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Development and Testing of a Collaborative Display for UAV Traffic Management and Tower Control

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***Abstract*—The forecasted increase in unmanned aerial vehicle (UAV) traffic in lower airspace raises concerns for maintaining the safety of flight operations at towered airports. Regulatory bodies envision a collaborative environment between UAV Traffic Management (UTM) and air traffic management to facilitate safe UAV operations within controlled airspace. This will require the development of an interface for tower controllers to interact with UTM concerning UAV flights within the aerodrome control zone. In this study we present relevant design considerations for such a display and introduce a concept for dynamically segregating UAVs from manned aircraft using geofences. Remote human-in-the-loop simulations with air traffic controllers were performed to test our assumptions. Results confirm the utility of several interface elements, in particular UAV priority and routing indications. Furthermore, results show that providing controllers with a grid of geofences was considered a useful tool in re-routing UAVs. Surprisingly, the control strategy for geofences was not different from existing control strategies for manned aircraft. Performance could be improved by increasing transparency and predictability of UAV routing with novel display elements, as well as providing more authority over UAV locomotion. Further work is needed to investigate controller behavior and performance in an environment which requires oversight of both UAV and manned traffic, higher levels of UTM sophistication as well as simulating a broader range of UAV missions and scenarios.**

Keywords- Unmanned Aircraft Systems Traffic Management; U-space; UTM; UTM-ATM collaboration; display design; air traffic control; tower control; geofences

I. INTRODUCTION

The European Drone Outlook Study predicts a large increase in the use of unmanned aerial vehicles (UAVs) in the coming years. Up to nearly 400,000 commercially operated vehicles in Europe by 2035 [1]. This expected increase in UAV operations poses a problem for existing manned air traffic, in particular near airports. An example of this is the Gatwick Airport incident in 2018, where unknown UAVs were spotted flying near the airfield. This caused air traffic control (ATC) to shut down the airport, cancelling 760 flights, affecting over 100,000 people directly, while also causing upstream delays [2]. Similar incidents have since occurred at principal airports in London, Frankfurt and Madrid [3], [4], [5].

In order to prevent further disruptions in the future, 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 [6]. Various UTM systems are under development around the world, the most prominent of which include the European Union's U-space system [7] and the United States' Low Altitude Authorization and Notification Capability (LAANC) [8]. 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 forecasted demand. This ambition includes the eventual opening of controlled airspace around airports to collaborative UAV traffic [9].

This will put an additional strain on tower controllers to perform their responsibilities for maintaining safe separation and efficient movement of aircraft within the airport environment [10]. The low operating altitudes of UAVs pose a collision hazard to departing and arriving aircraft, as well as 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 main (mostly manual) task of managing manned aircraft.

The development of a collaborative interface between the air traffic controller and the automated UTM system which is supported by an advanced tactical tower display, may be the solution to address these issues. This article will provide some initial interface design considerations for the development of such a collaborative display, by incorporating functionalities 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 for a given duration [11]. The assessment of a combined management of UAVs and manned aircraft was, however, not part of this analysis.

In this paper, we will discuss the implications on tower control which arise from introducing UTM-guided UAV operations into the airport environment (see section II). This insight was used to develop a simulation interface which supports tower controllers in maintaining manned traffic safety by allowing control over UAVs through the use of geofences (see section III). In order 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 use geofences to segregate UAV and manned air traffic, supported by the human-machine interface (see section IV). Results are presented in section V and discussed in section VI. Final conclusions are presented in section VII.

II. Implications of a UTM-ATM Collaborative Environment on Tower Control

The development of UTM and its inclusion into the existing air traffic system has been consistently and collaboratively developed over the last few years. The European Union funded several exploratory research projects which helped to develop the U-space Concept of Operations (ConOps) [11]. During the same period of time the United States' Federal Aviation Administration (FAA) developed its own UTM ConOps [12], 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 [13].

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 [14] on the regulatory framework through which U-space is to be implemented in Europe. According to EASA, U-space can be established within controlled and uncontrolled airspace, under the principle that air navigation service providers (ANSPs) provide services to manned aircraft while U-space service providers (USSPs) provide services to UAVs. In controlled airspace, however, it is up to the ANSP to manage the U-space designated airspace in order to guarantee the safety of flight operations. This is to be achieved through dynamic segregation of air traffic services (ATS) and U-space services – and subsequently, manned and unmanned vehicles – so as not to provide these services in the same volume of airspace simultaneously.

