Exploring the Limits of Uncrewed and Crewed Air Traffic Segregation by Tower Controllers

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Abstract—**As concepts for incorporating uncrewed aerial vehicles (UAS) into controlled airspace are being developed, the need for automated UAS traffic management (UTM) systems to guide UAS and maintain safety is becoming more apparent. A major point of concern for the implementation of UTM is how such systems could coexist alongside the human-centric air traffic management system that is already in place. The European Union's U-space concept proposes the use of dynamic segregation of airspace reserved for UAS within the control zone. We conducted a simulation experiment with ten air traffic control officer (ATCO) volunteers to gather insights into the feasibility of tower controllers performing the dynamic segregation task. An interface prototype that supports dynamic geofencing and low-level UAS control was developed for this purpose. We found that our proposed interface design helped ATCOs detect potential conflicts between UAS and crewed aircraft. However, they were not always able to adequately resolve them, which resulted in several loss of separation events. It appears that the limitations of the dynamic segregation concept do not fit well with typical air traffic control strategies used by ATCOs. To substantiate our findings, we propose future research to investigate how to overcome the limitations of dynamic segregation to resolve tactical conflicts by revising ATCO control strategies, reevaluating their role in dynamic segregation, as well as considering the definition of flight rules and separation minima for UAS.**

Keywords—**Uncrewed Aircraft Systems Traffic Management; dynamic segregation; UTM; human-machine interface; air traffic control; tower control; geofencing; control strategies; human factors**

I. Introduction

Concepts for safely incorporating flight operations of uncrewed aerial vehicles (UAS) into controlled and uncontrolled airspace are being developed around the globe. Initial regulations concerning the certification of UAS [1] and operational prerequisites for UAS operators [2] are already being implemented. However, as the demand in UAS flights with ever-increasing range and autonomy increases, the need for "UAS traffic management" (UTM) systems has become apparent. These systems provide services to support UAS operators in conducting safe and efficient flight operations, which include traffic management to avoid conflicts between individual UAS as well as between UAS and crewed aircraft. In this regard, UTM can be likened to the current air traffic management (ATM) system, since it tries to achieve many of the same underlying goals, as we have shown in a previous assessment [3]. Examples of concepts for UTM systems include the European Union's "U-space" [4] [5] and the United States' [6] and Australia's [7] respective "UTM" initiatives. Our research focuses particularly on addressing one of the main human-performance challenges of UTM, namely how such systems can coexist with ATM.

Current UTM concepts rely on segregated airspace reserved only for UAS flights to avoid issues in compatibility with the existing ATM ecosystem. According to the International Civil Aviation Organization (ICAO), the term 'segregated airspace' refers to an "airspace of specified dimensions allocated for exclusive use to a specific user(s)" [8], essentially blocking out any unauthorized users during the time frame that the segregated airspace is active. Using a static segregation of airspace reserved for UAS flights, UTM can be implemented separately from the existing ATM environment. However, static segregation itself becomes a liability as soon as a legitimate need for the use of segregated airspace by crewed aircraft arises. This is particularly relevant if this segregated airspace is implemented in an already capacity-constrained environment, such as the control zone around towered aerodromes.

In previous research, we tested the utility of providing a collaborative ATM-UTM interface with dynamic airspace segregation tools for tower control ATCOs [3]. We initially assumed that they would be suited to perform this task given their role as the main tactical airspace manager. However, our experiences from previous experiments made us doubt the utility of assigning an ATCO to perform dynamic segregation to resolve tactical conflicts between UAS and crewed aircraft, which we will highlight in the next section. For the experiment presented in this paper, we deliberately chose to explore the limits of the concept to substantiate these observations.

II. Challenges of Dynamic Segregation of UAS and Crewed Air Traffic

In our first assessment of the dynamic segregation concept, we identified information requirements for aerodrome tower controllers to understand and place restrictions on UAS traffic in their airspace [9] and extracted interface design requirements to support them [3]. To do so, we tasked ATCO participants to perform a series of simulations where they could use a radar-like control display to restrict UAS flights within a control zone using "geofences" - volumes of segregated airspace which an ATCO could dynamically activate or deactivate using the interface. It was the task of the UTM system to reroute UAS flights around or instruct any UAS captured within geofences to exit them. ATCO participants were instructed to use these tools to maintain safety within the control zone. We observed that, rather than simply blocking airspace, participants used geofences as tools to influence individual UAS flight routings, similar to how they would issue instructions to crewed aircraft.

