface to support tower controllers. This interface aims to visualise 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.

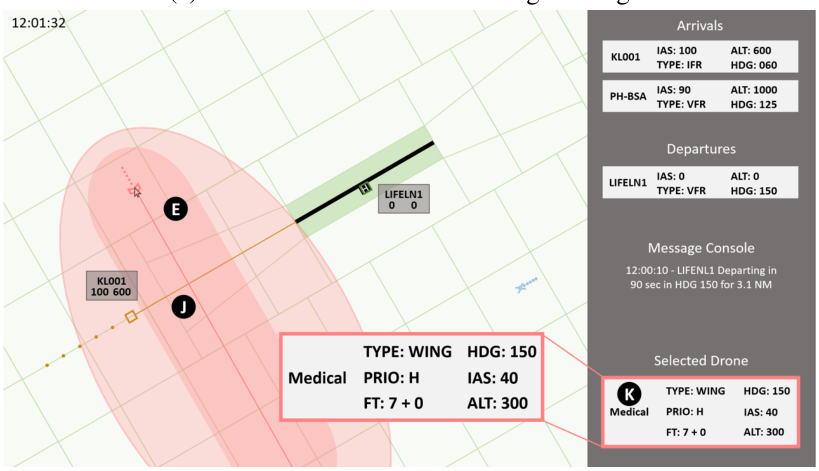
The interface presented here is a preliminary design and will therefore not fully contain all elements of the Abstraction Hierarchy, nor is it sophisticated enough to simulate a fully immersive tower control simulation as the emphasis was to assess the strands of the Abstraction Hierarchy highlighted in Figure 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 UTM-ATM 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 unmanned from manned 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 which could be incorporated into the tower controller's working station (e.g. the ground radar display) once the concept has been matured.

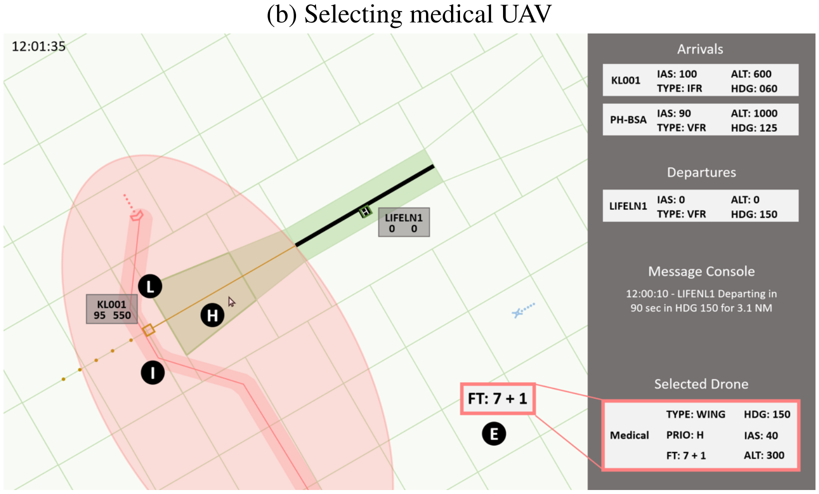
Figures 3 and 4 show a step-by-step representation of the structure and functionality of the interface for a simple scenario. The scenario consists of an arriving IFR flight, a departing emergency helicopter flight and two UAVs, one being a high-priority fixed-wing medical UAV and the other being a regular priority quad-copter delivery UAV. Relevant display elements are indicated by the letters A through S (see legend in Figure 4c), which also relate to specific levels of abstraction from Figure 2.