Additional opinions have been voiced by EUROCONTROL, the European Organisation for the Safety of Air Navigation, in their "UAS Airport Concept of Operations", an annex to their "UAS-ATM Integration, Operational Concept" [9], which confirms that all aerodrome users, including UAV operators, shall have equitable access to airspace via a single, U-space compliant "Local Airport UTM" system per airport. This UTM system will operate concurrently with the local control authority and should be interoperable with its airport and air traffic control systems. Although U-space service providers of this level of sophistication are not expected to be implemented in the short-term, the EASA opinion does affirm the possibility of a sophisticated and fully-certified USSP providing ATS-like services (such as a Local Airport UTM system) to UAVs in the future.

Introducing UTM operations into an airport's controlled traffic region (CTR) inevitably increases the complexity of the traffic picture and work situation that tower controllers will need to assess. As defined per regulation, the main responsibility of tower control is to "issue information and clearances to aircraft under their control to achieve a safe, orderly and expeditious flow of air traffic on and in the vicinity of an aerodrome with the object of preventing collision(s) between aircraft flying within the designated area of responsibility" [10], page 7-1].

As such, the main tasks of a tower controller are to provide information to flights in the CTR, issue clearances for take-off and landing, give flight instructions and coordinate with other instances of ATC, most importantly approach control. As part of our analysis of UTM operating procedures and their impact on tower control tasks we have identified several display design requirements for the collaborative interface between UTM and ATM. These are briefly summarized below and will be further elaborated on in terms of design considerations in section III.

1) Localization of UAVs: Due to the small size of UAVs, it is unrealistic to expect tower controllers to maintain visual sight of all vehicles, and as such information about their locations must be integrated into the radar display.

2) Understanding UAV locomotion: Within the UTM context, the flight plans of UAVs will be predominately dependent on the mission that they aim to achieve. Each mission profile has different implications on the locomotion of UAVs within the control zone and will ultimately affect the tactical decisions that an air traffic controller must make. The display must therefore make the mission transparent such that the controller can anticipate how UAVs will behave.

3) Separation of UAVs from controlled traffic: Since the tower controller will not be able to exercise direct control over UAVs – that is the task of UTM [14] – they must have access to mechanisms to dynamically segregate UAV traffic from manned traffic if necessary. As this has not yet been defined in regulatory literature, for this study, we propose a solution for tactical dynamic segregation of UAVs using geofences [11]. By dynamically activating and deactivating pre-defined geofences on their radar display, the tower controller would be able to segregate UAVs in a way that requires little effort from their side.

4) UAV endurance: Given the relatively small size and light weight of UAVs foreseen to operate within UTM, the overall flight time expected for these vehicles is much shorter, and as such also the contingency reserves they carry. Therefore, within the combined ATC and UTM domain, some tactical decisions made by ATC will affect UTM reroutings and might exceed the flight endurance of UAVs. ATC should be made aware of such limitations.

5) UAV priority: Some UAV missions may be of higher priority than others (such as medical flights, state or police operations, transport of dangerous cargo or even passengers) [11]. In some cases, this might even imply priority of UAVs over manned aircraft. As such, UAV priority should be known to the tower controller.

6) Collaboration with automation: Many UAV missions will need rely to a larger extent on automation in order to be economically viable [1]. These automated UAV operations will themselves be overseen by a more independent, fully machine-based UTM system. UTM will take care of many of the control elements that human air traffic controllers are used to performing on manned aircraft. The human relationship with automation is therefore another important factor to consider in the interface design. Our proposed approach of using dynamic geofences provides such a collaborative function by allowing guidance of UTM actions in a language that it understands.

It is worth mentioning that this list only focuses on nominal operations of both UAVs and manned aircraft. The existence of contingency and emergency scenarios, as well as other disruptions which negatively impact the conduct of the UAV mission (such as adverse weather phenomena or UTM service failures) would also need to be considered. However, for the purposes of this initial study, such situations have been left out of the preliminary design of the interface.

III. Interface Design

We have developed a preliminary tactical tower control display based on the design considerations mentioned the previous section. Its functions are introduced in this section by means of a graphical illustration.

Figure 1 shows 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 (see section II-5). The interface can be divided in two segments: the map view on the left and the flight information view on the right. Relevant display elements are indicated by the letters A through S.