These findings prompted us to investigate the control strategies of air traffic controllers in a follow-up experiment. The experiment was conducted under the PJ34 AURA project [10], in which tower control participants were tasked with performing their normal air traffic control tasks whilst applying a concept known as "dynamic airspace reconfiguration" (DAR). DAR is part of the European Union's U-space concept and is outlined in the Commission Implementing Regulation 2021/664 [11] and accompanying guidance material [12]. Using DAR, air traffic control units can dynamically adjust the boundaries of U-space airspace to impose limits on UAS air traffic, similar to the geofencing concept of our first experiment. We also included UAS-specific commands to the interface which allowed participants to influence UAS routes directly if necessary. From the results of the experiment, we identified "active" and "passive" control strategies for DAR. In the active control strategy, participants influenced UAS traffic directly using UAS-specific commands to support short-term conflict avoidance between UAS and crewed aircraft. However, a passive control strategy focused on using geofences to segregate a large portion of the airspace and was favored in situations with a high crewed traffic load, as it simplified interactions with UTM at the expense of less predictable UAS traffic behavior. From our analysis of the results, we could not single out a suitable strategy for all types of situations. The passive strategy was generally favored but seemed insufficient to resolve short-term conflicts between crewed aircraft and UAS.

These findings gave us the sense that the concepts we were testing were exposing important limitations of applying dynamic segregation to manage tactical conflicts from an ATCO perspective. There appear to be certain situations where traditional ATC strategies based on separation minima and flight rules may be preferable. We therefore developed the follow-up experiment presented in this paper, to provide answers as to whether the concept was adequate to resolve tactical conflicts, whether removing vertical separation requirements would improve performance, and whether the placement of the tower controller as the central coordinator was adequate.

III. Human-in-the-Loop Experiment

To test our assumptions, we incorporated the findings of our previous experiments into an updated interface design, and invited licensed ATCO volunteers to participate in a series of simulation scenarios.

A. Interface Design

Given that the final responsibility of assuring segregation lies with the air traffic control unit [11], the interface was designed to be similar to ground radar displays that tower controllers were already used to working with. Our previous experiments showed the utility of providing such a display design [3], [10]. This section introduces the novel elements added to the interface. Details on the original interface elements are provided in our previous publication [3].

Geofencing tools were improved in three different ways. Apart from simply activating and deactivating individual geofences, participants could also use a multiselect tool to "paint" areas on the interface that they wished to activate (see Figure 1, point 1). The interface also allowed participants to activate geofences along the entire projected flight path ahead of individual crewed aircraft with a single click (see Figure 1, point 2). Finally, pre-defined UAS corridors near the runway could also be activated and deactivated with a single click (see Figure 1, point 3).

We also incorporated additional tools for ATCOs to instruct individual UAS, should the need become necessary. For each UAS, the ATCO could issue: a "loiter" instruction, which would instruct a UAS to orbit in-place until instructed to "resume flying"; a "contingency" instruction, where UAS would head towards the nearest predetermined landing site; and a "land immediately" instruction, where UAS would abort the flight and land immediately (see Figure 2, point 4). To assist the ATCOs in identifying conflicts between crewed aircraft and UAS, a "conflict detection" tool was also developed, which would highlight areas where a loss of horizontal separation minima would occur (see Figure 2, point 5); vertical separation minima were however not considered by this tool, which participants were made aware of before the simulations.

Furthermore, to increase the realism of the simulation, we incorporated a "mission boundary" to each surveillance UAS flight that it would not be allowed to exit (see Figure 2, point 6). This feature was added to depict the operational limitations imposed by ground risk mitigation requirements of the "specific" category [2], which are expected to be the most common category of UAS missions [13]. If an activated geofence blocked the mission boundary of a UAS, it would loiter at a location just outside the geofence boundary until removed. Furthermore, a 2D variable wind field was included that could impact a UAS' endurance. As UAS would fly at a fixed airspeed, wind also impacted their arrival times at trajectory waypoints. Finally, should the UAS reach the limits of its flight endurance, or pass through an area of excessive wind speeds, it would automatically enter a contingency mode and head towards the nearest alternate landing site.