(a) Mission overview and selecting IFR flight

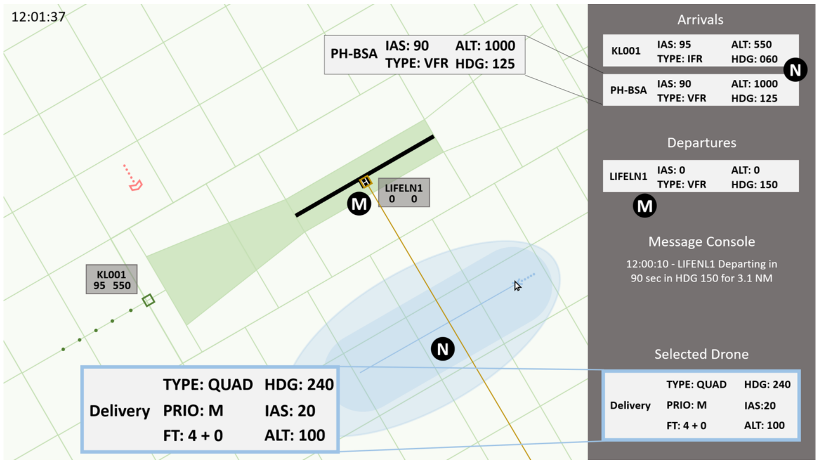


(b) Selecting medical UAV

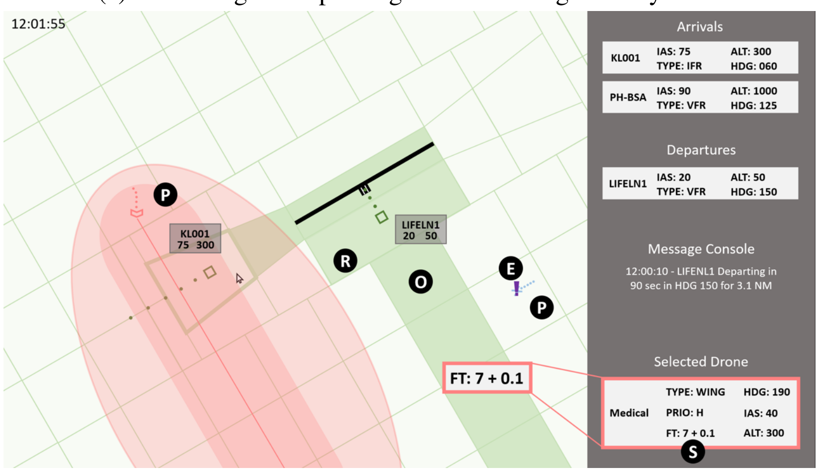


(c) Activating ILS geofences

Fig. 3 Step-by-step overview of the interface structure and functionality for a simple scenario (Part 1 of 2).



(a) Localizing helicopter flight and selecting delivery UAV



(b) Activating geofence grid for safety and deactivating ILS geofence for optimization

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

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

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

Abstract Function
- O Separation
- P Locomotion
- Q Timing

Functional Purpose
- R Safety
- S Efficiency

(c) Index of mapped Abstraction Hierarchy elements

Fig. 4 Step-by-step overview of the interface structure and functionality for a simple scenario (Part 2 of 2).

The initial map view in Figure 3a shows the situation overview with all UAVs routed directly to their destinations. First, the interface can be seen to display the physical location of all the vehicles in the area (A). Moreover, their velocity is indicated visually by means of trailing dots and numerically on the UAV information strip, flight strips and flight labels (B). 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 (C). Similar to tower control radar, the interface is updated every five seconds, indicated by the timer in the top left (D). Selecting a manned 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 which connects all subsequent waypoints (F). It should also be noted that the vehicle icon for UAVs also shows the type of air vehicle, which can either be a multicopter or fixed wing (G).

Figure 3b shows that selecting a UAV will display two endurance regions, highlighted in red or blue depending on the color scheme applied to the UAV icon. These regions are developed as a consequence of the rationale described in Section III.C. The inner region signifies the endurance the vehicle has available for re-routing (E). The outer region indicates the maximum deviation the UAV can make between its current location to its destination. Additionally, selecting the UAV shows its flight strip, which provides the controller with additional information about the UAV, including mission type (K). Having both a manned vehicle and UAV selected shows the routing involved (J) in a potential conflict. Two geofences are activated in Figure 3c, restricting the UAV from access (H). The active geofences are marked in dark green, directly indicating which parts of the airspace are shielded from UAV travel (L). In response to this, the red "medical" UAV can be seen to modify its route by adding waypoints around the active geofences (I). This allows the controller to perform dynamic airspace reconfiguration in order to achieve segregation, as well as manually enforce separation of UAVs from manned traffic if necessary. The impact of this re-route on the flight time can be seen on the UAV information strip (E) which displays the planned flight time and additional delay in minutes.

Next, it can be seen in Figure 4a that the message console prompts a departure of an emergency helicopter 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" helicopter flight (M). Selecting the blue multicopter UAV 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 UAV and manned air traffic (N). Activating the required geofences in Figure 4b creates a barrier beyond the outer endurance region of the blue multicopter UAV (E). This will cause it to loiter, indicated by the purple exclamation mark over the vehicle icon. Currently, all manned traffic routes in the airspace are shielded by active geofences, signifying segregation of manned and UAV traffic is achieved (O). The foremost top-level goal of tower control has been achieved: the safety (R) of all air vehicles in the CTR. Now other top-level goals, such as efficiency, can be addressed. The endurance regions displayed upon selection of a UAV give an indication of the vehicle's locomotion constraints, such as that of the red "medical" UAV (P) or lack of locomotion possibilities through the exclamation mark (E). By comparing UAV and manned traffic speeds in, it can be seen that the landing manned aircraft ("KL001") is no longer in conflict. The UAV can be allowed to proceed towards its destination