The initial map view in Figure 1a, 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) – see section II-1. 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 (C). Similar to tower control radar, the interface is updated every five seconds, indicated by the timer in the top left (D).

As seen in Figure 1b, selecting a manned air vehicle will highlight its flight strip in the flight information view and vice versa. Additionally, it shows the intended flight plan of the air vehicle (F). It should also be noted that the vehicle icon for UAVs also shows the type of air vehicle (G).

Figure 1c shows that selecting a UAV will display two endurance regions. These regions are developed as a consequence of the rationale described in section II-4. The inner region signifies the endurance the vehicle has available for re-routing (E). When an adjacent geofence is fully within this region, the UAV can fly around it when activated. The outer region indicates the maximum deviation the UAV can make between its current location to its destination. When a (group of) geofence(s) completely occupies this region, the UAV cannot fly around it. Additionally, selecting the UAV shows its flight strip, including mission type (K). Having both a manned vehicle and UAV selected shows the routing involved (J) in a potential conflict.

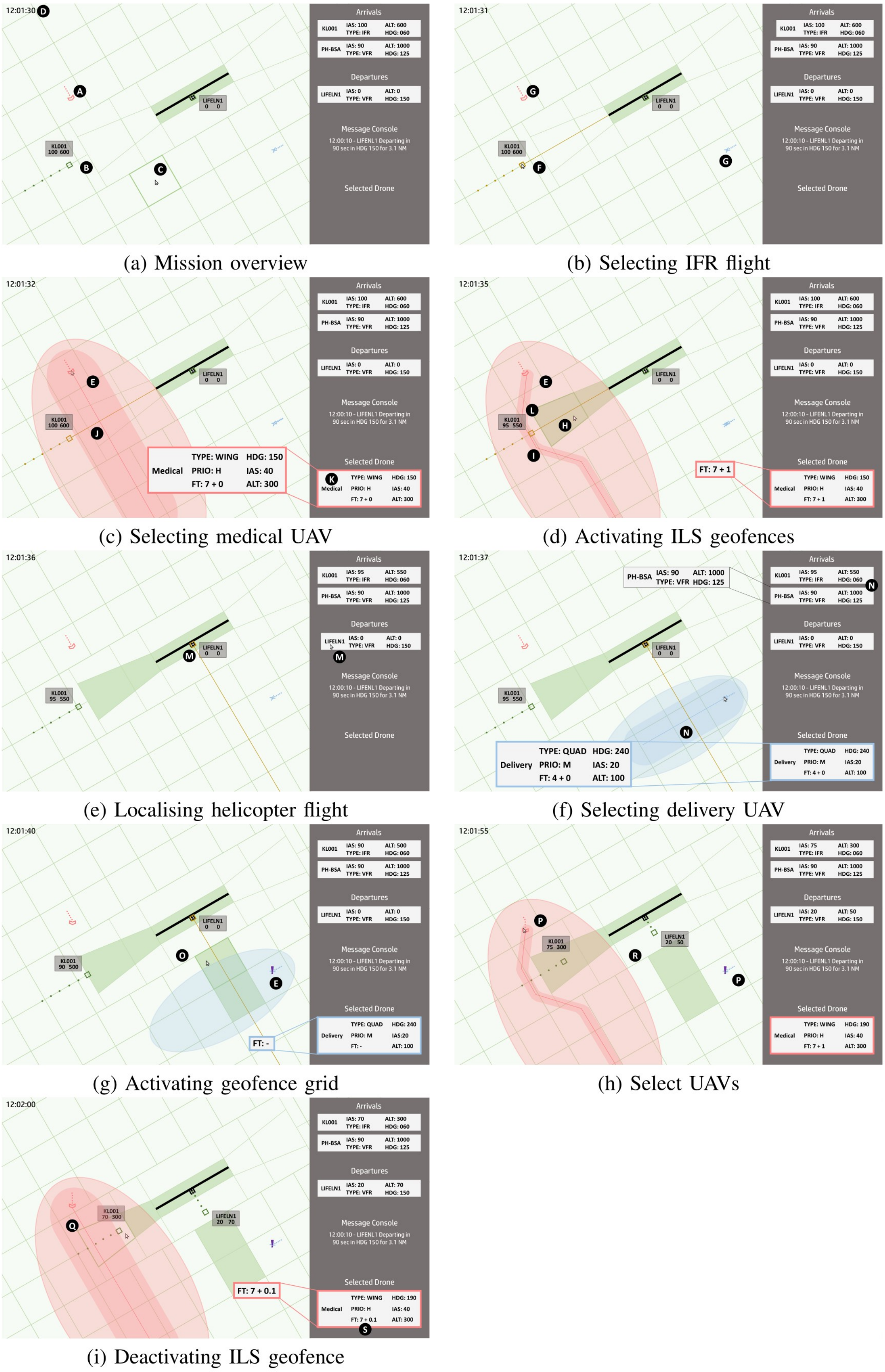
Two geofences are activated in Figure 1d, restricting the UAV from access (H). The active geofences are marked, directly indicating which parts of the VLL airspace are shielded from UAV travel (L). In response to this, the UAV can be seen to modify its route by adding waypoints around the active geofences (I). This allows the controller to manually enforce separation of UAVs from manned traffic (see section II-3). In this interface, UTM will not perform any deconfliction actions on UAVs from manned aircraft, thus situating itself below the tower controller on the decision hierarchy. This makes it easier for the controller to deal with the automated UTM system (see section II-6), at the expense of having to perform more control actions. The impact of this re-route on the flight time can be seen on the UAV information strip. This new route means the UAV has less endurance available, as is indicated by the decrease in size of the inner endurance region (E).