B. Participants and Tasks

In total, ten licensed ATCO volunteers participated in our simulation. It is important to note that participants had varying degrees of experience in working in a tower control environment (six active tower controllers, two former tower controllers and two ATCOs without a tower control rating) and

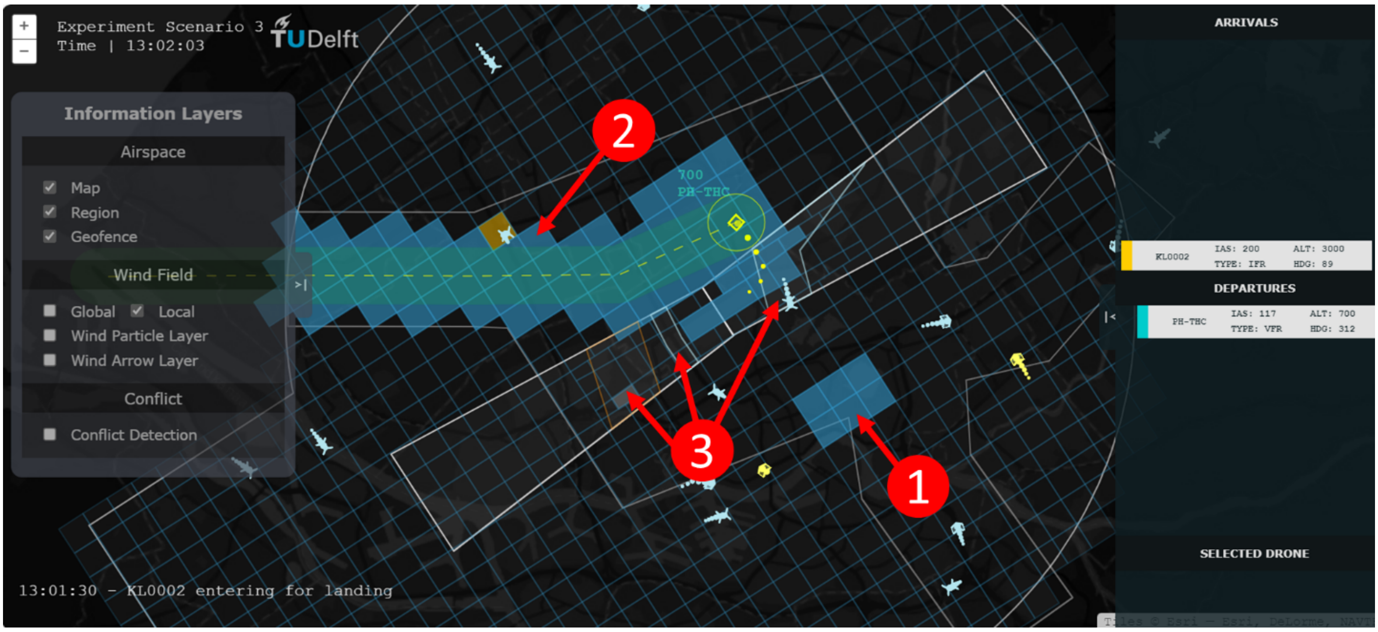


Figure 1. Overview of geofence tool improvements on the collaborative ATM-UTM interface for tower controllers. Online demo: http://dronectr.tudelft.nl/, Participant ID: `demo`.

Figure 2. Overview of new UAS intervention tools incorporated into the collaborative ATM-UTM interface for tower controllers.

stemming from different cultural backgrounds (nationalities from four European countries were present).

Participants were tasked to segregate UAS traffic in very low-level airspace from crewed air traffic around Rotterdam - The Hague Airport. They could achieve this by reconfiguring the airspace boundaries between UTM- and ATM-controlled airspace using dynamic geofences, similar to the DAR concept developed for U-space, but supported by minimum separation criteria between UAS and crewed aircraft which we used in all of our previous studies, namely 1000 meters horizontal separation and 500 feet vertical separation.

C. Independent Variables

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

Participants were divided into two groups of five. The first "horizontal group" (H) would be tasked with conducting dynamic segregation by only considering horizontal separation requirements between crewed traffic and UAS. The second "vertical group" (V) would have to consider both horizontal and vertical separation requirements. We defined these two groups under the assumption that vertical separation would play a lesser role in close proximity to the aerodrome, since the difference in altitudes between UAS and crewed aircraft would be very low.

All participants performed the same three traffic scenarios in a quasi-randomized order (to counterbalance presentation order), but were required to maintain different separation minima, depending on whether they were assigned to the horizontal or vertical group. Moreover, they were asked to minimize disruptions to the original UAS traffic routes as much as possible in all scenarios. This amounted to a total of 15 data points ($N = 5$ participants $\times$ 3 scenarios) per group.

