Faculty of Aerospace Engineering

Design and Evaluation of an Ecological Interface for Separating UAV from Manned Air Traffic in Tower Control

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by

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Preface

This document contains the final report of my master thesis project regarding "*Design and Evaluation of an Ecological Interface for Separating UAV from Manned Air Traffic in Tower Control*", conducted at the Control and Simulation group of the Faculty of Aerospace Engineering at the Delft University of Technology.

The year I spent working on this thesis was certainly an unusual one, with the COVID-19 pandemic hitting only a couple of weeks after I started. This lead to a lot of digital meetings and almost a full year of working from home. Special thanks to my housemates for their support and company during the multiple lock-downs we endured together. The pandemic also lead to the first remote human-in-the-loop experiment within our group, which in the end extended our reach beyond Dutch participants, making the experiment results stronger. Thanks to Jap-Jaap and Andries for their help in setting up the experiment server.

Over the course of the last year, I received generous support and feedback from my supervisors, which has been fundamental to the successful completion of my thesis. Max, thank you for your enthusiasm and energy, as well as sharp insights and feedback. Clark, thanks for the many (digital) meetings we had together, where you always provided excellent suggestions and feedback, brought me in contact with the right people, and motivated me to keep improving my work. Dominik, thanks for your interest in my work, and for your continuous support, from familiarising me with U-space to helping with the execution of the experiment. It has been a pleasure and an honor to work with all of you.

Pivotal to this research, were all the air traffic controllers willing to participate in the experiment. I am grateful for their enthusiasm for my work, their interest in our research, and the invaluable feedback they provided over the course of the experiment runs. Special thanks goes out to Vincent for providing me with insight on tower control in general and Rotterdam - The Hague Airport specially over the course of the last nine months. Your feedback was crucial in bringing the simulation environment to higher level.

Finally, I am extremely grateful for all the support from my friends and family over the last six and a half years in general and the last year specifically. Special thanks to Elly and Maarten for their endless support and love, bringing me where I am today.

Daan van Aken

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List of Abbreviations

Abbreviation	Description
ADS-B	Automatic Dependent Surveillance – Broadcast
AH	Abstraction Hierarchy
ANS	Air Navigation Services
ANSP	Air Navigation Services Provider
ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
ATM	Air Traffic Management
BVLOS	Beyond Visual Line of Sight
CAAC	Civil Aviation Administration of China
CTR	Controlled Traffic Region
CWA	Cognitive Work Analysis
EASA	European Aviation Safety Agency
EHF	Emergency Helicopter Flight
EID	Ecological Interface Design
ELOS	Equivalent Level of Safety
EU	European Union
FAA	Federal Aviation Administration
FMS	Flight Management System
GPS	Global Positioning System
HEMS	Helicopter Emergency Medical Services
HFR	High Level Flight Rules
HTL	High Task Load
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMU	Inertial Measurement Unit
LAANC	Low Altitude Authorization and Notification Capability
LFR	Low Level Flight Rules
LNVL	Dutch Air Traffic Control Agency
NASA	National Aeronautics and Space Administration
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
SORA	Specific Operational Risk Assessment
STAR	Standard Terminal Arrival Route
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UOMS	Civil UAS Operation Management System
UTM	Unmanned Aircraft System Traffic Management
VFR	Visual Flight Rules
VLOS	Visual Line of Sight
VVL	Very Low Level
WDA	Work Domain Analysis

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1 Introduction

1.1. Background and Scope

The European Drone Outlook Study predicts a large increase in the use of unmanned aerial vehicles (UAVs). By the year 2035, the fleet of UAVs operational in the industrial sector in Europe is expected to consist of nearly 400.000 vehicles. Additionally, the number of UAVs in circulation for personal use is expected to increase to 7 million. Moreover, the relative number of UAV operations with respect to manned aircraft operations is expected to increase from less than five percent now to around 25 percent by 2050 [11]. Apart from this absolute and relative increase in the total number of vehicles, UAVs will be applied over a broader range of applications, with increasingly complex missions [21]. For example, a significant portion of the current UAV operations occurs within visual line of sight (VLOS) of the operator. However, it is expected that the majority of the future demand for industrial UAV operations will be beyond visual lone of sight (BVLOS) [11]. The safe integration of BVLOS flights into the existing airspace poses a a risk to existing air traffic and forms a challenge for regulators. Therefore, the integration of BVLOS flights is being researched and flight-tested by various parties [22, 23].

The expected increase in UAV operations poses a problem for existing manned air traffic. An example of this is the Gatwick Airport incident, where unknown UAVs were seen 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 [24]. This incident exemplifies the increase in UAV-related air traffic incidents in the UK increasing from zero in 2013 to over a hundred in 2018 [25]. Unsurprisingly, there have been incidents similar to the one at Gatwick Airport at London Heathrow and Frankfurt [26, 27].

The interference of UAVs with existing manned air traffic gives rise to the demand for a framework that encompasses the management and safety of UAV operations. This demand is met by the development of unmanned traffic management (UTM) systems. A UTM system acts as a connection between aviation authorities and UAV operators. It allows UAV operators to carry out the desired missions, while enabling the authorities to ensure operators do so safely and orderly [28]. There are efforts by various authorities to set up a UTM system, for example the Low Altitude Authorization and Notification Capability (LAANC) in the United States, U-space in Europe and the Civil UAS Operation Management System (UOMS) in China [1, 29]. This research will focus on applications in European airspace, therefore, the European U-space system will be used as the referenced UTM system in this research.

U-space focuses on UAV operations in very low level (VLL) airspace, as this is where most UAV operations will likely occur [5]. Within this operational domain, U-space aims to integrate UAV UAV traffic into the existing airspace structure, rather than separate it [30]. Authorities supervise the provision of a set of services to UAV operators that enables them to perform their mission, forming the aforementioned connection between authorities and operators. Examples of these services are registration, identification, tracking and information provision. These services rely on automation, digitisation and an open-market structure, where different entities can provide services to UAV operators.

As the U-space system aims to integrate UAV traffic into the airspace, its interface with existing ATC is of importance. As indicated by the Gatwick Airport incident and the operational altitude of U-space, this interface is most relevant for tower control, as they are responsible for separation and efficient movement of aircraft within the controlled traffic region (CTR) [31]. In terms of collaboration, U-space plans to make real-time UAV information available to ATC. Moreover, a procedural interface will be implemented that allows ATC to accept or decline UAV flights in advance [32]. This does not, however, cover short term restrictions that occur in-flight, such as medical emergency helicopter flights. A possible solution for this is the use of temporary geofences, volumes in space that do not allow any UAV operations within their boundaries [2]. Apart from this temporary application, U-space will make broader use of geofences to restrict UAV flight where needed (e.g., royal palaces, runways, national parks, etc.). Moreover, geofences are seen as a possible means of interaction for tower controllers, as this alleviates them from having to interact with individual UAVs. By using geofences, they can shield the required area with a geofence without further interaction [33].

As indicated above, the interface between U-space and tower control is in development from a technological point of view. However, a crucial aspect in improving the interface between U-space and tower control is the consideration of human factors for tower controllers when UAVs are integrated into the airspace [34–37]. Despite its indicated importance, there is currently a lack of focus on this field of study, both in the U-space documentation and in ongoing research.

Although the use of geofences is seen as a feasible tool, there is a lack of understanding on how tower controllers should interact with them. In other research related to geofences, their shape and size have been scaled based on a map of the surrounding area or based on UAV capabilities [33, 38]. However, little is known of the influence of the size and shape of a geofence on its use a tool for tower controllers. The lack of understanding of human factors in this field is further emphasised by analyses of aviation safety reports involving UAVs [25, 36]. Most prominently, the lack of training on both the side of the UAV operator and the air traffic controller is emphasised. Moreover, various human factors challenges are identified, which are underlined by similar studies. First, the large variety in UAV missions and capabilities is considered a difficulty for tower controllers. Second, the low predictability of UAV operations, partially as a result of the previous point, is seen as a liability [35]. Finally, off-nominal situations, for example due to navigation or communication failure, is foreseen to play a crucial role [37]. This is further stressed by the listing of foreseen threats to UAV operation and possible mitigation measure in U-space documentation [20].

Concluding, research is needed to investigate the human factors of tower air traffic controllers interacting with UAVs integrated in the airspace, operating under the U-space system. Behind this lies the question of how information regarding these UAVs should be presented to the tower controller and how they should interact with them. To investigate the interaction between a display containing UAV information and the tower controller, the principles of ecological interface design (EID) will be applied. The research specifically regards geofences and their desired shape and size. The challenges of low predictability of UAV behaviour and off-nominal operation should be taken into consideration.

1.2. Research Objective

Following the above-described research background and the current scope of the problem, the primary research objective is set to be:

Contribute to the development of a decision support interface that visualises UAV operations in the U-space system for tower controllers by designing and human-in-the-loop testing a preliminary interface that uses geofences as a means of interaction.

To achieve this primary research objective, it is further specified into three secondary research objectives. The primary research objective concerns the novel U-space system, which has scarcely seen research on the human factors of tower control. Therefore, the first secondary research objective is to set up a visual simulation of the Rotterdam Airport traffic region including U-space capabilities, by gaining an understanding of the functioning of the envisioned U-space system, the current state of tower control and the interaction between the two. Once the simulation is in place, a decision support interface can be implemented into the simulation. Thus, the second secondary research objective is to develop a preliminary decisions-support tool for visualising UAV operations by applying cognitive work analysis to the work domain of a tower controller interfacing with the U-space system. Once this interface is developed, its effect on the task of the tower controller can be investigated. Therefore, the third secondary research objective is to quantify the effects of geofencing capabilities in the U-space system on tower controllers' measured control strategy, workload and task performance, by conducting a human-in-the-loop experiment, using the developed simulation environment and interface.

1.3. Research Question

Based on the research background, the scope and the research objective, the research questions can be formulated. The main research question aims to fulfil the objective within the scope and is therefore:

What is the effect of the shape and size of geofences on the ability of air traffic tower controllers to safely and efficiently separate UAV air traffic from manned air traffic in the U-space system?

To answer the main research question, it is further divided into three sub-questions. Each of the three sub-questions relates to one of the three secondary research objectives specified in Section 1.2.

1. What are the crucial elements for a human factors simulation of the Rotterdam Airport traffic region including U-space capabilities?
   (a) How does the U-space system operate and how does it interface with existing air traffic control?
   (b) What are the current responsibilities and tasks of tower controllers and how does this change with the integration of UAVs into the airspace?
   (c) What are the most critical operational conditions for the interaction between the U-space system and tower controllers?
2. How should information regarding UAVs and geofences be presented to tower controllers to support them in safely and efficiently separating UAV air traffic from manned air traffic in the U-space system?
3. What are the effects on control strategy, workload and task performance of geofence shape and size in a new decision support interface for tower controllers separating UAV traffic from manned traffic in the U-space system?

1.4. Outline

This thesis report is divided into two main parts, the first part containing the thesis paper and the second part containing the appendices. First of all, Appendix A contains the literature report, as previously submitted and graded for the course '*Literature Study*' (AE4020). It covers background information on U-space, tower control, Rotterdam-The Hague Airport, UAV operations, trajectory uncertainty and ecological interface design. Appendix B presents the theoretical background of the designed interface, as used during the experiment. Next, Appendix C contains an overview of the code written during this project that makes up the simulation environment and interface. Then, Appendix D gives a description of the design of the human-in-the loop experiments. Appendix E displays the combined experiment briefing and survey presented to the participants of the human-in-the-loop experiment. Consequently, Appendices F and G contain the full answers of the participants to the survey questions and the detailed experiment data results, respectively. Finally, Appendix H presents concluding remarks and recommendations for future work, beyond the scope of those presented in the thesis paper.

I

Thesis Paper

Design and Evaluation of an Ecological Interface for Separating UAV from Manned Air Traffic in Tower Control

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The expected increase in unmanned aerial vehicle (UAV) traffic in European airspace raises concerns regarding the human factors of tower controllers. Dynamic geofences offer tower control a means to safely separate UAVs from manned traffic, without direct interactions with individual UAVs. A preliminary support interface was designed, supporting the operator in separating UAV traffic from manned traffic, while minimising impact on (high priority) UAV efficiency. The effects of traffic conditions and geofence size on control behaviour, safety, efficiency and interface usage were investigated in a human-in-the-loop experiment with active tower and air traffic controllers. Results show that geofences are considered a useful tool in maintaining safety, that larger geofences significantly increase average traffic separation and that the effect on efficiency differs per traffic scenario. Performance could be improved by increasing transparency and predictability of UAV routing, for example by optimising the geofence structure around the runway and by more clearly presenting high-level UAV information to the controller. Further work is needed to investigate controller behaviour and performance in an environment with control over both UAV and manned traffic, considering the temporal aspect of geofences, as well as a broader range of UAV missions and capabilities.

***Index Terms*—UAVs, U-space, Geofences, Tower Control, Ecological Interface Design, Human Control Behaviour**

I. Introduction

THE European Drone Outlook Study predicts a large increase in the use of unmanned aerial vehicles (UAVs). By the year 2035, the fleet of UAVs operational in the industrial sector in Europe is expected to consist of nearly 400,000 vehicles. This results in an increase in the relative number of UAV operations with respect to manned aircraft operations from less than five percent in 2020 to around 25 percent by 2050 [1]. Moreover, UAVs will be applied over a broader range of applications, with increasingly complex missions, such as beyond visual line of sight flights [2], [3]. This expected increase in UAV operations poses a problem for existing manned air traffic. An example of this is the Gatwick Airport incident, where unknown UAVs were seen 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 [4]. Similar incidents occurred at London Heathrow and Frankfurt Airport [5], [6], exemplifying the increase in UAV-related air traffic incidents in the United Kingdom increasing from zero in 2013 to over one hundred in 2018 [7].

The interference of UAVs with current manned air traffic gives rise to the demand for a framework that encompasses the management and safety of UAV operations. This demand is met by the development of unmanned aircraft system traffic management (UTM) systems, which act as a connection between aviation authorities and UAV operators. It allows UAV operators to carry out the desired missions, while enabling the authorities to ensure operators do so safely and orderly [8]. Various UTM systems are in development by various authorities around the world, such as the European U-space system [9], [10]. This focuses on UAV operations in very low level (VLL) airspace, below 500 feet [11]. Within this operational domain, U-space aims to integrate UAV traffic into the existing airspace structure, rather than separate them [12].

The interface between ATC and UTM is most relevant to tower control, which is responsible for separation and efficient movement of aircraft within the controlled traffic region (CTR) [13]. In terms of collaboration, U-space plans to make real-time UAV information available to ATC. Moreover, a procedural interface will allow ATC to accept or decline UAV flights in advance [14]. This does not, however, cover real-time perturbation management due to (short-term) restrictions that occur in-flight, such as delays of scheduled flights, unplanned visual flight rule (VFR) flights and medical emergency helicopter flights. A possible solution is the use of temporary geofences, volumes in space that do not allow any UAV operations within their boundaries for a certain amount of time [15]. Using geofences to clear certain areas from UAV traffic alleviates the controller from individual UAV interactions [16].

Although the use of geofences is seen as a feasible strategy, there is a lack of understanding on how tower controllers should use them. In other research related to permanent geofences, their shape and size have been scaled based on a map of the surrounding area or based on UAV capabilities [16], [17]. However, little is known about the influence of the size and shape of a geofence on its use as a tool for tower controllers and on the safety and efficiency of UAV operations. The lack of understanding of human factors and control problem metrics (e.g., safety, efficiency) in this field is further emphasised by analyses of aviation safety reports involving UAVs [7]. Most prominently, the large variety in UAV missions and capabilities are difficult for tower controllers to integrate into their standard control patterns, which are optimised for larger aircraft with similar flight behaviour [18]. Additionally, the low predictability of UAV operations, which is strongly correlated with the previous point, is seen as a liability [19]. Finally, off-nominal situations, for example navigation or communication failure, are foreseen to play a crucial role [20]. This is stressed by a list of foreseen threats to UAV operations and possible mitigations in U-space [21].

This research aims to contribute to the development of a decision support interface that visualises UAV operations in the U-space system for tower controllers by designing and (human-in-the-loop) testing a preliminary interface that uses geofences as a means of interaction. To achieve this, an understanding is required of the functioning of the envisioned U-space system, the current state of tower control and the interaction between the two. This can be used to develop a simulation of the Rotterdam traffic area including U-space functionalities. Next, an interface is designed that presents UAV information to the controller and supports them in maintaining manned traffic safety. For the interface, the ecological interface design (EID) framework is used, focusing on the analysis of the work domain [22]. This has the advantage of supporting adaptive problem solving, which is essential in dealing with UAV traffic, especially when considering unpredictability and off-nominal operations [23]. Moreover, supporting human problem solving is often preferred by operators over a high level of automation. On the other hand, a complex work domain can lead to a complex interface, meaning it is important to validate whether the interface does indeed support the operator as intended. Therefore, the developed simulation and interface are evaluated by means of a human-in-the-loop experiment, investigating how tower controllers use geofences to separate UAV and manned air traffic and whether the interface aids them in their expected behaviour.

This paper is structured as follows: Section II gives background information regarding the current role of tower control and the impact of future UAV traffic and U-space have on it. Section III presents the work domain analysis that provides the basis for the ecological interface design. This interface design, including a review on its behavioural support is discussed in Section IV. Afterwards, Section V describes the developed simulation of the Rotterdam air traffic region. Next, the human-in-the-loop experiment is described Section VI, after which the results from the experiment are presented and discussed in sections VII and VIII, respectively. Finally, Section IX covers the conclusions of the research.

II. Tower Control and U-space

The design of an ecological interface requires knowledge of the work domain in question. Therefore, Sections II-A and II-B, provide background information on U-space and tower control, respectively, after which Section II-C describes the future influence of U-space on the task of the tower controller.

A. *U-space*

The U-space system was initiated by the SESAR joint undertaking in 2017, with the goal of providing safe, efficient and secure access to airspace for large numbers of UAVs. It is important to note that U-space should not be viewed as a separate, segregated airspace for the use of UAV operations [10]. U-space focuses on UAV operations in VLL airspace, up to 500 feet, as this is where most UAV operations are expected to occur in the near future [11].

Within this domain, U-space aims to allow for UAV operations in all types of airspace, supporting all operation environments, UAV types and mission types. This is to be achieved by providing a set of services that rely on a high level of digitisation and automation of functions, enabling complex operations with low human workload. Examples of these services are registration, identification, tracking and information provision. An important aspect of U-space is that these service are provided in an open-market structure (meaning services can be provided by various companies, not only authorities), while focusing on safety. Moreover, the U-space system also serves to provide an interface with (existing) manned aviation, air traffic management and air navigation services (ATM/ANS) providers and authorities [12].

UAV operations have a variety of vehicle types, capabilities and missions, resulting in varying ground and air risks. Therefore, U-space divides the VLL airspace into UAV airspace volumes of class X, Y and Z, each with access condition and provided services, as seen in Figure 1. Over urban areas and near airports, airspace volumes of class Z will be deployed, requiring an approved flight plan, continuous connection to the U-space system and tracking information provision. Furthermore, Z airspace volumes near airports (classified as Zu volumes) mandate that UAVs should be able to respond to dynamic geofencing information. Moreover, it mandates that UAVs have both a procedural and a collaborative interface with air traffic control, as described in Section II-C [15].

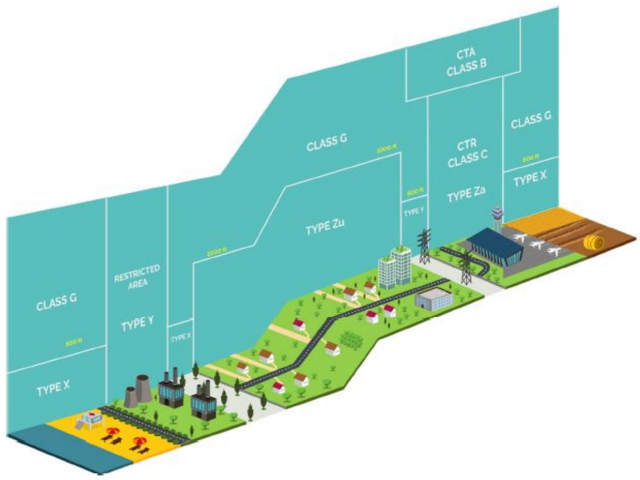


Fig. 1: Division of U-space into X, Y and Z volumes [15]

B. *Tower Control*

Regulations state that the main responsibility of tower controllers is that they *" shall 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 pre-venting collision(s) between aircraft flying within the designated area of responsibility"* [13, page 7-1], while also maintaining a continuous watch of all flight operation in this region.

The main tasks of a tower controller are to provide information to flights in the CTR (such as weather and traffic information), issue clearances for take-off and landing, give flight instructions to VFR flights and coordinate with other instances of ATC, most importantly approach control. The two most prominent tools used by tower control are the out-of-tower view and radio communication, taking up more than half of their work time. Secondary tools are flight strips, radar and weather information services [24].

Within the U-space system, tower controllers should have access to information regarding UAV operations. The separation between UAVs is maintained within the U-space system and is therefore not the responsibility of tower control. However, they should be able to apply both strategic and tactical restrictions to UAV operations, based on manned flight operations. This decision support interface focuses on supporting the tower controller in applying tactical (in-flight) restrictions to UAV operations.

C. Interaction

The interaction between U-space and ATC is envisioned to be twofold, consisting of a procedural interface and a collaborative interface. The procedural interface allows for easy digital submission and modification of a flight request. It also allows for the exchange of data, enabling UAV operations to be visualised on a display to tower control. Various industrial parties are working on the integration of UAV information into tower control displays [25], [26]. This is aimed to be extended by a collaborative interface that allows for verbal or textual communication, allowing tower control to send instructions and clearances to the UAV (operator) [14].

An important U-space service is the use of geofences, which are used to restrict certain volumes of air space from UAV flights permanently (e.g., royal palaces, nature reserves) or temporarily (e.g., events, accidents). Moreover, geofences are seen as a possible tool to interact with unmanned traffic, for example in shielding medical emergency helicopter flights [15]. Additionally, geofences can be used to temporarily shield airspace volumes near runways to allow safe manned traffic operations when needed, but not restrict UAV traffic otherwise [16]. The use of geofences instead of direct interaction alleviates controllers from coordinating individual UAVs.

Currently, the shape and size of geofences is often based on a combination of geographical landmarks and UAV capabilities [17]. However, this concerns permanent geofences, making it difficult to utilise this concept to keep UAVs clear from (dynamic) manned air traffic. An alternative is a grid of geofences being made available to the operator, similar to the system the Federal Aviation Administration (FAA) uses to specify what type of UAV operations are allowed for regions near airports [27]. An important aspect of a geofence grid is the size of the geofences used. When considering geofences, one perspective is that of the UAV, sizing geofences such that an average UAV can clear it in a timely manner, based on its expected capabilities. Although research has been done into geofence sizing based on UAV capabilities [28], [29], this has not been translated to designing larger, multi-UAV geofences based on UAV capabilities. The other perspective is that of the tower controller. The geofence shape and size should allow for easy activation and deactivation, while also accommodating sufficiently detailed selection for more fine-grained control (e.g., minimise additional flown track miles). Finally, the shape and size of geofences can be based on air traffic operations, such as the ILS slope and the traffic circuit.

III. Work Domain Analysis

In ecological interface design, the cognitive work analysis (CWA) is an important method in identifying the aspects required for effectively supporting the operator's work [23]. However, this requires a precise description of the considered system and is therefore less suitable in designing an interface for a first-of-a-kind system [30]. This proves a challenge, due to the current lack of a clearly established division of responsibilities between U-space and ATC and the immaturity of the U-space concept. As this study should be seen as a conceptual design in the development of an ATC interface for U-space interaction, it will focus on the work domain analysis (WDA) and the cognitive implication on the operator's behaviour. A similar approach has been applied by studies dealing with human factors of U-space operators and users [16], [31].

The considered system during the WDA is that of UAVs operating in the U-space system, responding to dynamic geofencing to separate them from manned traffic operations at Rotterdam - The Hague Airport. The purpose of the system is to keep manned air traffic safe from UAV air traffic by means of dynamic geofencing, while minimising the delay of (high priority) UAV flights. The top-level constraints that affect the system are the minimum required separation between manned air traffic and UAV air traffic, and the maximum flight time (endurance) of UAV operations. Further constraints that are considered in the WDA, but not in the interface design, are separation among manned air traffic, the communication range of UAVs, weather and terrain.

A. Abstraction Hierarchy

An important tool within the CWA is the abstraction hierarchy (AH), as it maps the functional structure of the work domain, independent of activities and performers. The AH contains five levels of abstractions, where higher levels describe the top-level purpose basis of the system, while the bottom levels represent its low-level physical basis [32]. The abstraction hierarchy can be extended by adding means-ends links between elements in different layers, signifying the coupling of these elements [33]. The Elements in a certain layer can be seen to answer the question *what?*, whereas elements in the layers above and below it can be seen to answer the question *why?* and *how?*, respectively. To aid in the design of the display for tower controllers proposed in this research, the abstraction hierarchy is applied to the role of a tower controller. Previous applications of the AH to ATC can be used as a baseline [34], supplemented by a description of the role of tower control, as described in Section II-B [13]. This can be combined with the functioning of the U-space system as described in Section II-A and most importantly with the interaction between the two, as described in Section II-C [15]. The resulting abstraction hierarchy is shown in Figure 2, each level of which is shortly elaborated upon below:

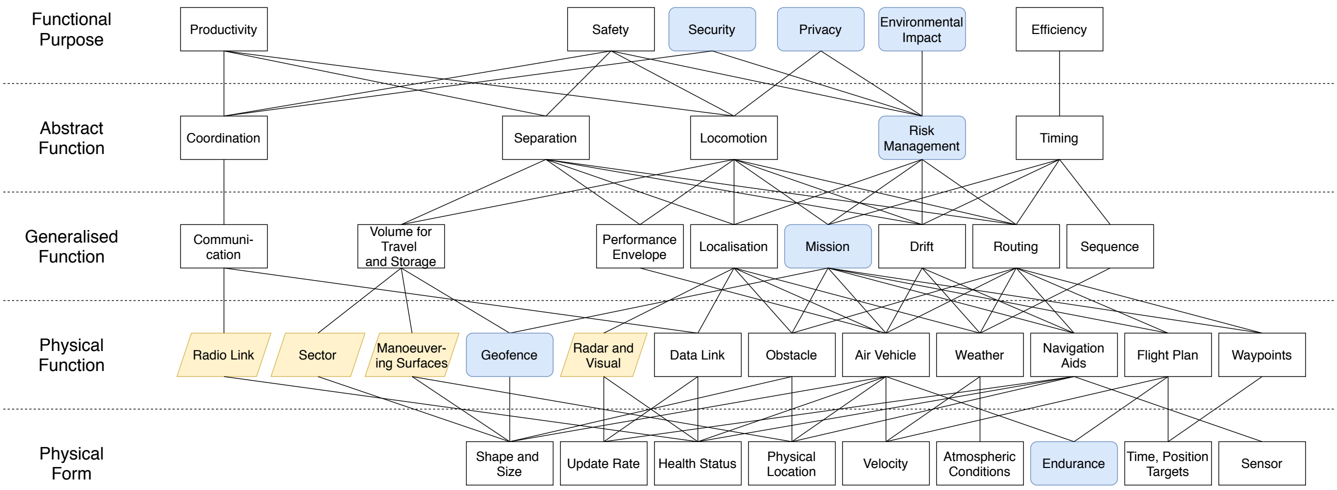


Fig. 2: Abstraction hierarchy of the work domain, where ATC specific elements are indicated by a yellow parallelogram and U-space specific elements are indicated by a blue rounded box, all other elements are shared. Contents from the ATC point of view are based on ICAO regulations [13], the additional U-space elements are based on U-space initiatives [15]

1) Functional Purpose: The function of tower control is to achieve safe, orderly and expeditious flow of air traffic. Similarly, the function of U-space is to provide safe and efficient access to airspace for UAVs. Moreover, U-space aims to provide secure access to airspace and pays close attention to data sharing and privacy, as well as impact of the environment (i.e., air risk, ground risk).

2) Abstract Function: This level describes the underlying principles that are used to achieve the purpose of the system. For tower control and U-space, these include the locomotion of air vehicles. Next, the timing of vehicle operations is essential in achieving efficient air traffic flow. Moreover, separation of vehicles and coordination between different parties (i.e., ATC, air vehicles, ground vehicles) are crucial in achieving safety and productivity in the airspace. Finally, risk management plays a pivotal role in U-space, adopting a risk-based approach over the traditional certification based approach [10]. This helps achieve security and privacy of data, as well as minimising air and ground risk (environmental impact).

3) Generalised Function: The generalised function describes the involved processes that make up abstract functions. For the separation, timing and locomotion of air traffic, these are routing, localisation and sequencing of flights, the vehicle's performance envelope, the available volume for travel and storage and drift (due to weather). The coordination is enabled by means of communication. Finally, the pre-defined mission plays an important role in the U-space system, as this determines its locomotion and timing and forms the basis for the aforementioned risk assessment. This is not relevant for manned air traffic operations, as these do often not have a specifically set out mission when flying in the CTR.

4) Physical Function: The physical function describes the main function bearing components of the system. Shared physical functions include: data link, obstacles, air vehicles, weather, navigational aids, flight plans and waypoints. Some elements are specific to ATC: radio link, visual localisation, airspace sectors and manoeuvring surfaces. The physical function element specific to U-space are the geofences, which can affect the mission profile of UAVs and can be used to create volumes of travel and storage.

5) Physical Form: This level describes states of the system's components, such as position, velocity, shape, size and status. For the U-space system it specifically includes the endurance a vehicle has left to carry out its mission and to divert due to geofence restrictions.

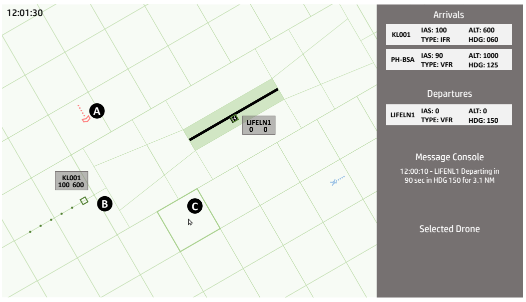
IV. Interface Design

The cognitive work analysis described in the previous section is used as a basis for the ecological interface design. The interface aims to visualise the elements of the abstraction hierarchy and the means-ends links between them, while also supporting the accompanying types of behaviour. The interface is a preliminary design, focusing on the interaction between U-space and ATC and will therefore not fully contain all elements of the abstraction hierarchy. For example, communication and coordination with vehicles and other ATC instances are currently not integrated. Moreover, the high-level elements of the U-space system are not directly integrated, as these are mostly fulfilled outside the realm of tower control.

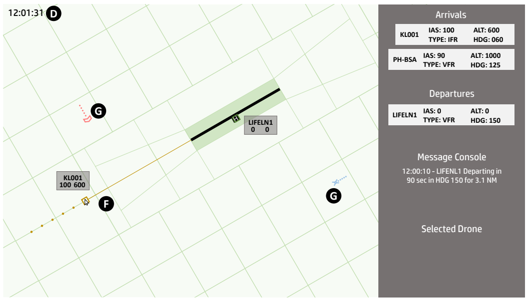
A. Structure and Functionality

Figure 3 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. The interface can be divided in two segments: the map view on the left and the flight information view on the right. The elements of the abstraction hierarchy are indicated by the letters A through S.

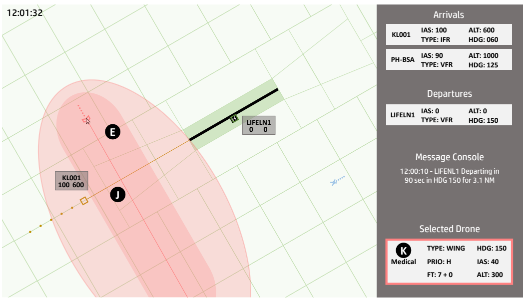
The initial map view in Figure 3a, shows the situation overview with all UAVs routed directly to their destinations. First, the interface can be seen to display the physical location



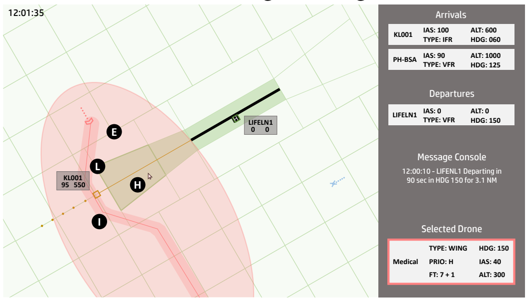
(a) Mission overview



(b) Selecting IFR flight

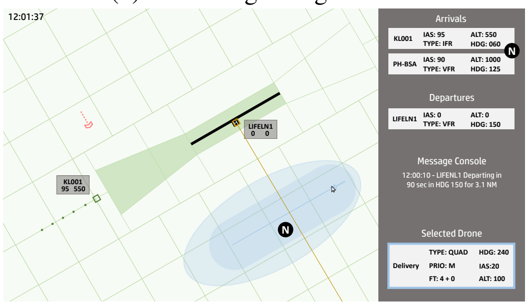


(c) Selecting medical UAV

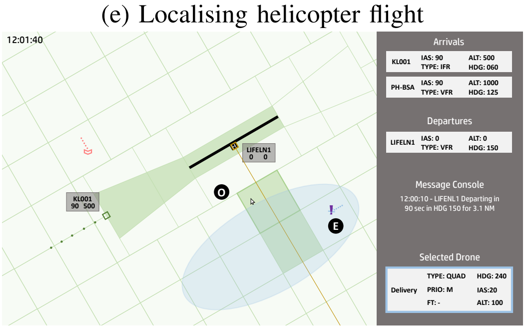


(d) Activating ILS geofences

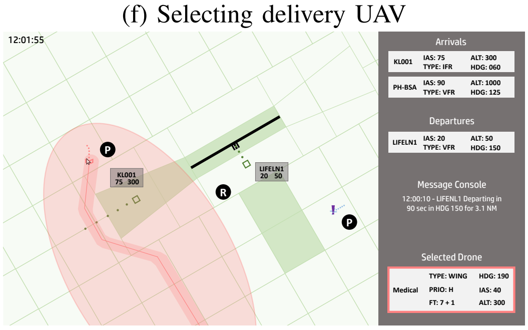
(e) Localising helicopter flight



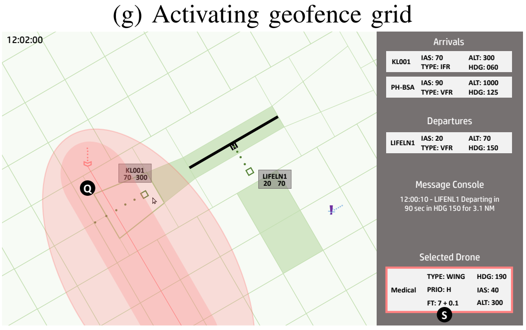
(f) Selecting delivery UAV



(g) Activating geofence grid



(h) Select UAVs



(i) Deactivating ILS geofence

Physical Form
- A Location
- B Velocity
- C Shape and Size
- D Update Rate
- E Endurance

Physical Function
- F Flight Plan
- G Air Vehicle
- H Geofence
- I Waypoint

Generalised Function
- J Routing
- K Mission
- L Volume for Travel
- M Localisation
- N Sequence

Abstract Function
- O Separation
- P Locomotion
- Q Timing

Functional Purpose
- R Safety
- S Efficiency

Fig. 3: Step-by-step overview of the interface structure and functionality for a simple scenario (the interactive version of the display, using three training scenario for the experiment can be found at dronectr.tudelft.nl)

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 (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 3b, selecting a manned air vehicle will highlight its flight strip in the flight information view and vice versa, establishing a means-ends link between the air vehicle's location and its low-level states and properties. 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 3c shows that selecting a UAV will display two endurance regions. 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) is not fully within 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 3d, 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). The impact of this re-route on the flight time can be seen on the UAV information strip. It should also be observed that this new route means the UAV has less endurance available to re-route even further. This is indicated by the decrease in size of the inner endurance region (E).

Next, it can be seen in Figure 3e that the message console prompts an emergency helicopter departure, as is also indicated by the flight strips. Selecting the flight strip highlights the corresponding air vehicle in the map view, allowing it to be used to localise the helicopter flight (M). As seen in Figure 3f, 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 3g 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 3h 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 analysed 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. Additionally, the purple exclamation mark indicates the current lack of locomotion possibilities.

By comparing UAV and manned traffic speeds in Figure 3i, it can be seen that the UAV will not reach the ILS-zone until after the IFR flight has passed. The UAV can be made to fly directly 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 operator to balance the top-level functions of the system.

B. Behavioural Support

An import aspect of an ecological interface is the support of different types of human control behaviour. It should therefore be considered how the designed interface supports the anticipated behaviour described above. When looking at human behaviour in terms of performance, a distinction can be made between three different levels of cognitive work. These three levels are skill-based behaviour, rule-based behaviour and knowledge-based behaviour [32]. The amount of cognitive work involved is lowest in the case of skill-based behaviour, increases for rule-based behaviour and is highest for knowledge-based behaviour [33]. It should be noted that the same task can be performed using different types of behaviour, depending on the level of training of the person performing it. Below, the expected instances of rule-, skill- and knowledge based behaviour in this work domain are described.