Next, it can be seen in Figure 1e that the message console prompts an emergency helicopter departure, 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 helicopter flight (M).

As seen in Figure 1f, selecting the UAV shows it to be a regular priority delivery flight. This means that it is considered desirable to make the emergency helicopter pass before it. Here geofences can be used to influence the sequencing of air traffic (N). Additionally, the sequencing of manned air traffic among each other is signified by the order of the flight strips in the flight information view.

Activating the required geofences in Figure 1g creates a group of geofences that spans the width of the outer endurance region (E), implying that the UAV does not have enough endurance to fly around it. This will cause it to loiter, indicated by the purple exclamation mark over the vehicle icon. Currently all manned traffic routes in VLL airspace are shielded by active geofences, signifying sufficient separation between manned and UAV traffic is achieved (O).

Figure 1h shows the same situation, advanced by fifteen seconds. The previously provided separation between manned and UAV traffic means the first and foremost top-level goal of tower control has been achieved; the safety (R) of all air vehicles in the CTR. This means the situation can now be analyzed bearing other top-level goals in mind. This can be done by selecting UAVs to display their intended routes, expected travel times and available endurance. The endurance regions displayed upon selection give an indication of the vehicle's locomotion constraints (P), as used before (see section II-2). Additionally, the purple exclamation mark indicates the current lack of locomotion possibilities.



(a) Mission overview (b) Selecting IFR flight (c) Selecting medical UAV (d) Activating ILS geofences (e) Localising helicopter flight (f) Selecting delivery UAV (g) Activating geofence grid (h) Select UAVs (i) Deactivating ILS geofence

Figure 1. Step-by-step overview of the interface structure and functionality for a simple scenario.