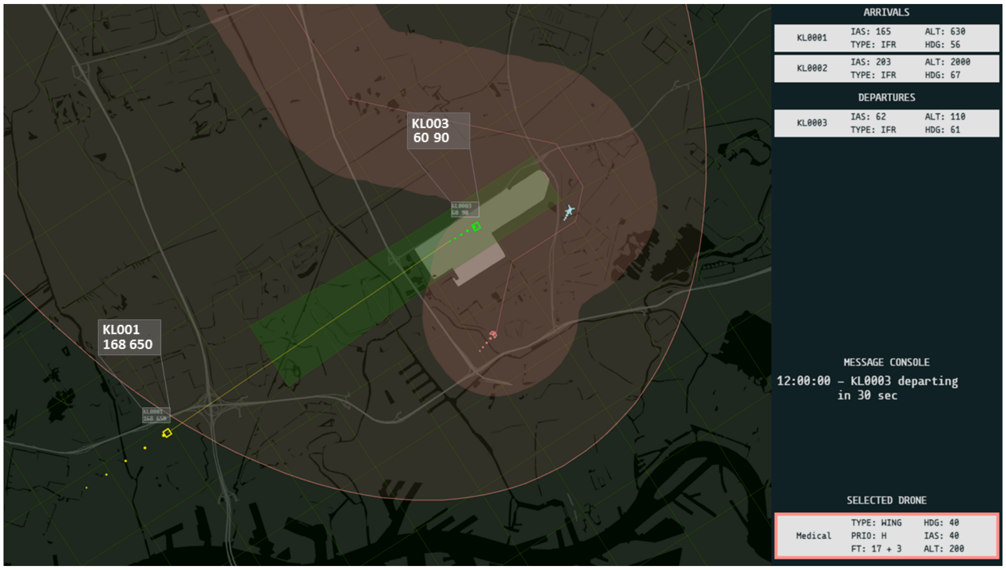


Fig. 5 Screenshot of the simulation environment used during the experiment. Flight labels are highlighted for clarity. Free access on: `http://dronectr.tudelft.nl`.

by deactivating one of the geofences at the most convenient point in time (Q). This action will increase the overall efficiency of the UAV operations, as indicated on the UAV information strip (S), which reduces the delay from one minute to 0.1 minutes. Monitoring UAV delays and shielding of manned traffic routes allows the controller to balance safety and efficiency of both manned and unmanned aircraft within the collaborative environment.

These considerations were developed into an initial tower control display, which was used to test our assumptions on safety and efficiency requirements of the collaborative UTM-ATM environment with professional air traffic controllers. Figure 5 showcases how these elements are represented in the final graphical display.

V. 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 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.

A. Experiment Setup

Nine licensed air traffic controllers from the Netherlands and Spain volunteered to participate in the experiment, five of which were active tower controllers. However, the experiment required no in-depth knowledge of the Rotterdam 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 home. 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 Zoom. 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.

B. Experiment Tasks

During the experiment, participants were placed in the role of a tower controller at Rotterdam The Hague Airport, in which UAV 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 (2000ft / 600m) separation between manned traffic and UAV traffic (vertical separation was not evaluated in this study). Second, they were tasked to minimize additional travel time for UAVs, especially high priority UAVs. 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 UAV traffic. The UAVs responded only to the activation of geofences and could not be instructed individually. UAVs would operate autonomously and use A* path planning [30] for tactical rerouting around geofences. Participants were given full authority over how to apply dynamic airspace reconfiguration using geofences and when to initiate it. However, we deliberately did not require the participants to achieve full segregation of U-space operations from manned operations, so that they could focus on using geofences for separation purposes. Additionally, manned aircraft could not be given instructions since the experiment aimed to investigate the proposed form of interaction with UAVs by using geofences. Participants did not receive feedback on their performance during the experiment run.

C. Independent Variables

The independent variables were the geofence size and the traffic scenario, which were 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 UAV 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 UAVs if the manned aircraft passes through its center. A finer, 1x1 kilometer scale was chosen for the second geofence size option, in favor of UAV capabilities allowing a typical small UAV 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 an emergency helicopter flight with some additional mixed traffic ("EHF scenario"). Finally, the fourth scenario considered a high task load use-case where all afore-mentioned scenarios were combined, and the number of UAVs and manned aircraft was doubled with respect to the first three scenarios ("HTL scenario").