Skill-based Behaviour: The interface allows the operator to directly interact with most interface elements by clicking on them or dragging them. This supports general skill-based behaviour, by presenting signals that can be directly used for control [32]. A first concrete type of skill-based behaviour is monitoring the signals indicating which geofences are active, non-active and pending. This is supported by means of color coding geofence states. A second type of skill-based behaviour is monitoring the state of the current arriving and departing flights, as well as monitoring those of emergency helicopter flights. This is supported by displaying their intended route when selected and by providing flight labels, flight strips and a message console. A third type of skill-based behaviour is monitoring states and routes of UAVs in (proximity of) active geofences, which is supported by displaying the intended route and flight strip when selected.

Rule-based Behaviour: Signs dictate rule-based-behaviour, triggering a certain set of rules or procedures known to the operator [32]. A first type of rule-based behaviour is identifying which geofences are to be switched on and off for clearing scheduled flights. Based on the route of the aircraft, the required geofences can be switched on before passing and switched off afterwards. Linked to this is the rule-based behaviour of using rules of thumb and common sense to identify which geofences will be crossed by an aircraft (either a UAV or a manned aircraft). This can be done by observing which manned traffic and UAV traffic routes cross which geofence and is further accommodated by shaping geofences according to the ILS. For estimating UAV and manned traffic locations with respect to geofences, rules of thumb can be used. A second type of rule-based behaviour is applying rules of thumb to know how long it will take a manned aircraft or UAV to clear/reach a certain geofence. Additionally, this is supported by numerically displaying speed, heading and trailing dots. A third type of rule-based behaviour is anticipating the new route of a rerouted UAV.This is supported by displaying the outer endurance ellipse to signify the region the new route will be in. Moreover, the inner endurance region gives an indication of whether a geofence activation will cause the UAV to loiter due to no route being available.

Knowledge-based Behaviour: Symbols show the functional properties of the system related to problem-solving and support knowledge-based behaviour [32]. A first type of knowledge based behaviour is reasoning at what point in time which geofences needs to be (de-)activated. This behaviour is a combination of two aforementioned types of rule-based behaviour, identifying geofences on a manned aircraft's route and identifying how long it takes for UAVs and manned aircraft to reach/clear a geofence. A second type of knowledge based behaviour is reasoning which geofences need to be activated to safely accommodate an emergency helicopter flight. These flights are very unpredictable in terms of desired routing and time of departure, but have the highest priority and are therefore most difficult to clear from UAV flights. Both previously mentioned instances of knowledge-based behaviour are supported by showing all vehicle routes on selection for manned and UAV traffic, as well as endurance ellipses and current delay for UAV traffic. This information can be used to combine the previously described forms of rule-based behaviour that help in determining which geofences to activate. A third type of knowledge based behaviour is minimising the total delay in UAV travel time due to geofence restrictions, which requires the controller to plan a sequence of times geofence (de)activations. This is supported by showing the impact of a geofence restriction on the UAV route and its endurance (by means of the inner endurance region). It is further supported by showing the current UAV delay due to geofence restrictions. Providing this information allows operators to form their strategy to keep UAVs clear from manned traffic, while minimising UAV delay.

V. Simulation Design

A simulation of the Rotterdam traffic area, including U-space functionalities is developed; this simulation environment is used for interface design and experimentation. The simulation contains three major aspects: manned traffic, UAV traffic and geofences. The functioning of each element will shortly be addressed below.

A. Manned Traffic

All manned traffic is categorised as either a generic instrument flight rule (IFR) flight, a generic VFR flight or a (VFR) emergency helicopter flight. Traffic movement is simulated by means of interpolation between a list of waypoints, each waypoint consisting of a set of coordinates, an altitude and an indicated airspeed. Turns between subsequent waypoints are modelled by means of a constant bank angle turn. As the current research focuses on the interaction with UAVs and geofences, the manned air traffic cannot be interacted with at the current stage. The manned air traffic patterns and routes are based on real traffic data and air traffic information [35].

B. Geofences

Geofences are modelled as a set of two-dimensional coordinates that form a polygonal area. A geofence can be in one of three states: non-active, active or pending. A non-active geofence inflicts no restrictions on UAV traffic, whereas an active geofence restricts UAV from entering that area. When a geofence is activated while a UAV is within its boundaries, the UAV will leave the geofence by the shortest route possible. While the UAV is leaving the active geofence, the state of the geofence is described as pending. Further interaction between UAVs and geofences will be described in Section V-C. Geofences can be switched between non-active and active (or pending) by clicking them with the right mouse button, except when a geofence is marked as permanent.

The geofences are configured in a grid with a constant cell size, which can be altered between experiment runs. To support the view of the operator, the geofences are shaped according to the ILS where it intersects VLL airspace. These are divided into segments longitudinally, as to not exceed the geofence grid cell size [16]. Transitional geofences are shaped between the ILS geofences and the geofence grid to connect the two, also while not exceeding the geofence grid cell size. The runway has its own permanent geofence.

C. UAV Traffic

All UAV traffic is categorised as either a fixed wing UAV or a quad-copter. UAV movement is modelled as a point to point operation with a starting point and one fixed destination. Furthermore, a high level is automation is assumed, where path planning can used for tactical and strategic deconfliction, as is intended by U-space [14]. In the developed simulation the A* path planning algorithm is used [36] to find (new) UAV routes. Each geofence is overlapped by a number of grid cells that are used by the algorithm, where the center points of the used grid cells are used as navigational waypoints by the UAV. Turns between subsequent waypoints are modelled by means of a constant bank angle turn for fixed wing UAVs and as a fixed rotational rate turn for quad-copters. Upon activation of a geofence, all associated grid cells are set as blocked and all UAVs with routes that cross the geofence are rerouted according to the path planning. An offset in the grid cells with respect to the geofences ensures a safety margin around the active geofence. Figure 4 shows an example of a UAV re-route due to an active geofence, based on the A* path planning.

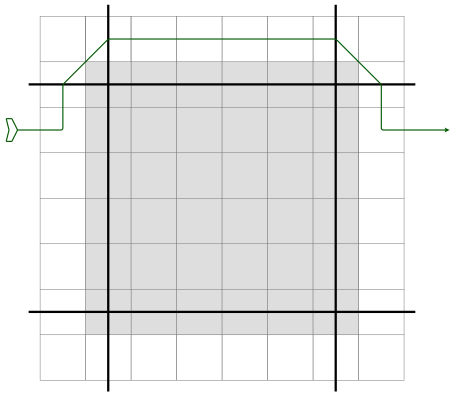


Fig. 4: UAV re-routing based on A* path planning. The geofence borders are indicated in black, the activated grid cells are indicated in grey and the UAV route is indicated in green

There are two special cases that require elaboration. First, it can occur that a geofence contains one or more UAVs at the moment it is activated. In this case, the UAVs inside this geofence will exit the geofence at the closest point of exit, as this strategy has been found the fastest and favoured by UAV operators [37]. From the closest point of exit, the UAVs find a new route to their destinations using the path planning algorithm. Although this strategy is found most favourable, it can lead to large diversion. Two examples of UAV re-routes in active geofences can be seen in Figure 5.

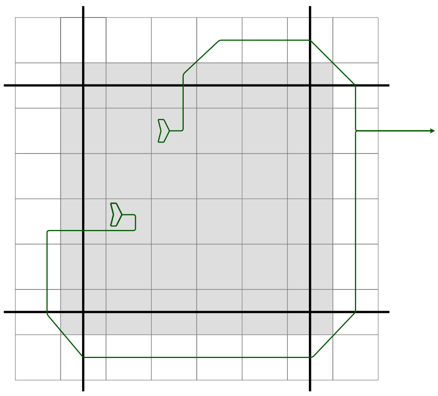


Fig. 5: UAV re-routing in an active geofence, combined with A* path planning. The geofence border are indicated in black, the activated grid cells are indicated in grey and the UAV route is indicated in green

Next, the destination of a UAV operation can be contained within an active geofence. Similar to the previous case, the closest point of entry is found and set as a new destination for the path planning algorithm. Once the closest point of entry has been reached, the UAV hovers/loiters at this location until the geofence is no longer active, as can be seen in Figure 6.

Finally, the case must be considered where the path planning algorithm is not able to find a solution that is contained with the endurance capabilities of the UAV. This prompts the UAV to hover/loiter, until the geofence situation changes and a new route can be found that satisfies the range constraint. In all cases of UAV navigation, when the UAV runs out of battery capacity, an emergency landing is triggered. The simulation environment used during the experiment, that results from the interface and simulation design, can be seen in Figure 7.

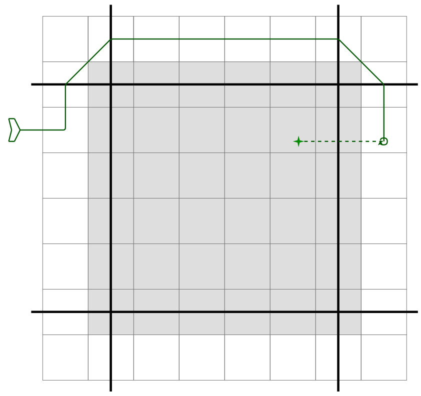


Fig. 6: UAV re-routing with its destination in an active geofence, combined with A* path planning. The geofence border are indicated in black, the activated grid cells are indicated in grey and the UAV route is indicated in green

VI. Human-in-the-loop Experiment

A human-in-the-loop experiment was conducted to investigate how tower controllers use geofences to separate manned air traffic from UAV air traffic and to assess whether the designed interface aided them in their expected behaviour. Additionally, the experiment investigated the effects of geofence size on the tower controller's behaviour, safety, UAV efficiency and interface usage. This was done for traffic scenarios that were expected to be critical in support tower controllers in maintaining traffic safety by means of geofences. Both subjective and objective experiment data were recorded and analysed to evaluate the geofencing concept and interface.

A. Participants

Nine active tower controllers from Rotterdam and Spain participated in the experiment. It should be noted that not all air traffic controllers were tower controllers and that not all air traffic controllers were active in the Rotterdam Airport area. This implies that the relation between the daily work and the task in the experiment differed per participant. 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. Additionally, limiting the sample group to only include tower controllers (active at Rotterdam Airport) would have severely decreased the sample group size, jeopardising the relevance of the experiment's results.

B. Experiment Tasks

During the experiment, participants were placed in the role of a tower controller at Rotterdam Airport, where UAVs are integrated into the airspace according to the U-space system.

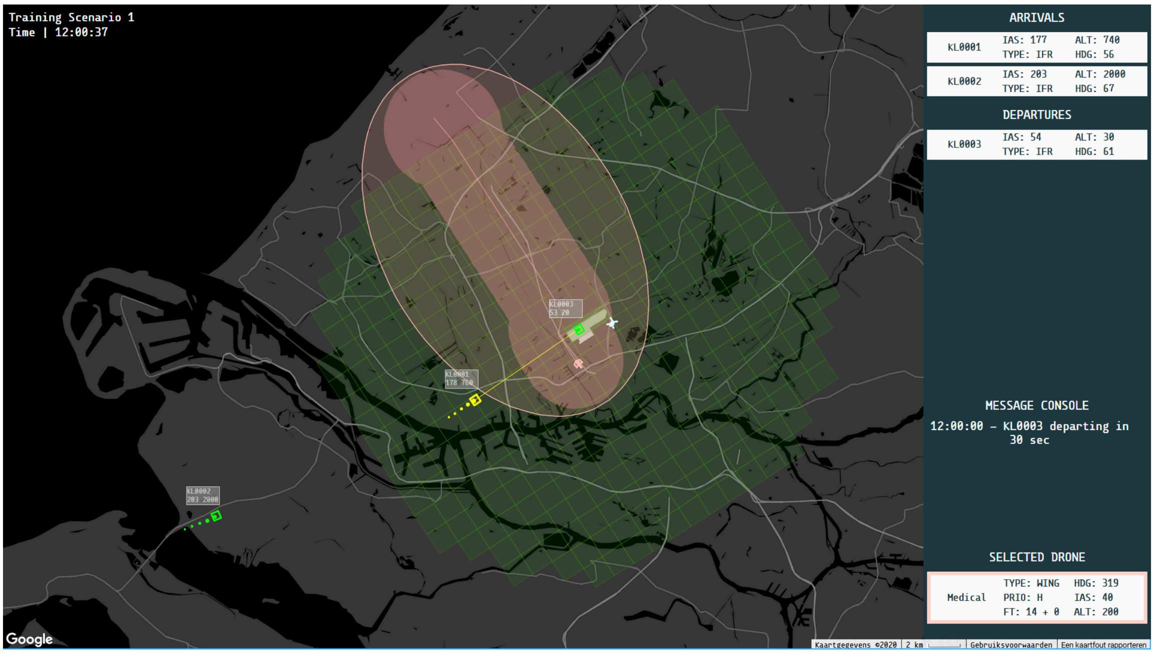


Fig. 7: Screenshot from the simulation environment used during the experiment

Within this environment, they had two main tasks. First, they were tasked to ensure vertical separation (250 feet) and horizontal separation (2000 ft / 600 m) between manned traffic and UAV traffic [38]. Second, they were tasked to minimise additional travel time for UAVs, especially high priority UAVs. The tasks were described as being of equal importance, the prioritisation 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 to the activation of geofences and could not be instructed individually. Additionally, manned aircraft could not be given instructions, since the experiment aimed to investigate the proposed form of interaction with geofences. Moreover, the main interaction between UAVs and manned traffic occurred either in the final approach or with emergency helicopter flights. The incoming and outgoing manned traffic was indicated by means of flight strips on the right side of the screen. The UAV mission and priority was displayed upon clicking on the UAV icon. 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 has not yet been tested using a human-in-the-loop experiment. Thus, little was known on the preferred geofence size and shape that allows for a balance been flexibility and efficiency. Moreover, this may have caused participants to make use of geofences in different ways. It was therefore considered valuable to vary geofence size and observe how each participant responded to all experimental conditions. The variation in traffic scenario is discussed in Section VI-D.

The geofence size was varied between one of two options. The used baseline were geofence cells with a size of 1 nautical mile. As this is a common unit in ATC, it allows for an easy grip of the size, it also corresponds to other UAV restriction systems initialised in the United States [27]. This resulted in a relatively coarse grid from the controller's perspective, requiring a smaller option to investigate the desired balance between usability for controller and efficiency for UAV traffic. The finer geofence size was based on UAV capabilities, yielding geofences with a size of 1 kilometre, allowing the average quad-copter 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 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.

A total of four traffic scenarios were considered. First, three scenarios were based on use-cases which bear relevance for the interference between UAV and manned air traffic. These contained a scenario regarding IFR approaches and departures, a scenario regarding 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 aforementioned use-cases were combined, and the number of UAVs and manned aircraft was doubled with respect to the first three scenarios. This last scenario aimed to provide insight in high task load situations and the possibility of interface clutter. The traffic conditions of the experiment scenarios can be seen in Figure 8.

(a) IFR scenario

(b) VFR scenario

(a) emergency helicopter flight scenario

(b) High taskload scenario

Fig. 8: Initial traffic conditions of the experiment scenarios

The manned traffic routes in the scenarios were based on Rotterdam airport traffic data, IFR and VFR routes and advice of Rotterdam tower controllers [35]. The UAV traffic in the scenarios was based on predictions of the European UAV Outlook Study, as well as expected applications in the Rotterdam area from the industry [1]. The number of manned traffic vehicles and UAV traffic vehicles was constant over the 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 to be activated. The type of conflict could be varied by varying UAV vehicle type, mission type (priority), endurance and relative position and velocity. These variables were used to create different conflict situations that test the full reach of the interface. The similarities between scenarios is described in the next section.

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 minimised. Only the first three scenarios were shuffled in the matrix, the high task load scenario was always presented last for a particular geofence size. The experiment matrix implies that each participant saw every scenario twice, potentially leading to learning effects. However, as the effect of recognition was considered small, the scenarios were not altered for different geofence sizes. Moreover, as these scenarios were specifically designed traffic situations, variations in the scenario could lead to large changes in the solution, interfering with measuring the effect of geofence size.

E. Control Variables

There were various control variables used during the experiment. First of all, 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 5 minutes, where the display updated every five seconds at real time speed. All UAV traffic was point-to-point and was quantified as either a generic quadcopter 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. As mentioned in the previous section, the number of UAV and manned traffic vehicles was constant over the 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.

F. Dependent Measures

To quantify the effects of the above-described independent variables, several dependent measures were recorded during the experiment. These were the task performance, in terms of traffic safety and UAV efficiency, control activity and control strategy. The information regarding task performance (both safety and UAV efficiency) served to provide insight in the influence of geofence size on the task being performed by the controller. The control activity and strategy 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).

Traffic safety was quantified by measuring the separation between a manned aircraft in VVL and all UAVs. Averaging the separation for pairs of manned and UAV vehicles yielded the average separation for a single time step. A further indication of safety is given by recording the losses of separation occurred during an experiment run.

The UAV efficiency was quantified by the average extra travel time per UAV due to geofence restrictions for each experiment run. Next, the average amount of time per UAV spent loitering was recorded. Finally, the total number of times a UAV re-routes was recorded.

G. Apparatus

The experiment was performed using a JavaScript simulation developed for the experiment, which was hosted on a server at the faculty of Aerospace Engineering at the Delft University of Technology. Due to the COVID-19 pandemic, the experiment was performed remotely. This meant participants were sent a login and a web link, which they could use to enter the experiment environment. 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 the participants a week in advance. It should be noted that, as the experiment was conducted remotely, the experiment procedures and physical environment were more difficult to control compared to an experiment on location.

H. Procedures

Before the experiments, participants were requested to read the experiment briefing 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 familiarise the participants with the Rotterdam air traffic region, the simulation environment, the interface and the control inputs. During these scenarios, all relevant features were explained and the participants could ask any questions they might have. The remaining three training scenarios were used to train the participants in using the interface to perform their experiment tasks. The training scenarios resembled the experiment scenario in that they each represented a traffic use-case deemed relevant for the geofence interaction. However, the number of UAVs operational in the airspace was decreased, proportionally decreasing the number of pending conflicts. The UAV traffic density slightly increased per training scenario, until it matched that of the experiment scenarios. The training scenarios used manned traffic patterns similar to the experiment scenarios, to familiarise the participants with the Rotterdam air traffic patterns. The traffic patterns were shortly highlighted during the experiment briefing. This was deemed important, as tower controllers in real-life also have knowledge on traffic patterns, which gives them some intent information regarding manned traffic.

From the fourth training scenario onward, the participants were asked after each experiment run to give a short explanation of their problem-solving strategy. After the training was completed, the participants started the experiment. Each experiment run had a fixed time limit of five minutes. 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 and the influence of their shape and size on their experiment tasks. Additionally, the participants were asked to give their opinion on the traffic scenarios and simulation environment. Next, the participants were asked to assess the usefulness of the interface and the use of colour in its design. Finally, the participants were given the opportunity to provide any miscellaneous comments or suggestions with respect to the experiment.

I. Hypotheses

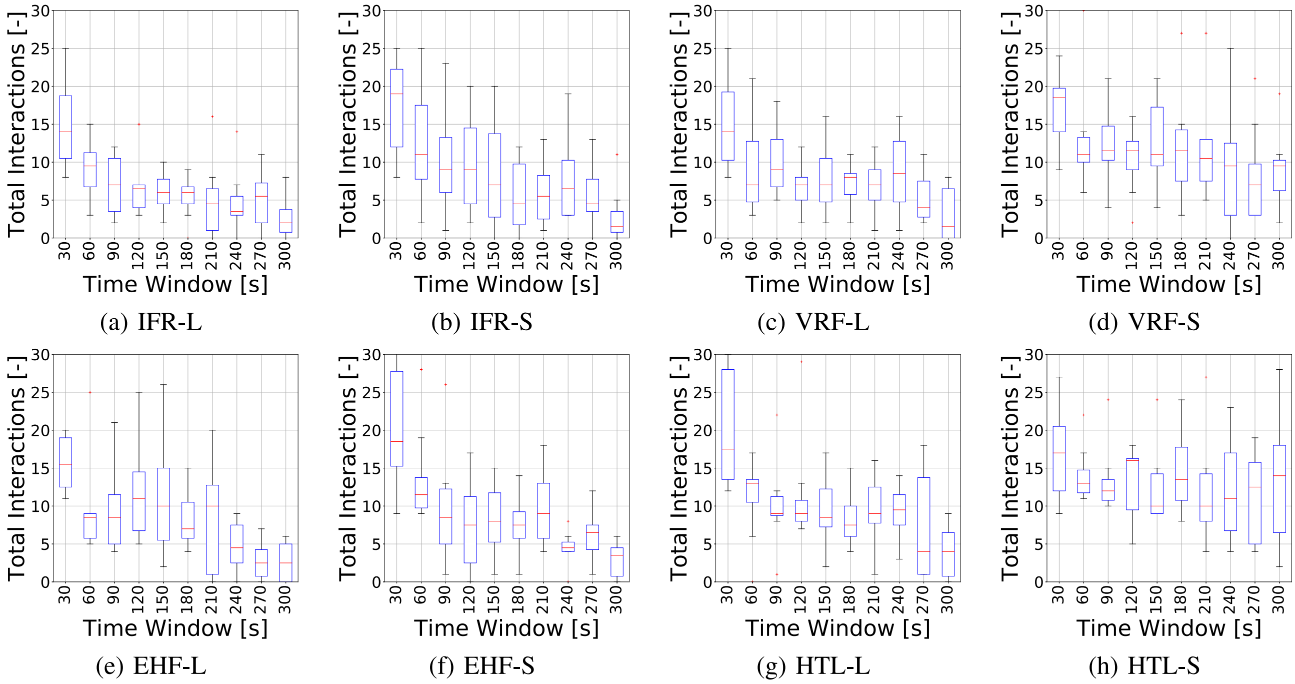
First, it was hypothesised that participants will prioritise manned traffic safety over UAV efficiency (*H1*). This would be reflected in control behaviour by the fact that participants would first apply all the required geofence restrictions based on the manned traffic and afterwards investigated if the UAV efficiency could be improved by making (small) alterations.

Moreover, it was hypothesised that the high task load scenario would further emphasise 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 hypothesised to decrease, due to interface clutter, caused by visualising all UAV traffic (*H2.2*).

In terms of interactions with geofences, it was hypothesised 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 hypothesised 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 geofence 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,



(a) IFR-L (b) IFR-S (c) VRF-L (d) VRF-S

(e) EHF-L (f) EHF-S (g) HTL-L (h) HTL-S

Fig. 9: Total mouse interactions over time per experiment condition, in thirty-second time windows

it was hypothesised that a smaller geofence size would leads to a lower average loiter time (*5.2*). However, it was hypothesised that it would lead to a higher number of reroutes, as more geofences were expected to be activated on average (*H5.3*).

J. Data Processing

The data was regarded as resulting from a within-participants experiment with two independent variables, namely the traffic condition and the geofence size. All statistical tests used a significance level of 0.05. The statistical data was found to violate the assumption of homogeneity of variance (see Figures 12 through 16). 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.

VII. Results

Sections VII-A through II-C discuss the results of the experiments for the dependent measures in terms of plots, statistical analyses and answers from the post-experiment survey. The traffic conditions are indicated as IFR, VFR, EHF (emergency helicopter flight) and HTL (high task load), and the geofence conditions are indicated by L (large) and S (small).

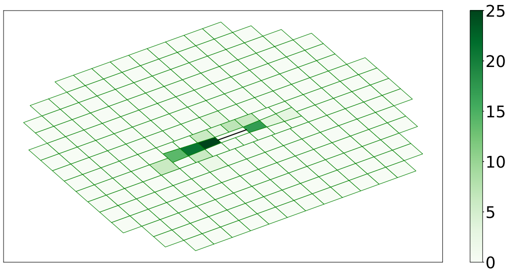
A. Control Strategy

During the experiment and from the post-experiment survey, it was observed that participants prioritised safety over UAV efficiency. Furthermore, it was observed that participants strongly favoured 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. The exception to these two parts was the (de)activation of geofences due to emergency helicopter flight and unforeseen conflicts (mostly with VFR).

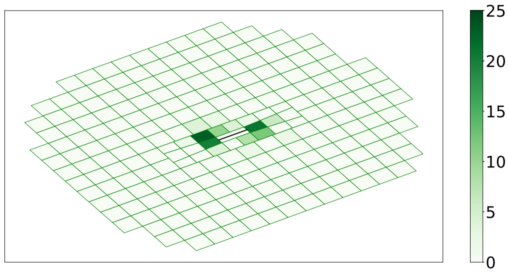
During the experiment it was observed that most participants opted for a control technique that resembles vectoring to fulfil the above-described control strategy. They used geofences to steer a UAV along a certain route, rather than simply activating a geofence and letting the UAVs find their way around it. This was mostly used to vector slower aircraft (UAVs) behind the faster aircraft (manned traffic), as is common practice in ATC.

Figure 9 shows box plots of the total mouse interactions over time for each experiment condition, divided into thirty-second time windows. It can be observed that the interaction distribution shows a similar pattern for most experiment conditions; a relatively high number of clicks early on, slowly decreasing over time. The high number of initial interactions can be linked to the control strategy of guaranteeing safety through activating geofences. The later decrease can be linked to maintaining situational awareness while optimising the solution for efficiency and tending to further conflicts.

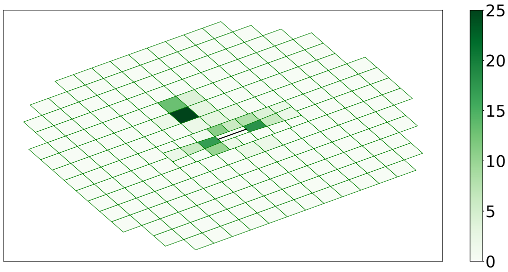
Figure 10 shows maps of the total geofence activation of all participants, for the four scenarios with large geofences. The geofence maps for the scenarios with small geofences are not shown, as they do not show a significantly different control



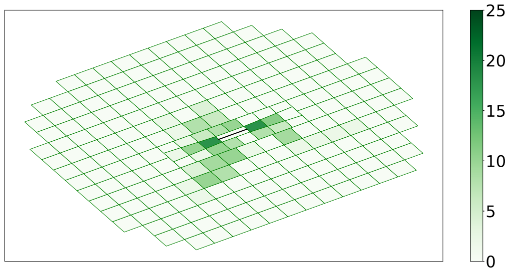
(a) IFR-L



(b) VRF-L



(c) EHF-L



(d) HTL-L

Fig. 10: Total interactions per geofence of all participants per large geofence scenario (runway in black)

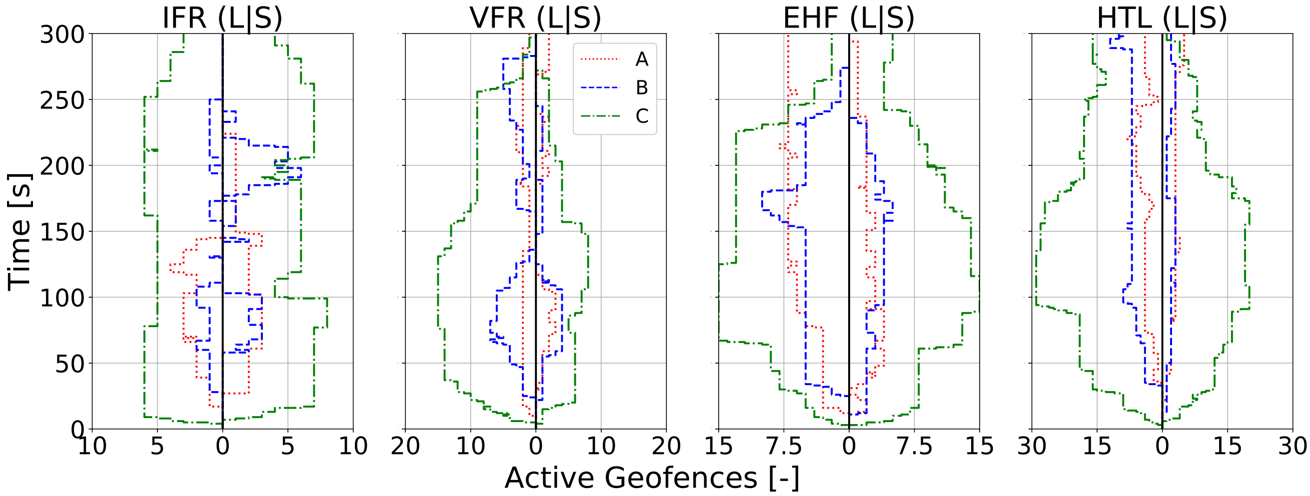


Fig. 11: Number of active geofences over time for three participants (A,B,C) with different control strategies. The large and small geofence variant of a scenario is shown on left-hand side and right-hand side, receptively. Note that scale on the x-axis differs per scenario

behaviour in pattern or magnitude. It can be observed that most geofence activations occured near the runway, to protect approaching and departing manned flights. The exception being activations that protected helicopter flights, as seen in Figures 10c and 10d.

Despite the similarities in top-level control strategy, various differences in control behaviour were observed during the experiment. Figure 11 shows the geofence interactions over time for three participants in all experiment conditions. It can be observed that participant A opted for a predominantly passive approach, making use of vertical separation and only activating geofences when required. Next, it can be observed that 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 can be seen that 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, emphasising the focus on safety.

Figure 12 shows box plots of the total geofence interactions per experiment condition. Statistical analysis shows that the experiment conditions had no significant effect on the differences between relevant experiment condition pairs.

Figure 13 shows box plots of the total interface interactions per experiment condition. These interactions include all clicks and drags that were not categorised as geofence interactions.

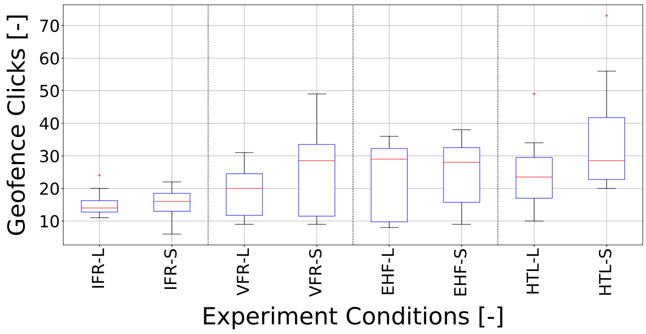


Fig. 12: Geofence interactions per experiment condition

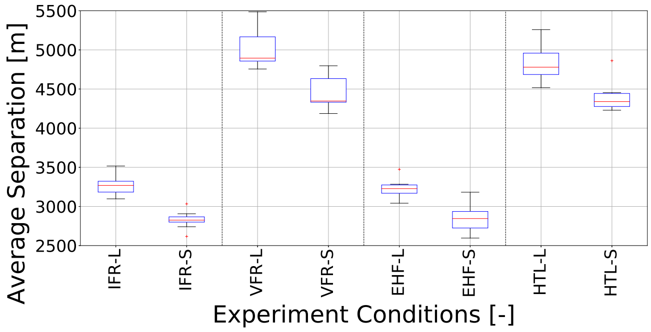


Fig. 14: Average separation between UAV and manned traffic in VLL airspace per experiment condition

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 ($\chi^2(3) = 12.3, p = .006$), 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 interfaces interaction 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. 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.

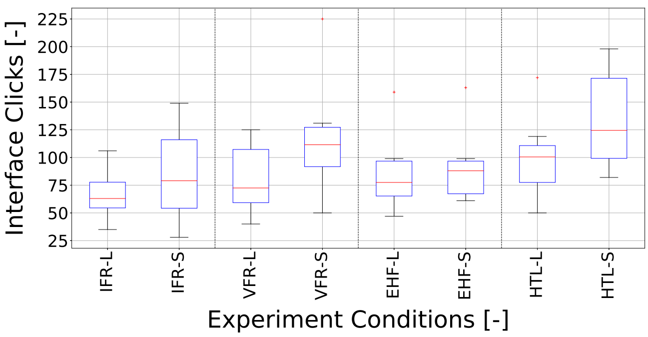


Fig. 13: Interface interactions per experiment condition

B. Safety

Figure 14 shows box blots of the average horizontal separation between UAV traffic and manned traffic in VLL airspace per experiment condition. This considers the average separation between a manned aircraft in VLL airspace and all UAVs that are within the vertical separation constraint. As participants strongly favoured horizontal separation over vertical separation, this separation definition was deemed an important indicator for air traffic safety.

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 ($\chi^2(3) = 19.5, p < .000$). 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 UAV and manned traffic.

Losses of separation occurred several times during the experiment runs. However, they predominantly occurred with participants with a less conservative control strategy; over half of the participants did not encounter a loss of separation at all. Figure 15 shows an overview of all the losses of separation that occurred during the experiment runs (a total of 9). It can be seen that over half of the losses of separation involved helicopter flights. Furthermore, it can be observed that most data points lie on the right-hand side of the figure (relatively high remaining horizontal separation), while being evenly spread vertically (remaining vertical separation). This corroborates the observation that controllers focused more on horizontal separation than vertical separation.

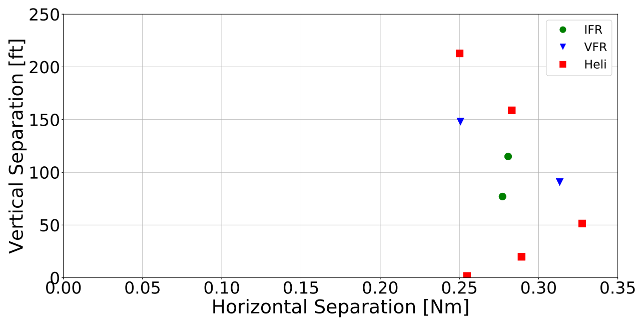


Fig. 15: Overview of the horizontal and vertical distance during loss of conflict, per flight type

C. UAV Efficiency

Figure 16 shows box plots of the average UAV flight time efficiency per experiment condition. For an individual UAV, this compares the scenario run time with the difference between the flight time at the beginning and the end of the scenario. The scenario efficiency was set to be the average of the efficiency of all UAVs in the experiment run.

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, the effect of geofence size varied per traffic scenario.

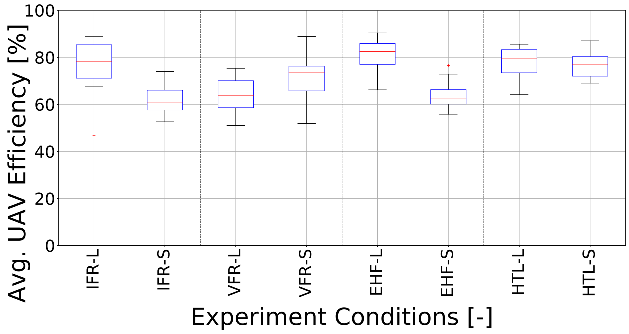


Fig. 16: Average UAV flight-time efficiency per experiment condition

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.

D. Interface Usage

Figure 17 shows the scores participants gave to the individual interface elements on a scale from 1 to 10. 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 colour and geofence state.

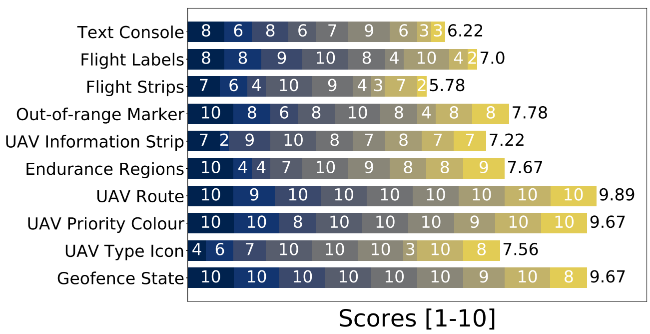


Fig. 17: Subjective scores of interface elements from all nine participants, displaying the average on the end of the bar

Special attention was paid to the endurance regions, as these were considered beyond the realm of common 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 intentions and potentials when loitering. As the endurance regions were only displayed upon selecting, they were never deemed intrusive. Participants with a control strategy that focused more on UAV efficiency indicated that they did use the endurance region. They commented that it helped them in predicting UAV behaviour and in making choice regarding geofence selection.

Regarding the use of colour in the interface, some participants indicated that they would prefer a slightly higher contrast between the "off" and "on" state colours of the geofences. Additionally, it was suggested to further simplify the background, as is common practice in ATC radar screens.

VIII. Discussion

Geofences were generally considered a useful tool by the participants to maintain separation between UAV and manned air traffic. As hypothesised, participants were found to opt for a strategy that prioritised safety over efficiency (*H1*). As hypothesised, 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, as there were no significant effects in separation, UAV efficiency and interface interaction (*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 hypothesised influence of geofence size on geofence interactions (*3.2*), they do show the expected significant increase in interface interactions for smaller geofences (*H3.1*). Moreover, the change to a smaller geofence size did give the expected effect of decreasing the average separation between UAV traffic and manned traffic (*H4*). The change to a smaller geofence size also had an effect on 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 emphasises the importance of tailoring geofences to traffic operations. Additionally, geofence size was not found to have a significant effect on loiter time or number of reroutes (*H5.2* and *H5.3*).

Geofences were considered particularly useful when the participants desired to restrict a certain area for a relatively long timespan, for example the lower ILS region or the landing spot of an emergency helicopter. However, most participants also used geofences to impose a desired route on UAVs, effectively vectoring UAVs behind manned aircraft. It was found that this strategy could cause complications, as UAVs did not always select the route that the participant intended it to. Moreover, the geofence(s) used for routing one UAV, influences the routing of other UAVs, creating an unwanted coupling in vectoring instructions. This was considered especially cumbersome when a UAV was still several minutes away from the geofence restriction that caused it to reroute. This less predictable UAV behaviour, in combination with late conflict detection, was found to be the primary reason for the losses of conflict that occurred during the experiment. A higher transparency in the UAV routing should therefore be considered, as providing this information to the operator could improve the predictability of the UAV routes, in turn improving the safety performance. Additionally, 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 higher efficiency. From this finding and the aforementioned re-routing issues, it can be concluded that the temporal aspect of geofences is important to consider in future iterations.