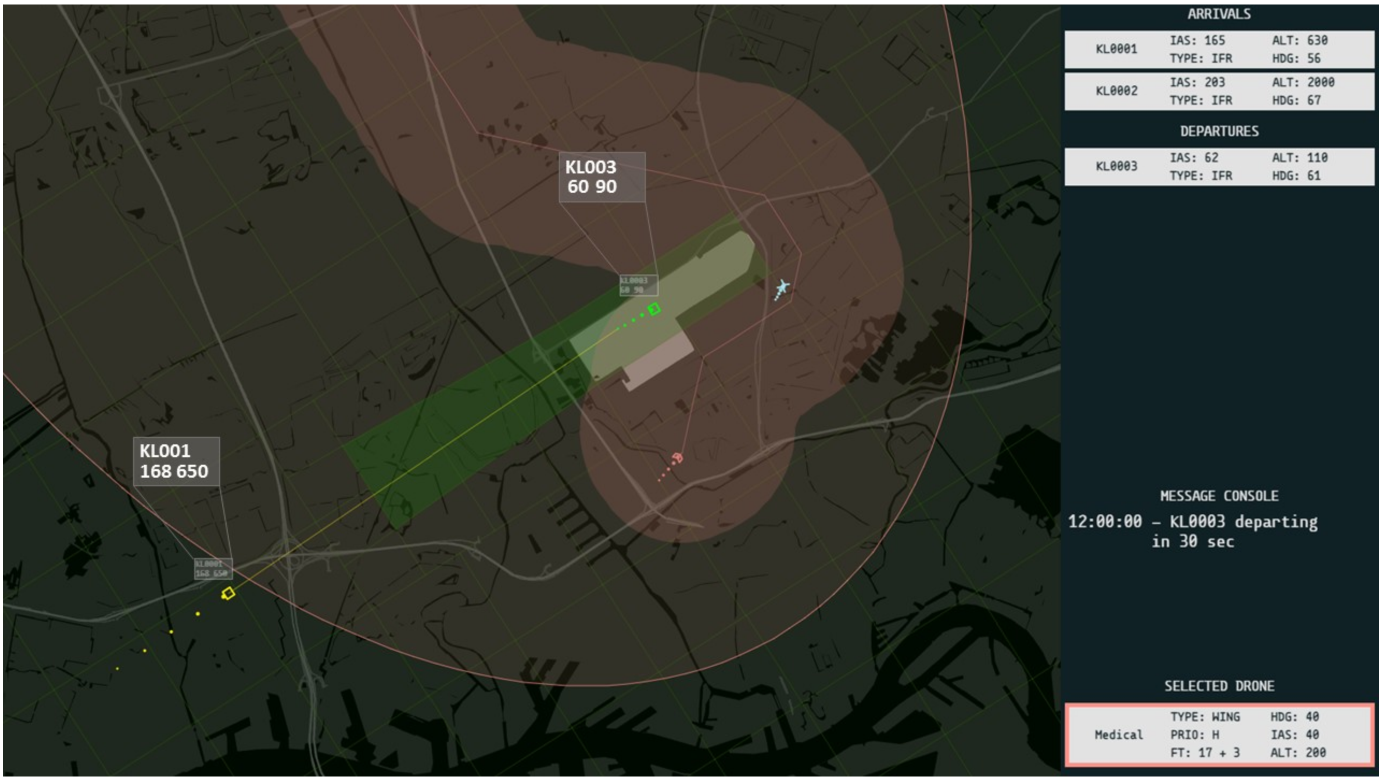


Figure 2. Screenshot of the simulation environment used during the experiment. Flight labels are highlighted for clarity. Free access on: http://dronectr.tudelft.nl.

By comparing UAV and manned traffic speeds in Figure 1i, it can be seen that the priority UAV will not reach the ILS-zone until after the IFR flight has passed. The UAV can be allowed to proceed towards its destination, 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 is demonstrated by the expected flight time and delay, as indicated on the UAV information strip (S). 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.

Figure 2 showcases how these elements are represented in the final graphical display.

IV. 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 geofences to separate UAV air traffic from manned air traffic in tower control. 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 participated 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 (feel free to access the environment yourself using the following link: http://dronectr.tudelft.nl). 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 flights have been integrated into the airspace according to the EASA and EUROCONTROL opinions [14], [9]. Within this environment, participants had to fulfill two main tasks. First, they were tasked to ensure adequate vertical and horizontal separation between manned traffic and UAV traffic. 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 layout of this grid is similar to the system the Federal Aviation Administration (FAA) uses to specify altitude restrictions for UAV operations near airports [15] (see Figure 3). The UAVs responded only to the activation of geofences and could not be instructed individually. UAVs would operate autonomously and use A* path planning [16] for tactical rerouting around geofences.

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 received no 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. 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 geofence cell was used as a baseline, as this is a common unit of reference in ATC. A finer, 1x1 kilometer scale was chosen for the second geofence size option, in favor of UAV capabilities allowing an average-sized multicopter to clear the geofence in one minute.

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 conflict between the manned traffic and the UAV traffic, which could be resolved by the controller by means of activating geofences.

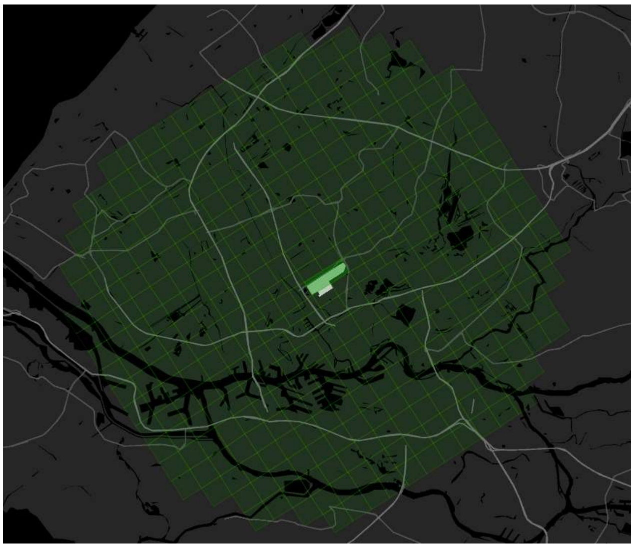


Figure 3. Screenshot of geofence layout developed for the simulation environment.