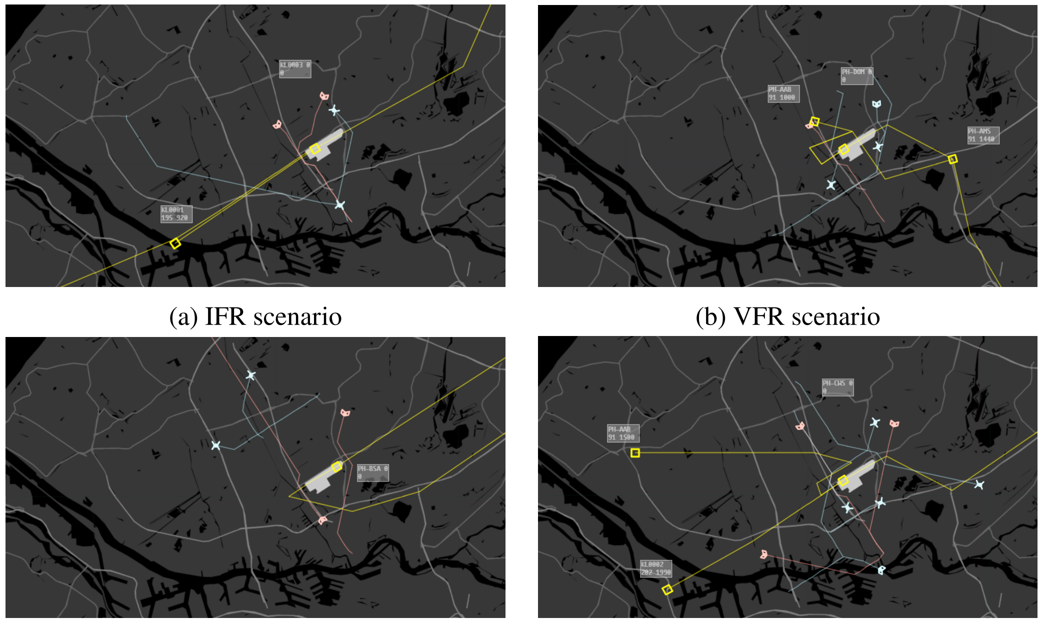
In total, (2 x 4 =) 8 experiment conditions were administered. All four scenarios were carried out for both geofence sizes. Therefore, the traffic scenario can be regarded as the second independent variable in a two-way repeated measures experiment. A balanced Latin square design was used to order the experiment conditions such that carry-over effects between the scenarios were minimized. Only the first three scenarios were shuffled in the matrix; the high task load scenario was always presented last for a given geofence size.

D. Scenarios

During the experiment, the participants were presented with traffic scenarios containing both manned and UAV air traffic in the Rotterdam The Hague air traffic region. These traffic scenarios contained potential conflicts between manned and UAV traffic which could be resolved by the controller by means of activating geofences. The manned traffic routes in the scenarios were based on Rotterdam The Hague Airport traffic data [31], published IFR and VFR routes and advice of Rotterdam tower controllers. The UAV traffic consisted of point-to-point delivery missions in the Rotterdam area, inspired by the missions introduced in Section II.A. The number of manned aircraft and UAVs 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 Figure 6.

E. 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 UAV traffic was quantified as either a generic multicopter or a generic fixed-wing vehicle with either high or regular priority. All manned traffic was classified as a generic IFR commercial flight, a generic VFR flight or a generic emergency helicopter flight.



(a) IFR scenario (b) VFR scenario

(c) Emergency helicopter flight (EHF) scenario (d) High task load (HTL) scenario

Fig. 6 Initial traffic conditions of the experiment scenarios

F. 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 UAV efficiency) were recorded by the simulation tool to provide insight on the influence of geofence size on the task being performed by the controller. Control strategy and activity served to obtain more generic insight on how controllers perform their work.

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).

G. Procedures

Before starting the experiment, participants were requested to read 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 the discussion section of this document.

H. Hypotheses

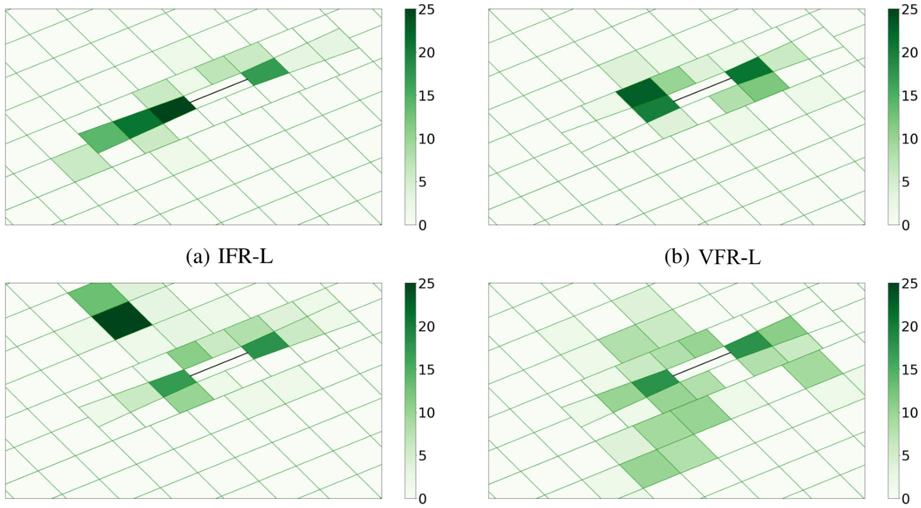
First, it was hypothesized that participants will prioritize manned traffic safety over UAV efficiency (H1). This would be reflected in control behavior by the fact that participants would first apply all the required geofence restrictions based on the manned traffic and afterwards investigated if the UAV 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 UAV efficiency, as there was less opportunity to alter the geofence configuration for UAV efficiency (H2.1). The interface usage was hypothesized to decrease, due to interface clutter, caused by visualizing all UAV 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 UAV 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 hypothesised that smaller geofences would lead to a decrease in average separation between UAV and manned traffic, as controlling geofences become a more tedious process, due to the increased number of mouse interactions required (H4).