While the change in geofence size was rarely noticed by participants, they commented more frequently on the geofence configuration. Especially the geofences adapted to the ILS were considered useful in protecting IFR flights with minimal impact on UAV efficiency. As the geofences near the runway were mostly frequently used (see Figure 10), the geofencing concept could be improved by further tailoring the geofence configuration to the traffic area. This could in turn lead to a more orderly and predictable UAV traffic flow, improving controller performance. A possible improvement would be a UAV corridor across or under the ILS zone, to give more accurate control over UAVs when crossing this critical zone, and to ensure they cross perpendicular to the standard arrival route. Such a crossing point would also be considered useful over the runway midpoint, which was currently permanently geofenced. Moreover, participants indicated they would have liked the geofences over the VFR traffic circuit to be similarly adapted to the manned traffic routes as for the ILS zones.

Although participants indicated they generally considered the simulation environment to be accurate, some improvements can be made. Most prominently, the addition of a wider range of UAV mission types (especially ones that are not point-to-point) and vehicle capabilities should to be considered. The separation criteria used during the experiment were considered disputable. Some participants indicate they deemed them as sufficient, others considered them too conservative, while some thought of them as too liberal. While not the scope of this research, more information is required regarding the desired separation between UAV and manned traffic.

The visualisation of the endurance regions received mixed results. The outer endurance region showing the vehicle locomotion range was generally considered more useful than the inner endurance region showing available endurance for re-routing. It should be investigated if substitutes for the (inner) endurance region(s) better support the operators in their behaviour. Examples of this could be an indication of UAV route uncertainty or 'what-if' probing for a potential geofence activation based on UAV mission type, route, endurance and capabilities. Regarding the interface in general, several control strategies were observed to be supported (although the non-temporal nature of the geofences did limit this). Although this could be contributed to the implementation of EID, it was partly due to the individual, active control employed over the UAVs in the current simulation. It is therefore important to consider the effects a higher UAV density and control of both UAV and manned traffic have on this.

It should be noted the current experiment design made it difficult to directly compare high and low UAV density, as all four scenarios were based on specific use-cases. The high task load scenario was generally considered to be of high complexity and to result in high workload (4 out of 5 and 3.8 out of 5 respectively). Participants indicated this is due to them actively controlling (vectoring) UAVs, which would be difficult to maintain next to other tower control task. It was remarked that also having control of manned traffic might lead to conservative activation of geofence without active control of UAVs, resulting in lower UAV efficiency.

Surprisingly, most participants indicated they regarded high priority UAVs more important than VFR flights. Moreover, they indicated that they would have preferred to make small diversions in VFR traffic to obtain better efficiency in high priority UAV flights, if they were given the option. 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 safety, rather than minimising individual 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 information presented to the operator regarding higher levels of abstraction from the UAV's side could be improved. The controller's behaviour 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 and UAV corridors), as discussed previously.

Finally, the relatively small sample size may have affected the statistical analysis of the results. If future research could build on the current group of nine participants from ATC, the statistical significance of the results can be improved upon. Finally, participants indicated they needed beyond the training scenarios to get accustomed to the simulation environment. Although they quickly comprehended the interface, they indicated to have trouble with the slow and sometimes unpredictable behaviour of the UAVs. This points toward the larger general problem of lack of training from both the side of the UAV operator and the tower controller [18].

IX. Conclusion

The goal of this study was to contribute to the development of an ecological decision support interface that visualises UAV operations in the U-space system to tower controllers by designing and (human-in-the-loop) testing a preliminary interface that uses geofences as a means of interaction. Results show that geofences are considered a useful tool to maintain safety between UAV and manned traffic. Although various control strategies were observed, the general strategy meant striving for safety first, efficiency later. Consequently, participants favoured large geofences over smaller ones, due to easier control, making the obtainment of safety easier. However, loss of separation did still occur, mostly involving emergency helicopter flights. This was caused by late conflict detection and less predictable UAV behaviour, meaning the safety performance could be improved, by better presenting information regarding higher levels of abstraction, for example by what if probing. Geofence configuration was found to be more important than geofence size, especially near the runway. Further work is needed to investigate control behaviour and performance in an environment with control over both UAV and manned traffic, considering the temporal aspect of geofences, and a broader range of UAV missions and capabilities.

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II

Thesis Book of Appendices

A

Literature Report

The content of this chapter has been graded as preliminary thesis report for the course AE4020

A.1. U-space

The increase in the number of UAVs and UAV applications gives rise to the need for the development of a regulatory framework for UAV operations. This would allow drone operators to be provided with services they require to perform their operations, while allowing authorities to oversee to safe, secure and efficient UAV operations in the areas under their responsibility. As mentioned in the introduction, various organisations are in the process of developing such a regulatory framework for UAV operations. For example, in the United States, the FAA and NASA are working on the unmanned aircraft system traffic management (UTM) system, The single European sky ATM research (SESAR) joint undertaking is collaborating with the EU and Eurocontrol on the U-space system and the Civil Aviation Administration of China (CAAC) is developing the Civil UAS Operation Management System (UOMS) [1, 29].

To study the interface between a UAV traffic management system and the existing ATM infrastructure for manned aircraft, it is important to have an understanding of the goals and structure of the foreseen UAV framework. As the current research is focused towards European airspace, SESAR's U-space system is considered here. Therefore, this chapter will outline the U-space system based on the current work and documentation of the SESAR joint undertaking by EASA, Eurocontrol and the EU. Section A.1.1 gives a top-level description of the U-space system and its design goals. Next, Section A.1.2 describes the planned U-space services, where the interface with ATC in addressed in more detail in Section A.1.3. Next, Section A.1.4 outlines the envisioned airspace structure for the U-space system, the operational conditions of which are related to the risk assessment of UAV operations, as explained in Section A.1.5.

A.1.1. Top-level Description

The U-space system was initiated by the SESAR joint undertaking in 2017, with the goal of providing safe, efficient and secure access to airspace of large numbers of drones. This is aimed to be achieved by providing a set of services that rely on a high level of digitisation and automation of functions, enabling complex operations with low human workload. Moreover, the U-space framework also serves to provide an interface with (existing) manned aviation, ATM/ANS (Air Navigation Services) providers and authorities. U-space should not be viewed as a separate, segregated airspace for the use of UAV operations. U-space aims to allow for UAV operations in all types of airspace, supporting all operation environments, drone types and mission types [1]. In order to achieve the realisation of the goals of the U-space project, its high-level key principles are laid out in several documents, the ones most important for the current research are elaborated upon below.

Competitive & Cost Effective

For manned aviation, air traffic management is provided by air navigation service providers (ANSP). They are government departments, state-owned companies or privatised organisations commonly being the sole provider in their region. This is where U-space will differ from the current architecture, as it aims to create a competitive market for U-space service providers. This implies that multiple service providers can be active in a single region. This competitive, open-market architecture is envisioned to lead to technical and business developments and to attract various investors. It does set the further need for a regulatory framework to allow for an equal playing ground for services providers and fair access for UAV operators [30].

Inter-operable
The U-space architecture should be designed to support all drone operations, both globally and regionally. It should provide equitable access to the airspace for all users of the system. This also implies that various U-space systems and service providers establish a connection. This inter-operability should extend to the interface with existing ATC, by means of data exchange between U-space and ATC [32].

Safety Focused
One of the most important goals of the U-space architecture is to always consider the safety of all the parties involved, as well non-involved people on the ground. When setting up the requirements for safety, the aim is to adhere to a risk-based, performance-driven approach [1, 32].

Modular & Flexible
The U-space system should be scalable and flexible and allow for changes in operational conditions (such as demand, mission types, technology, business model, etc.). This is further specified by stating that the system should be agnostic with respect to technology and deployment. This means the system shall operate consistently regardless of (future) implementation specifics. This further feeds into the modularity requirement for the architecture. This goal specifies that the system should be built up using functionality blocks with defined inputs and output, which can be reused and replaced. This feeds back into the flexibility requirement, while also allowing for an iterative design process [32].

Automated & Digitised
Manual operation of the U-space system is seen as too labour intensive. Therefore, the U-space architecture relies on a high degree of automation and digitisation in the provision of the U-space services. This holds true both for the vehicles in the air, the support for UAV operators on the ground and the U-space service providers [32]. This aspect combines with the flexibility requirement in the sense that U-space should be evolutionary in its core, by adapting to new technological and procedural developments [2].

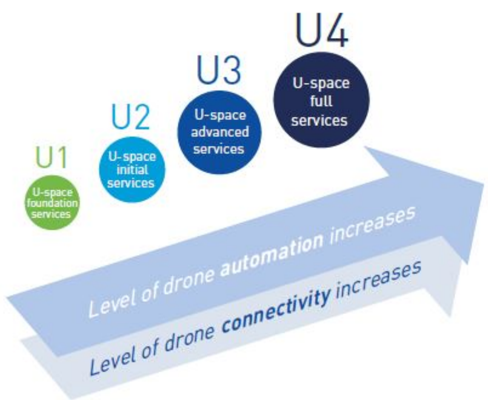


Figure A.1: Phases of deployment of the U-space system [1]

The U-space system is aimed to be deployed in four phases, a schematic representation of which from the U-space blueprint can be seen in Figure A.1. The first phase in expected by 2022 and lays the foundation for the U-space system and it services, by providing e-registration and e-identification. This phase is currently in the early implementation phase. The second phase is expected by 2027 and sets up the initial service supporting in the management of drone operations. This includes flight plan submission and reviewing, flight tracking, dynamic airspace information provision and an interface with existing ATC. For this phase, there have been demonstrations on the services, with more demonstrations planned. The third phase is expected by 2035 encompasses the more advanced services, allowing for more complex operations in more traffic and population dense areas. This may involve the provision of conflict detection capabilities among UAVs and active capacity management. For this phase, there are research projects ongoing regarding automation, ground systems, data-link, information management, cyber-security, etc. Finally, the fourth phase is expected beyond 2035 and implies full operational capabilities of the U-space system, including a fully integrated interface with manned aviation [1]. The U-space services will be covered in more detail in Section A.1.2.

A.1.2. Services

In all U-space documentation, U-space is described as: "*U-space is a set of federated services and associated functions within a complete framework designed to enable and support safe and efficient multiple simultaneous drone operations in all classes of airspace.*" [32, page 6]. These services can be provided by different entities operating within the same section of airspace, creating an open market. To ensure situation awareness and the possibility for traffic de-confliction, it is essential that these different service providers are connected and interoperable. An overview of the services that are currently expected in the U-space system can be seen in Figure A.2. Each of the eight groups of services will shortly be addressed, focusing on the impact it has on foreseen work of the air traffic controller [2]. The services group under the name "interface with ATC" is discussed in more detail in Section A.1.3, as it bears most relevance for this research.

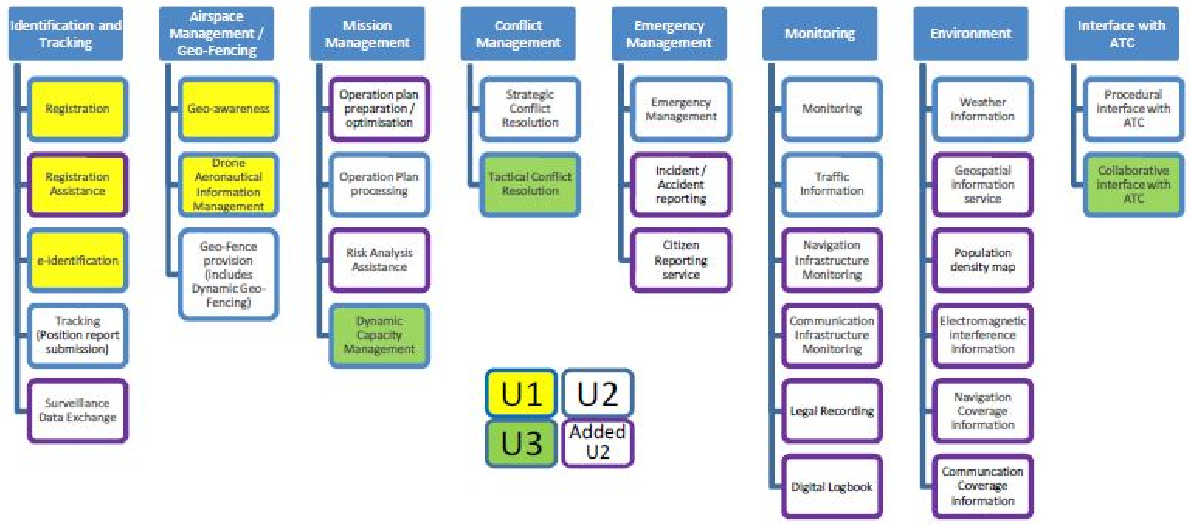


Figure A.2: Overview of the envisioned U-space services, with an indication of the implementation phase they are associated with [2]

Identification and Tracking

First and foremost, this services group contains the e-registration and e-identification services, which form the foundation of all other U-space services. The e-registration service implies that all users of U-space have to register as operators and pilots. The e-identification service allows operators to access information regarding their surrounding and the other way around. This means that all users of U-space have to submit position reports to the U-space system, including position, position uncertainty, time, means of navigation speed and identity. These position reports are used in the tracking service, producing track updates to U-space users and other stakeholders, such as air traffic control. The update rate of these reports is required to be compliant with airspace it is operating in, i.e., once every five section in case of towered airports.

Airspace Management and Geo-awareness

An important tool in the U-space system is the geofence, allowing a certain volume in space to be restricted from drone flight. It can be used to shield important regions, such as ground obstacles, runways and other traffic flows. The geo-awareness service provides these geofence restrictions to drone pilots and operators. In early stages of the U-space implementation, this will mostly involve fixed geofences shielding important volumes. However, in further stages of U-space implementation, geofences can be produced with immediate effect, for example to protect important unexpected manned air traffic, such as helicopter emergency medical services (HEMS). This more advanced application would be incorporated in an extensions of the geo-awareness services called geofence provision service.

Apart from geofence information, this service group also contains the drone aeronautical information management service, being the drone equivalent of the aeronautical information management service. This service will gather and manage information regarding the drone flight map which are only of interest for drone flights. The non-drone specific information will be obtained from the aeronautical information management service, meaning a good interface should be established. This service is responsible for providing geofence information, as well as the mission management and environmental information described below.

Mission Management
The main service of this service group is the drone operation plan processing services, which receives submitted drone operation plans and uses them to guarantee safety in the airspace. The operation plan contains information on who is flying, what is flying, where is will be flying and when it will happen. This information can be used to check registration, authorisation and send warnings regarding weather, geofences or other environmentally important aspects. Additionally, a probabilistic trajectory can be generated and checked. In case any controlled areas are possibly entered, air traffic control can be made aware. Based on the operation plan, a drone flight can be permitted, cancelled or modifications can be suggested. It should be noted, however, that not all drone operations can be precisely planned. The operation plan should be as specific as possible and contain indications of uncertainty if they are available. Some examples of this can be seen in Figure A.3, where blue represents the trajectory and orange the probably operation zone. Examples A and B are VLOS operations and can for example only indicate a zone of operation. Example C is a scanning surveillance flight and can give a trajectory within an operation area. Example D is a linear BVLOS survey and can give a more accurate operational prediction. This illustrates that not all drone operations can supply the same level of detail in trajectory prediction in their flight plan. This does influence their ability to access certain parts of the airspace, as is described in Section A.1.4.1.

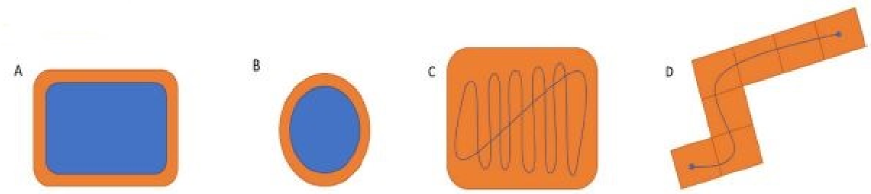


Figure A.3: Examples of different types of trajectories [2]

Apart for the main service described above, there are complementary services that help fulfilling the main service's goal, such as drone operation plan preparation assistance and risk analysis assistance. The role of risk analysis in the U-space system is described in Section A.1.5. Additionally, this service group contains the dynamic capacity management service, matching capacity and demand for drone flight in an airspace region.

Conflict Management
The conflict management services function to guarantee sufficient separation between drones. The first method to achieve this occurs pre-flight and uses the submitted flight plans to plan operations in a way to keep sufficient separation (strategic conflict resolution). The second service occurs in-flight, in the form of advises to locally change the flight plan to maintain sufficient separation (tactical conflict resolution). This means that, from the perspective of ATC, the drones can be assumed to be self-separating, as this happens within the U-space system.

Emergency Management
The emergency management service aims to assist drone pilots experiencing an emergency and allows for communicating regarding this emergency to interested parties. Additionally, accident and incident reporting is possible, both for U-space users and for citizens.

Monitoring
The monitoring services can be seen as an extension of the tracking service, that are of particular use in-flight. This includes a service that provides traffic data to drone operators, record U-space data and keeps a digital

logbook. Most relevant for this research is the monitoring service, which combines tracking data with information of obstacles, geofences, other traffic, etc. and communicates it to external parties. This could include reports on the conformance to flight plans and geofences.

Environment
The environmental services group contains information services regarding different environmental factors, such as weather, terrain, population density and navigation and communication coverage.

A.1.3. Interface with ATC

An important aspect of the U-space framework for this research is its interface with air traffic control. As the U-space system is in the early phases of development, this interface is not yet concretely designed. However, there are some short-term and long-term plans for this interface in the initial U-space plans, which are laid out in Section A.1.3.1. Next, Section A.1.3.2 looks at companies that are currently working on the development of the interface between U-space and ATC.

A.1.3.1. Interface Description by U-space

As mentioned in the top-level description, the U-space system and the ATM systems are envisioned to function concurrently. It is stressed that it is important to create an interface between the two, to allow for the coordination of flight authorisations, as well as the sharing of traffic and geofencing information [30]. The proposed interface between U-space and ATC is described as twofold, consisting of a procedural interface and a collaborative interface, as described below.

Procedural Interface
The procedural interface should allow for the coordination of flights into controlled airspace. This interface works before flight and allows ATC to accept or refuse flights and make alterations to the flight plan and set requirements to if needed. This is possible in the early stages of implementation and is already being applied in a limited form [2].

Collaborative Interface
The collaborative interface should allow for communication between ATC and the remote operator or the drone itself in case of automation and is part of implementation phase 3. This allows ATC to relay instructions and clearances to UAVs. It is noted that this does require ATC to have access to U-space surveillance data and requires the UAVs to have access to U-space service providing them with information on weather, geofences, traffic, etc. On top of this, the fourth implementation phase of U-space also considers UAVs with detect and avoid capabilities with respect to each other and manned traffic [1].

A.1.3.2. Interface Development by Companies

There are various companies involved in the development of tools that assist in creating the interface between U-space and airspace authorities. These mainly focus on the visualisation of surveillance data from U-space for the relevant airspace authorities. Additionally, they facilitate the procedural interface, allowing for reviewing and altering flight plans. Some of the bigger companies in this field are Altitude Angel, Unifly and Airmap, their work will be shortly addressed below.

Altitude Angel
Altitude Angel is based in London and has the goal to “enable the safe integration and use of fully autonomous drones into global airspace.” The platform they develop supports both UTM (USA) and U-space (Europe). Altitude Angel has a cooperation with the Dutch air traffic control agency (LVNL), which starts with the development of an app for drone users showing flight regions and regulations. The application allows the drone user to make a flight plan and submit to air traffic control if necessary. This mobile app makes use of the developed ‘drone safety map’, containing information regarding flight restrictions and requirements, as well as ground hazards, sample of this can be seen in Figure A.4.
Apart from this service, Altitude Angel is developing Guardian UTM, which is aimed at air navigation services providers and airports, allowing for UAV airspace management on a national level. This system would provide an interface between UTM and ATM to communicate flight plans and position from drone and airspace rules and restrictions from authorities [39]. This system has been tested on large scale at Manchester airport

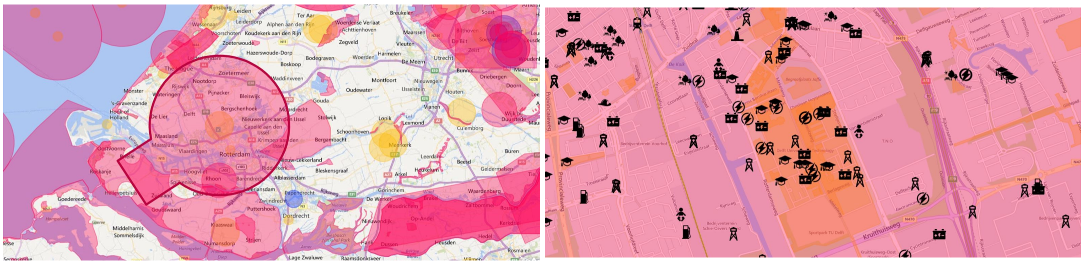


Figure A.4: Samples from Altitude Angel's mobile drone application, left showing flight regions and right showing ground hazards, displayed when zoomed in [3]

in cooperation with the National Air Traffic Services (NATS), which is referred to as Operation Zenith. During this test project, eight scenarios were carried out demonstrating various types drone operations in the airspace of Manchester airport [40].

Unifly

Unifly is based in Antwerp and aims to develop a platform that "connects authorities with pilots to safely integrate drones into the airspace." On the other hand, this would allow authorities manage no-fly zones and geo-fences, as well as authorising flight plans. It would allow drone pilots to plan their flight based on latest information and get approval in line with regulations [41]. Unifly started a cooperation with the Canadian air traffic control provider NAV CANADA. Moreover, Unifly is already in cooperation with various European air traffic authorities to enable the registration and validation of drone flights. These applications allow drone user access to dynamics airspace maps and allowing them to plan, submit and log flights. This is current applied in Belgium, Germany, Denmark and Austria. All of these systems are based on 'the map', an application showing airspace restrictions and ground hazards to drone operators, a sample of this for the Danish airspace can be seen in Figure A.5.

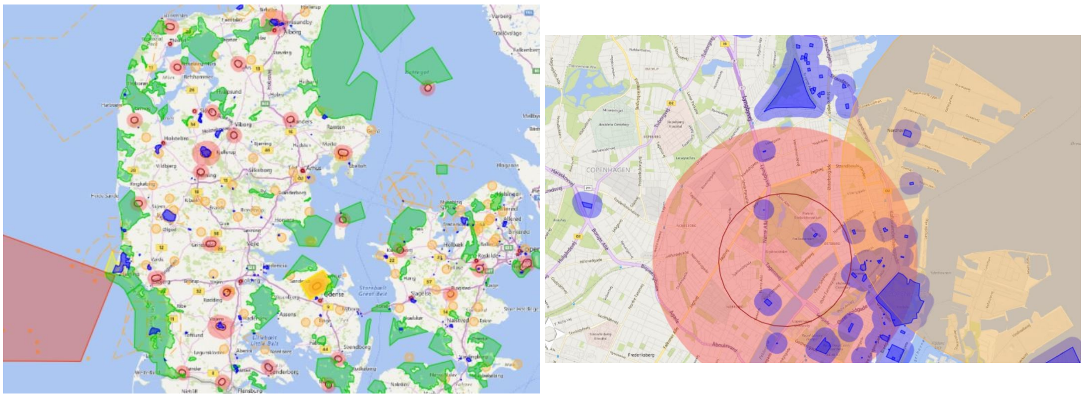


Figure A.5: Samples from Unifly's mobile drone application, left showing the global map and right showing a local map over a city [4]

More aimed towards the authorities, Unifly is also developing the Unifly Supervisor Portal, supporting authorities and ANSPs in regulation and management of (UAV) airspace. This tools aims at allowing for pre-flight validation and performing conflict resolution. It uses accurate aeronautical data and allows for geofencing, it has a flight viewer that visualises the airspace retractions and all manned and unmanned flights for a UTM supervisor [41]. Moreover, Unifly is the leader of SAFIR consortium, which, in service of SESAR, aims to demonstrate integrated UAV traffic management over a broad range of operations in Belgium. This will be done by means of demonstrations and studies over various operations. It will investigate telecommunication technology for data communication with both manned and unmanned aircraft and deploy a radar system capable of monitoring drones [42].

Airmap

Airmap is based in Los Angeles and aims to develop a platform that is a "secure, reliable, and accurate digital twin of the airspace." It offers services regarding airspace authorisation, identification, flight tracking and conflict resolution. On the other hand, it allows drone operators to plan missions safely according to the latest geo-awareness, weather, airspace and traffic data. Authorities, such a UTM centres, can manage airspace geometries and rules and monitor flight is real time. The future aim is to establish a connection between ATM and UTM, allowing the two systems to share data. This application focuses on UAS service providers [43].

A.1.4. Structure

A large portion of the future drone operations is expected to occur up to 150 meters (500 feet) above ground level [11]. This means they occur in the airspace classified as very low-level (VLL). This is why the U-space concept focuses on drone operations in VLL airspace. Section A.1.4.1 addresses the airspace structure foreseen for drones in VLL, while Section A.1.4.2 shortly explains the additional flight rules applicable to this airspace.

A.1.4.1. Airspace Structure

The U-space concept divides the VLL airspace into three separate airspace volumes, the reason for this being the difference in expected number of drone flights, varying ground and air risks and the variety in available U-space service per region. These three different airspace volumes are referred to as X, Y and Z airspace volumes. Each airspace volume is associated with certain access conditions and a list of provided services, which will shortly be addressed per airspace [44]. The focus here will be towards provided services and allowed operation. Special attention is paid to Z airspace volumes, as these are to be expected near airports and cities, making this airspace volume class the most relevant for this research. Figure A.6 presents an example of airspace division into the above-mentioned volumes.

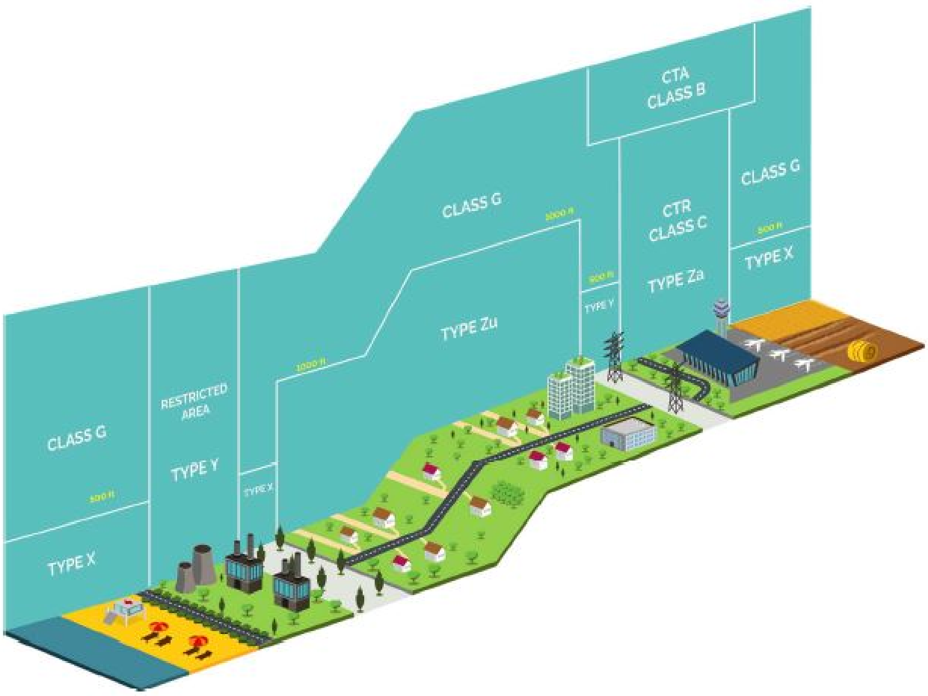


Figure A.6: Example of airspace division with X, Y and Z volumes [2]

X Volumes

Airspace volumes of class X are expected in regions with low demand for U-space services and low ground and air risk. In an X volume, the drone operator is responsible for separation between drones and all other vehicles and only limited services are offered. Flights within visual line of sight are easily possible, but more advanced operations require significant risk mitigation to be allowed.

Y Volumes

Airspace volumes of class Y can provide more U-space services that mitigate air and ground risks than airspace volumes of class X (e.g., pre-flight de-confliction, operation plan). This means Y volumes can for example be expected over areas more densely populated than for X volumes, or when there is demand for more advanced drone operations, such as beyond visual line of sight. Additionally, Y volumes can serve as a means to limit access to region, such as national parks, factories, etc. This is due to the fact that Y airspace volumes are more restricted to X volumes in the sense that they require an approved operation plan. In terms of provided services, this means that strategic (pre-flight) conflict detection and resolution are provided to drones.

Z Volumes
Airspace volumes of class Z are expected in areas with high ground and air risks, such as densely populated areas and in the vicinity or airports. Additionally, Z airspaces can be expected in areas with a high demand for complex drone operations (e.g., BVLOS). Similar to Y airspace volumes, Z airspace volumes require an approved operation plan. Additionally, it is required that the drone operator be continuously connected to the U-space system and that the drone provides position submissions sufficient for tracking with a update rate compliant with airspace requirements. In terms of provided services, this means that tactical (in-flight) conflict detection and resolution is provided to drones.

The Z airspace volume can be further divided into Za and Zu volumes. When the aforementioned tactical conflict resolution is provided by U-space, the airspace volumes is classified as Zu. When the airspace volume is controlled by ATS, it is classified as Za. Furthermore, Z airspace volumes mandate that drones should be able to respond to dynamic geofencing information. More, it mandates that drones have both a procedural and a collaborative interface with air traffic control, as described in Section A.1.3.1.

A.1.4.2. Flight Rules
The current flight rules, as described by ICAO, contain general flight rules, complemented by specific visual flight rules (VFR) and instrument flight rules (IFR). In order to allow for integration of drones into the airspace, without negatively impacting existing aviation, a modification to these flight rules is proposed by Eurocontrol as an operational concept [5].

To supplement the current flight rules, two new sets of flight rules are proposed, as can be seen in Figure A.7. The high-level flight rules concern operations above flight level 600, mainly focus on military craft. It should be noted that this is a soft boundary, as there is no common boundary for flights above IFR and VFR. The low-level flight rules concern operation in very low-level airspace and are applicable to near airport operations. These rules should be compatible with VFR traffic and contain specification for BVLOS and VLOS. Although this proposal does not go into detail, it stresses that drones should be responsible for maintaining clear from manned aviation and that VLOS should give way to BVLOS. In the early stages of U-space the LFR rules will be accommodated in VLL airspace, in the further stages of development they will be integrated.

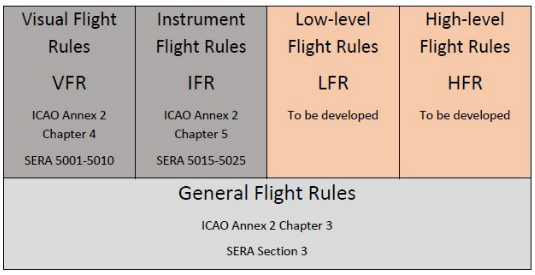


Figure A.7: Division of flight rules with integrated drone traffic [5]

A.1.5. Risk Assessment
As seen from the top level description, safety is an important aspect of the U-space system. Until recently, if drone operators wanted to make a BVLOS drone flight, the UAV required full certification. This would severely limit the possibilities for commercial drone flights in very low-level airspace in the vicinity of airports or densely-populated areas. A shift away from this seen in various UTM concepts is the use of a risk-based approach, rather than the certification-based method. These methods use safety risk assessment by looking at the drone operation and approving it if can be proven that mitigation requirements are met that reduce the

operation's risk to an acceptable level [2, 6]. This would allow non-certified drones to have more freedom in the operation they undertake. It should be noted, however, that the risk-based approach in not applicable to all types of drone operations. The risk-based method would apply to drones that EASA categorises as 'open' or 'specific'. This would for example not include drones with dimensions of over 3 meters, drones transporting passengers or dangerous goods and drone operation over groups of people [30].

U-space aims to perform the risk assessment for non-certified drone operations using the Specific Operational Risk Assessment (SORA), as developed by the Joint Authorities for Rule-making on Unmanned Systems (JARUS) [6]. The SORA method is based on assessing the ground risk and the air risk of a drone operation. It is used to identify the risks involved and categorise them as threat, a hazard or a harm, each with mitigation requirements. A schematic overview of the SORA process can be seen in Figure A.8.

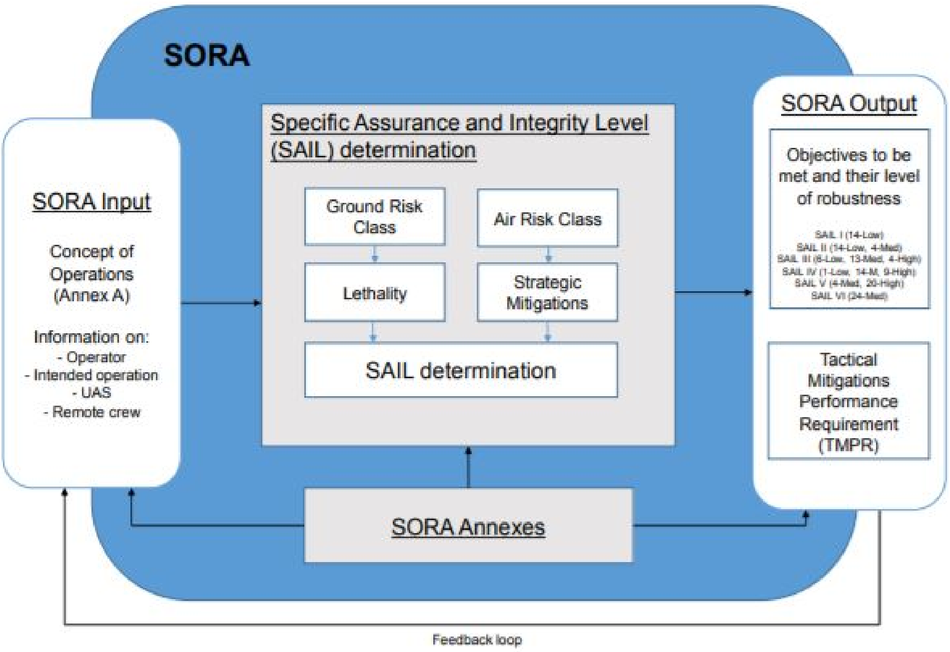


Figure A.8: Schematic representation of the SORA process [6]

As the SORA concept is relatively new, there are not enough data available to quantitatively identify risk classes. Therefore, the risk assessment is performed qualitatively, based on top-level features of the drone operation. The relevance of the SORA method for this research lies in composing the drone operations that are performed in the CTR. Although a full analysis might not be applicable, SORA can be used to obtain an indication of the types of drone operations that are possible. Moreover, SORA can be used to identify likely route for common drone operations. For example, when considering medical deliveries through the CTR, SORA can be used to estimate what routes the drone would likely take to minimise their air and ground risk.

By using this risk assessment and mitigation method, U-space aims to achieve the same level of safety as current manned aviation, both on-ground and in-air. The current ground impact equivalent level of safety (ELOS) of manned aviation is around 10^{-7} fatalities per hour. Based on current drone capabilities and predicted drone demand, simulation shows the ELOS for UAVs to range between 10^{-5} and 10^{-7}, depending on vehicle type, mission type and operational area (e.g., rural, urban, etc.) [45]. In terms of air safety between UAVs and manned aviation, simulations expect between 10^{-6} and 10^{-7} collisions per hour [45, 46]. The level of safety is highly dependent on the amount of UAVs that are operational within the airspace. Estimates for the amount of drone operations per day vary largely. For the average European city of one million inhabitants, estimates range from one thousand to one million UAV operations per day [2].

A.2. Tower Control

To support tower controllers when drones are introduced into the airspace, it is first important to know about the role of tower control and the flight operations they will encounter. The manned traffic operations and the expected drone operations a tower controller will interact with differ per location. Therefore, this research will focus on the integration of drones into the airspace at a specific airport. First, Section A.2.1 gives an overview of the current air traffic around the selected airport. Section A.2.2 describes the current role of tower control, after which Section A.2.3 discusses the current and future interaction with drones.

A.2.1. Rotterdam The Hague Airport

To keep this research close to real-world applications, it will focus on operations at Rotterdam The Hague Airport. Rotterdam Airport was chosen as it is located in an urban area, between the cities of Rotterdam and The Hague, and is near the harbour, highways, railways and the Technical University of Delft, allowing for a large variety of drone operations. Moreover, with one runway and around 50,000 flight movements per year, it is not a big airport (especially when compared to Schiphol). This means the restrictions for drones can be expected to be less strict when compared to a big airport. Finally, Rotterdam airport is a dispatch point for medical emergency helicopter flights, the operational conditions of which imply that drone traffic could interfere with them. This section aims to gives an overview of the current manned air traffic operations at Rotterdam airport. Section A.2.1.1 addresses the current flight operations, after which Section A.2.1.2 describes their foreseen interaction with drone operations.

A.2.1.1. Current Flight Operations

To get an indication of the operations at Rotterdam Airport, the traffic behaviour of the past year can be studied. This can be done by means of operation type, flight routes and procedures. Rotterdam Airport sees just over 50,000 flight movements per year; the distribution over different types of flights is seen in Figure A.9.