D. Traffic Scenarios

UAS traffic was based on potential point-to-point and surveillance missions in proximity to the airport. Use cases such as medical delivery between hospitals, railway or high-way infrastructure inspections and harbor patrol flights were used as a baseline for UAS flight profiles. We expected these types of missions to be the most common ones for commercial

TABLE I. TRAFFIC SCENARIO DETAILS.

	Crewed aircraft			UAS			Events	
Sceario	Comm-ercial	VFR	HEMS	Medical	Surv-eillance	Delivery	Conflicts	Contin-gencies
E1	3	2	0	2	15	3	2	2
E2	2	2	1	2	15	3	2	1
E3	2	2	1	3	17	2	4	0

beyond visual line-of-sight UAS flights, according to UAS industry growth projections [13]. Moreover, UAS missions could either have a high or medium priority, and had a maximum flight altitude of 120 meters above ground level – a value commonly referenced in European regulations. Crewed aircraft included a mix of commercial flights arriving and departing under instrument flight rules, single engine piston aircraft utilizing designated visual flight-rule (VFR) corridors and traffic circuits, and helicopter emergency medical service (HEMS) flights which departed the aerodrome directly in the direction of their destination at low altitude. An overview of the simulation scenarios is provided in Table I, and an example of the flight paths selected for the traffic scenarios is provided in Figure 3.

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

Finally, UAS contingency events were also added to the experiments to increase the realism of the simulation and to analyze how participants would use the interface to manage them. These events were triggered by pre-programmed UAS failures and flights into areas of excessive windspeeds. The interface would update every five seconds, a common update rate in air traffic control. Geofence restrictions could be activated and deactivated by the ATCO at any time. UAS routes would respond to airspace changes and ATCO commands instantly, as this allowed us to simulate the concept at a completely tactical level.

E. Control Variables

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

We would also like to highlight several limitations of the simulation. No “out-of-tower view” was provided and the fact that crewed aircraft could not be controlled meant that participants could dedicate their full attention to UAS traffic and the interface. Moreover, no voice communication with crewed aircraft was available. Instead, text messages (see bottom-left corner in Figure 1) provided information about departure or landing intentions of crewed aircraft.

F. Dependent Variables

In the experiment, we measured a series of qualitative and quantitative metrics to support our assessment. System data recordings (i.e., UAS and crewed aircraft positions, speeds, altitudes and routes) provided the necessary information needed to assess the achieved level of safety and efficiency in each experiment run. Conclusions concerning the participants’ control strategies were obtained by measuring which geofences were activated at which point in time through time-stamped mouse clicks, through reviews of video and audio recordings made during the experiment, as well as through post-experiment questionnaires. These questionnaires also provided information about the participants’ perceived task performance and other subjective data.

G. Experiment Procedure

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

Each participant, regardless of their assigned group, would complete seven training scenarios of 5 minutes each to familiarize themselves with the interface and its functionalities, before conducting three, 15-minute simulation sessions. After each simulation run, participants would also fill out a subjective assessment survey with specific questions to the traffic scenario. Moreover, a dedicated post-experiment survey was also presented to participants with more general questions regarding the concept as a whole.

H. Hypothesis

We hypothesized that participants in the horizontal group would perform the tasks better than participants in the vertical group, because we assumed vertical separation would play a lesser role in close proximity to the aerodrome. The hypothesis was tested by aggregating experiment data in terms of safety, efficiency and the amounts of interface interactions of ATCOs to judge their performance.

IV. RESULTS

To facilitate data analysis, we plotted the interface and UAS traffic interactions on a timeline, to allow for a better comparison between participants. Figure 3 shows an example of a timeline for participant P01, who experienced several conflicts between UAS and crewed aircraft in experiment scenario E3. The map depicts the routes of crewed aircraft in the scenario in continuous lines and UAS in dash-dotted lines. The intensity of the blue shading highlights the number of times a specific geofence was activated. The timeline graph depicts the duration when crewed aircraft (top bars) and UAS (bottom bars) were flying in the simulation. The continuous vertical lines across all UAS bars highlight when geofences were activated (in green) and deactivated (in black). Moreover, the smaller vertical lines within each UAS bar highlight UAS-specific commands that were issued. The red colors in both crewed aircraft and UAS bars depict the duration that both aircraft were experiencing a loss of separation.

Based on the raw data, we extracted aggregate metrics for performing statistical analyses. Given the small sample size and presence of outliers, a normal distribution of the underlying data could not be assumed. Therefore, the non-parametric Mann-Whitney U Test was used to compare metrics and identify if there was a difference between the horizontal and vertical groups. However, none of the tests showed any statistically significant differences between samples on any of the metrics depicted in Figure 4, leading us to reject our hypothesis that the type of separation requirement would impact ATCO performance. Although our manipulations regarding horizontal and vertical separation minima were not significant, we did identify several loss-of-separation events that merit further discussion.