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

VI. 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 UTM-ATM 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. We will focus in particular on how the interface aided controllers in achieving their



(a) IFR-L (b) VFR-L

(c) EHF-L (d) HTL-L

Fig. 7 Total interactions per geofence of all participants per large geofence scenario (runway in black).

control strategy and its impact on safety and efficiency.

A. Control Strategy

Observations during the experiment and from the post-experiment survey showed that participants prioritized safety over UAV efficiency and resulted in a control strategy that can be divided into two parts. First, participants checked the states and intent of UAV and manned traffic, scanning for potential conflicts. This was combined by the initial activation of geofences that resolved conflicts as quickly as possible, establishing a safe airspace. Second, participants maintained vigilance of the UAV state and intent after the geofences were activated. This was combined with the deactivation or tweaking of geofences to increase UAV 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 ILS approach, as well as the [standard instrument departure] SID 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 our 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 7 shows maps of the total geofence activation of all participants, for the four scenarios with large geofences. The geofence maps for the scenarios with small geofences are not shown, as they do not show a significantly different control behavior in pattern or magnitude. 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 manned flights and low-altitude helicopter flights, as seen in Figure 7c and Figure 7d.

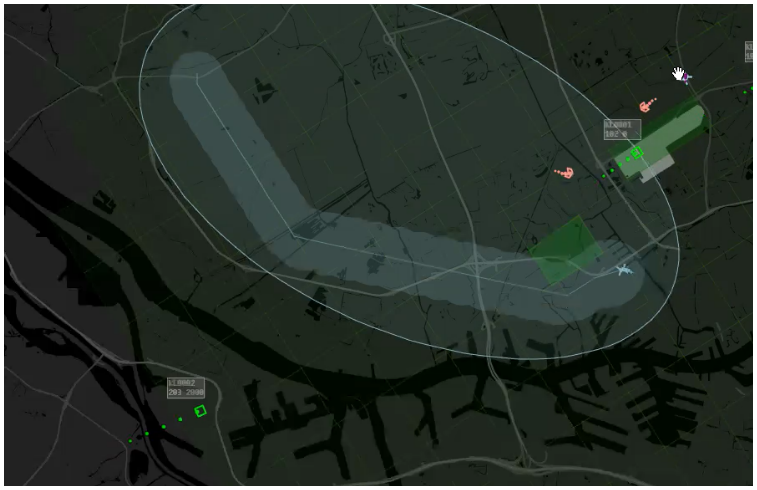
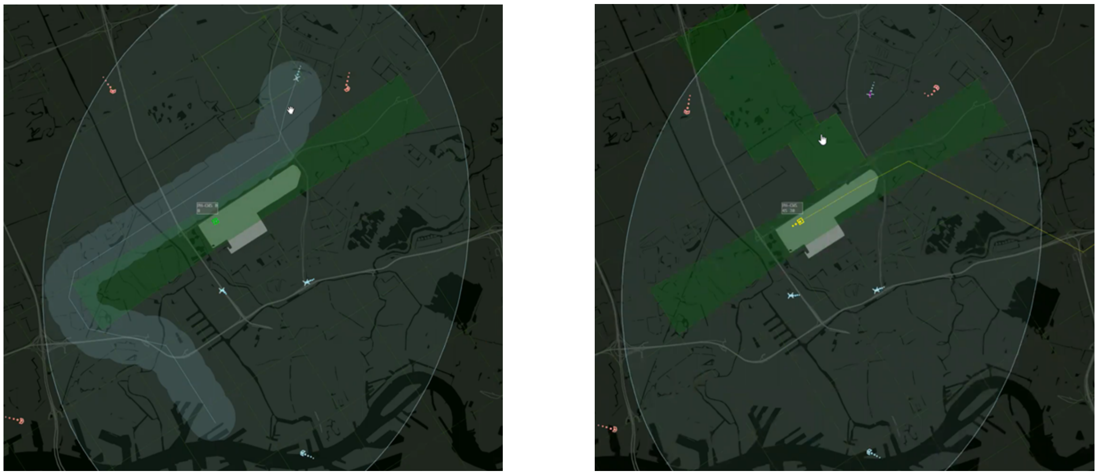


Fig. 8 Geofence activated not to protect an area from UAV operations but to vector the selected UAV behind the landing manned aircraft.