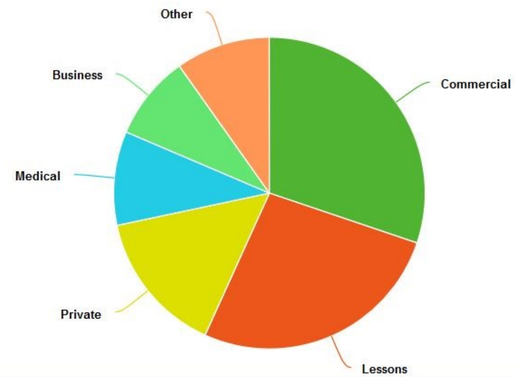


Figure A.9: Distribution of traffic movements at Rotterdam Airport in 2019 [7]

On a busy day, for example in July, Rotterdam airport sees about 170 aircraft movements per day, 80 percent of which is scheduled. On a calm day, for example in January, Rotterdam airport sees about 80 flights per day, again 80 percent of which is scheduled. It can be seen that the majority of traffic movement is derived from commercial flights and flight lessons (30 and 25 percent, respectively). Moreover, it can be seen that medical helicopter emergency flights also form a significant portion (over 5 percent) of the flight movements [7]. As these flight operate with high flexibility, they are an important interface with drone traffic. Therefore, these three categories of traffic are shortly elaborated upon below.

Commercial and Training Flights

Rotterdam airport has one runway of 1300 meters, oriented at heading 060-240, which is used for departure and take-off in both directions. The flight patterns of commercial flights at Rotterdam Airport can be seen in Figure A.10, clearly visualising set departure and arrival routes. Apart from commercial flight, flight lessons make up a large part of the flight movements at Rotterdam Airport. These training flight are categorised as light air traffic, with a maximum take-off weight less than 7000 kg. The flight patterns of these training flights can be seen in Figure A.11. It should be noted that are VFR flights that traverse the CTR but do not land or depart at Rotterdam, on average about two an hour.

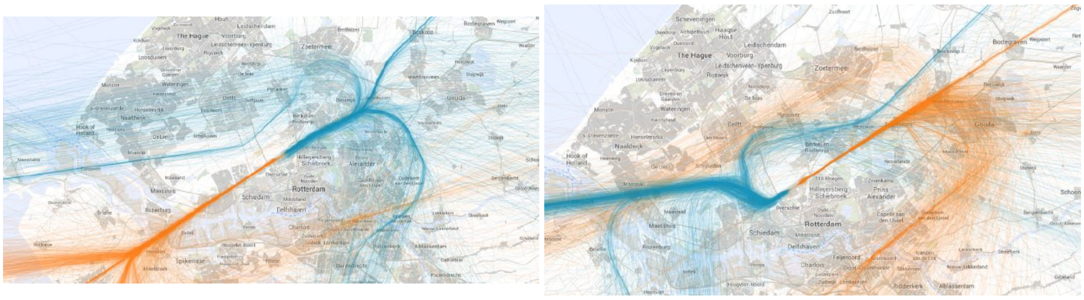


Figure A.10: Flight patterns for Rotterdam Airport, left for departure from 06, right for departure from 24; blue indicates departing traffic, orange indicates arriving traffic [8]

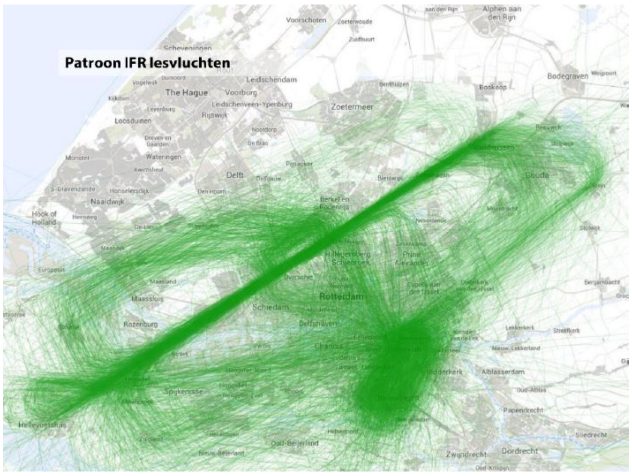


Figure A.11: Flight patterns of IFR flight lessons, accounting for around 25 percent of traffic arriving/departing at Rotterdam Airport [8]

Helicopter Emergency Medical Service

As mentioned before, medical emergency helicopter flights account for around 5 percent of the traffic operations, which translates to between 15 and 20 flight movements per day. In case of dispatch, the helicopter is usually airborne two minutes after the initial call. Air traffic control is immediately made aware in case of dispatch, after which they are given a destination or a departure direction. This gives the air traffic controller two minutes two start clearing the route for the helicopter, as it has highest priority. At the destination, the pilot is responsible for finding a suitable landing spot.

A.2.1.2. Interaction with U-space

The previous section discussed traffic operations for commercial and training flights and for helicopter medical emergency services. For both of these operations, the interaction with drone operating in U-space is discussed below.

Commercial and Training Flights

The only instance where commercial flights and training flights operate below the 500-foot limit of VLL airspace is when they are landing. Therefore, the interaction between these operations and U-space is fairly limited. It should be noted that the same holds for the other flight types presented in Figure A.9 (e.g., private, business and other). The main requirement for the perspective of air traffic control is that the final approach is protected from drone traffic by a geofence when a manned aircraft is approaching. Additionally, the airport itself should also be protected from drones by means of geofence, as proposed by the U-space proposal and the additional rules of the air for drones [2, 5].

Helicopter Emergency Medical Service

Medical emergency helicopter flights could encounter the most direct interference with drones operating in U-space. First of all, these flights operate at an altitude around the 500-foot upper limit of VLL airspace. This means they are in the vicinity of drones for the complete duration of their flight, not only during take-off and landing. Additionally, these flights commonly have to find a landing spot in populated areas, where drones could pose a potential threat. There have already been accounts of medical emergency helicopter flights being obstructed by drones [47].

A second aspect that renders the interaction between medical emergency helicopter flights and drones relevant is the flexibility of helicopter operations. As described before, air traffic control has around two minutes between notification and take-off the helicopter to start clearing the indicated direction. Moreover, the pilot has to find a place to land near the desired destination. These flights can occur at any time and to anywhere and have the highest priority. This means they cannot be account for beforehand and drones have to respond quickly to clear the route. This combination of altitude and unpredictability makes medical emergency helicopter flights relevant for drones operating in U-space.

In the vision of U-space, drones can be kept clear from medical emergency helicopter flights by means of a short-term restriction, as provided via the geo-awareness and geofencing services. This allows approaching drones to re-route and drone currently in the area to make way. In case a drone cannot make way in time, it will have to loiter, land or decrease its altitude [2].

A.2.2. Tower Controllers

To support tower controllers when drones are introduced into the airspace, it is first important to gain an understanding of the current responsibilities and task of tower controllers. This section first explains the current responsibilities of tower control in Section A.2.2.1. Next, the current tools used by tower control are described in Section A.2.2.2.

A.2.2.1. Responsibilities of Tower Control

Airport traffic tower control is responsible for efficient movement and separation of aircraft at the airport and in the control zone (CTR) around it. The official main function statement according to the International Civil Aviation Organization (ICAO) is:

"Aerodrome control towers shall 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 of the control tower, including the aerodrome traffic circuits." [31, page 7-1]

It further stated that tower control should maintain a continuous watch of all flight operations in the CTR, as well as those on the manoeuvring area. The task they perform to achieve these overarching goals are described in more detail below.

Information Provision

Tower control provides pilots within the CTR and on the airfield with information relevant for the current operation, several of which will be highlighted here. First of all, information is provided on the operational conditions of the runway, including possible incursions or obstructions. Second, information is provided regarding essential local traffic. Next, meteorological information is often provided by tower control, based on the supporting meteorological services. Finally, if required, information is provided regarding emergencies in the vicinity. All the above-described information is commonly provided via radio communication.

Coordination

Tower control plays an important role in the coordination between different actors in and near the CTR. Most directly, they coordinate traffic within the CTR, as described by the two sections below. Additionally, they coordinate with other departments of air traffic control, most relevantly with approach control. Approach control provides air traffic control in the terminal control area, around and above the CTR. Tower control and approach control coordinate the handover of aircraft, as well the coordination of the issuing of holding commands for approaching aircraft. Additionally, tower control should offer every assistance to aircraft experiencing an emergency situation. This could involve coordination with on-ground emergency services.

Issuing Clearances
Tower control is responsible for providing clearance for landing and take-off to aircraft in the CTR. In doing so, first and foremost, tower control assures conflict free operations on the runway. Additionally, they make sure that both departing and arriving aircraft are sufficiently spaced, according to the wake turbulence categories. They are aided in this by the approach controller, who is in charge of sequencing the aircraft that approach the CTR. When not provided clearance to land, tower control issues a go-around to the aircraft. If a problem regarding landing clearance is detected earlier on in the descent, the aircraft can be put into holding, in coordination with approach control.

Flight Instructions
As described in the section above, tower control issues clearance to aircraft departing and taking-off. Moreover, they provide pilots with instructions required to perform the landing or take-off. In case of VFR traffic, tower control provides instructions and information required by the flight crew to perform the operation, based on visual detection. In the case of IFR traffic, this process is aided by fixed approach and departure routes (STARs and SIDs, respectively) and equipment such as the instrument landing system (ILS). This provides a 2D-trajectory to follow by means of waypoints, as well as an altitude profile based on the ILS. An example of the standard instrument departure route for Rotterdam airport can be seen in figure A.12.

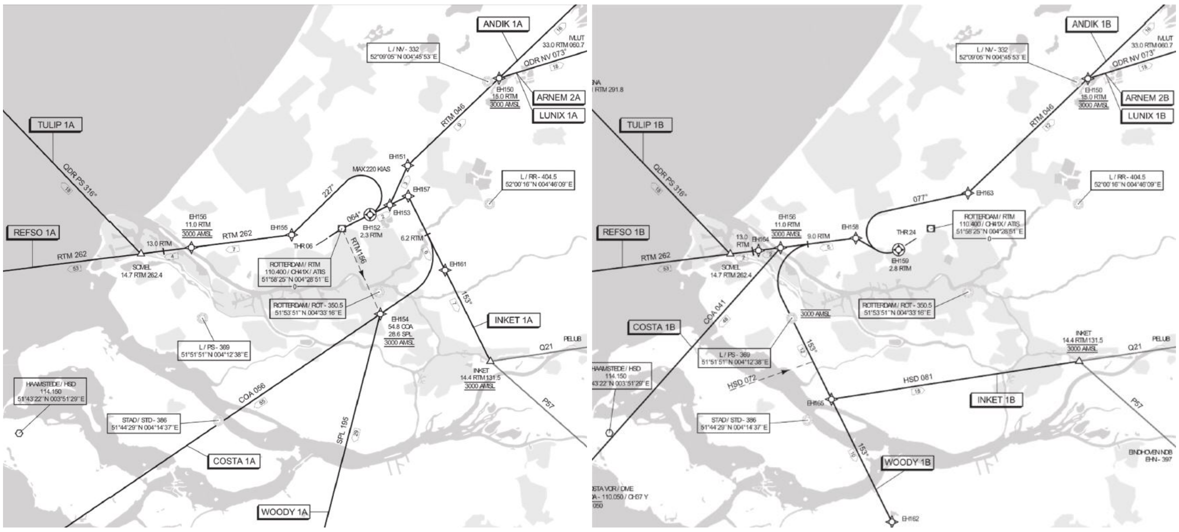


Figure A.12: Departure route for Rotterdam airport, left showing departure with heading-06, right with heading-24 [8]

Apart from instructions regarding take-off and landing, tower control is also responsible for the separation of controlled traffic with the CTR. In order to achieve this, they can give instruction to pilots to keep all aircraft sufficiently separated. These are issued in the form of a speed and a heading for horizontal separation and an altitude or rate of climb/descent for vertical separation. It should be noted that emergency services, such as helicopter emergency medical services will always have priority over other flight operations, meaning a tower controller will clear their flight path from other traffic.

A.2.2.2. Current Tools used by Tower Control
Tower controllers can rely on various digital and analogue tools when performing the tasks described in the previous section. Below, the most important of these tools are elaborated upon, examples of which can be seen in Figure A.13.

Out of Tower View
The most direct tool used by tower controllers is scanning the surroundings outside of the tower's windows. This allows them to visually identify and follow the vehicles they are giving instruction to, both in the air and on the runway. Scanning the view outside of the tower's windows is classified as head-up time and is found to be the most prominent tool used by tower controllers, taking up more than half of their working time [48].

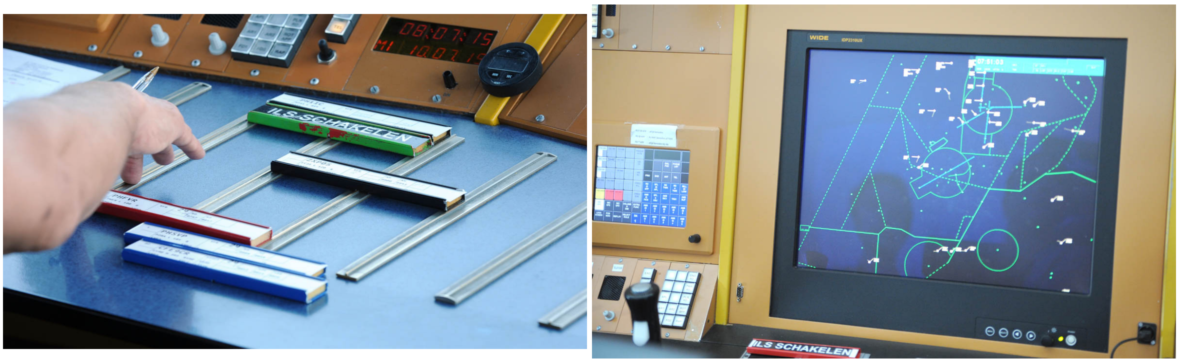


Figure A.13: Examples of the use of flight strips and a back-up radar system showing the Rotterdam and Schiphol airspace at Rotterdam The Hague Airport.

Voice Communication
Commonly, head-up time of tower controllers is combined with voice communication with vehicles in their surroundings. Voice communication is used for giving instructions and clearance to pilots, as well as coordinating with airport services and approach control. The combination of the out of tower view and voice communication forms the primary tool in fulfilling their task for tower controllers.

Flight Strips
The most prominently used tool during head-down time (when not looking out the tower's window) is working with the flight strips. Flight strips are used to keep track of the status of flights in the area, keeping track of the issued instructions and clearances, while also allowing this information to be easily transferred to other controllers. Although there is no universal standard for flight strips, they contain information regarding the aircraft's call sign, type and wake turbulence category, on-board equipment, origin and destination, estimated and actual times at waypoints and clearances and instructions. The flight strips are moved around to keep track of different flight phases (i.e. taxiing, take-off, approach). This allows the tower controller to keep track of the situation around them. Working with the flight strips takes up over half of the head-down time of a tower controller [48].

Radar
The radar shows the movement of aircraft currently operational in the control zone. It shows aircraft information such as current position and past few positions, flight level and ground speed. Radar forms a supplement or back-up for the head-up activities (out of tower view and voice communication) and scanning it is estimated to take approximately 10 percent of a tower controllers work time.

Automatic Terminal Information Service (ATIS)
The Automatic Terminal Information Service (ATIS) shows meteorological data to the tower controller. Depending on the weather conditions, this is scanned frequently and used to give weather information to aircraft or to re-route them if needed.

Ground Movement Radar
The ground movement radar displays the positions of the vehicles that are on the airfield, including ground vehicles. This can be used by a tower controller to supplement their out of tower view, for example during bad weather conditions.

A.2.3. Drones and Tower Control

This section investigates how tower controller deals with drones currently in Section A.2.3.1 and how they aim to do so under the U-space framework in Section A.2.3.2.

A.2.3.1. Current Interaction

Currently, the Dutch government makes a distinction between recreational and professional drone use. An overview of the limitation to recreational drone use in The Netherlands can be seen in Figure A.14. Under the current rules, recreational drone use is prohibited with the CTR. Professional flights have to request permission for their flight at least 24 hours in advance. Moreover, they are to be carried out a certified operator. During the flight, the drone is classified as VFR traffic and has to remain within the area allocated to it based on the flight request. The drone operator is required to have access to two-way radio communication with tower control [9].

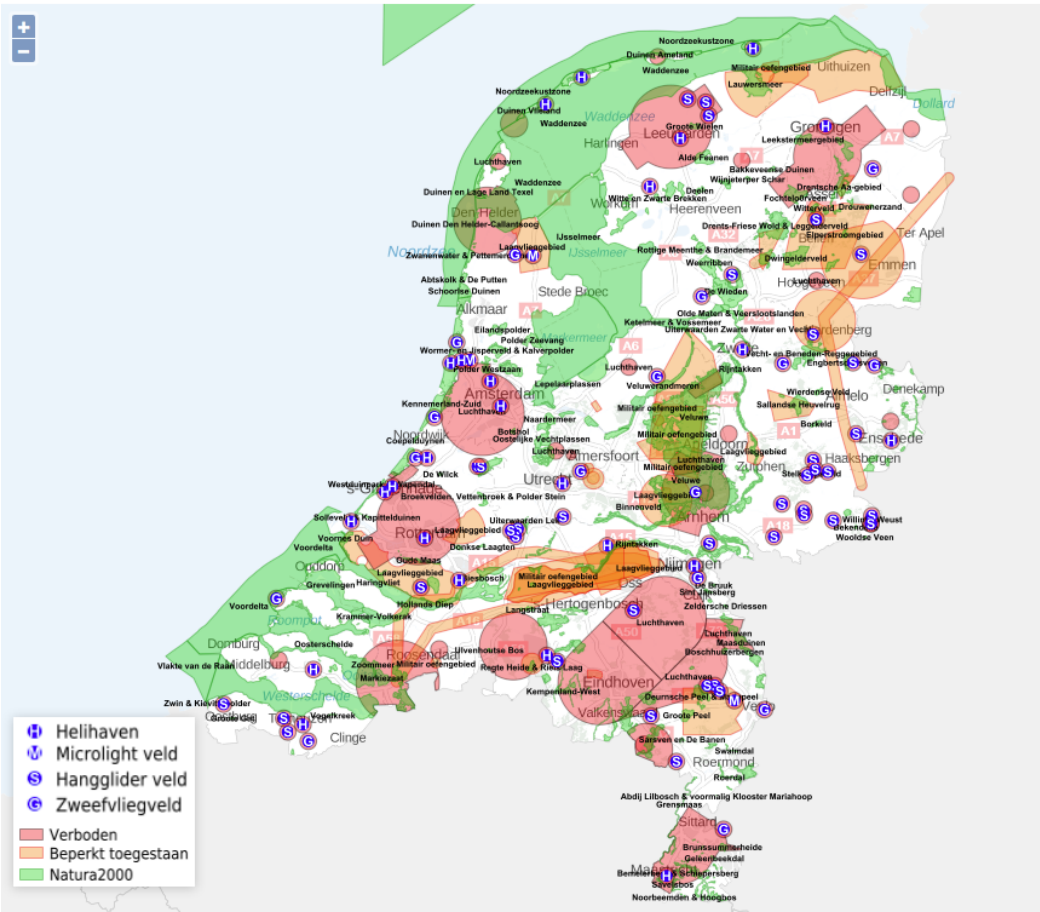


Figure A.14: Drone map of The Netherlands, red indicating prohibited areas, orange indicating limited access and green indicating limited access due to nature reserves [9]

Although these drone flights are commonly not visible on radar, tower control has an indication of the position of the drone based on the filed flight request. Moreover, they can be informed by the operator over the radio. When required, tower control can issue instruction to the drone via the radio communication with the drone operator.

A.2.3.2. U-space

First of all, the implementation of U-space changes the current set of restrictions for drones, as it aims to integrate drone traffic into the airspace, rather than separate it from it. For example, this means that part of the Rotterdam CTR is available for drone operations, instead of being completely shielded from it, as can been seen in Figure A.14. This means that there are stronger restrictions and requirements for drone flights in this region, as described in Section A.1.4. Being able to use the CTR airspace allows for useful drone operations to be carried out, such as medical deliveries between The Hague and Rotterdam, highway patrols and railway inspections.

The interface between U-space and ATC is described from the U-space perspective in Section A.1.3. U-space will first provide a procedural interface that allows for easy digital submission of a flight request when needed. This means that the region containing drone operations can also be shown to tower control. Various industrial parties are working on using this as a means to visualise drone operations to tower control. This is aimed to be extended by a collaborative interface that allows for verbal or textual communication, allowing tower control to send instructions and clearance to the drone (operator) [32].

U-space also aims to make use of geofences, shielding certain areas from drone operations, for example runways, royal palaces or festivals. These geofences consist of a set of coordinates that are provided to all drone operators in the immediate area. These can be permanent if based on geographical information or temporary in case of events or emergencies. A relevant aspect of this for tower control is its relation to emergency operations involving medical and police helicopters. These unpredictable operations are foreseen to be protected by temporarily shielding their route from any drone operations [2].

The combination of the procedural and operational interface proposed by U-space would mean a tower controller would still have to interact with each drone individually to clear a certain area for (emergency) manned traffic. Allowing tower controllers to impose temporary geofences in the CTR would alleviate them from these individual interactions and allow then to safely guide manned aviation [33]. Although this is a promising concept, there is little known about the practical implementation. The main challenge comes from the fact that geofences can be activated and deactivated during flight. This makes the shape and size of the geofence critical to their effectiveness. There are various factors that could determine the shape and size of geofences, which are listed below.

Geographical Landmarks
Currently, the shape and size of geofences is often based on geographical landmarks. However, this usually concerns geofences around a building or a certain area to keep it clear from drone traffic [38]. This would therefore make it difficult to utilise in keeping drones clear from the flexible emergency helicopter flights.

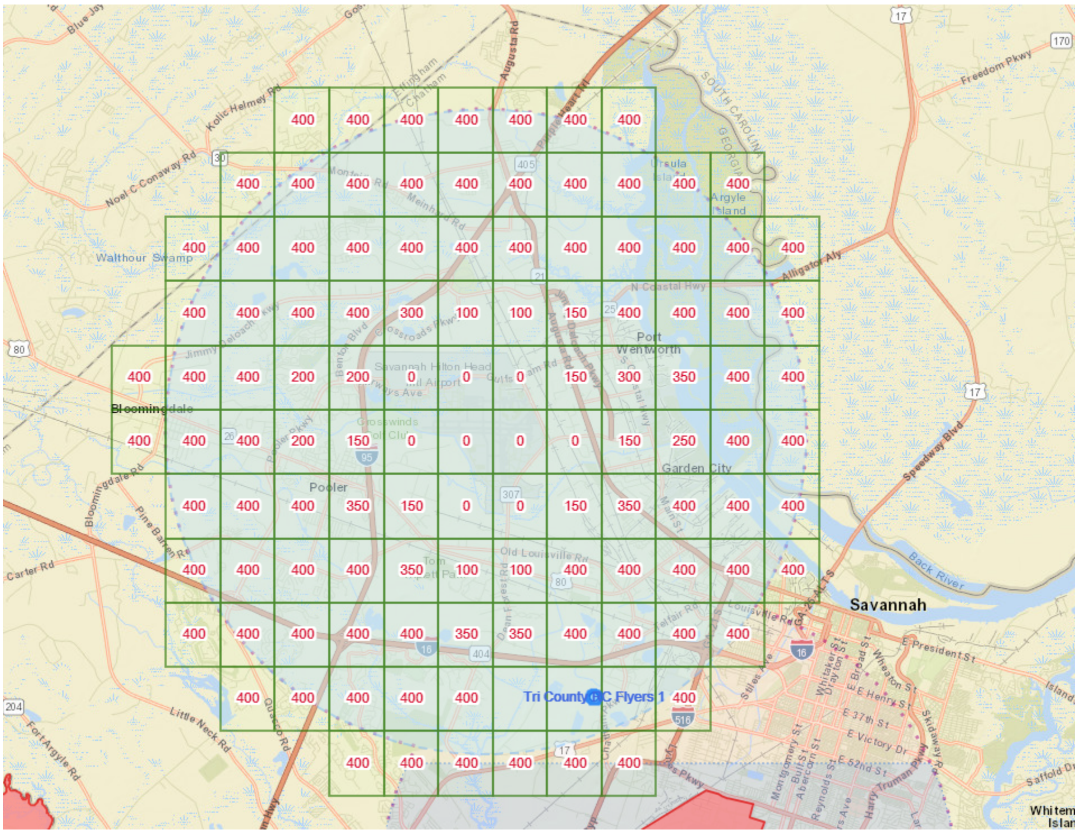


Figure A.15: Example of a grid of 1 NM cells specifying the allowable drone operational altitude around an airport [10]

Geofence Grid
To account for emergency helicopter flights, a grid of geofences could be made available to the operator. This system resembles the one used by the FAA to specify what type of drone operations are allowed for regions

near airports. It consists of a grid with cells of 1 nautical mile, specifying the allowable altitude for drone operations, an example of which can be seen in Figure A.15 [10]. An important aspect of a geofence grid is the size of the geofences used. When considering these geofences, one perspective is that of the drone. The geofence could be shaped and sized such that the drone can clear it in a timely manner, based on its expected capabilities. There have been efforts to design geofences around a drone operation based on their capabilities [38, 49, 50]. However, this has not been translated to designing larger, multi-drone geofences based on drone capabilities. The other perspective is that of the tower controller. The geofence shape and size should allow for easy control, while also accommodating sufficiently detailed selection.

Air Traffic

The shape and size of geofence could also be based on air traffic operations. For commercial aviation flights, this would concern traffic routes [2]. Based on SIDs and STARs, interference with U-space can be identified and geofences can be places accordingly. However, this does not cover unpredictable operations such as emergency helicopter flights. This would require the ability to add new geofences in real time, such that these flexible flights can also be shielded from drone operations.

A.3. Drone Operations

To investigate the effect of drones on tower controllers, the drone operations involved have to be described in more detail. This involves the amount of drone operations, the types of missions, the types of vehicles used and possible contingencies they might encounter. This chapter aims to address these aspects. First, Section A.3.1 explores UAV operations that can be expected in the vicinity of Rotterdam airport and indicates the vehicle types and mission types used. Next, Section A.3.2 addresses possible threats to the selected UAV operations based on U-space documentation. It also identifies the most relevant of these UAV threats for the interaction between U-space and ATC.

A.3.1. UAV Operations

It is important to know what type of drone operations can be expected in the future within the CTR of Rotterdam Airport. This is done based on anticipated applications by companies and government institutions, as well as data on the expected drone operations per sector [11]. Figure A.16 shows the distribution of expected drone operation by 2035, divided over different industrial sectors.

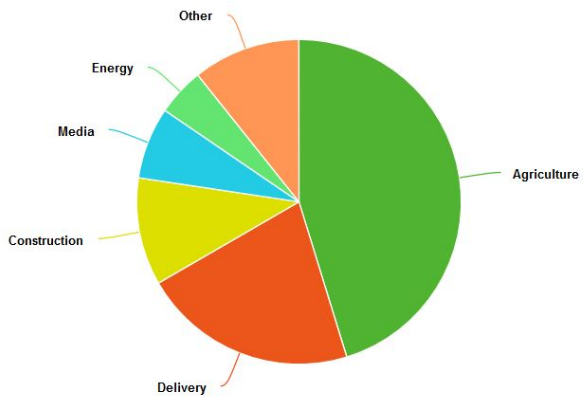


Figure A.16: Overview of expected drone operations by 2035 per industrial sector [11]

Although agricultural applications are expected to be most numerous, they are expected to occur in rural areas, not near cities or in the vicinity of airports. Therefore, these will not be considered during the current research. More relevant sectors for the current use-case are delivery services, construction and the energy sector. Based on developments in the industry, some expected drone operations will be elaborated upon below. When possible, an indication is provided on the type of drone and the mission type associated with the operation. It should be noted that this research makes a distinction between two vehicle types, a multi-copter and a fixed-wing UAV.

Delivery

One of the most well-known examples of (future) drone applications is delivery. These missions consist of flights between a distributor (e.g., a warehouse or distribution centre) to the desired location of delivery. This can be described as a point-to-point flight, as there is no set trajectory to be followed, only a departure point and a destination. This means that are no intermediate waypoints the drone should follow, it will rather take the most direct route possible between the points. The largest portion of (anticipated) delivery drones are multi-copters. In the Rotterdam areas deliveries can for example be expected from the harbour to the surrounding or for supplying ships [51].

Delivery drones are also expected to prove particularly useful for medical deliveries, as these have higher urgency than regular package deliveries. The Erasmus University Medical Centre is cooperating with drone companies to work towards medical delivery drones. It is envisioned that this can be used to deliver for example medicine and blood samples to nearby hospitals. A relevant example are medical deliveries between Rotterdam and The Hague, crossing through the centre of the Rotterdam Airport CTR, as depicted in Figure A.17. The Rotterdam Erasmus University Medical Centre is currently in cooperation with a drone manufacturer to enable these flights. Similar to regular deliveries, these operations are point-to-point, however, they are expected to be carried out with fixed-wing UAVs [52].

Figure A.17: Example of a medical delivery flight between Rotterdam and The Hague

Infrastructural Inspection and Patrol

Two infrastructural applications that are in the early phase of implementation are the inspection of railways and patrol of highway in aid of traffic management. Both operations follow a pre-set trajectory following the highway or railway along a certain segment, as can be seen in Figure A.18. Both applications will also likely make use of multi-copter, as they benefit from the capability to hover for closer inspection [53, 54].

Drones are also increasingly used in the inspection of infrastructural elements, such as bridges and pipelines. Bridge inspections would consist of an inspection flight around a particular point. Pipeline inspections, on the other hand would follow a fixed trajectory along a pipeline, similar to railway inspections. Both applications will likely make use of multi-copters, as these are capable of hover flight for closer inspection [55].

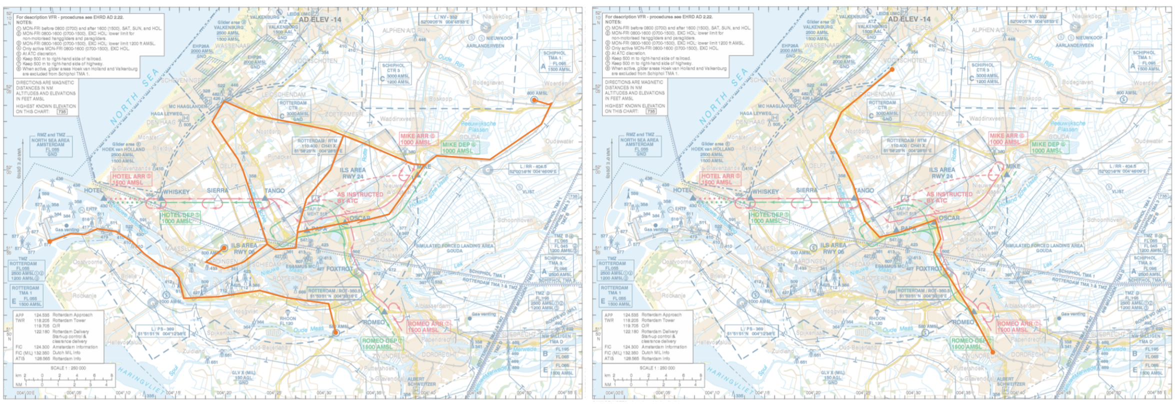


Figure A.18: Examples of railway inspection flights (left) and highway patrol flights (right).

Navaid Measurements
There are various companies that aim to use drones to perform measurements regarding the aviation navigational aids. Example of this are measurement on ILS equipment, runway lights and other on-airport equipment, as well as the inspection and calibration of Navaid in the Rotterdam Airport CTR. This mission would consist of a mapped out trajectory in close vicinity to the Navaid in question, as can be seen in figure A.19. From an air traffic control point of view, it is regarded as an inspection flight around one particular point. These operations will most likely be carried out by multi-copters [56].

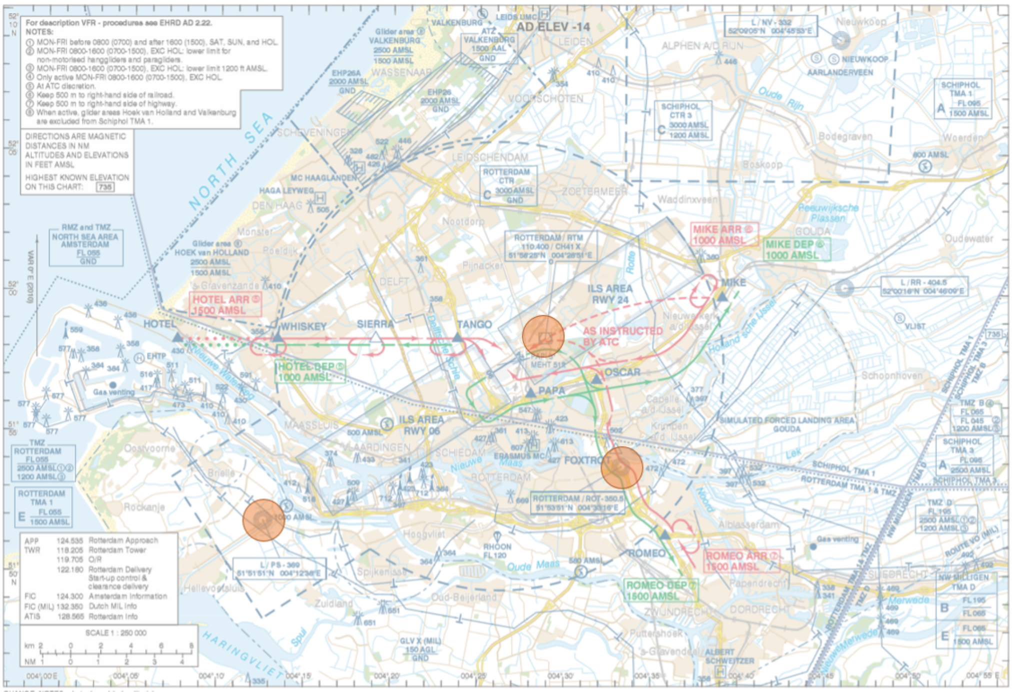


Figure A.19: Examples of NavAid calibration flights near Rotterdam Airport

Mapping and Surveying
Drones are already being used for mapping of terrain, forests, agricultural sites, etc. Moreover, emergency services are also incorporating drones into their work, for example for search (and rescue) missions, surveying large events or for quick visual access of emergencies. For the current urban, near airport use-case, the emergency service application is more relevant. In case of a survey mission, the mission pattern would be a point-to-point flight, followed by a local search pattern, such as a loiter or hover. In case of a search mission, this would be a search pattern over a certain area. An example of a survey flight over the Delft area can be seen in Figure A.20. The use of a multi-copter or a fixed wing UAV depends on the application. In case of a local, scheduled survey, a multi-copter is more likely due to its hover capabilities. For emergency response, fixed-wing UAVs have the advantage of higher flight speeds [57].

A.3.2. UAV Contingency Operation

As described in Section A.1.3, U-space aims to set up an interface with the existing air traffic control infrastructure [1]. This implies that, under nominal operation, ATC can approve or deny flights that plan to enter controlled airspace. Moreover, position updates of the drones in the airspace can be provided to ATC. In more advanced stages, it could include possibilities of communication and the activation of geofences. In terms of interaction, ATC can approve the mission, see where the drone is and shield certain areas for all drones if needed. Maintaining sufficient separation among drones and between drones and geofences all happens within the functionality of the U-space systems [2]. As mentioned before, unpredictable manned flight operations, such as emergency helicopter flights for a critical operational condition. Similarly, drone operations become more critical for ATC when drones encounter threats to their nominal operation, which could for example mean they encounter reduced performance or cannot comply with instructions or restrictions. Therefore, this section explores the threats most relevant for the interaction between U-space and ATC.

Figure A.20: Examples of a surveying flight over Delft

A.3.2.1. Anticipated Threats to Drone Operations

As mentioned in Section A.1.5, the U-space system aims to rely on risk assessment, rather than the complete certification of all drone operations. Because of this, a list of threats can be composed that the UAV and compromise the safety. From a system point of view, threats can be identified that compromise the safety of the drone that are derived from the provided U-space service. This analysis has been performed in the U-space concept of operations and will be used as a basis to identify relevant contingency operations for the use case described above [2]. Additionally, SESAR's Project Airpass performed risk analyses of the airborne communication, navigation and surveillance (CNS) systems for drones operational in U-space [20]. Based on this, a list can be composed of the threats that can lead to contingency operations relevant of the U-space-ATC Interface, which can be seen in Table A.1.

From this initial list of relevant threats, a more defined selection can be made, identifying which have the most impact on the tasks of the air traffic controller. Some mentioned threats will be grouped, as their impact on air traffic control is similar. This will be done for each of the groups of threats set in the overview.

A.3.2.2. Technical and Mechanical Threats (RT)

The list of technical and mechanical threats is most substantial and will therefore be broken down into several groups, which are addressed below.

Telemetry and Telecommand

First of all, loss of telemetry and telecommand (RT001.2 and RT002.2) imply that the drone loses the ability to send or receive data to/from the ground station. Most of the envisioned drone operations in this research are BVLOS and rely on a significant level of automation. These threats will therefore not imply a loss of control, but more likely the inability to send/receive (measurement) data to/from the ground station. In case this means the mission plan can/should no longer be completed, a safe termination is possible [20]. These threats are therefore of reduced relevance for ATC.