A total of four traffic scenarios were considered. First, three scenarios were based on use-cases which bear relevance for different types of interaction between UAVs and manned air traffic within the CTR. These contained a scenario emphasizing IFR approaches and departures, a scenario emphasizing VFR approaches and departures and a scenario including an emergency helicopter flight with some additional mixed traffic. 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.

The manned traffic routes in the scenarios were based on Rotterdam The Hague Airport traffic data, published IFR and VFR routes and advice of Rotterdam tower controllers [17]. The UAV traffic consisted of point-to-point delivery missions in the Rotterdam area. 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.

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.

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 point-to-point and was quantified as either a generic multicopter or a generic fixed-wing vehicle and as either high or regular priority. All manned traffic was classified as a generic IFR flight, a generic VFR flight or a generic emergency helicopter flight.

F. Dependent Measures

To quantify the effects of the above-described independent variables regarding the use of geofences and the interface, 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 in 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. 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 beginning the experiment, participants were requested to read briefing documentation supplied to them, explaining the research background, experiment goals and set-up, control inputs, control interface and the experiment procedures. Next, a total of six training scenarios were conducted. The first three scenarios were used to familiarize the participants with the Rotterdam The Hague air traffic region, the simulation environment, the interface and the control inputs. From the fourth training scenario onward, the participants were asked after each experiment run to give a short explanation of their control strategy. After the training was completed, the participants started the experiment runs. After each run, the participants were asked to answer the same post-scenario question about their control strategy. The experiment was concluded with a post-experiment survey. This survey required the 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.

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). Moreover, 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).

I. Data Processing

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.

V. 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. We will focus in particular on how the interface aided controllers in achieving their control strategy, which is summarized below.

A. Control Strategy

Observations during the experiment and from the post-experiment survey showed that participants prioritized safety over UAV efficiency. Furthermore, it was observed that participants strongly favored horizontal separation over vertical separation, as this is common practice in tower control. These priorities resulted in a control strategy that can be divided into two parts.

First, participants obtained situational awareness by checking 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 situational awareness by checking the UAV state and intent after the geofences were activated.

This was combined by the deactivation or tweaking of geofences to increase UAV efficiency following a control technique that resembles vectoring to fulfil the above-described control strategy. Geofences were used 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 the slower UAVs behind the faster manned aircraft, a technique that is common practice in ATC.

Despite the similarities in high-level control strategy, various differences in control behavior were observed during the experiment. Figure 4 shows the geofence interactions over time for three participants in all traffic scenarios - IFR, VFR, emergency helicopter flight (EHF) and high task load (HTL) - in both large and small geofence sizes. The extension of the surface area of the plot provides an indication on the quantity of geofences active during the simulation run, whereas changes in the plotted lines indicate the participant's willingness to (de)activate them. It can be observed that participant A opted for a predominantly passive approach, making use of vertical separation and only activating geofences when required. In contrast participant B opted for a more active approach, (de)activating geofences in groups. Participant B can also be seen to have waited and assessed the situation before activating the first geofences. Finally, it seems participant C generally opted for an active, conservative control strategy. Moreover, participant C can be seen to have activated geofences right after the start of the scenario, emphasizing the focus on safety.

Figure 5 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 most geofence activations occurred 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 5c and Figure 5d.

Figure 6 shows box plots of the total geofence interactions per experiment condition. Statistical analysis shows that the geofence size had no significant effect on the differences between relevant experiment condition pairs.

B. *Interface usage*

Figure 7 shows box plots of the total interface interactions per experiment condition. These interactions include all 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). 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 EHF 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.

Figure 8 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 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.

Surprisingly, the flight strip information was hardly used in these experiments and scored low in terms of usefulness as a result. When asked about this, participants remarked that the most useful information was already available on the flight labels, eliminating the need to refer to the flight strips.

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).

Some comments were obtained regarding the use of color in the interface. 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 pending conflict. Some participants indicated that they would prefer a slightly higher contrast between the "off" and "on" state colors of the geofences. Additionally, it was suggested to further simplify the background, as is common practice in ATC radar screens.