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

Table II summarizes the instances where a loss of separation (with respect to the minimum LOS criteria) occurred during the experiment. There were slightly more LOS situations in the horizontal group (9 LOS) than the vertical group (8 LOS). Most of the LOS situations involved VFR aircraft (9 LOS), followed by HEMS flights (5 LOS) and then commercial aircraft (3 LOS). Out of all LOS occurrences (17 in total), three involved high-priority medical UAS.

TABLE II. Overview of the severity of loss of separation events between crewed aircraft and UAS.

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

TABLE III. Main contributions to losses of separation.

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

V. Discussion

From the assessment of results we could not identify significant differences between horizontal and vertical groups in terms of safety, efficiency or the amounts of interface interactions. However, the number of severe losses of separation in the experiment surprised us. We specifically designed the experiments in a way that excessive workload or task saturation could be ruled out when analyzing performance results, since participants were not performing any other ATC tasks, traffic load was average and that participants could focus their attention entirely on the display. This was also confirmed by participants in their responses to workload and situation awareness questionnaires. Surprisingly, ATCOs also reported a high level of perceived safety performance in these questionnaires, which was not reflected in the data we collected. We therefore reevaluated whether the interface design and tools were adequate in highlighting and resolving conflicts, as well as whether ATCO control strategies influenced the results.

A. Contributing Factors to the Observed Losses of Separation

We found several contributing factors to the LOS that occurred in the simulations, which are summarized in Table III. We believe that in seven LOS events participants could not properly judge what the minimum horizontal separation distance was on the interface. The interface did provide indications about the minimum horizontal separation distance required in the form of a circle around the crewed aircraft blips (see Figure 1). However, upon reviewing the experiment recordings, we could not confirm whether participants considered this indication when resolving conflicts. It appears that they were more focused on making sure that the actual trajectories between UAS and crewed aircraft would not overlap.

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

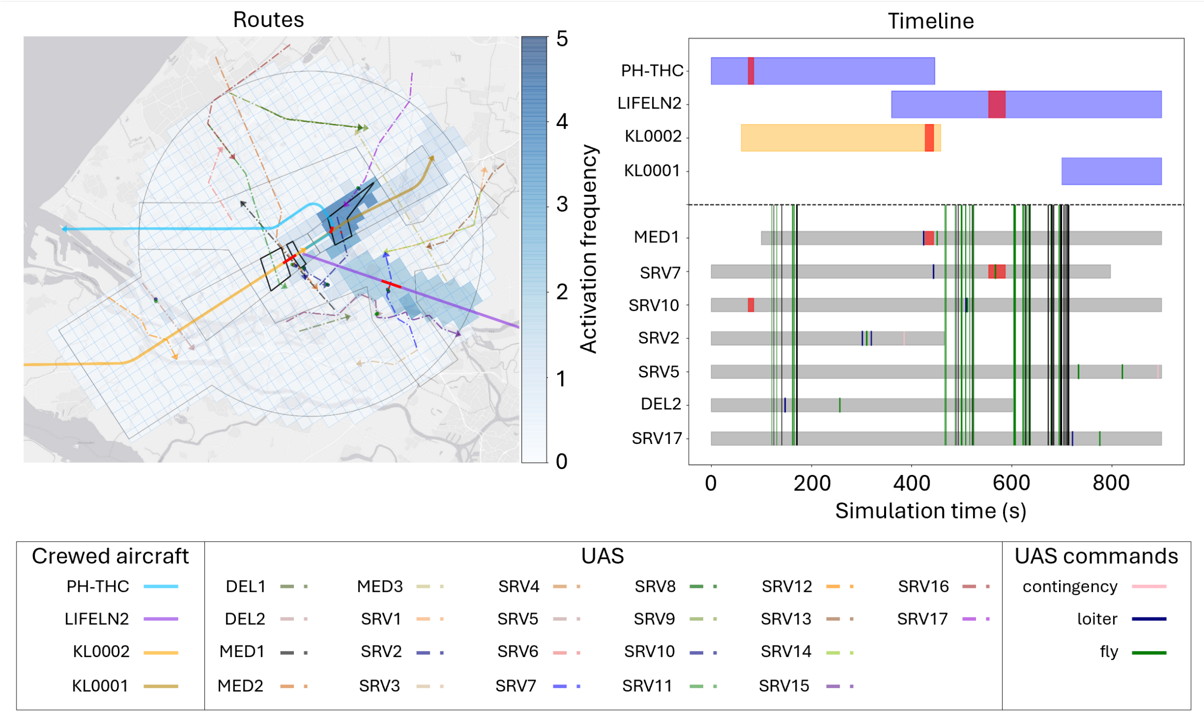


Figure 3. Exemplary timeline visualization of participant P01 in scenario E3.