Reduced Navigation Performance

Threats RT004 and RT006.1 through RT006.3 all concern reduced navigational performance and an increase in position uncertainty, due to failure of GPS, compass or inertial measurement unit (IMU), respectively. This

Table A.1: Operational UAV threats most relevant for the U-space ATC interface. The IDs correspond to those used in the U-space concept of operation, RT indicates technical/mechanical, RM environmental, RH human/operational, RI security and RS services [2, 20].

ID	Threat	Description
RT001.2	Indirect datalink loss (telemetry)	Reduced telemetry
RT002.2	Indirect datalink loss (telecommand)	Reduced telecommand
RT004	Sensor/Camera failure	Reduction in position accuracy and/or controllability of the drone.
RT005	Emitter/Receiver failure	Complete loss of drone information for UTM and ATC.
RT006.1	GPS failure	Drone has to resort to other methods, decrease the position accuracy.
RT006.2	Compass failure	Drone has to resort to other methods, decrease the position accuracy.
RT006.3	IMU failure	Drone has to resort to other methods, decrease the position accuracy.
RT006.4	Altitude sensor failure	Drone has to resort to other methods, decrease the position accuracy.
RT008	Unintentional loss of altitude	Can lead to a sudden decrease in altitude and possible the incapability to regain it.
RT008.3	Electronic speed control failure	Can lead to a sudden increase in altitude and possible emergency procedure.
RT012	Erroneous data	ATC receives incorrect data.
RT013	Latency	ATC receives data later.
RM002.2	High wind	Can alter drone performance.
RM002.4	Gusty wind	Can change drone trajectory in an unpredictable manner.
RH002	Drone enters segregated airspace inadvertently	Drone does not follow planned mission and enters segregated airspace.
RH006	Collision with manned aviation	Should be prevented by UTM, then ATC.
RH009	Human error (skill-based, decision, perception)	An error made by drone operator or UTM manager
RI002	Intentional interference	May lead to counter-drone equipment at airports
RS001.3	Processing error	ATC receives incorrect data (RT012)
RS002	Total loss	Sudden complete failure of U-space service provider, leads to latency
RS003	Latency	ATC receives data later (RT013).

has a significant impact on the functioning of the air traffic controller, as it reduces the position accuracy and the ability of the drone to follow its mission plan. This means the future behaviour and position of the drone is more unpredictable. Flight tests with BVLOS fixed-wing UAVs have shown navigation performance to significantly decrease when relying solely on the IMU when faced with a GPS failure [58]. On the other hand, reliability analyses show that accelerometers as used in IMUs are among the least reliable components in terms of failure [59, 60]. Therefore, reduced navigation performance is considered as an important contingency operation in this research.

Emitter/Receiver Failure

Threat RT005 considers the failure of the drone's emitter/receiver. This would mean that the U-space system no longer receives position updates from the drone and has to rely on surveillance data (e.g., radar) for position information, which increases position uncertainty. Moreover, the drone can no longer relay up-to-date intent information and information regarding other possible malfunctions. As this would be a strong disadvantage to the air traffic controller, this threat is taken into further consideration.

Altitude Change
There are various threats that consider a (sudden) change in altitude of a drone (RT006.4, RT008 and RT008.3). As U-space focuses on drone operations in VLL airspace, it most likely that they will operate below practically all manned aviation. Therefore, a loss of altitude of limited importance to the air traffic controller. Apart from a loss in altitude, an increase in altitude due to electronic speed control failure is also considered. However, this is more likely to result in an emergency operation in which the drone mission is terminated and the drone is safely recovered, for example by means of parachute [20]. Therefore, unexpected changes in altitude of drones will not be considered as a contingency operation for this research.

Erroneous and Latent Data
The final technical threat is sending erroneous or latent data (RT012 and RT013). The most relevant data relayed to air traffic control are vehicle states and intent. When it is known that these data are erroneous, they can be supplemented or substituted by surveillance data, similar to the situation concerning a failure of the drone's emitter/receiver (RT005). In the case of latent data, the air traffic controller should be able to take into account that the position update of a drone lags behind with respect to other vehicle's position updates. This could influence the interaction between drones and manned traffic and will therefore be taken into further consideration.

A.3.2.3. Environmental Threats (RM)
The most important environmental threats, especially seen the use-case of Rotterdam Airport are high wind speeds and gusts (RM002.2 and RM002.4). The former can alter the performance of the drone and cause it to drift, while the latter changes the position/trajectory of the drone in a unpredictable way. Constant high wind speeds are considered more relevant for this research, as they can alter the performance of the drone in ways that renders it unable to follow the mission plan. Moreover, the combination of constant high wind speeds with reduced navigation performance could lead the drone to drift away from the flight path. Therefore, constant high wind speed is to be considered as a contingency operation for the simulation.

A.3.2.4. Human and Operational Threats and Secrity Threats (RH and RS)
The human and operational threats that influence the U-space interface with ATC are: entry of segregated airspace, collisions with manned aviation and human errors (RH002, RH006 and RH009). As the current research aims to investigate the safe interaction of tower controller with U-space traffic, emergency situations such as entering segregated airspace or collisions are not considered for the first set of threats. Moreover, human errors that emerge from the drone operator and/or UTM system and propagate to the air traffic controller are considered beyond the scope of this research. The only security threat listed as relevant is intentional interference of drones (RI0002). Similar to the aforementioned emergencies, this threat is considered beyond the scope of the current research.

A.3.2.5. U-space Service threats (RS)
The most direct threat from the U-space system is partial loss of data by a U-space service provider or the complete loss a U-space service provider (RS001.2 and RS002). In both of these scenarios, other services providers have to step in to cover the work that cannot be done by the troubled service provider. In practical sense, this would lead to latency in the data provided to air traffic control [32]. The complete failure of all available service providers is not considered in the current stage of research, as this is a scenario that the U-space architecture aims to prevent at all time. This means that an important U-space threat is latency of data for multiple drones under the same U-space service provider (RS003), similar to RT013.

A.3.2.6. Summary
To summarise, there are four individual threats that are identified as most relevant for this preliminary research into the interaction between a tower controller and U-space. These are:

- Failure of a drone's emitter/receiver, leading U-space and ATC to rely on surveillance data;
- High wind speeds;
- Latency of data for a single drone or for multiple drones under the same U-space service provider, due to service failure.
- Reduced navigation performance in the form of failure of GPS, IMU and/or compass;

It should be noted that combinations of these are also taken into consideration. For example, the combination of reduced navigation performance due to GPS failure and high winds could lead the drone to drift away from its planned route.

A.4. Trajectory Uncertainty Prediction

In most current plan view displays, positions and trajectories of vehicles are visualised discretely as points and lines on the map. In reality, however, there is an uncertainty in the displayed position of the vehicles. It is envisioned that drones connected to U-space relay information regarding their position uncertainty to the U-space systems [20]. This uncertainty in position also implies that the future trajectory of the vehicle is subject to an uncertainty that grows over time. This trajectory uncertainty is commonly applied in flight planning and conflict prediction. However, when visualised it could also give an indication of the possible future positions of an aircraft.

In the context of UAV traffic in the CTR, the unpredictability of drone behaviour is seen as a large challenge for tower control [35]. For example, it is difficult to indicate whether a geofence is clear of drones and will stay clear, when the drone positions are uncertain. Modelling these uncertainties and possibly visualising them to the controller could reduce unpredictability in drone operations and allow for higher task performance.

Therefore, this chapter reviews trajectory uncertainty for UAVs, by first addressing the most important components of trajectory uncertainty in Section A.4.1 and the sources in Section A.4.2. Next, Section A.4.3 explores the available models for trajectory uncertainty prediction and A.4.4 elaborates on the implementation of the most relevant model. Section A.4.5 look at the effects of the contingency operations defined in Section A.3.2 on the trajectory uncertainty. Finally, Section A.4.6 shortly lays-out which means of visualisation of trajectory uncertainty have been used in previous research.

A.4.1. Trajectory Uncertainty Components

Three types of trajectory error can be identified: horizontal, vertical and temporal. Each of these errors is discussed below, including their relevance for this research.

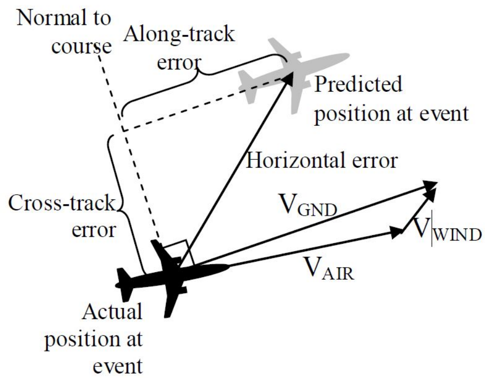


Figure A.21: Schematic representation of horizontal position error, broken down into along-track and cross-track error [12]

Horizontal Error

The horizontal spatial error is defined as the distance between the actual aircraft position and its predicted position for a certain point in time. This consists of an along-track component and a cross-track component, as can be seen in figure A.21. For manned air traffic, the cross-track error is commonly bound by the flight management system (FMS) compensation for wind. This results in the along-track error commonly being larger than the cross-track error.

Vertical Error

The vertical spatial error is defined as the difference between the actual flight path and the predicted flight path and is therefore most relevant during climb and descent. For manned aviation, a major contribution to this error comes from weight uncertainties. This is less relevant for UAVs, as these usually carry no passengers and limited cargo. Additionally, the weight is easy to control and measure for UAVs. Moreover, UAVs are not likely to take off and descent in the vicinity an airport, making the climb and descent phases less relevant for tower controllers. Therefore, vertical uncertainty will not be considered in this research.

Temporal Error
The third and final error is the temporal error, defined as the difference in time between the predicted position and the closest on-track position at a particular instance (e.g. at waypoints). This error bears a limited relevance to drone traffic, as drone flight plans vary largely from mission to mission, making a set planning as common in manned aviation unlikely.

A.4.2. Trajectory Uncertainty Sources

There are various sources for the uncertainty in the actual trajectory of flights. For manned aviation, research has been devoted to investigation these sources and their influences [61]. Some of these sources also hold true for UAV flights and will be shortly listed below.

Battery Capacity
The battery capacity of a drone has effect on its performance capabilities. Moreover, it determines the ability of the drone to take a certain re-route. The future use of battery capacity is relatively difficult to predict, implying a scenario where a drone has less power available than anticipated. Therefore, battery capacity is an important source of trajectory uncertainty.

Automation
U-space foresees a large degree of automation in the drones operational in the airspace. The automation will determine the behaviour of the drone, based on what the sensors perceive. This will introduce some form of stochastic behaviour. If a drone were to be controlled manually, this effect would still be present due to the stochastic element in the behaviour of the operator.

Position estimate
Uncertainties in surveillance systems influence the estimation of the current position and velocity of a UAV. These uncertainties propagate when looking at the expected trajectory of the UAV, adding to position uncertainty. The magnitude of these uncertainties depend on the surveillance systems used (i.e., Radar, GPS data via ADS-B).

Weather
Finally, the most significant error source is deviations in wind speed and direction. This is especially relevant for UAVs, as there are usually more prone to wind effects than manned aircraft. This might also cause a UAV to drift away from its course, as it cannot maintain course under the current wind conditions.

A.4.3. Trajectory Uncertainty Models

Quantifying the position uncertainty and trajectory uncertainty can be achieved by estimating the probability distribution of the spatial error parameters with respect to the expected flight path. These can be combined to form an uncertainty region around the displayed position of the aircraft, also known as a covariance ellipsoid in three dimension or a covariance ellipse when only considering the horizontal plane. This uncertainty region changes over time and can be used to visualise probable future position in combination with the trajectory. These uncertainty regions are often used to estimate the conflict probability by means of the joint probability distribution of two aircraft. This will not be addressed in this research, as the focus lies towards the visualisation of the uncertainties. As the field of trajectory uncertainty estimation originates from commercial aviation, some of the most relevant commercial aviation models will be addressed first. Following this analysis, trajectory uncertainty models for drone operations are summarised.

A.4.3.1. Trajectory Uncertainty Models for Commercial Aviation

Models involving trajectory uncertainty can be divided into short-term medium-term or long-term predictions and commonly use Monte Carlo simulations or rely on parametric estimation. For this research short-term and medium-term prediction are most relevant, looking around five to ten minutes and ten to twenty minutes ahead, respectively.

Medium-term Parametric Models
When looking at medium-term parametric models for trajectory prediction, the aircraft's covariance matrix is often used. A lot of early examples consider the two dimensional case [13, 62, 63]. In these models the cross-track and along-track variance components are modelled as Gaussian distributions with zero mean

and a variance that increases over time. This is modelled as having an initial position uncertainty and two separate rates of increase for the along-track and cross-track variance. The values for these variances are obtained empirically from flight data [63]. When combining this with flight plan data (in terms of waypoints with time markers), future positions can be estimated. As the cross-track variance is commonly smaller than the along-track variance, due to flight management system corrections, an error ellipse is formed. This ellipse represents the 95 percent confidence interval of the future possible position of the aircraft at a certain point in time, as can be seen in figure A.22.

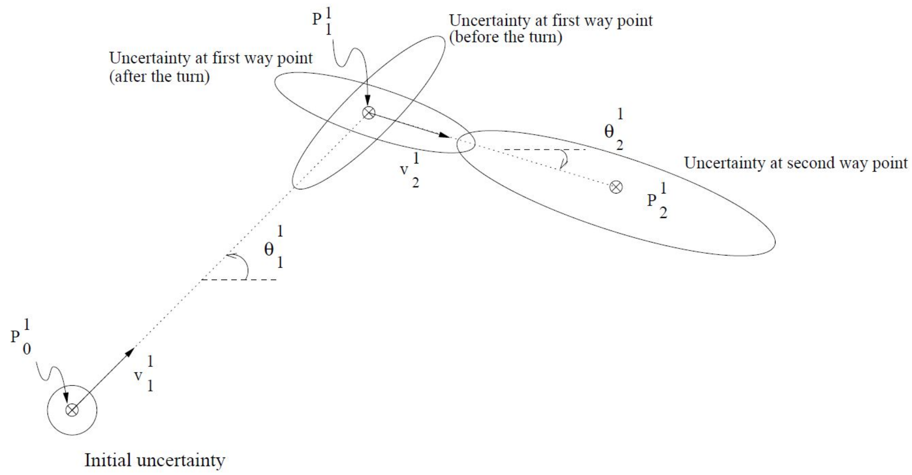


Figure A.22: Uncertainty ellipses based on medium-term trajectory parametric prediction [13]

Medium-term Monte Carlo Models
The parametric models for trajectory uncertainty estimation can be expanded to include intent. This is modelled by likelihood distributions for certain manoeuvres. The conflict probability is simulated by means of Monte Carlo simulation [62]. An alternative method is to model aircraft states with an uncertainty and apply a Monte Carlo model to this [61]. Although these Monte Carlo simulation can aid in trajectory uncertainty modelling, they are computationally expensive and are therefore not further considered.

Short-term Parametric Models
Medium-term models rely on future waypoints and time markers to estimate future aircraft positions. Short-term trajectory prediction models, on the other hand, make use of the current velocity vector and add a random component to this. An example of this is the use Brownian motion, where the future position is modelled as a Gaussian distribution with zero mean and the time as variance. As cross-track error commonly increases at a slower pace than along-track error, a scaling matrix is added to the distribution. Combining the current velocity vector and the Brownian motion gives an uncertainty ellipse for future aircraft positions [64].

A.4.3.2. Trajectory Uncertainty Models for UAVs
Compared to commercial aviation, there are significantly less trajectory uncertainty modelling available for UAVs. This can be attributed to a lack in need for them, as there are currently few UAV operations where flight plan execution is overseen by a traffic controller. However, there are some models available that build on the aforementioned commercial aviation models.

First of all, an extension of the standard parametric medium-term trajectory estimation models is available [65]. However, the modifications are mainly focused on conflict resolution, not on trajectory modelling. Moreover, as mentioned before, the medium-term time scale is probably not applicable to all drone operations.

There are UAV trajectory uncertainty predictions available that use Monte Carlo simulation regarding the thrust vector of UAVs [66]. However, Monte Carlo simulations are computationally expensive. As this research aims to provide the position uncertainty is real time, this type of model is deemed less favourable.

Another model that can be considered is a parametric short-term model, again making use of Brownian option to model trajectory uncertainty [14]. Based on the current velocity vector and the cross-track and along-track scale factor, an error ellipsoid is generated, as can be seen in figure A.23. This model functions on a short time scale and provides a quick, computationally inexpensive estimate based on relatively little information. This fits the real-time application of providing trajectory uncertainty estimations for controllers based on U-space data. Therefore, this model is selected to be implemented in this research.

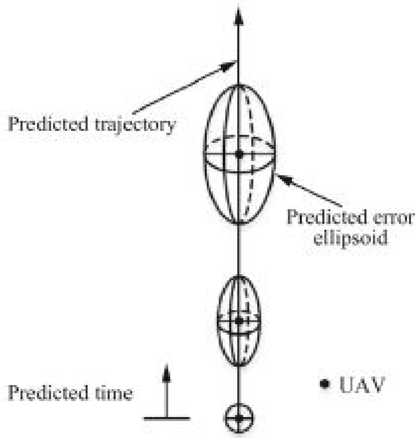


Figure A.23: Uncertainty ellipses based on short-term trajectory parametric prediction for UAVs [14]

A.4.4. Trajectory Uncertainty Model Implementation

The previous section described various trajectory uncertainty models and selected a parametric short-term model based on Brownian motion. In this model, the future position of the vehicle depends on the nominal trajectory and the position uncertainties. The governing equation can be seen equation A.1 [14].

$$X(t) = X_0 + \int_0^t v(s)\mathrm{d}s + Q(t)\Sigma B(t) \tag{A.1}$$

In this equation, X is the position of the vehicle, while v is its velocity trajectory. This can either be a planned path or, if no intent information is available, the current velocity vector. Next, Q is an orthogonal matrix containing the speed vector, Σ is a diagonal matrix containing the variance growth rates of the perturbation along the different axes. For the horizontal case, these are the in the along-track and cross-track directions. Finally, B is a standard two dimensional Brownian motion starting from the origin. Its variances are given by the matrix $Q(t)\Sigma$ and increase linearly with time. As this research considers the horizontal case, all the aforementioned matrices are two dimensional.

In this model, the variance growth rate in along-track and cross-track direction characterise the uncertainty in the UAVs future position. As mentioned in Section A.4.3, they have been empirically determined for manned aviation. As this field of research is focused towards manned aviation and relatively new to drones, estimates for the variance growth rate of drones are scarce. An estimation can be made based on manned aviation data, the drone-oriented research available and a breakdown of the component of variance growth rate [14, 61, 63]. Using this, the position and trajectory uncertainty of the drone can be modelled, after which the uncertainty ellipse can be used for further calculation or for visualisation, an example of which can be seen in Figure A.24.

A.4.5. Effect of Contingencies on Trajectory Uncertainty

As described in section A.3.2, contingency operations of drones will be considered next to nominal operation, as they bear relevance to the interaction between U-space and ATC. These are the situations where the position uncertainty of drones increases, making it more difficult to determine whether they are adhering to geofencing restrictions. Moreover, it could also lead to situations where drones (temporarily) might not be able to comply with geofencing restrictions at all. This is where trajectory uncertainty modelling can help in reducing this unpredictable factor in drone operations. Based on U-space documentation, four contingencies are identified as being most impactful, which are:

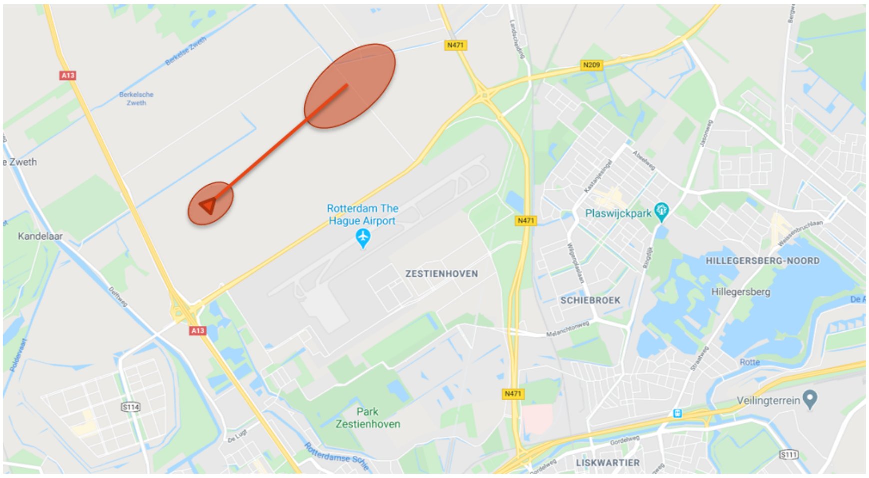


Figure A.24: Example of drone uncertainty ellipses in a nominal scenario

- Failure of a drone's emitter/receiver, leading U-space and ATC to rely on surveillance data;
- High wind speeds;
- Latency of data for a single drone or for multiple drones under the same U-space service provider, due to service failure.
- Reduced navigation performance in the form of failure of GPS, IMU and/or compass;

Below, each of these contingency operations will shortly be addressed in terms of its influence on the trajectory uncertainty prediction, including its effect on the visualisation of the uncertainty ellipses.

Emitter/Receiver Failure
As described in Section A.3.2, a emitter/receiver failure would lead to the loss of state updates and new intent information. This means state updates (e.g., position, velocity, heading), have to be obtained from surveillance data. As GPS data send by ADS-B, as envisioned by the U-space system, is more accurate than for example Radar data, both the current and future position uncertainty increase. The quantity of this increase depends on the systems used, but can be estimated to be at least double [67]. Apart from this increase in position uncertainty, intent information will also no longer be available. This means that trajectory predictions have to be made based on the last known intent information or simply by extrapolating the current velocity vector. This significantly decreases the quality of the prediction, making it worth considering if the trajectory uncertainty prediction is still valuable in this case. An example of the effect of transmitter failure can be seen in figure A.25 and should be compared to the nominal case displayed in figure A.25.

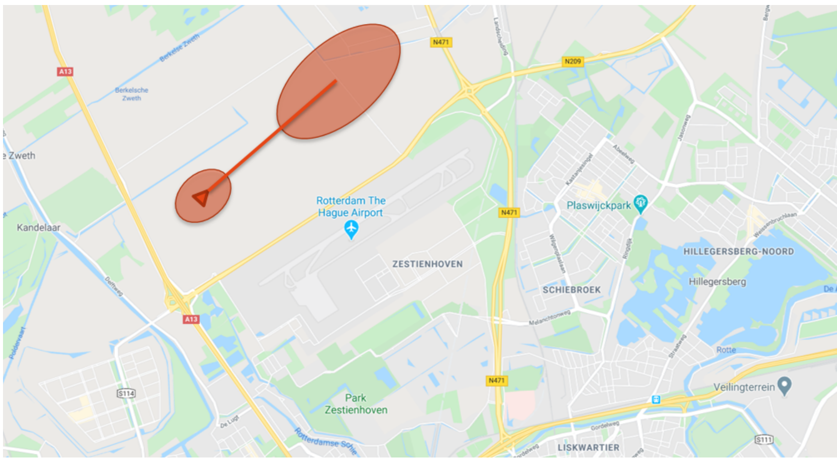


Figure A.25: Example of drone uncertainty ellipses in a scenario with transmitter failure

High Wind Speeds

High wind speeds affect the performance of the drone and can lead to higher achievable speeds in case of tail winds and lower achievable speeds in case of head-winds. Cross-winds can also cause a slower achievable speed, as they have to be corrected for by flying a longer path. Moreover, when cross-winds become high enough, they can no longer be corrected for, leading the drones to be blown off course. It should be noted that these effects are caught in the conversion between true airspeed and ground speed, not in increasing or decreasing standard deviation in position uncertainty. An especially relevant case when considering winds, is when combined with reduced navigation performance. In case of GPS failure, even a smaller cross-wind could cause the drone to drift from the desired track, as it no longer has an indication in difference between true airspeed and ground speed. An example of the uncertainty regions under high crosswind conditions can be seen in figure A.26.

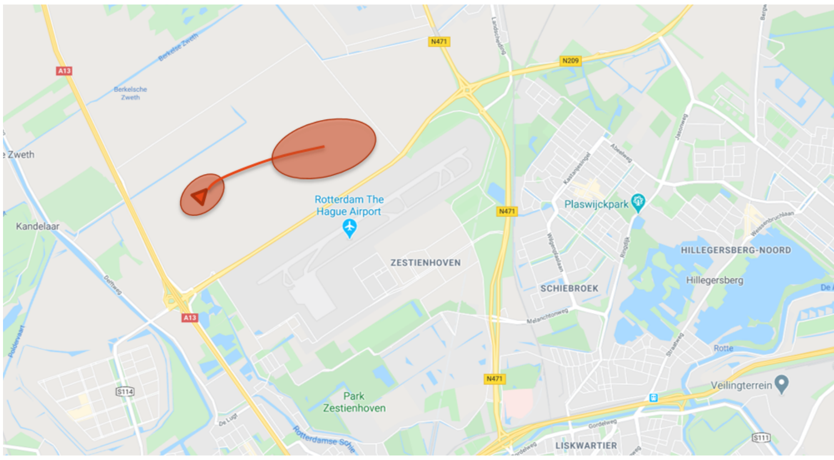


Figure A.26: Example of drone uncertainty ellipses in a scenario with high crosswinds

Latency

Latency in the provision of data regarding one or more drones does not directly influence to current or future position uncertainty, as all sensors work properly. It does, however, mean that the predicted trajectory uncertainty is based on older data. Although this does not change the prediction, users should be made aware of this lag in the system, such that they can account for it. This also means that the visualisation of the uncertainty regions does not change, other than being slightly delayed.

Reduced Navigational Performance

A reduced navigational performance will have a significant influence on the trajectory uncertainty prediction. The three navigational performance failures considered are: GPS failure, IMU failure and compass failure. Each of them will be shortly addressed below. First of all, a GPS failure would make the drone reliant on the compass and the IMU, significantly reducing navigational performance. The current position uncertainty increases to that of surveillance data, similar to the emitter/receiver failure case. However, the increase in position uncertainty over time significantly increases, especially in case of winds, as described above. Next, an IMU failure would slightly decrease navigation performance and increase current and future position uncertainty. Finally, compass failure would not alter the current position uncertainty, as the drone can still rely on GPS and IMU. However, the future position uncertainty along the cross-track is expected to increase, as heading determination is hindered. An example of the effect of this scenario can be seen in Figure A.27.

A.4.6. Trajectory Uncertainty Visualisation

To present the trajectory uncertainty predictions and the possible effect of the contingency operations to the user, it will have to be visualised. As mentioned before, the trajectory uncertainty prediction is commonly a means to determine conflict probability and is therefore not often visualised of itself. However, there have been some methods applied in the past. First of all, the calculated uncertainty ellipse, as shown in Figures A.22 and A.23 can be displayed for a given look-ahead time. Apart from serving as a visual tool in development, there has also been an effort to visualise this to users [68]. In this case the shape, size and location

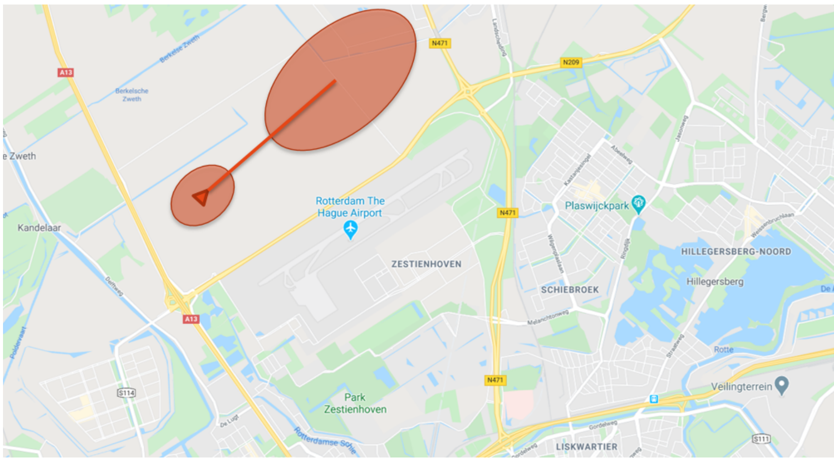


Figure A.27: Example of drone uncertainty ellipses in a scenario with reduced navigation performance

of the uncertainty region would be indicative of possible contingency operations. Alternatively, they could be shown around the complete future trajectory, growing in size. This has been applied for descend limits, as well as in a three-dimensional case, resulting in 'tunnel' around the future trajectory of the aircraft [15]. Examples of both of these methods can be seen in figure A.28. As the current research focuses on the two-dimensional (horizontal) case, this would be a diverging region around the future trajectory. The displayed future trajectory, as well as the rate of divergence of the 'uncertainty tube' would be indicative of possible contingency operations.

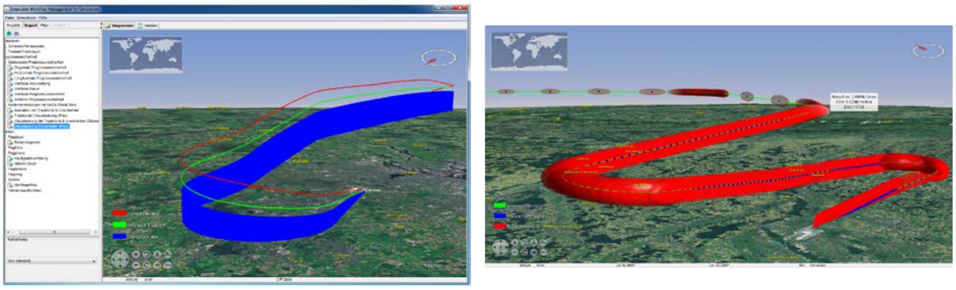


Figure A.28: Examples of visualisations of trajectory uncertainty predictions. Left showing upper and lower limit during an aircraft descend, right showing uncertainties around the complete trajectory [15]

A.5. Interface Design

To support tower controllers in their tasks when drones are introduced into the airspace, a decision support interface will be designed. An important aspect of designing an interface is knowing what information should be presented to the user and how it should be presented to them. A framework to aid this human machine interaction design is ecological interface design. This chapter aims to give an overview of human machine interaction in general and ecological interface design specifically. First, Section A.5.1 addresses the human behaviour involved when dealing with human machine interaction. Next, Section A.5.2 outlines the rationale of ecological interface design and the tools available within the framework. Finally, Section A.5.3 gives a preliminary view of the interface designed in this research and applies the knowledge from the previous sections to it.

A.5.1. Human Behaviour

In the context of human machine interaction, when automation is applied incorrectly it can negatively impact the human performance. It can reduce the understanding of the system or even cause over-reliance, boredom or complacency of the operator. This means automation should be applied with caution and understanding [69]. Therefore, a thorough understanding of human behaviour is essential when designing a human machine interface.

Humans cannot simply be regarded as deterministic input-output system. Rather, they are they are goal-oriented, actively selecting their goals and gather the required information to do so. This means that human behaviour changes during its course, based on (new) information concerning the goal. A framework used to quantify human behaviour is that of skill, rule and knowledge-based behaviour, in compliance with signals, signs and symbols, as are described in Section A.5.1.1 and Section A.5.1.2, respectively. This can be linked to the decision ladder, visualising the human decision making process, as addressed in Section A.5.1.3

A.5.1.1. Skill, Rule and Knowledge-based Behaviour

When looking at human behaviour in terms of performance, a distinction can be made between three different levels of cognitive work. These three levels are skill-based behaviour, rule-based behaviour and knowledge-based behaviour. The amount of cognitive work involved is lowest in the case of skill-based behaviour, increases for rule-based behaviour and is highest for knowledge-based behaviour [16]. It should be noted that the same task can be performed using different types of behaviour, depending on the level of training of the person performing it. The relation between the different types of behaviour, including the perception of information as described in Section A.5.1.2, can be seen in Figure A.29. Each of the three behavioural performance levels is shortly addressed below.

Skill-based Behaviour
Skill-based behaviour relies on sensor-motor performance, where the sensor input is directly transferred to the motor output. This results in a smooth, highly integrated pattern of behaviour, over which no conscious control is exerted once initiated. Examples of skill-based behaviour are lane-keeping in a car, riding a bike, or working with tools, given that the user is trained to do so.

Rule-based Behaviour
Rule-based behaviour relies on the execution of a recognised set of rules or procedures. These may have been communicated by others, self-developed or prepared for the occasion. Mapping the input to the output is slower than for skill-based behaviour, as some thought is required to selected the most appropriate rule on past experiences and to execute it. Examples of rule based behaviour are baking a cake according to a recipe or completing a checklist.

Knowledge-based Behaviour
Knowledge-based behaviour relies on significant cognitive processing and is therefore commonly applied in unfamiliar situations. It requires considering goals, selecting the best approach and developing a plan. Consequently, knowledge-based behaviour is slowest in mapping input to output and is the most prone to errors. Examples of knowledge-based behaviour are completing a puzzle or making a painting.

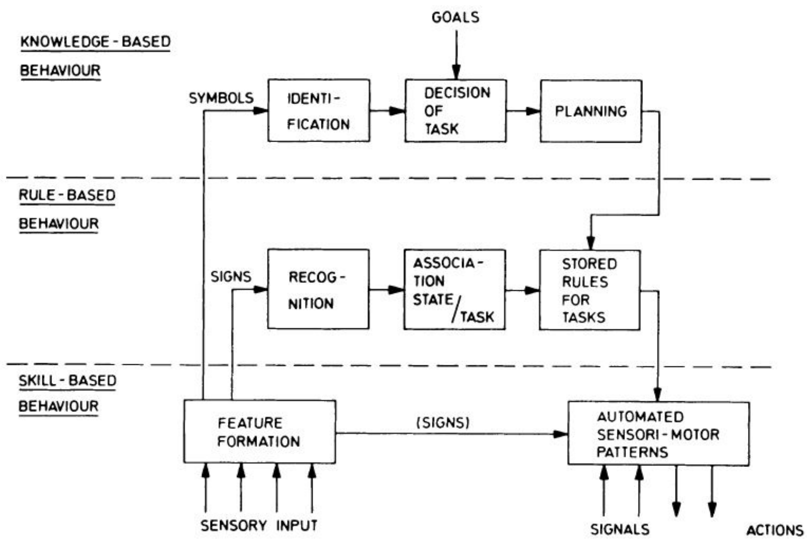


Figure A.29: Simplified illustration of three levels of performance of skilled human operators. Note that levels are not alternatives but interact in a way only rudimentarily represented in diagram. [16]

A.5.1.2. Signals, Signs and Symbols

Where human behaviour can be divided into skill, rule and knowledge-based, the corresponding information used can be segmented into signals, signs and symbols. For skill-based behaviour, information is perceived as a signal, to which the human responds immediately. For rule-based behaviour, information is perceived as a sign, which leads to the human to use a certain set of rules or procedures. For knowledge-based behaviour, information in perceived as a symbol, showing the functional properties of the system and sparking the reasoning of knowledge-based behaviour. Information can be perceived as either a signal, a sign or a symbol, depending on the human operator, as is illustrated by Figure A.30.

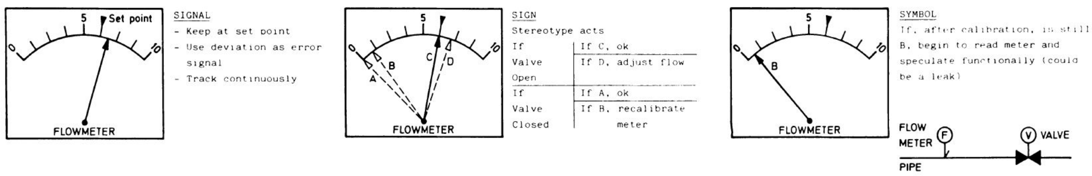


Figure A.30: Same physical indication on control panel can serve to communicate to operator in form of signal, sign, and symbol [16]

A.5.1.3. Decision Ladder

The information on human behaviour of the previous sections can be used to investigate the human decision-making process. A tool that aims to visualise the human decision-making process is the decision ladder, the concept of which can be seen in Figure A.31 [17].

The diagram starts at the lower left with the activation, in the form of the detection of the need for an action and ends in the lower right with the execution, where manipulations are coordinated. The left, upward leg of the ladder signifies analysis of the situation, whereas the right, downward leg signifies planning for the following actions.

The different cognitive levels of human behaviour can be identified in different parts of the diagram. The direct line between activation and execution, based on pre-set responses signifies the use of skill-based behaviour. When moving into rule-based behaviour, a set of observations is made, from which the state of the system is identified. On the planning side of the ladder, rule-based behaviour involves defining tasks based on the goal state and formulating a planned set of actions to achieve this. On the highest level is knowledge based behaviour, where the system state is interpreted and evaluated to formulate a new goal state.