During the experiment it was observed that most participants opted for a control technique that resembles aircraft vectoring to fulfil the above-described control strategy. They used geofences to steer a UAV along a certain route, rather than simply activating a geofence and letting the UAVs find their way around it. This was mostly used to vector slower aircraft (UAVs) behind the faster aircraft (manned traffic), a common tactic in en-route air traffic control [32]. 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 UAV 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 8 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 UAV path planning would not always reroute the vehicles in a way that the controller expected them to. In several occasions, when a particular geofence was activated for the purpose of vectoring a UAV, that activation happened to interfere with the path planning of another UAV, causing that second vehicle to reroute as well. In some cases, this would even cause the second UAV to enter in another conflict with a manned aircraft which would need to be resolved.

Another unexpected behavior which was observed during the execution of the simulation runs was that some participants utilized geofences to force a UAV to loiter. They did this by excessively activating geofences in a way which depletes the UAV 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 9 shows such a situation. The activation of geofences along the extended runway centerline (see Figure 9a) triggers a long reroute of the highlighted blue UAV. The participant proceeded to activate several more geofences towards the north of the airport (see Figure 9b), so that the UAV would loiter near its current position, prepared to cross the runway centerline once the departing manned flight had passed. This effort was made to improve the efficiency of partictular UAVs, given that



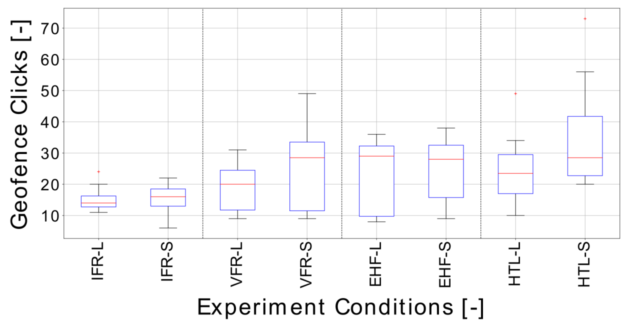
(a) Path planning routes UAV towards the west (b) UAV forced to loiter by activating additional geofences

Fig. 9 Utilization of geofences to force UAV loitering, rather than rerouting.

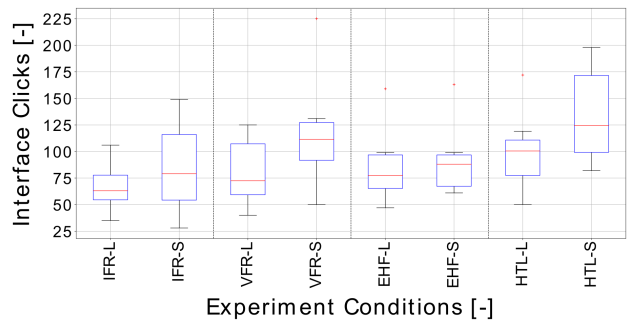
the controller had more knowledge about the rationale for activating geofences than the UTM system did. From the UTM perspective, any active geofence was considered to remain in this state for an undisclosed amount of time. These observations point to a shortcoming in the definition of the geofence concept for this experiment, which applies equal and time-invariant restrictions to all UAVs. However, the efficiency benefit obtained from forcing UAV behavior using geofences also came at the expense of restricting freedom of movement to other UAVs, which in some cases were forced to reroute substantially to reach their destination.

B. Interface Usage and Preferences

Figure 10a shows box plots of the total geofence interactions per experiment condition. At first glance, it appears as if the inclusion of VFR and emergency helicopter 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 EHF scenarios. Statistical analysis, however, shows that the geofence size had no significant effect on any of the differences between relevant experiment condition pairs. Figure 10b 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 ($\chi^2(3) = 12.3, p = .006$), where a Dunn-Bonferroni post hoc test shows significant differences between the IFR and HTL scenarios ($p = .012$) and the EHF and VFR scenarios ($p = .04$). Moreover, the number of interface interactions was significantly different between geofence sizes ($\alpha = .05/4 = .0125$) for the VFR ($Z = -2.524$, $p = 0.012$) and HTL ($Z = -2.524$, $p = 0.012$) scenarios.



(a) Geofence interactions



(b) Other interface interactions

Fig. 10 Interface interactions per experiment condition.

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 EHF. But only in HTL-S, interface clicks are signifcantly increased compared to HTL-L, meaning that smaller geofence sizes increase the information provision effort when the task load is high.