In one incident a participant was tracking a particular UAS which they believed caused a conflict with a crewed aircraft, when it was in fact another UAS. Even though the conflict detection tool had been indicating the correct UAS, the ATCO was initially too focused on the other aircraft. When they realized the mistake, they only had a few seconds remaining to resolve the conflict, and failed to do so.

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

B. Interface Effectiveness in Detecting and Resolving Conflicts

In general, participants quickly identified conflicts between UAS and crewed aircraft using the interface. In fact, of the conflicts that resulted in a loss of separation, the average lead time between the initial conflict detection (measured from the time that the ATCO used interface functionalities to gather information) and the LOS occurring was over 2 minutes.

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

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

Yet, we believe shortcomings in interface functionalities only partially explain why they failed to resolve conflicts in time. We therefore looked further into the control strategies that ATCOs applied, to identify whether any particular strategy contributed to the observed LOS events.

C. ATCO Control Strategies Used to Resolve Conflicts

Geofence activations were the primary means of structuring UAS traffic for most participants. On average, participants would change the number of active geofences 37 times over the 15-minute duration of each experiment scenario. This is a high rate by typical ATM standards. In comparison, the dynamic airspace configuration concept developed for en-route crewed aviation defines a 20-minute minimum time interval between airspace configuration changes [14]. When UAS-specific commands were used, it was frequently the combination of "loiter" and "fly" commands to support geofence