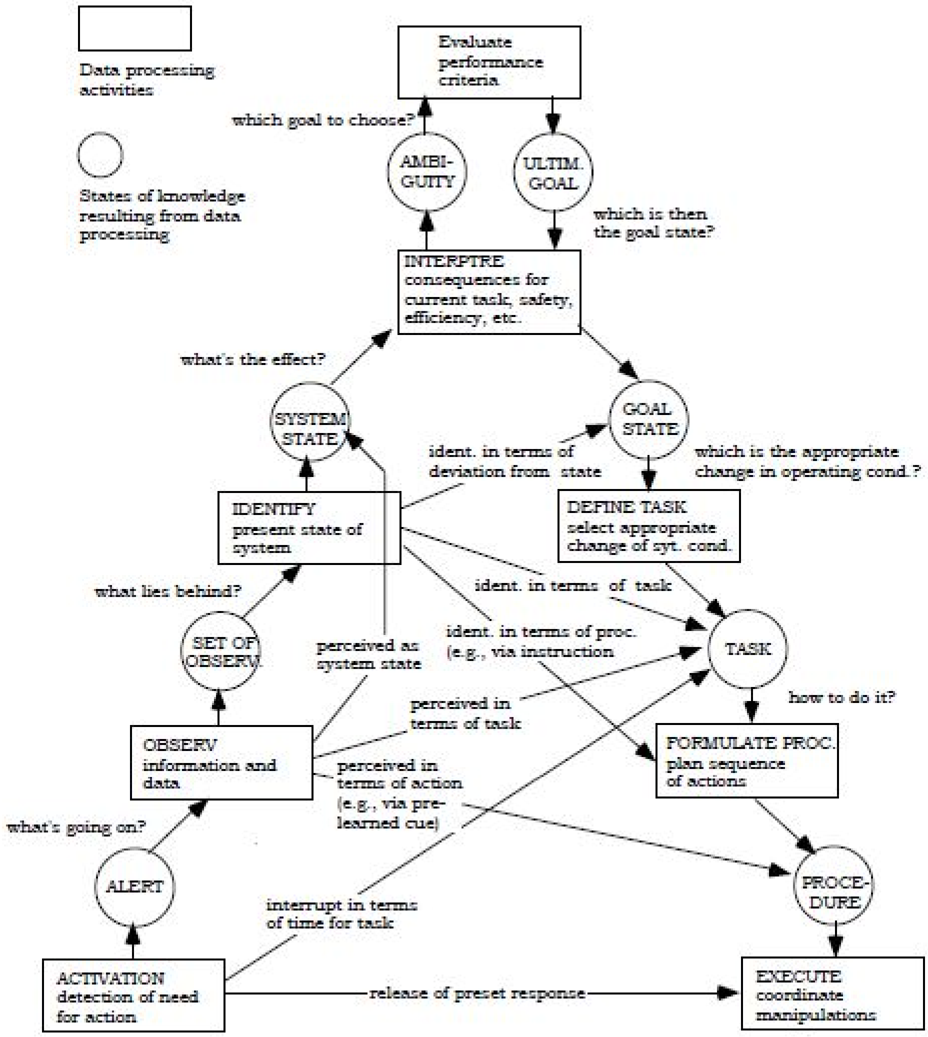


Figure A.31: Schematic map of the sequence of mental activities between initiation of the response and the manual actions. The diagram illustrates typical shunting routines in skilled performance. Associative leaps directly between states of knowledge are not shown [17]

Shortcuts can be made between various states of the decision ladder, based on skill and experience of the operator performing the task. The decision ladder can be used to identify currently existing shortcuts and to map shortcuts that can be achieved by means of interface design.

A.5.2. Ecological Interface Design

A framework for interface design that focuses on use rather than user or technology is ecological interface design. The benefit of this, is that it allows the operator to deal with system complexity and unanticipated events. Therefore, this framework will be elaborated upon in this section. First, Section A.5.2.1 describes the general design philosophy of ecological interface design. One of the most important tools in ecological interface design, the abstraction hierarchy, is addressed in Section A.5.2.2. Finally, section A.5.2.3 outlines the design step involved in ecological interface design.

A.5.2.1. Design Philosophy

The ecological interface design framework aims to allow for effective cooperation between human and machine. Other interface design approaches are user-centred, technology-centred or control-centred, whereas the ecological approach is described as use-centred. Its main focus is the work domain, where the tasks are analysed without taking into account whether they will be performed by a human or a machine. In a later stage, task can be allocated to either one, depending on their qualities [70]. The schematic of this framework can be seen in figure A.32.

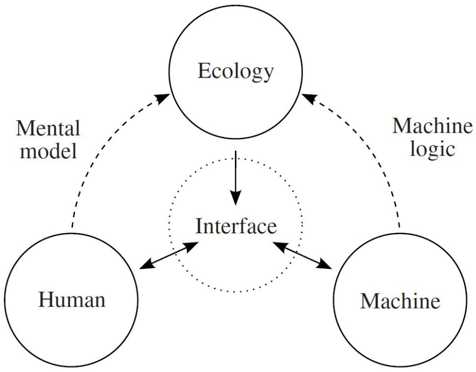


Figure A.32: Schematic of ecological interface design [18]

The focus of ecological interface design on the work domain is reflected in the two main questions of the framework. The first question is: "How to describe the domain complexity?" As discussed above, an understanding of the work domain is seen as vital for good interface design. A key tool in answering this question is the abstraction hierarchy, as described in section A.5.2.2. The second question is: "How to communicate the information?" This question regards what information should be presented to the user, when it should it presented and how it should be presented. This depends on the cognitive capabilities of the human operator. An important tool in answering this question is the taxonomy of skill, rule and knowledge-based behaviour and the corresponding decision, as described in Section A.5.1.1 and Section A.5.1.3, respectively. As the interface design should allow the human operator to rely the lowest level of cognitive processing [71].

A.5.2.2. Abstraction Hierarchy

An important tool within ecological interface design is the abstraction hierarchy. The abstraction hierarchy is used to map the work domain using different levels of abstraction. The higher levels described the top-level purpose basis of the system, while the bottom levels represent its low-level physical basis [16].

The abstraction hierarchy consists of a total of five different levels. The functional purpose describes the overarching purpose of the system as a whole. The abstract function describes the underlying (physical) governing principles of the system. The generalised function describes the involved processes and system choices. The physical function describes the main function bearing components. The physical form describes the states of the system's components. It should be noted, however, that each level in the abstraction hierarchy represents the complete system [19].

The abstraction hierarchy can be extended by adding means-end links between elements in different layers. These signify the coupling of these elements [72]. Elements in the layer above a certain element can be seen to answer the question *why*? Whereas, elements in the layer below a certain element can be seen to answer the question *how*? An illustration of the why-what-how structure can be seen in Figure A.33. The abstraction hierarchy can be further extended by adding a second axis, decomposing from the whole system to individual parts. It should be noted that this is an aggregation decomposition, rather than an abstraction [72].

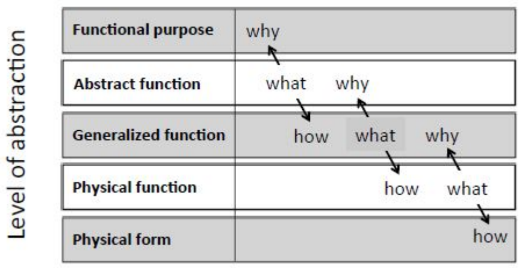


Figure A.33: An abstraction hierarchy containing the why-what-how coupling [19]

To aid in the design of the display for tower controllers proposed in this research, the abstraction hierarchy can be applied to the role of a tower controller. As a baseline, an existing abstraction hierarchy for upper area control is used [19]. Furthermore, the abstraction hierarchy is based on the description of the tasks of tower controllers given in section A.2.2, based on ICAO regulations. This stipulates that tower controllers *"shall 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 pre-venting collision(s) between aircraft flying within the designated area of responsibility"* [31, page 7-1], while also maintain a continuous watch of all flight operation in this region. This gives the three main functional purposes of expeditiousness, orderliness and safety. These main responsibilities are further unfolded in ICAO documentation, which forms the basis for the tasks in the abstraction hierarchy. The resulting abstraction hierarchy can be seen in Figure A.34.

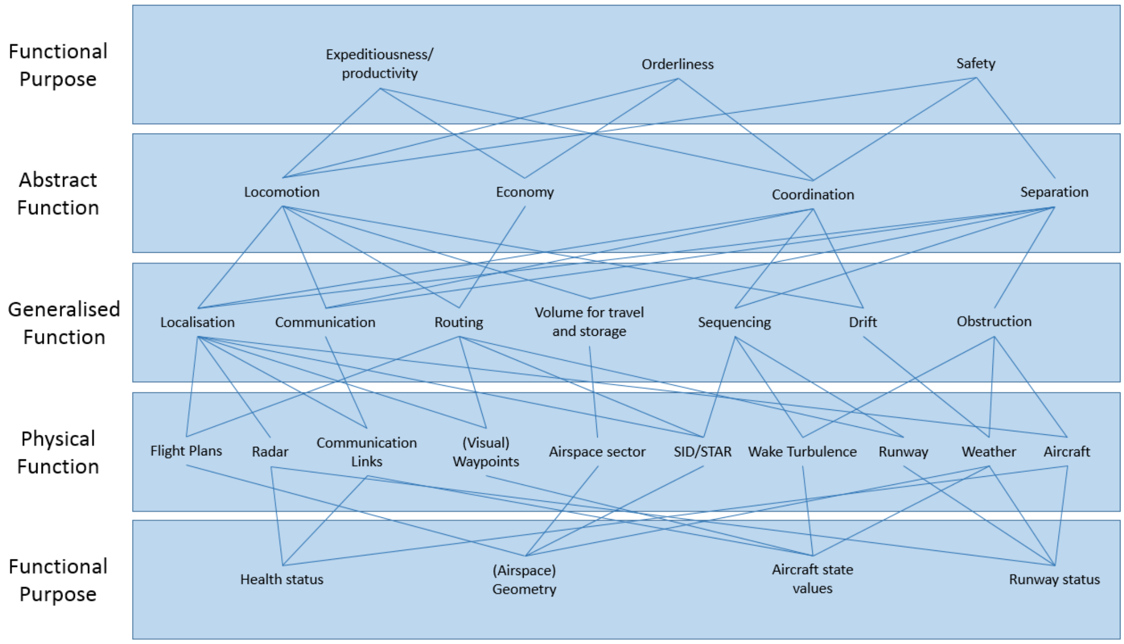


Figure A.34: An abstraction hierarchy of the work domain of a tower controller

With the abstraction hierarchy of the tower controller in place, geofencing capabilities can be added to the tasks set. First of all, it should be noted that the functional purpose and abstract function do not change, as the overarching goals and underlying principles of tower control do not change. The ability to use geofences (named geofencing) is considered a new generalised function available to a tower controller, linked to vehicle locomotion and separation. On the level of the physical function, two new elements appear, namely the UAVs and the geofences themselves. On the level of the functional purpose, this gives rise to the geofence status (on/off/pending) and the UAV state values. The resulting abstraction hierarchy can be seen in Figure A.35.
In the abstraction hierarchy for a tower controller including geofencing tasks above, the elements and links related to geofencing are highlighted. While also indicating clearly what has been added, it also bears relevance for further work. As this research focuses on the new possible geofencing tasks of the tower controller, these elements will form the focus of the rest of this research.

A.5.2.3. Design Steps

In ecological interface design, the cognitive work analysis (CWA) is used as an analysis tool. It consists of five main steps and forms the basis for the design of an interface [19, 73]. Each of the five steps is addressed below.

Work Domain Analysis

The work domain analysis aims to find information regarding the system is and its purpose. It analyses the work domain, its constraints and its relations, irrespective of the tasks involved or who is performing them. The main tool for this is the abstraction hierarchy, as described in Section A.5.2.2.

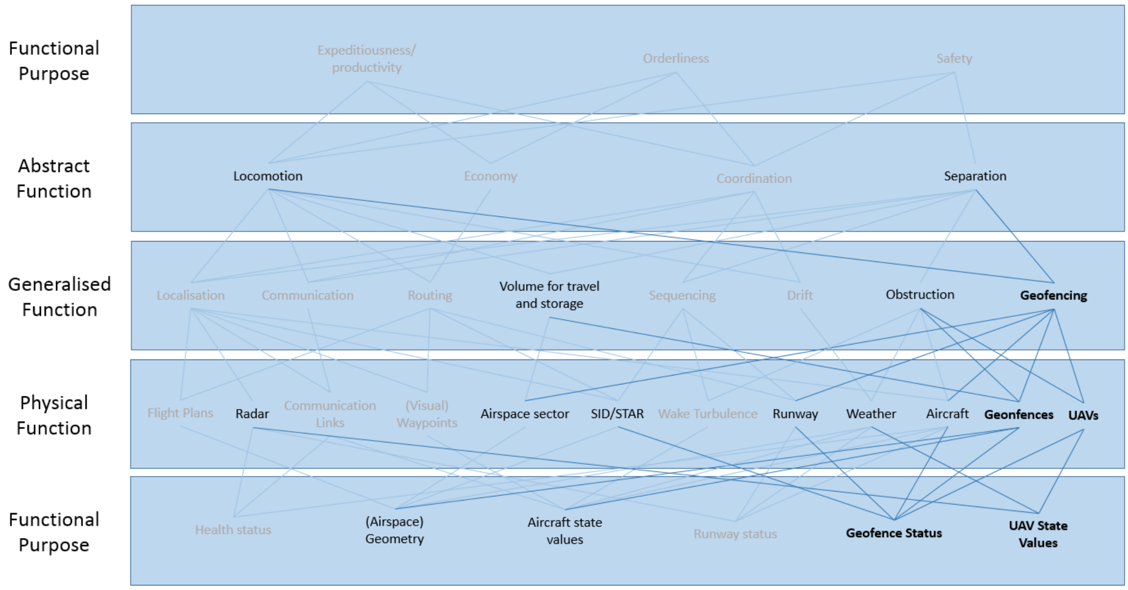


Figure A.35: An abstraction hierarchy of the work domain of a tower controller including geofencing tasks

Control Task Analysis
The control task analysis aims to find what it is that needs to be done. It identifies the goals and states of the system that can or should be achieved. It is important to note that the control task analysis does not regard how and by whom the tasks are performed. The main tool for this step is the decision ladder, as described in Section A.5.1.3. This also allows shortcuts to be identified, substituting knowledge-based behaviour with rule-based behaviour.

Strategies Analysis
The strategies analysis aims to find how the identified tasks can be performed. It identifies how to achieve the set task goals, still irrespective of the actor. The main tool for this is the generation of information flow maps for the tasks that have to be performed.

Social Organisation Analysis
The social organisation analysis aims to find who should perform which task. It identifies which actors should be allocated to which part of the work domain, which tasks and which strategies. This implies that this is where the control tasks are divided between human and automation. Here, the level of automation should be taken into account, considering the strengths and weaknesses of both. There is no specific tool for this step, it rather uses the tools of the first three steps combined.

Worker Competencies Analysis
The worker competencies analysis aims to find what skill, rule and knowledge-based behaviour the human requires the perform their tasks. This step again uses the decision ladder described in Section A.5.1.3, paying specific attention to the taxonomy of the different levels of behaviour.

A.5.3. Tower Control Interface with Geofencing

To develop an interface for tower controllers with geofencing tasks, first, a functional simulation of the work domain is required. Within this simulation the interfacing elements can be added and developed to support the controller in the decision making process. A working example of the such a simulation including some interfacing elements can be seen in Figure A.36. In this interface, geofences are applied in a grid form, as proposed in Chapter A.2. They can be switched on and off to keep drone traffic clear from aircraft in final approach and from helicopter emergency flights by clicking on them. Green geofences are non-active and red geofences are active. Active geofences that still contain drone traffic are labelled as pending and are amber. Within this work domain, various sets of skill- rule- and knowledge based behaviour can be identified, as will be done below. It should be noted that these might differ if the configuration of the geofences is altered.

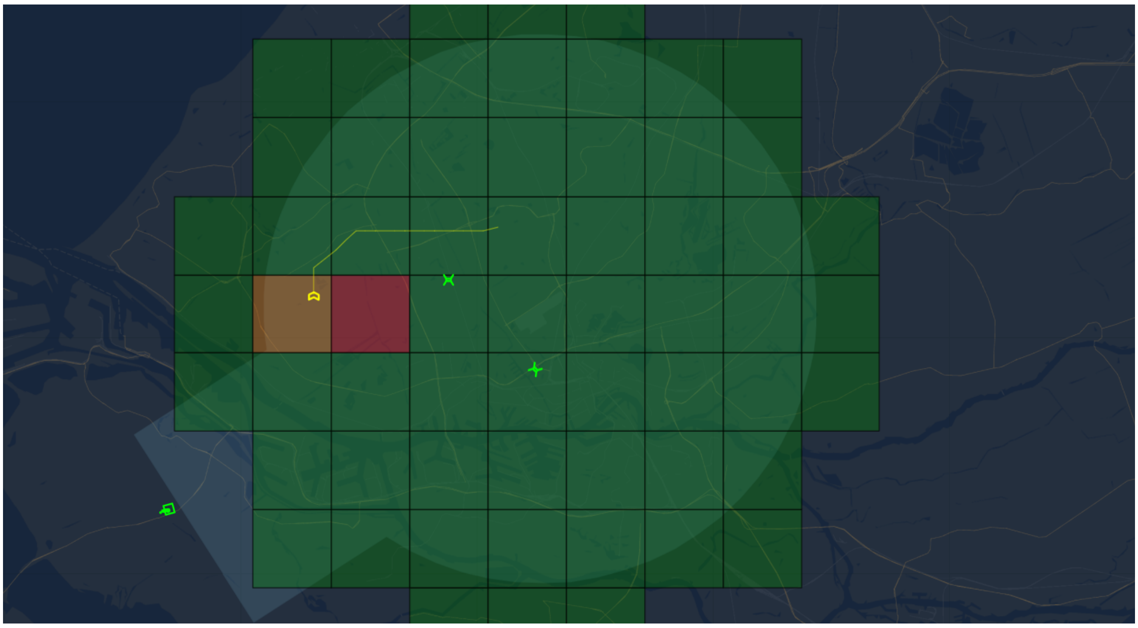


Figure A.36: Example of the Rotterdam airport area with geofences and drone traffic. Green indicating non-active geofences, red indicating active geofences and amber indicating pending geofences

Skill-based Behaviour

The first type of skill-based behaviour is monitoring the signals indicating which geofences are active, non-active and pending. An example of this, as seen in Figure A.36 is a colour indication for all the geofences. A second type of skill-based behaviour is monitoring the state of the current arriving and departing flights, as well as monitoring those of helicopter emergency flights. An example of how this can be done is by means of marker tags and flight strips, as explained in Section A.2.2. A third type of skill-based behaviour is monitoring states and routes of drone in (proximity to) active geofences. This can for example be dones by means of marker tags and indications of future routes, as can be seen in Figure A.36.

Rule-based Behaviour

The first type of rule-based behaviour is identifying which geofences are to be switched on and off for clearing scheduled flights. Based on the route of the aircraft, the required geofences can be switched on before passing and off afterwards. Linked to this is the rule-based behaviour of using rules of thumb and common sense to identify which geofences will be crossed by an aircraft (either a drone or a manned aircraft). For drones, this can be achieved by visualising their route, if this information is reliably available. For manned aircraft, this could for example be achieved by visualising the ILS approach. This process could be further accommodated in the shape and size of the geofences in question in further iterations. A second type of rule-based behaviour is applying rules of thumb to know how long it will take a drone to clear a activated geofence. A possible way to accommodate for this would be to add a time estimation to pending geofence, provided that the estimation is reasonably accurate. A third type of rule-based behaviour is using rules of thumb to estimate how long it will take a manned aircraft to reach a certain geofence. Displaying aircraft state information is an example of the most rudimentary form of supporting this behaviour.

Knowledge-based Behaviour

The first type of knowledge based behaviour is reasoning at what point in time which geofences need to be (de-)activated. This behaviour is a combination of the three aforementioned types of rule-based behaviour of identifying geofences on a manned aircraft's route, identifying how long it takes for a drone to clear a geofence and how long it takes for a manned aircraft to reach a certain geofence. It should be noted, however, that this is only the case when the task is performed while trying to minimise the time geofences are active. When focusing on activating the required geofences for a manned flight to pass safely, this behaviour is more likely to be rule-based. A second type of knowledge based behaviour is reasoning which geofences need to be activated to safely accommodate an emergency helicopter flight. These flights are very unpredictable in route and departure time but have the highest priority and are therefore most difficult to clear from drone flights. A possible way to support the user in this is to visualise the (estimated) destination of the flight. A third type of knowledge based behaviour is reasoning when to activate which geofences in case an approaching aircraft makes a turnaround or unexpectedly has to loiter. A possible way to support the user in this is to show the location of holding patterns. Alternatively, these locations could be accounted for in the design of the shape and size of the geofences, as described in the previous section for the ILS approach.

The most rudimentary tools to support the above-described types of behaviour can already be seen in the prototype shown in Figure A.36. Some of the more advanced supports can be seen in the concept sketch in Figure A.37. This concept sketch of the display should be further refined based on the analyses described in Section A.5.2.3 and based on frequent prototype testing.

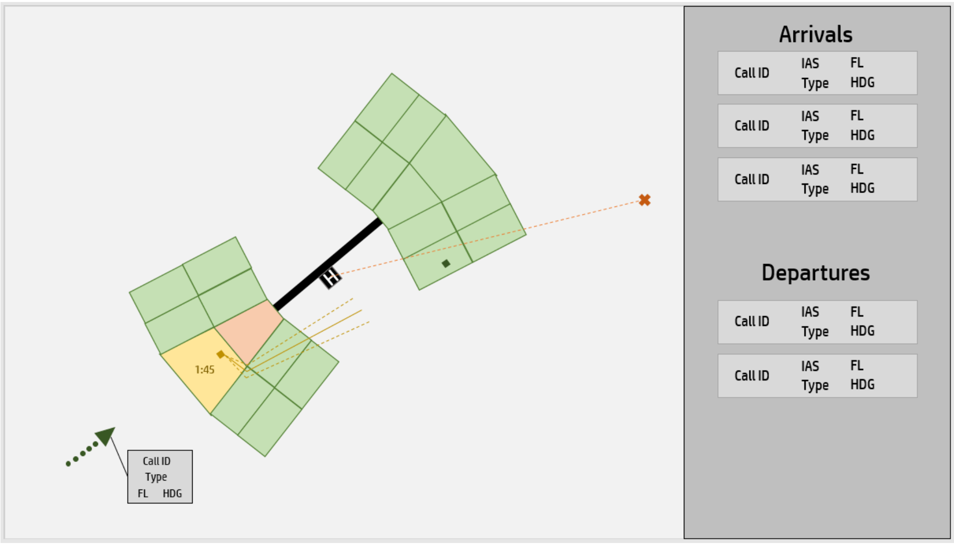


Figure A.37: Concept sketch of a display involving various support tools, such as geofences shapes after ILS, geofence timers, flight strips, marker tags, uncertainty regions and helicopter flight indications. Note that only geofences near the ILS are drawn to highlight this new feature. In a final version, more geofences should be present

A.6. Further Work

This chapter aims to describe the further work in this research past the current literature study. Based on this review, a decision support interface to support tower controllers keeping manned traffic safe from drone operations will be developed and tested. The steps that need to be taken to achieve this are outlined here. First, Section A.6.1 describes the research scope of the further work based on literature. Next, Section A.6.2 addresses the most important aspects of the simulation environment in which the interface will be developed and tested. The most important steps in configuring this interface are outlined in Section A.6.3. Finally, the foreseen conditions of the experiment will be presented in Section A.6.4.

A.6.1. Scope

Chapter 1 described the lack of research in the field of human factors of tower controllers dealing with drone operations. This literature study further underlines this statement, by identifying various worthy research topics within this field. However, it is essential to further scope the current research to make a valuable contribution. To support this, an overview if possible research topics can be seen in Figure A.38.

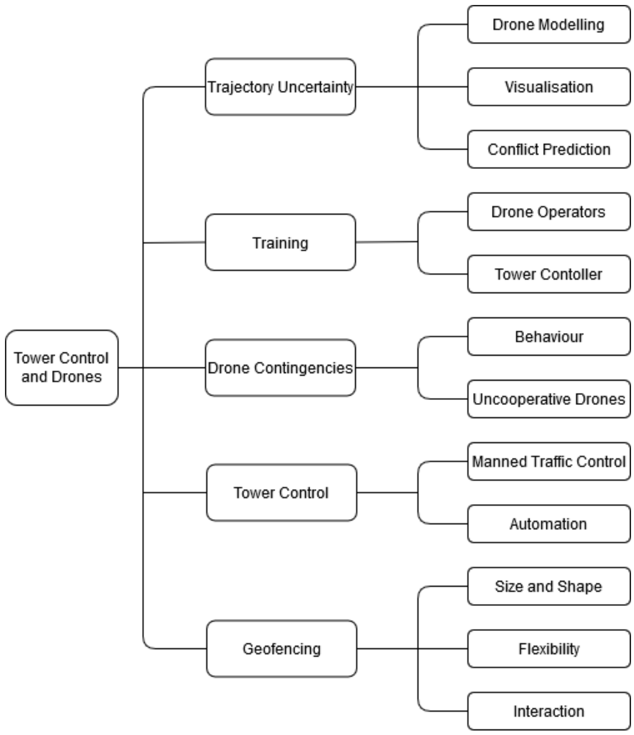


Figure A.38: Overview of important topics within the field human factors of drone operations on tower control

Regarding the trajectory uncertainty modelling of drones, first, it should be considered that this has mostly been applied to manned traffic in past past. Consequently, there is little data available on the trajectory uncertainty of drones. Obtaining and validating this data and these model would be a valuable contribution. Moreover, the possible visualisation of this information to the tower controller poses an interesting interface design problem. Finally, position uncertainty is often utilised in conflict prediction. Extending this to drone operations, geofence breaching prediction could be explored.

As mentioned in Chapter 1, one of the major causes of current drone related incidents are a lack of training. First, drone operators are often unaware of aviation rules and practices. On the other hand, tower control is often unaware of performance characteristics of drones and are not equipped and informed to deal with them. Both sides of this problem are relatively unresearched.

Chapter A.3 describes the contingency operations of drones as an important factor for tower control, identifying various of these operational cases. It remains uninvestigated how exactly these contingency operations influence the behaviour of drones. Moreover, these contingency operations assume all drones cooperate with

U-space, whereas the Gatwick incident was caused by uncooperative drones. How to counter uncooperative drones in the airspace poses a research topic of its own.

In the current stage of research, the first form of a decision support tool of tower control is considered. It is assumed that tower control will always re-route drone traffic to maintain safety of manned traffic, as the former has priority over the latter. Therefore, the current simulation will allow tower controllers only to interact with geofences (as outlined in Section A.6.2). However, in further work the full task set of tower of the tower controller can be considered, also enabling them re-route manned traffic in wanted/required. Moreover, it could be investigated whether the geofencing tasks of a tower control can be automated and how this can best be done.

The final main research topic identified are the geofence themselves. These form the basis of the human machine interaction between the tower controllers and the drone operations. Due to the little research available in this field, this research focuses on this fundamental aspect of the problem. Within this topic, there various sub-topics to consider. First of all, what should be the shape and the size of the geofence offered to the operator. Second, flexible geofences can be considered, where the operator can manipulate the shape and size of a geofence. Finally, the interaction of an operator with geofences can be investigated. This considers how geofences are activated and to what extent this process can be automated. Again, aiming to start with the fundamentals of the problem, this research aims to investigate the influence of the shape and size of the geofences.

A.6.2. Simulation

As described in the introduction, the effect of shape and size of geofence on supporting tower control with keeping manned traffic safe from drone operations will be investigated by means of a decision support interface. In order to design and test this interface, it is first required to set up a function simulation of the airspace surrounding Rotterdam Airport. The most important elements of this simulation are shortly addressed below.

Manned Traffic

Within the simulation, the operator will not be able to interact with manned traffic. The simulation aims to investigate how to make use of geofences to keep manned traffic safe from drone traffic. Therefore, there is no focus on standard interaction with manned traffic. This allows historical flight data to be used to form a playback of representative manned traffic operations in the Rotterdam Airport area. For this traffic, basic information can be displayed, such as position, heading, velocity and flight track. In addition to the playback of flight data, elements can be added to generate relevant scenarios for testing the interface. For example, emergency helicopter flights can be added to create conflict with drone flights for the operator to resolve.

Drone Traffic

Within the simulation, the interaction with drone traffic will through the use of geofences. As described in Section A.2.3, tower control will have limited interaction with drones and will mainly interface with them by means of geofences. Drone traffic will be divided into a fixed-wing UAV and a multi-copter UAV, both which will be modelled using a simple drone flight model. This allows the drone traffic to respond to input from the operator, in the form of activating and deactivating geofences. The drone traffic patterns can be based on the operations described in Section A.3.1. Similar to the manned traffic operations, these can be implemented to create possible conflict with manned traffic for the operator resolve.

Geofences

The main form of interaction between the operator and the simulation are geofences. These allow the operator to shield certain regions of the airspace from drone operations. In terms of simulation, the most important aspect is the interaction between drones and geofences. When a drone is in a geofence that gets activated, it will have to clear it as quickly as possible. An example of this first form of interaction can be seen in Figure A.39. In the first panel the drone can be seen the follow the given route. In the second panel, the geofence is activated, causing the drone to exit it via the shortest route possible. In the third panel the drone continues its route. Additionally, a drone should be able to re-route if it encounters an activated geofences on its future path. Moreover, the case should be considered where a drone cannot leave a geofence in time or has no benefit in re-routing. This should cause the drone to make an emergency landing or to enter a loiter or hover phase, depending on the situation.

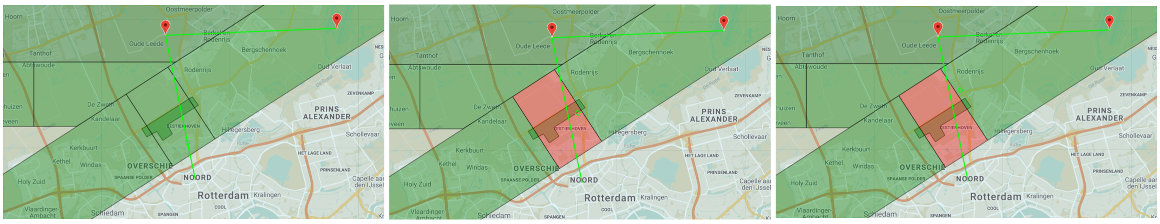


Figure A.39: Example of the interaction between a geofence and a drone

As described in the previous section, the shape and size of the geofences is seen as the starting point in this field of research. Therefore, the geofence configuration can should be alternated within the experiment. As described in section A.2.3, geofences can, among other things, be based on ground elements, airspace structure, drone capabilities and their controllability from the perspective of the operator. It should be noted that from a simulation perspective, the interaction between drones and geofences remain largely the same for all above-mentioned configuration of geofences.

A.6.3. Interface Design

The simulation described in the previous section gives a more complete view of the work domain of a tower controller using geofences to protect manned traffic from drone operations. This is essential in order to perform a cognitive work analysis, as described in Section A.5.2.3. The cognitive work analysis can be used as an input for the design of a display that allows tower controller to interact with geofences within the simulation. This forms the basis for the development of the decision support interface. It should be noted that ecological interface design in an iterative process of analysis design and testing. Prototyping is considered the most efficient method for designing an ecological interface [74].

A.6.4. Experiment

Following the development of the simulation of the Rotterdam Airport area and the design of a decision support interface, the interface can be tested and evaluated. This can be in the form of an experiment where participants are asked to steer drone traffic clear of manned traffic using the geofences available to them. In order to keep the interface close to a real world application, tower controllers (especially from Rotterdam Airport) can be asked to participate. Less experienced participants can also be recruited to obtain a larger dataset. During this experiment, the control strategy of the participants can be observed and analysed. Moreover, the task performance should be quantified, such that it can be measures and compared. An important aspect of any experiment are the independent variables, those that are controlled by the experimenter. These will likely be the shape and size of geofences available to the operator and the density of drone traffic, both are addressed below.

Geofence Shape and Size

Geofences are the first form of human machine interaction between tower control and drone flights. As described in Section A.6.1, there is little known about what shape and size of geofence best support tower control. Therefore, this lies in the heart this research's main research question. Consequently, the shape and size of geofences is an important independent variable for experimentation. Section A.2.3 explains that geofence shape and size can be based on various aspects. The aim of the experiment is to select the most relevant configurations of geofences and test their influence on the performance of the operator.

Drone Traffic Density

There is large uncertainty in the expected amount of drones to be operational in Dutch airspace by 2035. As described in Section A.1.5, the amount for an average European city of one million inhabitants, the number may vary between one thousand and one million. Moreover, the amount of drones operational in the airspace will significantly impact the ability of the operator to keep them clear from manned traffic. Therefore, the drone traffic density is selected as an independent variable. Apart from the density of drone traffic, this also incorporates the different traffic scenarios the operator will encounter. For example, emergency helicopter flight can be scheduled to occur during the experiment, creating a conflict with drone operations. The design of these traffic scenarios enables the experimenter to stimulate the operator to actively utilise geofences.

B

Interface Design

This chapter provides additional information on the designed interface. Section B.1 shortly explains all the interface elements presented to the controller, as seen in Figure B.1. Section B.2 pays special attention to the endurance regions and their theoretical background, as they are considered to be the most significant extension beyond the realm of regular radar screen elements.

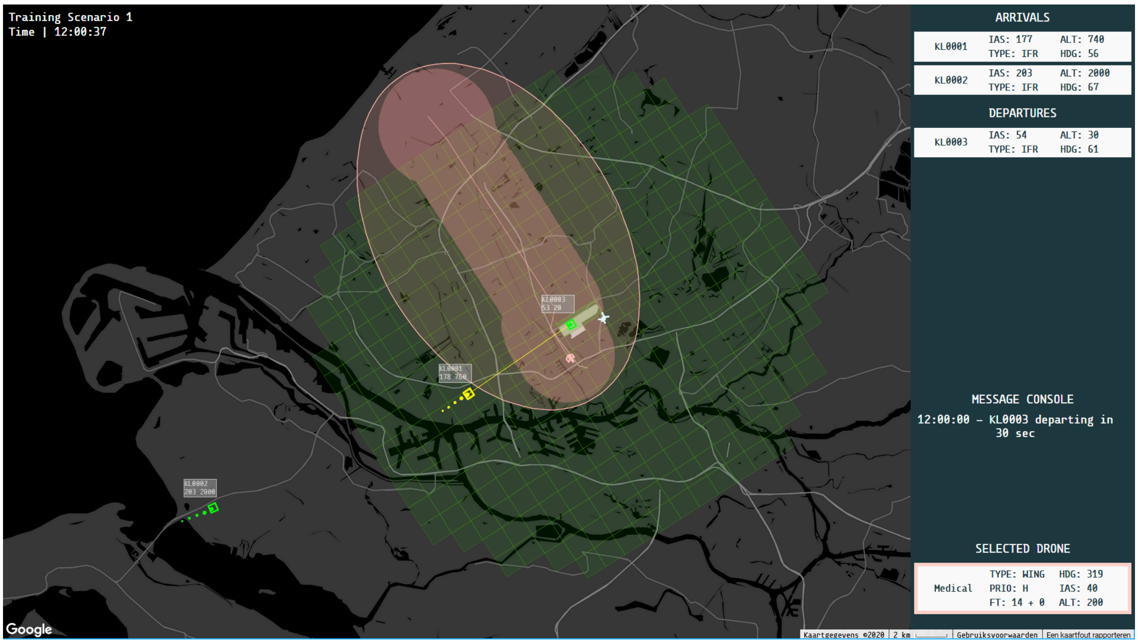


Figure B.1: Screenshot of the Interface presented to the controller

B.1. Interface Elements

Each of the interface elements seen in Figure B.1 is shortly explained below.

Background Map

The background map provides a low-detail overview of the area surrounding the airport. It should be noted, however, that is this map has a larger amount of detail than those commonly used in air traffic control. This background map displays locations of airports, major (rail)roads and bodies of water. These elements are important for various UAV missions (e.g., railroad inspections, highway surveillance) and therefore contain information that could be relevant for the controller. Especially when a larger variety of missions is implemented in the simulation, the map view could tell the controller something about a UAV's behaviour.

Manned Vehicle Icons
Manned vehicle icons are modelled after those currently common in air traffic control, being a square with trailing dots for the most recent location updates. Hovering the mouse over a manned vehicle icon will highlight the corresponding flight strip, providing a means-ends link.

Manned Vehicle Route
Clicking a manned vehicle icon will select it, displaying the intended route to the runway or the border of the CTR for an arriving or departing flight, respectively. This information is commonly not provided to the tower controller, but was deemed important in the current iteration of the interface, as not all experiment participants had knowledge on traffic procedures at Rotterdam - The Hague airport. Clicking on the manned vehicle icons again, on another manned vehicle icon or on the map will deselect the manned traffic icon.

Flight Labels
Each manned vehicle icon is accompanied by a flight label that moves along with the icon. These flight labels are commonly used in air traffic control and display the aircraft's ID, altitude and indicated airspeed. The flight labels can be dragged around the icon to prevent them from obscuring other information.

Flight Strips
The right part of the screen contains a digitised version of the flight strips commonly used by tower control. The digital flight strips contain the aircraft's ID, altitude, heading, indicated airspeed and type (IFR/VRF). Hovering over a flight strip will highlight the corresponding manned vehicle icon. In real-life, the flight strips often contains information regarding wake turbulence category, expected arrival times at navigational waypoints, last given instruction, etc. However, this information exceeds the fidelity of the current simulation environment and is therefore not included.

Text Console
The text console serves as a substitute for incoming communication from aircraft to tower control. It gives prompts regarding new departures, new arrivals, and helicopters initiating landing. All messages are given a time stamp, which can be compared with the timer in the top left of the screen for reference.

Geofences
The grid of geofences is drawn over the background map of the CTR in a light shade of green. The shape and size of the each geofence is indicated by the bright green borders, which are highlighted if the mouse cursor hovers over the geofence in question. Each geofence can be activated using the right mouse button, causing the geofence to be displayed in a bright shade of green. If an activated geofence still contains UAVs, they will leave by the closest point of exit. In the meantime, the geofence will be marked amber, indicating its pending state. Once all UAVs have left the geofence, it is no longer considered pending and is displayed as active (bright green). Geofences can be deactivated by clicking them again with the right mouse button.