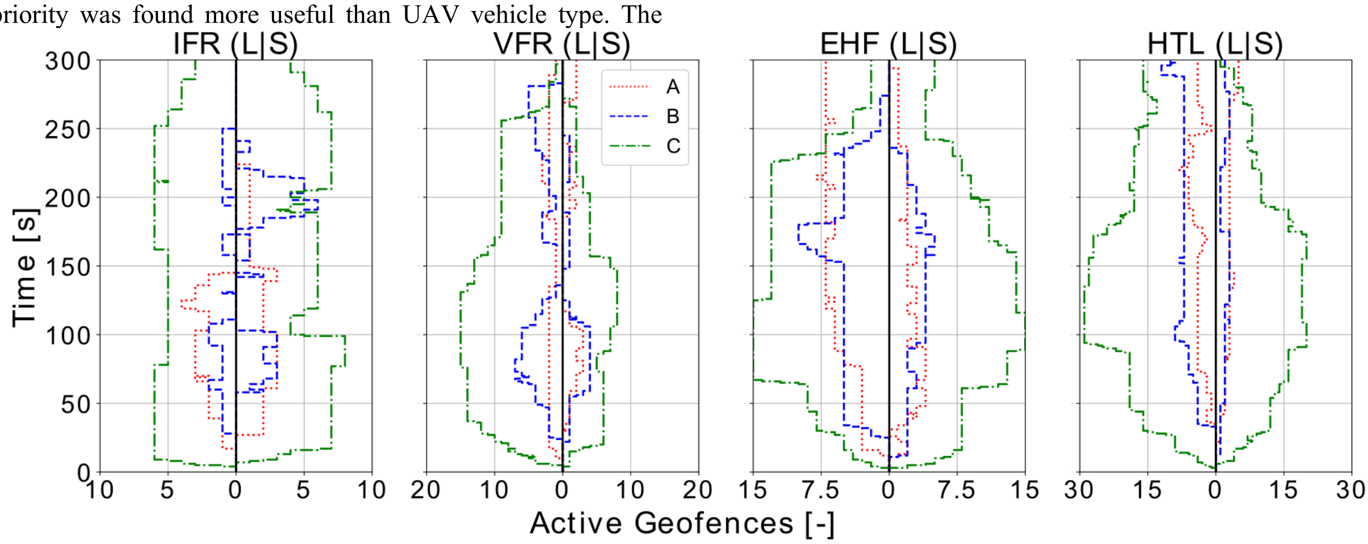


Figure 4. Number of active geofences over time for three participants (A, B, C) with different control strategies. The large and small geofence variant of a scenario is shown on left-hand side and right-hand side, respectively. Note that the scale on the horizontal axis differs per scenario.

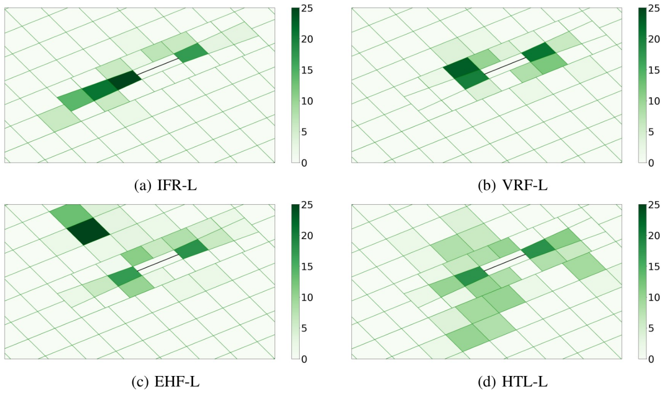


Figure 5. Total interactions per geofence of all participants per large geofence scenario (runway in black).

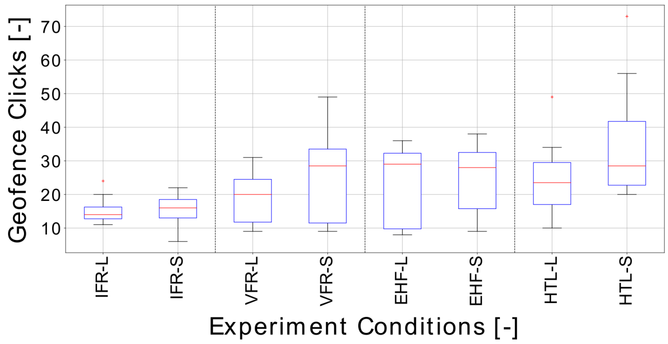


Figure 6. Geofence interactions per experiment condition.