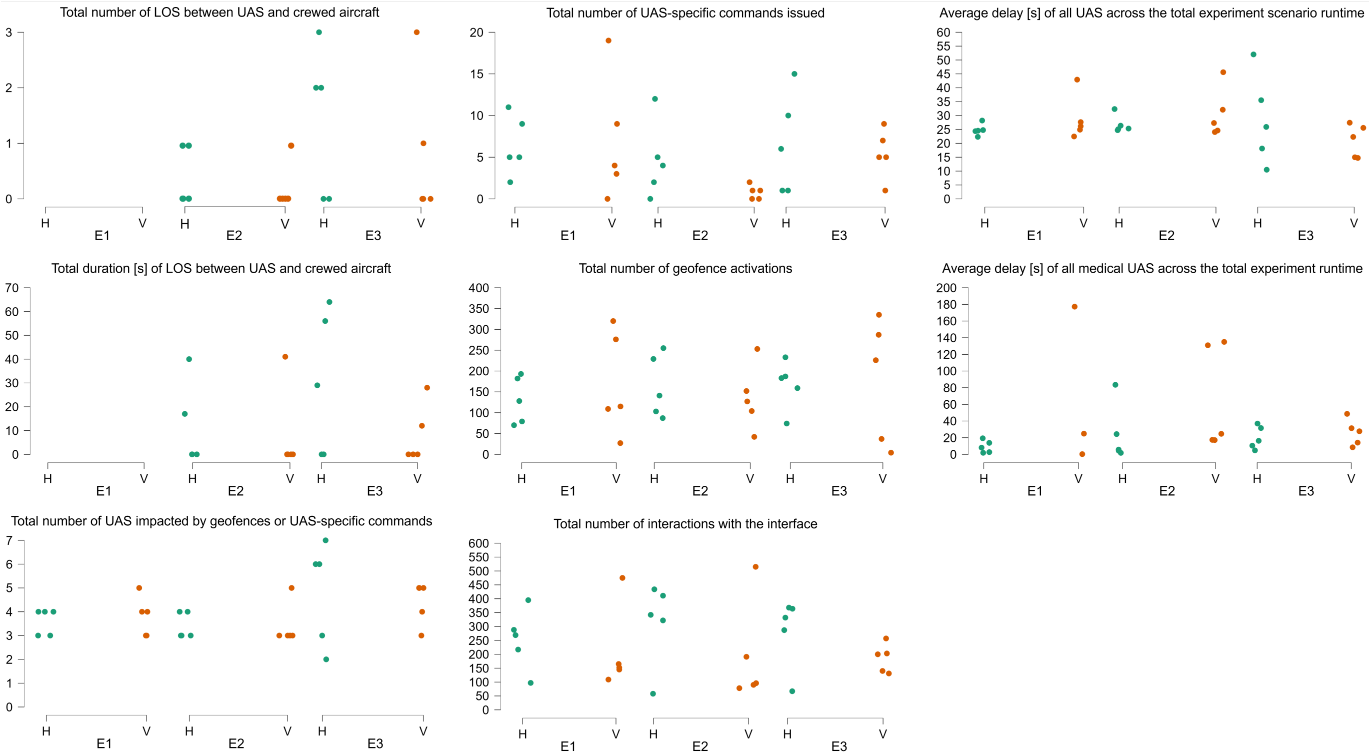


Figure 4. Overview of aggregate samples of each dependent variable, separated by group (H - V) and simulation scenario (E1 - E2 - E3). No significant differences were found between samples. A dot plot was used given the low sample size per group.

activations and create a predictable UAS traffic behavior when crossing the final approach and departure areas upwind and downwind of the runway.

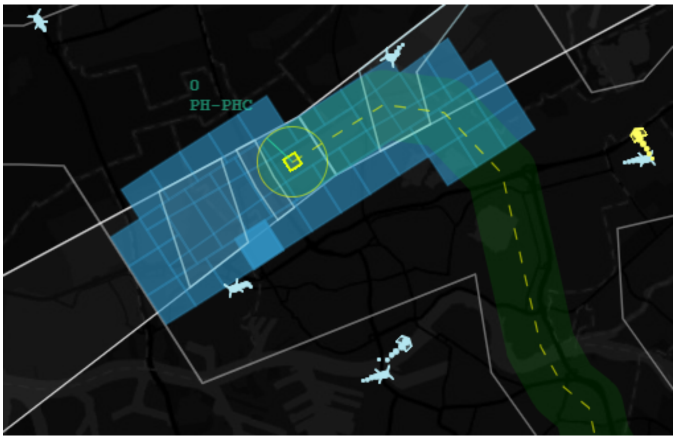
According to the concept, the intended use of the interface would have been primarily to segregate the airspace using geofences in such a way that crewed aircraft would not come into conflict with UAS, and then trust the UTM system managing the UAS to reroute them around the airspace restrictions, as depicted in Figure 5a. UAS-specific commands would have served as a last means for intervention to resolve a pending loss of separation. We termed this the “passive strategy” in our previous experiments.

Instead, we observed that a majority of ATCOs (7 out of 10) used the interface tools to force a particular UAS trajectory following control strategies they typically apply when issuing instructions to crewed aircraft – we refer to this as the “active strategy”. Figure 5b shows a situation where an ATCO applied this strategy. Two geofences were activated along the route of a UAS which conflicts with a departing crewed aircraft, with the purpose of forcing the UAS to divert from its original route. Since the UTM system would search for reroutes around segregated airspace, UAS would sometimes go in unwanted directions and even cause additional conflicts with traffic which the ATCOs had not foreseen. This was particularly problematic when participants opted to activate geofences locally, as it provided more room for UTM to reroute UAS around them. Additionally, knock-on effects would occur, as new geofence restrictions affected all UAS routes passing through that area, not just the specific UAS the ATCO was attempting to reroute. Therefore, some participants opted to manually intervene using UAS commands to maintain a high level of predictability by overriding UTM decisions, as depicted in Figure 5b through the UAS command selection tool, and in some cases even foregoing the use of geofences alltogether.

The active strategy seems to be the most “natural” to how ATCOs manage air traffic today. However, since the interface did not allow them to issue routing instructions to UAS, it was difficult for them to apply it. The discrepancy between the intended active control strategy and limitations of the operating concept to support it was a major contributor to the LOS that occurred. Surprisingly, the remaining three participants who followed the passive strategy had no instances of LOS at all. We assume that had all participants opted for the passive strategy, the results in terms of safety might have been better across the board. We therefore propose to incorporate several mitigation measures to the interface and operating concept in order to improve safety performance, which we will elaborate on in the next section.

D. Potential Mitigations

One option to reduce the active control tendency exhibited by ATCOs may be to provide more transparency into the UTM decision making process on UAS routings. By revealing more information which helps ATCOs understand the rationale behind UTM decision making, both their engagement and



(a) Use of geofences to block larger areas in the passive control strategy.

(b) Use of UAS-specific commands to manage conflicts in the active control strategy.

Figure 5. Exemplary screenshots of different control strategies applied in the simulation.

situation awareness could be improved. Promising concepts for this are being explored by Zou and Borst [15], who focus on means to visualize automation decision-making to human UAS supervisors.