UAV Icons
Similar to the manned vehicle icons, the UAV icons indicate the positions the UAV, including trailing dots indicating its five last known position updates. Two different UAV icons are used, indicating the vehicle type as being either quad-copter or a fixed-wing UAV. This information aids the controller in anticipating the UAV's behaviour and capabilities (e.g., rotation and hovering or turns and loitering). Additionally, each UAV icon has a colour indicating regular UAV operations (blue) and high-priority UAV operations (red). This aids the controller in prioritising which UAVs to tend to first when considering UAV efficiency.

UAV Route
Clicking a UAV icon will select it, displaying the intended route and the endurance regions, as will be described in Section B.2. The route is based on the most efficient route around the geofence restrictions, as found by an A* path-planning algorithm. The UAV route changes with display updates (every five seconds), according to emerging geofence restrictions.

UAV Information Strip
Clicking a UAV icon will also display the UAV's information strip in the bottom right of the screen. This contains numerical information on the UAV's heading, indicated airspeed and altitude. Additionally, it displays

the UAV's mission type and vehicle type, while indicating its priority by a coloured border. Finally, the UAV information strip displays the current estimated flight time, including the delay caused by geofence restrictions. The aids the controller in minimising the impact of geofence restrictions on UAV efficiency.

B.2. Endurance Regions

As seen from Figure B.1, selecting a UAV displays two endurance regions, an outer ellipse and an inner tube around the route. The meaning and theoretical background of both regions is discussed below and has been previously applied in ecological interface design [75].

Outer Endurance Region

The outer endurance region visualises the flight time constraint, being the maximum distance the UAV can divert from a direct route between its current position and its destination. This considers the total endurance the UAV has available for the remainder of the flight, as signified by Equation B.1.

$$t_{available} = t_{total} - t_{used}(t) \tag{B.1}$$

Under zero wind conditions, the available endurance can be directly used to form the outer endurance ellipse. The ellipse is defined as having the current position and the destination as focal points, while having the semi-major axis a, semi-minor axis b and linear eccentricity c. The resulting ellipse, including its parameters, can be seen in Figure B.2.

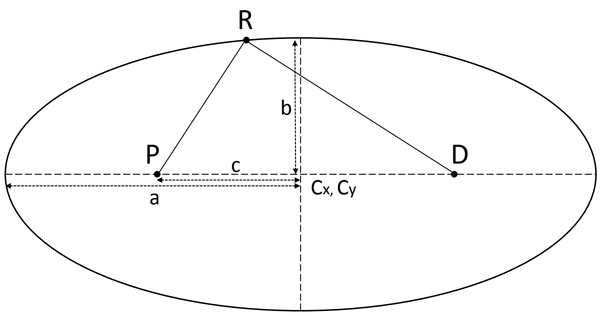


Figure B.2: Definition of the outer endurance ellipse

The total distance from the current position (P) to the destination (D), via the outer-most re-route point (R), is equal to the available endurance multiplied by the expected average speed. This distance is equal to twice the semi-major axis, as this axis signifies the distance the UAV can fly in a straight line with the available endurance and the expected average speed. The linear eccentricity is found to be half the direct distance between the current position and the destination. From this, the semi-minor axis can be computed using Equation B.2, after which the coordinates of the ellipse can be determined using Equation B.3. Finally, the ellipse can be adjusted to the UAV's heading (θ), by means of Equation B.4.

$$c^2 = a^2 - b^2 \tag{B.2}$$

$$x, y = (c_x + a \cdot \cos(\alpha), c_y + b \cdot \sin(\alpha)), \quad 0 \leq \alpha < 2\pi \tag{B.3}$$

$$\begin{aligned} x' &= x \cdot \cos(\theta) - y \cdot \sin(\theta) \\ y' &= x \cdot \sin(\theta) + y \cdot \cos(\theta) \end{aligned} \tag{B.4}$$

Inner Endurance Region

The inner endurance region visualises the flight time constraint with respect to the current route, being the maximum distance the UAV can divert from current route. Its calculation is similar to that of the outer endurance region. The main difference is that it considers the remaining available flight time excluding the current route, as described in Equation B.5.

$$t_{remaining} = t_{total} - t_{used}(t) - t_{flight}(t) \tag{B.5}$$

Consequently, the ellipse is now drawn up with two consecutive waypoints as focal points and the uses the remaining endurance calculated above as semi-major axis. Using Equations B.2 through B.4 yields an endurance ellipse for each route segment. Combining all these ellipses gives the inner endurance region around the UAV route.

Endurance Regions and Geofences

When a geofence on to the current route is fully within the inner endurance region, the UAV has sufficient endurance to re-route around it when activated. The updated route also contains an updated inner endurance ellipse, as there is now less endurance available to re-route. If a geofence adjacent to the one previously activated is within the new inner endurance region, the UAV can also fly around this geofence. However, this re-route might not go the same way around the the geofences as the previous re-route, since the shortest route could be the other way around the geofence. This could make the re-route behaviour of UAVs unpredictable to the operator. Therefore, the outer endurance region visualises the locomotion constraint of the UAV. This information will help the operator to see that the UAV can also choose to go the other way around the geofences. This makes it visually clear that the 'unexpected' re-route in fact lead to a shorter route.

Additionally, a large group of active geofences might lead to a UAV having insufficient endurance to find a route to its destination. This occurs when the outer endurance region is completely blocked across its width, shielding the complete locomotion region of the UAV. In this manner, the outer endurance region also aids the operator in estimation which geofence activation(s) will cause a UAV to loiter. When a UAV has to loiter because of this region, the out-of-endurance marker is displayed over the vehicle icon (currently shown as a purple exclamation mark).

C
Code Overview

Th chapter presents an overview of the code written for the simulation and experiment (Javascript, supplemented by HTML, CSS and PHP) and for the data analysis (Python). First, Section C.1 presents the top level code architecture, after which Section C.2 explains the simulation environment in more detail. Finally, the post-experiment data processing script are elaborated upon in Section C.3.

C.1. Code Architecture

The top-level architecture of the code developed for the simulation and experiment is presented in Figure C.1. Each of the files in the central structure or in one of the folders is shortly explained below, with the exception of 'main.js' and the 'modules' folder, which are explained in more detail in Section C.2.

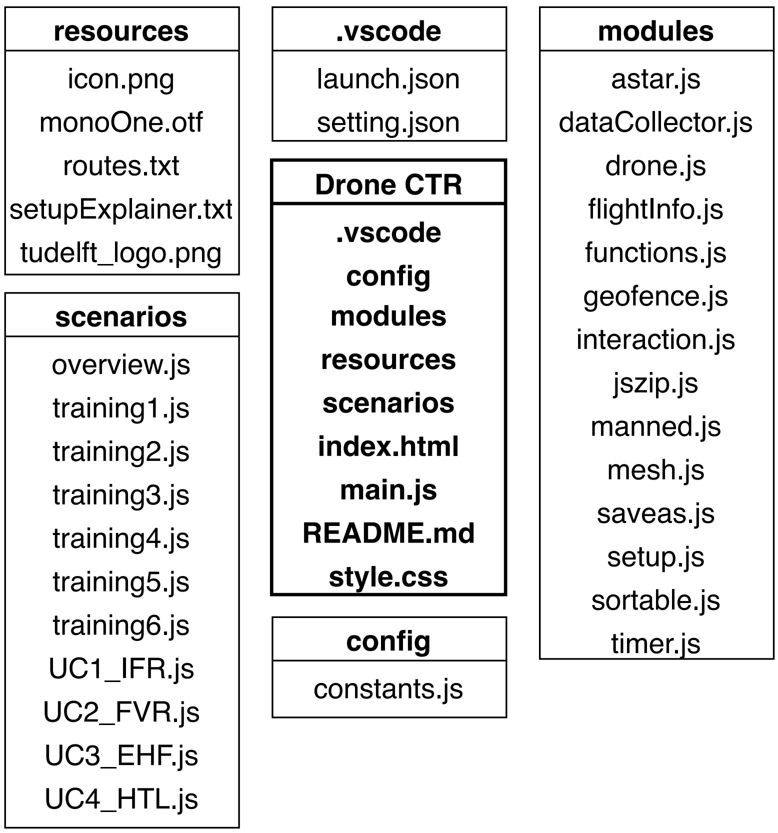


Figure C.1: Top-level code architecture, the central box in bold indicates the file structure, names without an extension are folder and are further laid out in the surrounding boxes

First of all, the '.vscode' folder contains two files that allow the complete simulation to be run on a live server from the user's device. This function is mainly used for development, debugging and testing, before the code is run on the TU Delft server for use in experimentation. Next, the 'config' folder only contains the 'constant.js' file, containing some timing interval parameters. It also contains constants regarding the interface's colour scheme and the map style (`https://mapstyle.withgoogle.com/`). The 'modules' folder contains the main functionality of the simulation and will be explained in C.2. The 'resources' folder contains some files that are used by the main simulation code, such as logos of the TU Delft and the simulator, font files and text files containing manned traffic routes and an explanation of how to set up a new scenario. The 'scenarios' folder contains all the traffic scenarios used during the experiment. The 'overview' file specifies in what order geofence sizes and traffic scenarios should be loaded, based on the participant's ID. All the following files contain an initiator for UAV and manned traffic and an updater that adds flight during the scenario when needed.

Apart from the contents of the folders described above, four more files are used. The 'index.html' file is the file that is called on first when the server runs the program. It specifies the elements that should be on the web page, such as the map, the flight information view and the menu elements for the experiment. Afterwards, it specifies that all other Javascript files should be loaded to run the simulation. The 'main.js' file essentially runs the experiment, specifying which functions from which files should be run in what order. Next, the 'README.md' file gives an explanation of the prerequisites and how to get the simulation running on the user's own device. Finally, the 'style.css' file specifies the layout of all the elements defined in the 'index.html' file, apart from the map style, which is defined in 'constants.js'.

C.2. Drone CTR Simulation

An overview on all the functions used by the code, ordered per module file, is laid out in Figure C.2. Below, the main functionalities of each module are elaborated upon. All of the modules listed below are classes, except for 'astar', 'sortable', 'jszip', 'saveas', 'interaction', 'setup' and 'functions', which are collections of functions.

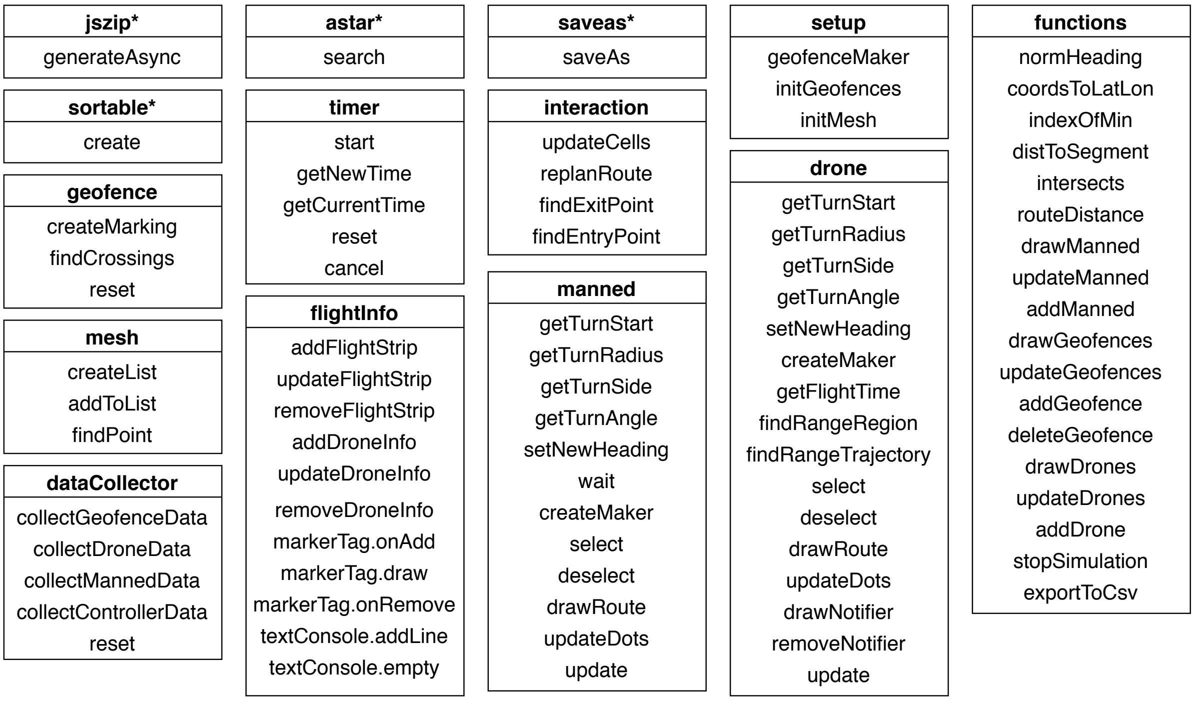


Figure C.2: Functions per module file, Existing modules are indicated by an asterisk and only the used functions are list below it

Astar, Sortable, Jszip and Saveas

Four existing modules are used by the simulation, indicated in the overview by an asterisk. The module 'astar' contains the A* path planning algorithm, the module 'sortable' allows drag-and-drop use of the flight strips, and the modules 'jszip' and 'saveas' are respectively used to store experiment data in a zip file and download it client side. For the existing modules, only the used functions are listed.

Timer
The 'timer' class, starts a timer for the simulation. This means the current time can be request, allowing timed events. The timer can be stopped and reset when the simulation is complete.

Setup
The 'setup' module prepares the routing structure of the next scenario. First, the 'geofenceMaker' function generates a list of geofence coordinates, based on geometrical properties of the runway. Next, this is converted into a list of geofence objects by the 'initGeofences' function. Finally, the 'initMesh' function overlays the map with a mesh for the path planning, based on the geofence configuration.

Geofence
The 'geofence' class contains the 'createMarking' function that draw the geofences. This function also checks for geofence clicks, which in turn activates the re-routing of UAVs. The 'findCrossings' function is used at the beginning of the scenario to identify all the UAV's whose routes cross the geofence in question. Finally, the 'reset' function allows the geofence to be reset when the next simulation uses the same geofence configuration.

Mesh
The 'createList' function of the 'mesh' class generates a grid mesh based on the geofence configuration. Additionally, it generates a list of geofences that overlap with a certain mesh grid cell for every cell. The 'addToList' function allows this list to be expanded. Finally, the 'findpoint' function identifies the mesh grid cell that contains a specified set of coordinates.

Manned
The 'manned' class is used for all non-UAV VFR and IFR traffic. Each vehicle follows a set list of waypoints, consisting of a set of coordinates, an altitude and an indicated airspeed to target. To navigate between the waypoints, constant bank angle turns are used, which are initiated by the 'getTurnStart' function. The turn is mapped out by the 'setNewHeading' function, using the 'getTurnRadius', 'getTurnSide' and 'getTurnAngle' functions, whose names are self-explanatory. The 'wait' function can be used to make the aircraft stationary before departure. The 'createMarker' function creates the manned traffic icon and checks whether the vehicle is select or deselected. The 'select' function highlights the manned traffic icon and displays the intended route (by means of the 'drawRoute' function), while also deselecting any other manned vehicles. The 'deselect' function reverts these changes. The 'updateDots' function updates the trailing dots behind the manned traffic icon, indicating its five last position updates. Finally, the 'update' function updates the aircraft position, based on the instructed waypoints. A simulation position update is made every second, while the visual position update is only given every five seconds.

Drone
A large number of the functions of the 'drone' class are similar to that of the 'manned' class. The only change in navigation being that the waypoints can change in-flight. However, this re-routing occurs in the 'interaction' module, not in the 'drone' class. Additionally, selecting a drone will not only display its intended route, but also the endurance regions, as explained in Appendix B. This is done using the 'findRangeRegion' and 'findRangeTrajectory' functions, which in turn use the 'getFlightTime' function to calculate the remaining flight time. Finally, the 'drone' class also contains the 'drawNotifier' and "removeNotifier' functions, to display and stop displaying the out-of-endurance marker when a UAV cannot find a route within its endurance.

FlightInfo
The 'flightInfo' class contains various elements that present information regarding UAV and manned flights to the operator. The 'addFlightStrip' function creates a flight strip for every manned flight that is initiated. This flights strip is updated upon every interface update by 'updateFlightStrip' and removed together with the flight by 'removeFlightStrip'. A similar setup is used to generate the flight labels (indicated here as marker tags). The flight strip functionality is carried over to the drone information strip, with the modification that the information strip is only created for the UAV currently selected. Finally, lines can be added to the text console using the 'textConsole.addLine' function. The text console can be reset using the 'empty' function.

Interaction
The 'interaction' module manages the interaction between geofences and UAV traffic and is triggered by the activation of a geofence. First, the 'updateCells' function updates the mesh grid by (de)activating the cells associated with the geofence in question. Next the 'replanRoute' function generates a new route around the geofence restrictions for all affected UAVs. This is done using the A* path planning algorithm from the 'astar' module, the resulting waypoint of which are send to the UAV in question. The 'replanroute' function also updates the list of the involved geofence that register which UAV routes cross their perimeter. When a UAV's position or destination is within the boundaries of an activated geofence, modifications are made to the route to fly via the closest point of exit or closest point of entry, respectively. This is done by the 'findExitPoint' and 'finEntryPoint' functions.

dataCollector
The 'dataCollector' class gathers data during a simulation run regarding the geofences, the UAVs, the manned vehicles and the controller. The collected data lists can later by stored as a CSV file in a zip file. The 'reset' function empties all the data lists and starts the data collection anew for the next simulation run.

Functions
The 'functions' module contains a variety of general functions that are used by various parts of the program, but do not specifically belong to any of the other modules. First of all, it contains various navigational functions, such as 'normHeading', 'coordsToLatLon' and 'routedistance'. Next, it contains some geometrical function, used to find the closest point of exit and closest point of entry, these functions include: 'indexOfMin', 'distToSegment' and 'intersects'. Additionally, it contains a range of functions that draw, update, add and remove geofences, UAVs and manned vehicles. As these operate over the complete lists of these objects, these functions cannot be contained within the respective classes. Moreover, the 'functions' module contains the 'stopSimulation' function, which stop and resets the simulation at the end of a simulation run. Finally, the 'exportToCsv' function converts a data list from the 'dataCollector' class to a CSV file and stores it in a zip file.

Main file
With all the program's functionalities explained in the paragraphs above, the structure of the main file (main.js), can be seen figure C.3. Blocks of code with a pivotal function are indicated by a rectangle, whereas actions of the user are indicated by a hexagon. Note that interactions with the interface are not included in this diagram, as these are not tied to the interval update, but happen directly based on mouse events. This also includes the interaction with geofences and re-routing of UAVs, as was described in the paragraphs above.

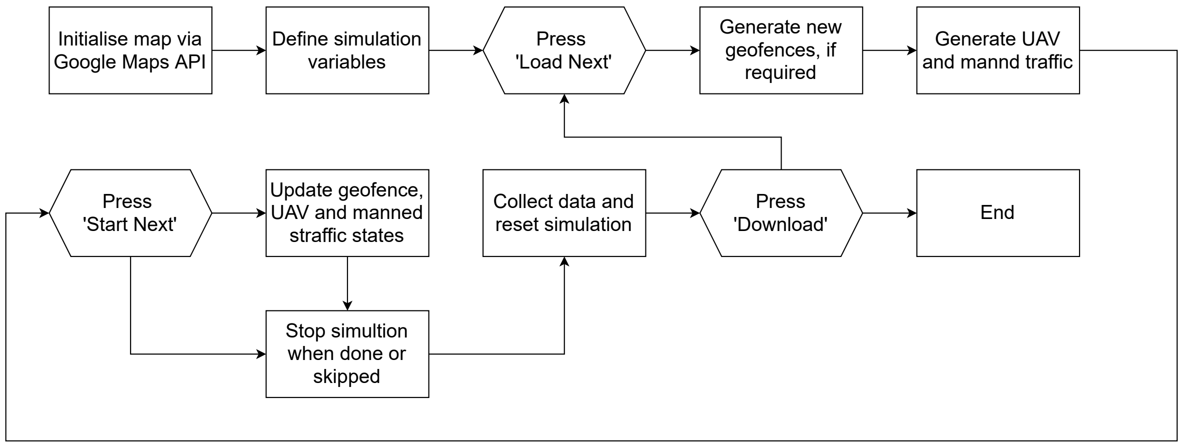


Figure C.3: Flow diagram of the main file running the simulation. Block of code with a pivotal function are indicated by a rectangle, whereas actions of the user are indicated by a hexagon

C.3. Post-Experiment Data Processing

The experiment data is stored during the simulation in CSV files. Three Python scripts are used to extract the data regarding the traffic safety, UAV efficiency and control activity from these files. Each of these three Python scripts then parses the data to a new CSV file, suited for further use in statistical analyses. Additionally, each script generates box plots regarding the parsed data. Three further Python scripts are used to generate plots of the geofence interactions over time, the geofence interaction maps and the resulting traffic pattern maps. The resulting boxplots can be seen in the Thesis Paper, whereas the more detailed figures regarding the geofence interactions and traffic patterns can be found in Appendix **??**.

D

Experiment Design

This chapter gives an overview of the design of the human-in-the-loop experiment performed during this research. Section D.1 shows the experiment conditions, whereas Sections D.2 and D.3 present the traffic scenarios used in the training runs and experiment runs, respectively.

D.1. Experiment Conditions

The human-in-the-loop experiment consisted of a total of six training scenarios and eight experiment scenarios. The conditions of the eight experiment scenarios are summarised in Table D.1.

Table D.1: Experiment conditions

	IFR Traffic	VFR Traffic	Emergency Heli	High Task Load
Large Geofences	IFR-L	VFR-L	EHF-L	HTL-F
Small Geofence	IFR-S	VFR-S	EHF-S	HTL-S

All experiment scenarios had a duration of 5 minutes. The first three traffic scenario are modelled after traffic use-cases, expected to play crucial role in the interaction between tower control and UAV traffic. Each of these scenarios contained three manned traffic vehicles and four UAVs. The fourth scenario contained a mix of all three use-cases and included six manned traffic vehicles and eight UAVs. This scenario was considered a high ask load scenario and was always presented last for a particular geofence size. This allowed the participant to get familiar with the geofence size, before presenting them the high task load scenario. All scenarios contained a mix of quad-copters and fixed-wing UAVs, and a mix of regular and high priority UAVs. Table D.2 shows the experiment matrix, presenting an overview of the ordering of the scenarios.

Table D.2: Experiment matrix

ID	**Experiment run**													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
531001	T1	T2	T3	T4	T5	T6	IFR-L	VFR-L	EHF-L	HTL-L	VRF-S	EHF-S	IFR-S	HTL-S
531002	T1	T2	T3	T4	T5	T6	EHF-L	IFR-L	VFR-L	HTL-L	IFR-S	VRF-S	EHF-S	HTL-S
531003	T1	T2	T3	T4	T5	T6	VFR-L	EHF-L	IFR-L	HTL-L	EHF-S	IFR-S	VRF-S	HTL-S
531004	T1	T2	T3	T4	T5	T6	IFR-S	VRF-S	EHF-S	HTL-S	EHF-L	IFR-L	VFR-L	HTL-L
531005	T1	T2	T3	T4	T5	T6	EHF-S	IFR-S	VRF-S	HTL-S	VFR-L	EHF-L	IFR-L	HTL-L
531006	T1	T2	T3	T4	T5	T6	VRF-S	EHF-S	IFR-S	HTL-S	IFR-L	VFR-L	EHF-L	HTL-L
531007	T1	T2	T3	T4	T5	T6	IFR-L	VFR-L	EHF-L	HTL-L	VRF-S	EHF-S	IFR-S	HTL-S
531008	T1	T2	T3	T4	T5	T6	EHF-L	IFR-L	VFR-L	HTL-L	IFR-S	VRF-S	EHF-S	HTL-S
531009	T1	T2	T3	T4	T5	T6	VFR-L	EHF-L	IFR-L	HTL-L	EHF-S	IFR-S	VRF-S	HTL-S

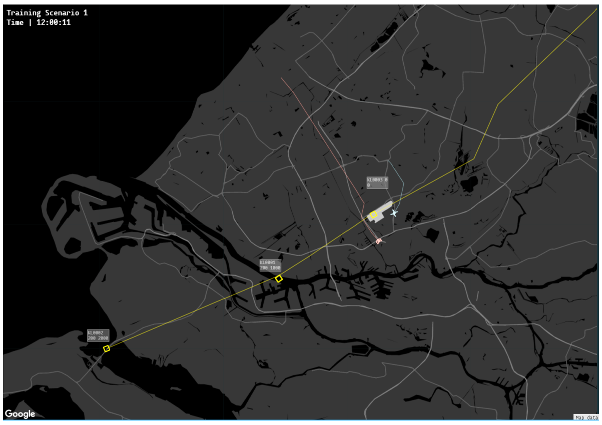
D.2. Training Scenarios

The six training scenario included in the experiment were split up into three scenarios used to familiarise the participant with the interface and simulation environment, and three scenarios used for training with the interface. The training scenarios used a geofence size between the large and small sizes used in the experiment. In this way, training scenarios transitioned into experiment scenarios, independent of the geofence size first resented to the participant. An overview of the conditions of the training scenarios can be seen Table D.3.

Table D.3: Overview of training runs

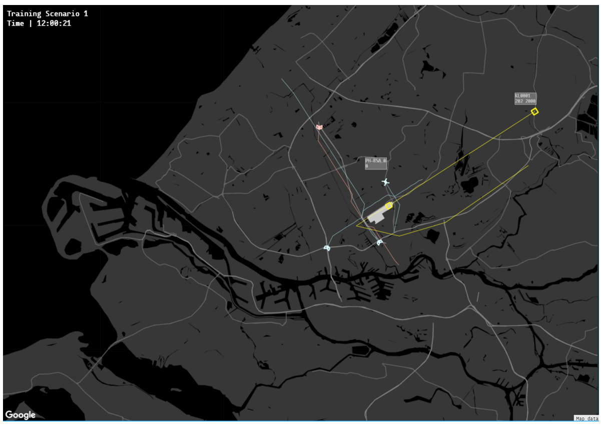
Scenario	Type	Characteristics
T1	Familiarisation	Manned traffic
T2	Familiarisation	Geofences
T3	Familiarisation	UAV Traffic
T4	Practice	IFR - 2 UAVs
T5	Practice	VFR - 3 UAVs
T6	Practice	EHF - 4 UAVs

The initial traffic conditions for the last three training scenarios can be seen in Figure D.1. These traffic scenarios are performed using the training geofence size; The geofences are currently not displayed for illustrational purposes.



(a) Training scenario 1 (IFR)

(b) Training scenario 2 (VFR)

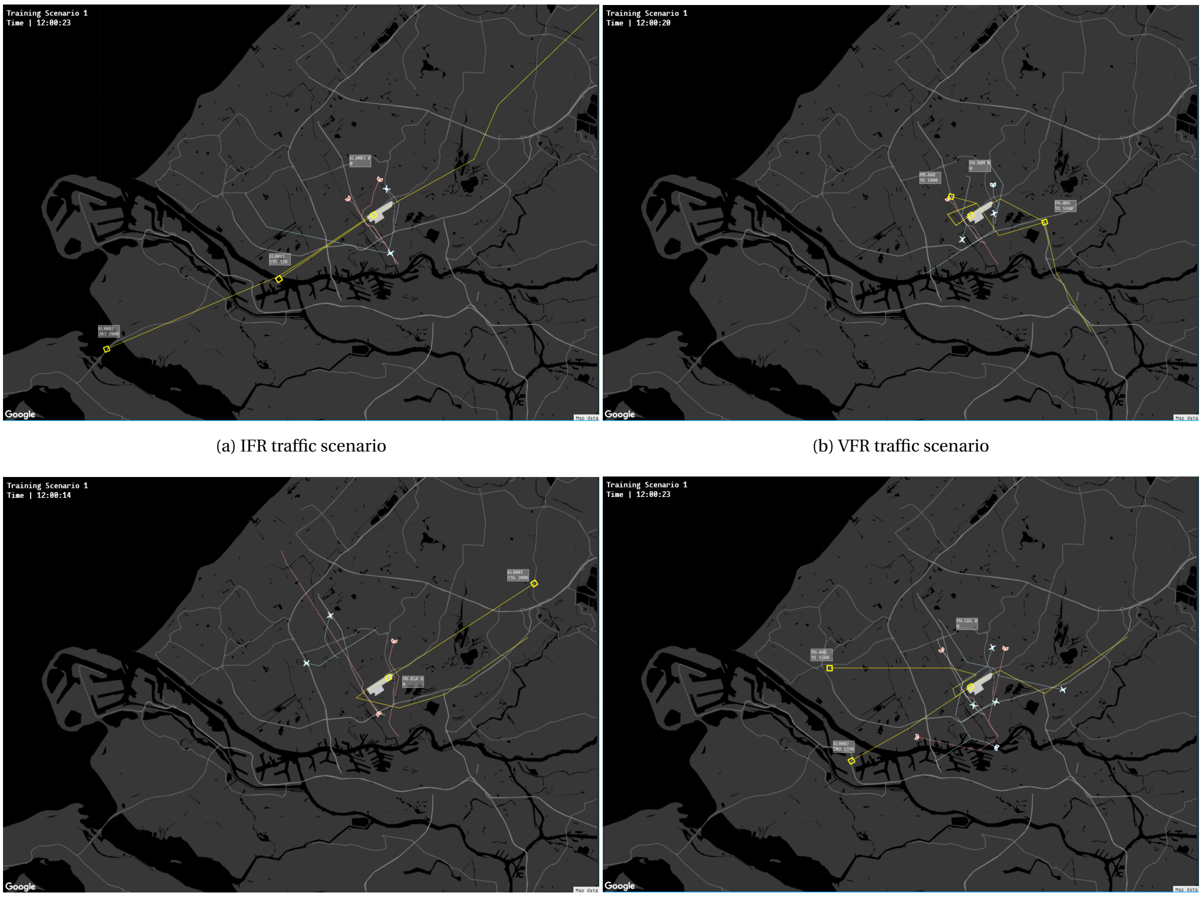


(c) Training scenario 1 (EHF)

Figure D.1: Initial traffic conditions of the training scenarios

D.3. Experiment Scenarios

The initial traffic conditions for the experiment scenarios can be seen in Figure D.2. These traffic scenarios are performed using both geofence sizes. The geofences are currently not displayed for illustrational purposes.



(a) IFR traffic scenario

(b) VFR traffic scenario

(c) Emergency helicopter flight scenario

(d) Emergency helicopter flight scenario

Figure D.2: Initial traffic conditions of the experiment scenarios

E

Experiment Briefing and Survey

This chapter integrally shows the experiment briefing and questionaire, as presetned to the participants during the experiment

E.1. Introduction

Thank you for participating in this experiment! The goal of this experiment is to investigate the influence of drone traffic and geofencing capabilities on the work behaviour of tower control. The first section of this survey will provide you with a background to the experiment, explain the task you have to fulfil during the experiment and give an overview of the experiment set-up. The second section consists of a few pre-experiment questions regarding your work position. The third section provides a step by step guide through the experiment and poses one question after the completion of each experiment scenario. The fourth and final section will provide you with a post-experiment survey. If you have any questions during the experiment preparation and training, feel free to ask the experimenter(s).

E.1.1. Problem Background

Drone operations in urban areas could have large potential benefits, such as medical deliveries, infrastructural inspections, surveillance, etc. However, as indicated by several incidents, the increase in drone traffic could pose a threat to manned air traffic operating at low altitudes, for example to emergency helicopter flights and commercial and private aviation during landing and take-off.

To manage the increase in drone traffic safely, the SESAR joint undertaking initiated the U-space system in 2017, with the goal of providing safe, efficient and secure access to airspace of large numbers of drones in very low-level airspace (below 500 feet). This is aimed to be achieved by providing a set of services that rely on a high level of digitisation and automation. One of these services is the use of geofences, which shield certain volumes in space from drone traffic. These geofences are currently only used permanently to protect buildings, royal palaces, nature reserves, etc. In the near-future however, U-space aims to use temporary geofences for events, emergencies and to protect manned air traffic. This research aims to investigate how geofences can be used in the near-future by tower control to shield manned traffic operations from drone traffic. This is currently applied to the use case of Rotterdam - The Hague Airport.

E.1.2. Experiment Tasks and Goals

As described in the introduction, this experiment investigates the influence of drone traffic and geofencing capabilities on the work behaviour of tower controllers. Consider the example of a high priority medical delivery drone flight crossing the final approach of Rotterdam - The Hague Airport, or a pipeline inspection drone flight in the landing area of a medical emergency helicopter flight. These drone flights bring (lifesaving) benefits, but can create interference with manned traffic around Rotterdam - The Hague Airport. Maintaining the safety of manned air traffic requires restrictions on drone operations, however, these should have the smallest impact possible on the efficiency of drone operations. Awareness of, and interaction with drone traffic from the side of tower control is essential for safety in the airspace and efficient travel of high priority drone flights.

In this experiment, it is your task to use geofences to separate drone traffic in very low level airspace (below 500 ft) from manned traffic around Rotterdam - The Hague Airport.

You will be presented with various scenarios, representing traffic use-cases important to the interaction of tower control with drone traffic. During the experiment, you are in control of activating and deactivating geofences to shield certain areas from drone traffic. The manned air traffic cannot be influenced. The drone air traffic cannot be influenced directly, but does respond dynamically to the geofence constraints. Please consider the following two goals during the execution of your control tasks:

1. Ensure vertical separation (250 feet) and horizontal separation (2000 ft / 600 m) between manned traffic and drone traffic;

2. Minimise additional travel time for drones, especially high priority drones.

Before the actual experiment starts, you will first be guided through 6 training scenarios, to familiarise you with the display. Afterwards, the 8 experiment runs will be done, taking 5 minutes each. Once the experiment is completed, we will ask you to submit your simulation data and fill out a survey regarding the experiment.

E.1.3. Experiment Setup

You will be able to perform the experiment on your own computer, using a weblink that will be provided to you in the part of this survey concerning the experiment. Please note that it is required to use your full screen for the experiment with high screen brightness, additionally, it is required that you use a computer mouse. It is recommended to use Google Chrome of Mozilla FireFox as a browser to run the simulation. If you are not using one of these browser at the moment, you can switch now by re-opening this survey in a new browser window. The interface you will be using during the experiment consists of two windows: the map view and the flight information view (see image below).

The map view on the left contains a map of the Rotterdam area (grey), overlapped by a grid of geofences (green). The map view also shows icon for manned traffic (green), including trailing dots and flight labels, as well as icons for regular drone traffic (light blue) and high priority drone traffic (red). This part of the display is crucial in performing the experiment tasks; the map view is updated every five seconds. You can use the scroll wheel for your mouse to change the zoom of the map and drag the map with the left mouse button to move it around.

The flight information view on the right contains flight strips with information regarding the manned traffic flights, as well as message console providing information regarding new flights. It also contains an information strip regarding the selected drone flight. The flight information view is also updated every five seconds. The image below shows the interface you will use during the experiment. The functionalities on the display will be explained step-by-step in more detail further on in the experiment.

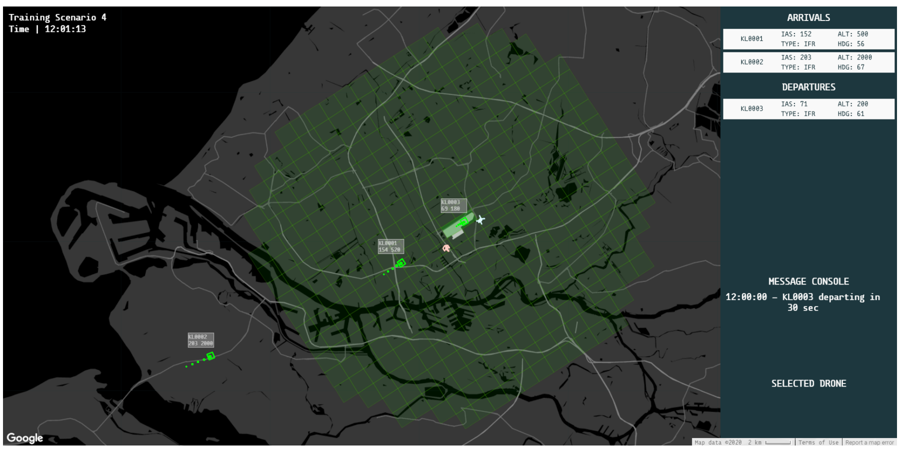


Figure E.1: Experiment Interface

E.2. Pre-Experiment Questions

These question are to be answered before the experiment starts.

Please enter your participant ID.

Please select the most applicable option regarding your tower control rating and tower control experience:

- I am an active tower controller.
- My tower control rating has expired, but I have a lot of experience in tower control.
- My tower control rating has expired and I do not have a lot of experience in tower control.
- I have never been in possession of a tower control rating.

Please select the most applicable option regarding your knowledge of control procedures for Rotterdam-The Hague airport:

- I am very familiar with them.
- I have some knowledge of them.
- I am unaware of them.

E.3. Experiment Instructions and Questions

These instructions will guide you through the experiment, the questions are to be answered during the experiment, after the completion of each experiment run.