Concerning our 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 11 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 manned traffic were consistently scored lower than those concerning UAV traffic. It was recorded during the post-experiment survey that participants scored these interface elements lower due to their inability to interact with manned traffic. It can further be observed from the data that UAV priority was found more useful than UAV vehicle type. The interface elements regarded as most useful were UAV route, UAV priority color and geofence state.

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 the UAV's 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 UAV efficiency indicated that they did

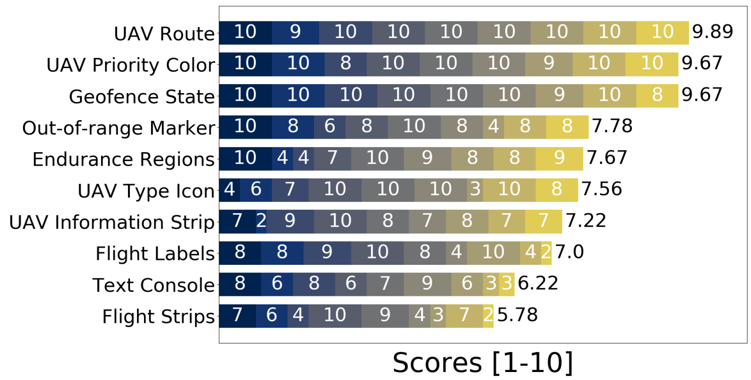


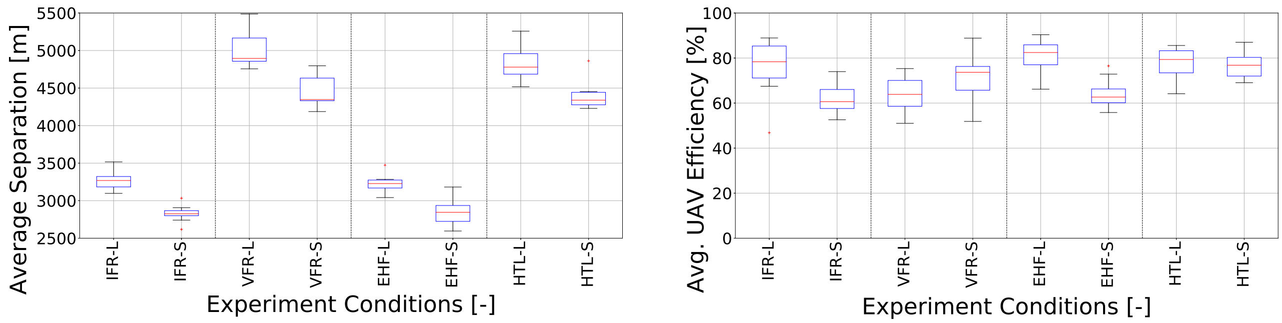
Fig. 11 Subjective scores of interface elements from all nine participants, displaying the average score at the end of the bar.

consider the endurance region in their decision-making. They commented that it helped them in predicting UAV behavior and in making choices regarding geofence selection.

The grid layout of geofences was generally well received, but additional structure, such as designated "UAV transfer corridors" to cross the runway midfield and extended runway centerline at 90-degree angles were preferred. The use of distinct markers to distinguish UAVs from manned aircraft was considered useful, however the UAV 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 UAV 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.

C. Achievement of Safety

Figure 12a shows box blots of the average horizontal separation between UAV traffic and manned traffic per experiment condition. This considers the average separation between a manned aircraft in airspace and all other UAVs. Statistical analysis of the results shows that the average separation distance between UAV and manned traffic was significantly influenced by the traffic scenario for both geofence sizes ($\chi^2(3) = 19.5, p < .01$). The effect of geofence size on average separation was found to be significant for all traffic scenarios ($\alpha = .05/4 = .0125, Z = -2.521, p = 0.012$). It can therefore be concluded that the traffic scenario influenced the average separation and that smaller geofences lead to a lower average separation between UAVs and manned traffic, as was initially expected (H4). Losses of separation (<600m) between manned aircraft and UAVs 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 involved emergency helicopter flights. 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.



(a) Average separation between UAV and manned traffic

(b) Average UAV flight-time efficiency

Fig. 12 Average separation and UAV efficiency per experiment condition.

D. Achievement of Efficiency

Figure 12b shows box plots of the average UAV 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 UAV efficiency was significantly influenced by traffic scenario for both large ($\chi^2(3) = 10.05$, $p = .018$) and small geofences ($\chi^2(3) = 13.65$, $p = .003$). The effect of geofence size on UAV efficiency can be seen to have differed per scenario, while it was only found to be significant for the EHF scenario ($\alpha = .05/4 = .0125$, $Z = -2.521$, $p = 0.012$). It can be concluded from the results that the combination of traffic scenario and geofence size influenced the UAV efficiency. However, rather than increasing efficiency, the effect of geofence size on UAV efficiency was found to be negative, positive or negligible, depending on the traffic scenario (H5.1). This emphasizes the importance of tailoring geofences to traffic operations. The statistical analysis of the average UAV loiter time shows that only the traffic scenario had significant influence on the average loiter time for large geofences ($\chi^2(3) = 13.65$, $p = .003$) and are therefore not shown. Similarly, results for the average reroutes per UAV 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).