Another option may be to approximate UTM traffic management decisions on UAS towards air traffic control strategies for crewed aircraft to increase predictability. Thus, UAS would behave in a similar manner to crewed aircraft, both in regards to conflict avoidance with other aircraft as well as routings around geofences. The former would require the definition of flight rules for UAS similar to those of crewed aircraft (potential candidates to be explored include the “Digital Flight Rule” [16], “Enhanced Flight Rule” [17] and “U-space Flight Rule” [18] concepts). The latter could be supported by a more capable path finding algorithm for UAS that also considers dynamic obstacles, such as Zeta*-SIPP [19].

The segregation concept could also be revised based off of findings in these and similar simulations. For instance, a majority of participants (6 in total) favored vertical separation requirements over horizontal ones, citing that horizontal separation minima would only be necessary if crewed aircraft were operating at low altitudes. This comment essentially inverts our original assumption that achieving horizontal separation between UAS and crewed aircraft would be the main criteria for airspace reconfiguration. The enforcement of these separation criteria would also need to be supported using more sophisticated conflict detection tools and visualizations on the interface, as previously discussed.

Dedicated ATCO training towards a more passive strategy concerning UAS may be beneficial, supported by interface updates which limit the use of UAS-specific commands to very concrete situations. Schwoch et al. [20] provide some suggestions on how UAS-specific ATC commands could be used on for instructing UAS to hold position before implementing a DAR change or ahead of low flying crewed aircraft, as well as guidance on how to manage crewed and uncrewed aircraft contingency situations supported by automated system messages.

Finally, we must also consider that in our post-experiment survey, all but one participant agreed that an additional airspace manager position would be required to perform the tasks in the experiment. We initially came to the same conclusion from our assessment considering that geofencing and dynamic segregation of airspace are tools more akin to strategic airspace management, which ATCOs are not typically trained for, and might explain the tendency to actively manage UAS traffic. The assignment of a separate role within ATC to manage DAR was explored in experiments conducted by Teutsch et al. [21], [22]. This would remove a substantial task load from the tower controller in times where UAS or crewed aircraft operations are high, as results from their study confirm. However, the interplay between the tower controller and the, now delegated, “DAR Manager” would need to be supported by clear procedures on how tactical interventions on UAS traffic conflicts with crewed aircraft would need to be managed. Moreover, the addition of another human actor in the decision making process incorporates additional human performance challenges which would need to be addressed in future studies.

Perhaps this role could also be assigned to UTM using automation, where the UTM system is tasked with activating geofences to resolve conflicts with crewed aircraft, rather than the ATCO. Sharing crewed traffic information with UTM, or making crewed aircraft electronically conspicuous will allow UTM to proactively take corrective actions ahead of conflicting air traffic, and therefore assisting the ATCO in maintaining a safe airspace. Insights gained from work on UAS fleet supervision within the field of Human Autonomy Teaming could provide valuable guidance in this matter, such as in the studies by Smith et al. [23] and Sadler et al. [24].

VI. Conclusion

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

The interface provided sufficient indications to alert ATCOs to potential conflicts and allow them enough time to deal with them. However, the tools provided were inadequate to meet the demands of the control style applied to resolving conflicts. Most ATCO participants tended to actively influence UAS routing in the control zone. Instead of simply opting to segregate sufficient airspace and allowing the UTM system to reroute UAS by itself, participants were more likely to attempt to accommodate UAS routings among their crewed air traffic by themselves. However, geofences and UAS instructions alone would not always resolve the conflicts in a way that they expected. This took away time for ATCOs to focus on other conflicts and maintain an overview of the airspace situation.

This experiment showed the limitations of using strategic airspace management tools to resolve tactical conflicts between UAS and crewed aircraft using typical air traffic control strategies. It appears that applying the dynamic segregation concept to such a short-term time horizon breached the limits of how such a concept could be successfully used. A majority of participants therefore mentioned that the role of reconfiguring UTM airspace should be a separate entity from the ATCO performing tower control. Perhaps letting the UTM system automatically detect and resolve conflicts using geofencing would yield better results.

Otherwise, to resolve tactical conflicts between crewed traffic and UAS, perhaps the definition of UAS flight rules, separation minima and accompanying ATCO control strategies should be considered to support dynamic segregation. A follow-up experiment in which participants are instructed specifically which strategy to use and when, supported by interface improvements on visualizing UTM decision-making could shed some light on this question.

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