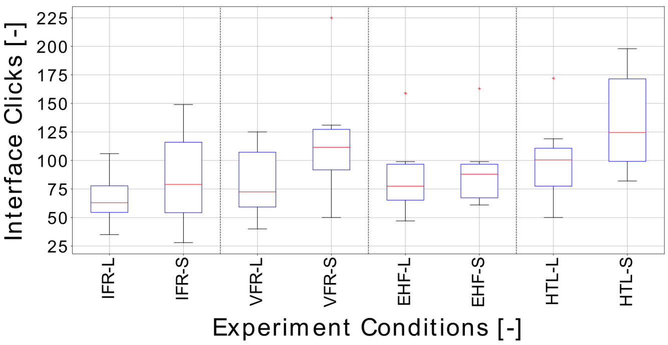


Figure 7. Interface interactions per experiment condition.

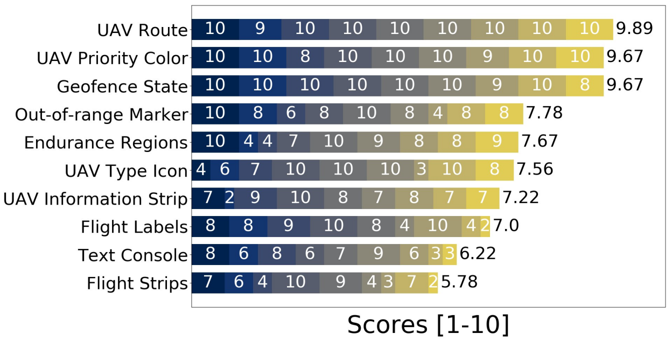


Figure 8. Subjective scores of interface elements from all nine participants, displaying the average score at the end of the bar.

VI. Discussion

Geofences were generally considered a useful tool by the participants to maintain separation between UAV and manned air traffic. As hypothesized, participants were found to opt for a strategy that prioritized safety over efficiency (H1).

As hypothesized, participants indicated they focused more on safety in the high task load scenario and had less time to focus on efficiency (H2.1). However, this is not reflected by the data. 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).

Given the lack of a 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. It was found that this strategy could cause complications, as the UAVs' path finding did not always select the route that the participant intended it to. A higher transparency in UAV (re)routing decisions should therefore be considered as part of the display visualizations. As a consequence, participants expressed the desire to be able to instruct UAVs to shortly loiter, until a geofence restriction was lifted, as this would lead to a more predictable UAV routing behavior.

The high task load scenario was generally considered to be of high complexity and to result in high workload. Participants indicated this was due to them actively controlling (vectoring) UAVs, which would be difficult to maintain next to other tower control tasks. 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, which is reflected in this response. 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 ATC 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.

Surprisingly, most participants indicated they would have prioritized high priority UAVs over VFR flights had they had the opportunity to control VFR traffic. These findings and those from the high task load scenario described above indicate that future research should consider a simulation environment where participants have control of both manned traffic and UAV traffic (through geofences). The combination of high

UAV traffic density and control over UAV and 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. This implies the operator would have less use for the individual endurance regions implemented in the current interface and would mostly focus on UAV routes (as was indicated to be most important interface element). Although the current interface still offers flexibility in problem solving, the controller's behavior could for example be supported by more transparent and predictable UAV routing (by means of "what-if" probing) and a more orderly UAV traffic structure (by means of tailored geofences), as discussed previously.

VII. 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 emphasis of the proposed interface was put on supervising and managing UAV traffic, surrounded by manned aircraft that could not be controlled, within the CTR by dynamically activating and deactivating geofence areas. Results of a small-scale human-in-the-loop experiment with nine professional tower controllers indicated that various interface elements (e.g., UAV priority, UAV routes and geofence state) were deemed useful in supervising current and planned 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. This suggests that controllers may need or want to have more control over UAV traffic than initially expected.

This result, however, could be partially explained by the lack of needing to control manned aircraft. Further work is therefore needed to investigate control behavior and performance in a high task load environment which allows control over both UAV and manned traffic, a broader range of UAV missions, situations which would require controllers to look away from the interface, higher levels of UTM-system sophistication as well as non-nominal situations.

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