VII. Discussion

Geofences were generally considered a useful tool by the participants to maintain separation between UAV and manned air traffic. Given the lack of needing to instruct manned aircraft and that UTM did not provide any separation actions on UAVs, most participants used geofences to actively influence UAV routings and vector them behind manned aircraft. This type of control style differs from the original intent of using geofences as a means to protect manned aircraft, and caused some complications, as the UAV's path finding did not always select the route that the participant intended it to. A higher transparency in UAV (re)routing decisions, supported by a more sophisticated path planning algorithm, such as that proposed by Xue and Wei [33] or Jung and Kartik [34] should therefore be considered as part of the display visualizations. Moreover, a geofence structure that would allow UAVs 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 UAVs to briefly loiter until a geofence restriction was lifted, as this would lead to a more predictable UAV routing behavior. This strategy is at odds with the concept proposed by the U-space regulation [14], which does not foresee an air traffic controller exercising direct control over UAVs. Future studies would therefore need to assess the implications of allowing the controller to instruct individual UAVs 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 UAV, but affecting multiple UAV routings through the same area, also merit further investigation. Such situations required the controller to activate additional geofences to resolve new conflicts, which could lead to instability in terms of the control task when more UAVs are introduced. Such situations may be avoided by implementing geofences which can be assigned to individual UAVs, rather than those used in this study which apply to all UAVs at once. Moreover, results highlight the need to incorporate the notion of "geofence activation time" into the dynamic airspace reconfiguration concept so that UAVs 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 UAV traffic. Surprisingly, most participants indicated they would have prioritized high priority UAVs over VFR flights had they had the opportunity to control VFR traffic. This indicates that the allocation of flight priorities among manned and unmanned aircraft may not be as trivial as first thought.

The observed "active UAV control" approach to using geofences is a limitation of the study conducted with regards to the current U-space regulation [14], which mandates segregation of ATC and U-space operations. In this study, however, participants were specifically asked to enforce a pre-defined minimum separation of UAVs from manned 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 which simulates the stricter limits set by the U-space regulation (which would alleviate their responsibility to separate manned aircraft from individual UAVs) with one which 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 UAV 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 III.B. 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 manned air traffic is a noteworthy constraint in the interpretation of the results of this study. Participants were able to give their full attention to UAV traffic displayed on the interface, and thus micro-manage UAV 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 numbers of manned aircraft are high. This, however, would need to be validated in another human-in-the-loop experiment which also allows for control of manned 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 manned 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 UAV traffic density, a full segregation requirement and control over manned 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 UAV traffic pass safely, rather than minimizing individual UAV 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 manned aircraft on the tarmac or on final approach, as well as managing runway operations. We assume that this will likely reduce the frequency of participants actively controlling UAV 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 EHF scenarios. The latter could be achieved by predicting where a manned aircraft and a drone would meet and highlighting that grid cell, so that a controller would know which geofence to activate to prevent the separation loss.

At this point it is also important to mention that, given the limitations of this preliminary design study, we have not been able 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 UAVs 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 which 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 UAV 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. Finally, the "energy level" of UAVs, 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.

VIII. 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 modelled onto an Abstraction Hierarchy. The emphasis of the proposed interface was placed on supervising and adjusting UAV traffic within the CTR of Rotterdam The Hague airport, surrounded by manned 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 UAV 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., UAV priority, UAV routes and geofence state) were deemed useful in both supervising and controlling UAV behavior in relation to manned aircraft trajectories. Surprisingly, participants opted to use geofences for a more active, "vectoring"-style approach to re-route UAVs, rather than passively protecting manned aircraft as the current U-space regulation indicates. This suggests that controllers may want to have more control over UAV traffic than initially expected.

This result, however, could be partially explained by participants not needing to control manned 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 having control over manned traffic and adding situations which 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 UAVs, the simulation of environmental factors such as wind drift and the incorporation of UAV contingency scenarios. The geofencing concept would also need to be updated to avoid "knock-on" effects on several UAV missions. Such effects could be mitigated by assigning geofences to individual UAVs and specifying how long a geofence will be active. Tailoring the geofence grid to better fit established manned air traffic routes as well as providing fixed transfer corridors for UAVs would also improve the interface. Finally, the interface could be further improved by incorporating conflict detection and alerting functionalities.

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