E.3.1. Experiment

You are now ready to start the experiment, for which you will be provided a weblink. Please do not close this experiment page after opening it until you are instructed to do so, which will be after completing all scenarios and downloading your data. You can switch tabs in your browser between the experiment and this survey. When you enter the experiment page you will have to enter your participant ID and press 'OK'. Afterwards, read through this survey for a step by step guide through the experiment. You can now start the experiment by visiting: dronectr.tudelft.nl. Please only enter your participant ID and confirm, after which you can continue reading this document, which will provide a step by step guide for the experiment. You will not need to load or start the first scenario until after reading the next two sections.

E.3.2. Training Scenarios

You will now go through six training scenarios, that help familiarise you with the simulation and the interface. The first three scenarios explain the different elements of the simulations, being the manned traffic, the geofences and the drone traffic, in that order. The second three training scenarios present you with mixed traffic scenarios similar to the experiment scenarios, where you are performing the experiment tasks of ensuring horizontal separation between manned traffic and drone traffic, and minimise additional travel time for drones, especially high priority drones.

E.3.3. Training Scenario 1

The first training scenario demonstrates the manned traffic in the simulation and does not yet contain any geofences or drone traffic. The manned traffic cannot be influenced during the run of the simulation and can be assumed to remain separated. However, there are various forms of information provision regarding the manned traffic.

First, the map view (left) shows icons for all the manned air traffic, including trailing dots for its five last known position updates. Additionally, each marker has a flight label, specifying flight ID, the indicated airspeed in knots and the altitude in feet.

Second, the flight information view (right) contains flight strips for both arriving and departing traffic. The flight strips specify flight ID, indicated airspeed in knots, altitude in feet, heading in degrees and whether the flight is IFR or VFR. These can be used to keep track of the order of incoming and outgoing flights; note that the flight strips are not in order at the start of the experiment. However, you have the option to drag the flight strips and change their order and use them as an optional tool.

Finally, the message console in the flight information window provides information regarding new flights. Regular departures are prompted 30 seconds before initiating take-off. Emergency helicopter departures are prompted 90 seconds before initiating take-off and also contain the flight heading and the flight length in nautical miles. This can be compared to the scale measure in the bottom right of the screen. Helicopter flights can be assumed to fly in a direct line from origin to destination. The moment the message console prompts a new departure, the icon and flight strip also show up on the map view and flight information view, respectively. A second message is promted when the helicopter descends into very low level airspace. Emergency helicopter flights are marked by a flight ID beginning with "LIFELN".

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

1. Drag and zoom the map view using your left mouse button and scroll wheel, respectively.
2. Observe the messages in the message console in the flight information view.
3. Hovering your mouse marker over the flight strips on the flight information view (right) highlights the corresponding flight on the map view in orange (left) and vice versa.
4. The flight strips on the flight information view can be changed in order by clicking a flight strip with the left mouse button and dragging it up or down.
5. Each manned traffic marker on the map view contains a flight label, that can be dragged around by clicking it with the left mouse button and dragging it around.
6. Clicking a manned traffic icon will select it and shows its intended route. This can be deselected by clicking the icon again, clicking the background map or selecting a different vehicle.

The scenario runs for five minutes, but can be ended prematurely by pressing the 'next' button in the upper left corner, if you feel you have sufficiently performed all the interactions. However, it is advised to play at least 3 minutes of the scenario, as an emergency helicopter flight is prompted after 30 seconds and departs after 2 minutes.

When going to the experiment page, you should see a menu with a 'load next' button (once you entered your participant ID), press this to load the next scenario. Once the scenario has been successfully loaded, the menu shows a 'start next' button, press this to start the next scenario. Please note that loading later scenarios can take up to 60 seconds. Please do not press the 'Load next' button multiple times, this will cause the scenario to start immediately once loaded. Instead, wait until the scenario is loaded and the 'start next' button is shown. You can now load and start the first training scenario.

E.3.4. Training Scenario 2

The second training scenario demonstrates the geofences in the simulation and does not show any manned or drone traffic. The map view is now overlapped with geofence areas, indicated as green shaded areas. These geofences are your main tool of interaction during the experiment and allow you to restrict certain regions from drone traffic. Hovering your mouse marker over the geofences will highlight the borders of the geofence you are currently selecting. To prevent drone traffic from using a certain part of the geofence grid, a geofence can be activated by clicking on it with you right mouse button, which will result in the complete geofence being highlighted. Once a certain geofence restriction is no longer needed, the geofence can be deactivated by clicking it with the right mouse button again. When a geofence is activated, but still contains drone traffic, it will be marked yellow. The drone traffic will leave by the closest point of exit, after which the geofence turn highlighted green again.

The geofences are shaped in a grid, aligned with the orientation of the runway of Rotterdam - The Hague Airport. The exception to this grid are the geofences close the runway. The geofences on the ILS are shaped to cover the part of the ILS that is in very low level airspace (below 500 ft) and can cause interference between drone traffic and manned traffic. Between these ILS geofences and the geofence grid, there is a layer of transition geofences.

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

1. Hovering your mouse marker over the geofence will highlight their borders.
2. Clicking with your right mouse button on a non-active geofence will activate it.
3. Clicking with your right mouse button on an active geofence will deactivate it.

You can now load and start the next scenario, the loading might take some time. Again, the scenario lasts 5 minutes, but can be prematurely ended by pressing 'next' button once feel you have sufficiently performed all the interactions.

E.3.5. Training Scenario 3

The third training scenario demonstrates drone traffic; it does contain geofences but no manned traffic. Drone traffic cannot be directly influenced during the simulation, however, it can be indirectly influenced by activating and deactivating geofences. It can be assumed that drones among each other maintain sufficient separation. There are various forms of information provision regarding geofences.

First, the icon of a drone symbolises its vehicle type, being a quadcopter or a fixed wing vehicle. The colour of the drone icon specifies whether the drone is considered to have a high priory mission (red) or not (light blue). High priority drones have important missions, such as medical deliveries and should be diverted to a minimal extent.

Next, a drone can be selected by clicking the icon in the map view with your left mouse button, which will prompt a drone flight information strip in the bottom of the flight information view. This includes drone mission type, drone vehicle type, heading in degrees, priority (high or regular), indicated airspeed in knots and altitude in feet. It also contains the remaining flight time in minutes, followed by the amount of that travel time that due to expected delay, caused by geofencing restrictions.

Moreover, selecting a drone icon will show the planned trajectory to its destination. Second it will show the range regions of the vehicle (see image below).

The outer range ellipse signifies the maximum distance the drone can divert from a straight line between destination and current position. This illustrates the size a group of active geofences can have before the drone can no longer fly around it. This means that when a geofence is not fully within this ellipse, the drone cannot fly around that geofence. When the outer ellipse is fully blocked along the width, there is no route possible. This will cause the drone to loiter and a purple exclamation mark to show up over its icon.

The inner range region signifies how far the drone can divert from the current route. This is based on the battery capacity it has left besides that required to fulfil the current flight plan, this means the size of this region changes according to the current geofence constrictions. If a geofence adjacent to the current route is not fully within this region, the drone cannot fly around it.

When a geofence is activated that contains a drone, the drone will always leave by the closest point of exit, even if that is behind the drone. Additionally, the geofence will be marked yellow to indicate this pending state. When the destination of a drone is inside an active geofence, the drone will fly to the closest point of entrance and hover/loiter until the geofence in deactivated.

You will notice that the drone traffic during the experiment is concentrated around the airport. In reality, there would be drone traffic over the entire CTR, but this is currently not included in the simulation, to focus on the direct interaction. Please make sure to test all interaction with drone traffic during this training scenario:

1. Select the fixed wing drone with high priority by clicking it with your left mouse button.
2. Observe the drone flight information strip on the bottom of the flight information view.
3. Activate a geofence along the drone's route.
4. Observe the route changing and the range region around the trajectory decrease, as less endurance is available for re-routing. Also observe the expected travel time and delay on the information strip change. Activate and deactivate some geofence to get a feeling for this.
5. Activate a row of geofence along the width of the range ellipse (short axis) and observe when the drone can still fly around it and when there is no route available. Observe the marker over the drone icon indicating there is currently no route available (purple exclamation mark).
6. Deactivate all geofences.
7. Activate the geofence the drone is currently in. Notice the closest point of exit and the yellow geofence indicating the pending state. Notice the geofence turning green (active) when the drone leaves the geofence.
8. Activate the geofence the drone destination is in and notice the closest point of entry.
9. Deselect the drone by clicking the icon again, on a different drone icon or on the background map. Repeat the steps for the quad-copter with regular priority.
10. Feel free to experiment with the geofence interaction and ask the experimenters about any elements of the interface or simulation that might still be unclear.

You can now load and start the next scenario. Again, the scenario lasts 5 minutes, but can be prematurely ended by pressing 'next' button once feel you have sufficiently performed all the interactions.

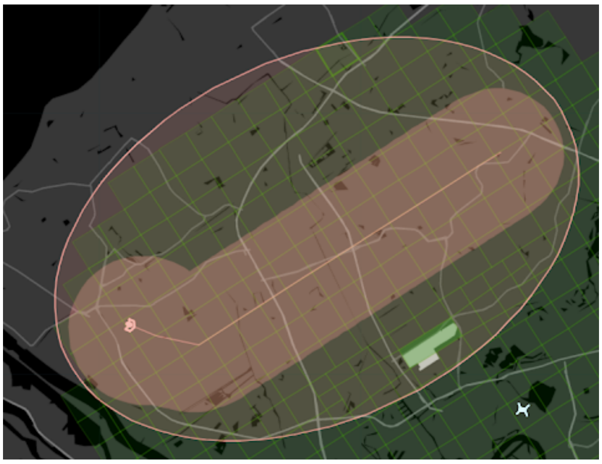
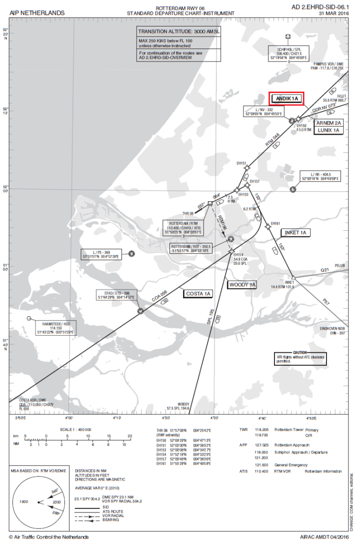


Figure E.2: Drone Endurance Regions

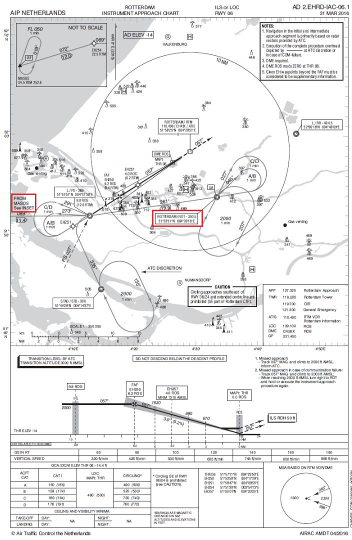
E.3.6. Training Scenario

You have completed the first three training scenarios, aimed at demonstrating the interface. The next three training scenarios allow you to practice with performing your experiment tasks using the interface. From this point on, you will not get specific instructions per scenario, your goals during the scenario are those of the main experiment, described in the introduction. Please remind yourself of these goals. Moreover, please refrain from using the 'next' button in the top left corner unless you are instructed by the experimenters to do so.

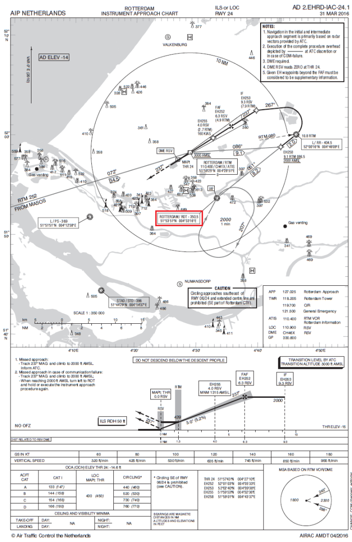
The next scenario involves three IFR flights and two drone flights; the scenarios takes three minutes. Below you find the relevant IFR charts, which the traffic in the simulation will adhere to. Please take some time to observe them before starting the scenario. The traffic in the experiment scenarios will be similar to that in the next training scenario and will also follow the IFR charts. The four IFR routes used during the experiment are indicated with a red box. Note that the marked routes are the only ones that will occur during the entire length of the experiment. The runway direction used during the scenario is denoted on the start button before the scenario. After you have completed the scenario, you can press the 'download' button to download your data as a zip file, this is done after each experiment run. Please fill out the question below before loading and starting the next scenario.



(a) IFR - Departure 06



(b) IFR - Approach 06



(c) IFR - Approach 24

Training Scenario 4 - Please explain your solution strategy during this scenario.

E.3.7. Training Scenario 5

The next scenario involves three VFR flights and three drone flights; the scenarios takes four minutes. Below you find the VFR charts, which the traffic in the simulation will adhere to. Please take some time to observe them before starting the scenario. The traffic in the experiment scenarios will be similar to that in the next training scenario and will also follow the VFR charts. Please download your data and fill out the question below once you have completed the scenario.

(a) VFR Chart

(b) VFR Traffic Circuit

Training Scenario 5 - Please explain your solution strategy during this scenario.

E.3.8. Training Scenario 6

The next scenario involves an IFR flight, a VFR flight, an emergency helicopter flight and four drone flights; the scenario takes five minutes. Please download your data and fill out the question below once you have completed the scenario.

Training Scenario 6 - Please explain your solution strategy during this scenario.

E.3.9. Experiment Scenarios

You are now ready to start the experiment scenarios. Please ask the experimenter(s) any questions you have left regarding the experiment, as this will not be possible during the experiment. Remind yourself of the goals of your control task and the 5 minute time limit on the scenarios. Also, please do not forget to answer the questions below after completing a scenario. You can now load and start the first experiment scenario (the loading might take some time), good luck!

Experiment Scenario 1 - Please explain your solution strategy during this scenario.

Experiment Scenario 2 - Please explain your solution strategy during this scenario.

Experiment Scenario 3 - Please explain your solution strategy during this scenario.

Experiment Scenario 4 - Please explain your solution strategy during this scenario.

Experiment Scenario 5 - Please explain your solution strategy during this scenario.

Experiment Scenario 6 - Please explain your solution strategy during this scenario.

Experiment Scenario 7 - Please explain your solution strategy during this scenario.

Experiment Scenario 8 - Please explain your solution strategy during this scenario.

E.3.10. Experiment Data

You have now successfully completed the experiment and should have gather 11 zip files. Please attach these files to an email to ... and ..., titled "Experiment Results - ID" where ID should be replaced by your participant ID. Once you have send the email, please notify the experimenter(s), such that they can verify that the data was received correctly. Once they confirm that everything is in order, you can close the experiment tab and continue to the post-experiment questions of this survey.

E.4. Post-Experiment Questions

These question are to be answered after the completion of the experiment.

E.4.1. Workload and Situation Awareness

The fourth and eigth traffic scenario (the last scenario for each geofence size) was a high taskload scenario. Please answer the following questions regarding these two high taskload scenarios only.

How complex would you consider the traffic mix (drones and manned aircraft) to be, if encountered in real life (1-5)?

Any comments on the traffic complexity?

How high would you rate your overall workload during the high taskload scenarios (1-5)?

Any comments on the workload?

How high would you rate your overall situation awareness during performance of the task? (1-5)

Any comments on the situation awareness?

E.4.2. Geofence Size

During the experiment, you were given control over the same scenarios with differently sized geofences.

How do you assess the usefulness of geofences as a tool to perform the tasks given to you? Please provide examples in your answer.

What size geofence do you think would support you best in performing the tasks given to you and why? (This can be one of the sizes presented to you during the experiment, or your own suggestion)

E.4.3. Geofence Shape and Layout

During the experiment, you were given control over a grid of square geofences, with an exception for the ILS region.

How do you asses the usefulness of the shape and layout of geofences to perform the tasks given to you. Please provide examples in your answer.

What shape and size of geofence do you think would support you best in performing the tasks given to you and why? (This can be one of the sizes presented to you during the experiment, or your own suggestion)

There are currently no concrete U-space regulation for separation criteria between drones and manned traffic. How do you assess the separation minima provided to you during the experiment (250 feet vertically, 2000 ft horizontally)?

E.4.4. Traffic

During the simulation you were presented with different types and quantities of drones and manned traffic.

In your opinion, how accurate were the flight profiles of manned aircraft?

Which of the traffic scenarios presented to you during the experiment do you think provide the largest challenge to tower control and why?

Do you think there are any other traffic scenarios not presented during the experiment that would provide a challenge to tower control?

E.4.5. Experiment Interface

During the experiment, you were presented with an interface that focused on the range capabilities of drones.

Did you consider the "drone endurance indications" as useful elements to complete your task? Please provide examples in your answer.

Please score all display elements on how useful they were during the experiment on a scale from 1 (not useful) to 10 (very useful).

1. Highlighting of geofence state
2. Drone vehicle type icon
3. Drone priority colour indication

4. Drone future route
5. Drone endurance regions
6. Drone information strip
7. Drone out of range marker
8. Flight strips
9. Flight labels
10. Text console

How do you asses the usefulness and clarity of colour in the display? Please provide examples in your answer

Do you have any other remarks?

This is the end of the experiment, thank you for you participation!

F

Experiment Survey Answers

Tables F.1 through F.28 list all the responses to all the questions asked during the experiment survey presented in the previous chapter. The table caption shows the question at hand, the left column shows the participant ID and the right column shows the response.

F.1. Pre-Experiment Questions

Table F.1: Please select the most applicable option regarding your tower control rating and tower control experience

Participant	Answer
531001	I am an active tower controller.
531002	My tower control rating has expired and I do not have a lot of experience in tower control.
531003	I am an active tower controller.
531004	I am an active tower controller.
531005	My tower control rating has expired and I do not have a lot of experience in tower control.
531006	My tower control rating has expired, but I have a lot of experience in tower control.
531007	My tower control rating has expired, but I have a lot of experience in tower control.
531008	I am an active tower controller.
531009	I am an active tower controller.

Table F.2: Please select the most applicable option regarding your knowledge of control procedures for Rotterdam-The Hague Airport

Participant	Answer
531001	I am unaware of them.
531002	I am unaware of them.
531003	I am very familiar with them.
531004	I am unaware of them.
531005	I am very familiar with them.
531006	I am unaware of them.
531007	I am unaware of them.
531008	I am unaware of them.
531009	I am unaware of them.

F.2. Training Scenarios

Table F.3: Training Scenario 4 - Please explain your solution strategy during this scenario

Participant	Answer
531001	I decided to use the geofence in order to separate (or stop) the drones to not interfere with the manned airplanes.
531002	First approach was close, the time it would take the drone to cross the ILS would produce a conflict. Therefore, activating a couple of geofences in the last squares of the ILS would make the drone make a slight left turn to allow the aircraft to land and the drone to later cross the ILS safely. Regarding the departure, I thought that the best option would be to set the drone to loiter some seconds and then as soon as the aircraft had departed and because there were no consecutive departures it would be able to cross safely.
531003	I decided to keep the high-priority drone on it's current track, checking if the IAS was high enough for the crossing to be made in front of inbound IFR-traffic (assuming the latter would reduce more speed). But it wouldn't fit. Next time I will block a path so the drone would fly to S-W, opening up a gap after the conflict. Like I tried to achieve with the low-priority drone.
531004	I tried to maintain vertical separation between arrivals and drones by rerouting the drone behind the first arrival.
531005	Priority drone: first block the direct line to cross it behind KL001. Other drone: no conflict because of the altitude.
531006	1) Assess planned route of drones and proximity to departure and arrival paths of incoming and arriving traffic. 2) Assess crossing time of NFZ for drones based on their relative speed. 3) See if a cross behind or a cross before approach is better depending on the path. 4) Block the drone as close to the NFZ as possible to release the geofencing as soon as flight is clear of the drone.
531007	"1) Traffic on final approach would block both arrival and departure areas close to the airport to protect for potential go around. 2) I intended to facilitate the crossing of the runway axis by the drones, however, not being familiar with the speed of these, and the actual distance of the approach traffic it was hard to assess if the crossing was going to be possible and safe. 3) It seems to me that the approach area could be one single block of geofences.
531008	I activated geofences to protect both the ILS approach, as well as the 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. Same thing for the quad-copter that was left hovering south of the field waiting for the traffic on departure to clear its trajectory.
531009	Give priority to the medical drone. Always protecting the "go around" path and making any drones there hold position or hover until the runway heading is clear. Manned aircraft have priority over any drones, with or without priority.

Table F.4: Training Scenario 5 - Please explain your solution strategy during this scenario

Participant	Answer
531001	I tried to give priority to the red drone. The light blue ones are secondary for me because I give more priority to the VFR traffic instead.
531002	To avoid conflicts, set drones to loiter. Try to prioritise the red drone. Solve the issues with it first. I was trying to avoid conflicts between drones too.
531003	Tried to make as little deviations as possible for the drones crossing final 06. The delivery-drone had a long range so it couldn't find a way through (it's not deviating off-track as much as I hoped for). But it's low-priority anyway so it just waited for the manned traffic to fly by
531004	Taking into account the trajectories of arrivals and departures, I tried to manage the route to avoid conflicts maintaining the best available route. Sometimes the purple marker appeared so conflict was difficult to prevent.

531005	Drone crossing departure: low altitude so manned flight will cross overhead. Drones crossing first landing traffic: try to let them cross behind the landing traffic as quickly as possible.
531006	1) Overall evaluation of incoming and departing traffic and their trajectories. 2) Assess their positions and relative speeds. 3) Check whether any drone has to be immediately geofenced due to proximity to VFR traffic (considering VFR traffic separation has to be provided and not just information) 4) Keep the drones as close as possible to their original flight path with a 'the sooner away of the airport the better' principle. 5) Keep an eye on those couples/tuples of traffic being more prone to lose separation (in this case, near threshold of runway 06). 6) Use pan/zoom as needed to concentrate the view on those areas where conflicts are being resolved.
531007	1) Prioritize manned flight over drone activity. 2) Tried to facilitate drone operations. Controlling small geofence areas can be time consuming and may be too much workload in a congested tower. Better to have fixed areas, also for the VFR corridors.
531008	Same strategy as in scenario 4, provided that I tried to keep the VFR circuit patterns cleared for the traffic. A fixed wing drone trajectory seemed to be incompatible with the fact of clearing the circuit for the VFR traffic.
531009	I tried to interact with drones the same way we do with real traffic. Giving stop-and go instructions bearing in mind manned traffic won't stop. Always trying to give priority to drones with it.

Table F.5: Training Scenario 6 - Please explain your solution strategy during this scenario

Participant	Answer
531001	I prefer to keep the route for the emergency helicopter clear and safe at all times. Second, separate the drones from the manned aircraft and finally give a little priority to the medical drone.
531002	Drones are slower than other traffic. So the basic principle of separation techniques is to send the slowest traffic towards the 'tail' of the faster traffic, so basically I am activating and deactivating geofences according to this procedure. For instance, when the helicopter departed, there was a conflict with the blue drone that was going to go above the runway, and what I did was to activate a geofence for the drone to take more time to reach the conflict point.
531003	Closed final 24 for drones, regarding inbound IFR traffic. Drone had to wait. I closed upwind 24 for drones regarding the outbound VFR movement, but it had soon departed so I could open the airspace up again and drones resumed intended routing.
531004	By looking at the expected trajectories, I routed drones training to avoid same paths. I could understand the trajectories followed by helicopter and descends to avoid conflicts in the next scenarios.
531005	Drone crossing landing traffic: low priority so it can wait and continue after traffic has landed. Drone crossing departure traffic: make sure it will not interfere with manned traffic and when the departure is above the drones, the drones can proceed direct. Helicopter and priority drone: as long as the priority drone is not in the same box when helicopter is landing, it can proceed as much direct as possible.

531006	1) This exercise is extremely similar to a normal IFR/VFR mixed traffic airport. Thus, the complexity increased accordingly. 2) The strategy has been, as in previous cases, to plan for a 3-5 minutes horizon and check where the main short-term problems were, to find whether some of them could be avoided from the very beginning. An azimuth-distance coupling line for couples of plots was something that was missed, as it is available in real world but not in the exercise, to both measure but as well, to keep linked traffics that can affect each other. 3) Keep the traffic as close as possible to its original path, specially near the airport area, then keep it holding (geofenced in its surroundings) once it is at a fast-to-cross-from location and, once according to the speed of VFR and IFR traffic, no conflict is expected, release the geofencing. 4) Apply cross behind but, as well, specially when separating from arriving traffic, use a cross in front of techniques. Mind that no wake turbulence has been considered in the exercise. 5) VFR and IFR free routes, just meant for drone operations in the vicinity of the airport seems a good aid. Then, the separation is procedural, not tactical. Shorter flight paths for drones would be possible, apart from the defined drone route when no IFR/VFR traffic is operating. I.e., cross on top of the ARP of the airport seems a good approach. In this case, the VFR route crossing the ARP should be modified to keep it procedurally separated from the drone operations route. 6) Deactivation of geofences right on top of RWY were missed. They would be very helpful and would, in same cases, enable a shorter crossing route for drones operating N->S and S->N.
531007	1) I prioritized having 'my' traffic under control. Protecting all areas where they would evolve. This time not taking too much into account drone trajectories. 2) I cleared reserved areas as soon as it was possible.
531008	The strategy followed has been a dynamic activation and deactivation of geofences, similar to when a VFR vehicle is told to cross a field 'behind' another vehicle, that is to say, a strategy based on 'conditional instructions' given to drones by activating and deactivating geofences. Also important to mention the fact of taking advantage of the drone speed or the fact that quad-copters can hover.
531009	I protected the ILS area and the go-around path fencing the area and basically forcing the drones to wait. I changed the drone route few times according to availability due to manned traffic using the area. I protected every 'moving dots' from other traffic.

F.3. Experiment Scenarios

Table F.6: Experiment Scenario 1 - Please explain your solution strategy during this scenario

Participant	Answer
531001	I started looking at the routes for the manned aircraft in order to keep them safe and clear. After that I looked at the routes for the red drones in order to 'play' with the geofences in order to keep as shorter as possible the routes for them. The last priority for me was the light blue drones.
531002	Activate geofences for drones to make longer routes until conflicts are solved then deactivate everything
531003	The medical drone in the north was re-routing all the time due to opening/closing some geofences. Those actions were intending to block other drones, but this medical drone was effected all the time. It's (obviously) not taking into account that some fences are to be removed in a few minutes.
531004	I activated one geofence to be sure that departure was able to climb and be higher than the drones in its trajectory. Once it happened, geofence was disabled again. Regarding the arrival, I tried to calculate its altitude during the descend and considering the altitude of drones in its trajectory, no geofence was needed to secure their separation. Vertical separation was maintained during the descend.

531005	In short: used geofencing to direct the drone in a certain direction. Actively block the final approach and beginning of the departure, and when the manned traffic is gone unblock it for drones to fly direct. Block helicopter final approach route so the low-priority drone was proceeding southbound. Higher priority drone was able to proceed northbound, because it was fast enough to be clear with the track in time.
531006	Sometimes pressure to push high-priority drones in the sequence can make you lose separation near the RWY threshold. I had the chance to make a cross-before with the first priority fixed wing drone, but there was no room for the second. Not being able to make the drone hover in a geofenced area for a sec or two is a big deal in this case. The drone tries to leave the geofence but, sometimes, just hovering/circling (fixed-wing drones) is enough, so that would be helpful to make flying distances much shorter.
531007	I prioritized IFR traffic, protecting approach and potential go-around areas. That implied that some drones would not find a trajectory so I would unblock some area so that they get closer to be ready to cross the runway axis when an opportunity would arise later on.
531008	Strategy similar to the previous scenarios. In this experiment the protection of possible missed approach paths has been considered. When doing so, a quad-copter has been ruled out of moving since it was hovering north of the field and when protecting the MA for RWY 06 there was no possible trajectory for it.
531009	I tried to plan straight routes for drones when crossing the critical aerodrome areas (both ILS and go-around patterns). I also played with fences to make the drones to hold position and I missed a button to make the drone hold short to the next geofence.

Table F.7: Experiment Scenario 2 - Please explain your solution strategy during this scenario

Participant	Answer
531001	I started like in the first scenario. As the blue drones has the lowest priority for me, I prefer to stop them instead of reroute them in a way that will cause me a trouble later.
531002	Trying to activate the minimum amount of geofences which affect the maximum amount of drones, to solve conflicts efficiently.
531003	I tried to achieve horizontal separation all the time, but halfway through I realised the extremely low altitude of drones gave me the opportunity to keep them rather close to manned traffic. Only the final-area and upwind-area are to be avoided.
531004	Experienced a conflict with a slow and low drone which trajectory was in conflict with an arrival. Trying to reroute this slow drone to avoid this critical area, I ended up with a conflict an a difficulty to move the drone out of the area given its IAS. IAS should be taken into account much earlier to avoid slow and low drones in critical areas.
531005	Again block routes that require the crossing of the final approach and beginning of the departure. When the traffic is clear (or in a base or final turn), the drones can proceed direct, because the drones will not "hit" the traffic anymore.
531006	In this exercise I estimated the crossing altitude of incoming traffic (arrivals) to check whether vertical separation of about 500ft was secured or not. When I was not sure, I kept a foot on the safer side, and geofenced the final left-base turn area to runway 06.
531007	I protected all VFR trajectories in the area potentially affected by the drones that appeared in the exercise. In a real situation, as there could be more drones departing somewhere else, I would have protected their complete trajectory in the CTA. Then I started freeing the areas as soon as there was enough separation guaranteed (vertical or horizontal), and they were no longer needed.
531008	Strategy the same. Comment on drone trajectory: a geofence can be deactivated so that a particular drone passes through it i.e. a geofence protecting the missed approach for the runway in use can be deactivated so that a drone can cross as long as there are no traffics approaching. But this does not mean all drones must pass through that deactivated geofence. At a moment, it can be interesting that one drone flies the shortest trajectory within its ellipse, whereas another drone should fly a longer one so that it surrounds the field, for instance.

531009	I tried to change drone routes but the geofencing system limited my planning since the fences affect all drones in the area even those I planned to reroute in advance. Geofencing is the way we have to change the route but maybe a pre established alternatives such as IFR standard departures should be available.

Table F.8: Experiment Scenario 3 - Please explain your solution strategy during this scenario

Participant	Answer
531001	I decided to give the highest priority to the medical helicopter, so I created like a street of geofences all along its route. This means that one of the delivery drones couldn't go along his route, but this is not a main problem for me in the case I have an emergency helicopter.
531002	ILS conflicts easier to solve. Loiter drones to solve conflict with helicopter.
531003	I made the medical drone (crossing final 24) fly N-E a bit, to make sure it could cross final at a larger distance from the field, in order to be able to cross below IFR inbound traffic (because that is still at higher altitude). The helicopter destination was closing some routes for the low-priority drones in the north. Only option was to wait for the helicopter to land.
531004	First I tried to maintain separation between arrival and departure with drones in their trajectory. To that I had to reroute two urgent drones, adding some delay in their route just to avoid them to enter into the critical areas. One of them suffered much more delay when route changed to the other side of the airport to avoid conflict with departure, I tried to rerouted as soon as possible to the original path once the departure was higher. Finally, to allow the helicopter descend, I activated one geofence which was destination point for one of the drones, causing a lot of delay for this one (purple mark).
531005	Priority drone in conflict with landing traffic: try to let it hold on the location by adding geofences (basically flying circles). When landed traffic got past, geofences removed but flying around the airport was in the end quicker. Priority drone in conflict with departure traffic: move it a bit more to the west, so the departure could proceed southbound. Other drones in conflict with helicopter: target was on the northern side of a fence, so also blocked the neighbouring northern fence to let the West-East drone fly via the South. One drone was stuck, too bad.
531006	This exercise is beautifully designed, because it gives the opportunity to apply: Procedural separation (geographical) in the example of drones operating north of the field with traffic landing on a helipad on that area too, but being situated apart of the drone landing pad. The vertical separation of the helicopter operating north with a W->E crossing drone was not clear, so I kept the quad-copter hovering for a sec to be sure that it was going to cross behind the helicopter, which indeed was what happened. In the airport vicinity, a fixed wing drone was intending to cross over THR RWY24, but no vertical separation could be provided with the incoming IFR traffic, so a left base on north pattern was forced through geofencing of the approach cone of RWY 24. Then wen possible, geofencing was cancelled and the fixed wing drone returned to its original path. Maybe I could have let it go back to is original route and reduce the 2.7 minutes delay, but I was busy with the north helipad and drone-landing pad on the north side of the field. For another quad-copter operating E->W where vertical separation could not be provided with an IFR/VFR arrival a horizontal separation with geofencing was provided, and left the problem solved. The huge speed difference between IFR/VFR and drones is challenging to analyze whether some actions are needed at all.
531007	I protected again approach and 'go-around' areas for IFR traffic. And whole trajectory of VFR. By the end of the exercise I was not certain about separation of VFR with drone so I selected an additional geofence. And then liberated areas as soon as possible.
531008	No major differences regarding the strategies used before. Possible missed approaches are not taken into account.
531009	I was missing the 'hold position' button all the time for drones. As I was very focused to attend a medical drone and to make it fly as fast as I could to the destination I missed the helicopter leaving the field.

Table F.9: Experiment Scenario 4 - Please explain your solution strategy during this scenario

Participant	Answer
531001	It was not so easy to keep clear and safe the medical helicopter route. I tried to use the geofences near the final destination of the helicopter but the final situation was that the delivery drone stayed so close to the helicopter because it could not calculate another route to his final destination.
531002	More drones, important to know where they are going, know the routes.
531003	Closing airspace in order to create a safe track for the helicopter affected the intended routing of a medical drone in the north, unable to find a path. But I couldn't keep it flying in the right general direction, because it would be unsafe south of the field if I didn't close the airspace there.
531004	There were two drones in conflict with departure, both at different altitude. To deal with the departure, I rerouted the highest one avoiding the conflict and I had to decide the best route for the lowest, one of the options was in conflict with an arrival so finally I decided to route it one way of the airport, causing a huge delay. Also, to deal with the helicopter and its descend, some geofences were activated to avoid the destination point and allow its descend.
531005	In general, try to block the direct routes so manned traffic can depart and land. When departed traffic is high enough, remove geofences. Landing location and approach of LIFELN is blocked for the slow, low-priority drone. The faster priority drone was able to cross the track in time and absorb just a bit of delay.
531006	This was a playful scenario. This time vertical separation has been our friend. I took about 500ft as a reference to separate drones from IFR/VFR traffic, considering that WTC information had to be provided with VFR and WTC separation had to be provided with IFR traffic. Not having vertical information of the flights on the raster zone made the simulation a little bit more difficult, but still doable. Once again, I tried to leave some conflicts solved as soon as possible but, as it happens in reality, those 'solved' problems could not be forgotten because additional traffic was happening (i.e. departing traffic) so new conflicts could arise. To sum up, vertical separation was extremely useful in this case but made me the task a little bit tough since I had to check for vertical position on the flight strips bay in every case.
531007	Similar strategy, protecting IFRs first, VFRs second. And try to liberate areas when possible. This last point made me make a mistake, not protecting the full trajectory of an emergency helicopter, so not ensuring separation during its descent.
531008	Strategy is the same. In a scenario where significant volume of drone traffic comes up, specially a high number of fixed wing ones, it would be crucial to constantly give traffic information to manned aircraft since sometimes separation might be not achieved, or TA may occur.
531009	As the traffic increased it was more difficult to identify the conflicts. I found geofencing not fast enough to resolve all the conflicts. I was also missing a tool we call "LAD" (Lateral distance and azimuth, at least in Spain with SACTA system) which allows you to draw a line between 2 dots when the controller identifies a possible conflict.

Table F.10: Experiment Scenario 5 - Please explain your solution strategy during this scenario

Participant	Answer
531001	My solution strategy was to find the possible future conflicts that I will encounter which each of the possible routes I can choose for the drones.
531002	Same procedure, vectors to avoid collision (via activating geofences). Loitering when no viable deviation
531003	Closing upwind and final actually did the job. I had to open upwind once to let a drone do the crossing.

531004	Avoiding the conflict between the departure and the drones in its trajectories, I considered that manned aircraft would be much higher than drones in the point of conflict so I barely needed geofences to solve this conflict, just to make sure that urgent traffic suffered minimum delay with safety. Same happened with arrivals, being much faster than drones allowed to avoid conflicts without the use of geofences.
531005	Highest priority is manned traffic, so at first deviate the drones to make sure manned traffic can continue. When clear of the manned traffic, the drones can proceed direct. Apparently one drone could not make its destination anymore, not sorry for him, he is no priority.
531006	See Previous. This time, with 6 traffics in total, I had to put some priorities in place. That is, solve the 2 fixed-wing drones although they were quite free of conflict and then deal with the two quad-copters. One of them was left solved with a geofencing that, maybe was active for too much time, but that left me free to keep an eye on the runway because I knew that north of the airport things were already solved.
531007	Priority to IFR traffic, trying to find moments between arrivals for drone traffic to cross the runway line.
531008	Strategy idem, see notes.
531009	I had a close call. It is clear after that that a drone (even it has priority status) has to wait and there's no problem if it has a delay. Safety must be first. Crossing the field should be an option. By default, a static geofence was placed over the airport.

Table F.11: Experiment Scenario 6 - Please explain your solution strategy during this scenario

Participant	Answer
531001	The strategy was to study first all the best routes for all the drones that will not interfere so much the manned aircraft. After that, I keep to clear in my mind the priorities for each of the airplane.
531002	Same strategy.
531003	Dynamically opening/closing airspace for better routing for drone A effected the intended routing for drone B in a negative way.
531004	I had difficulties in finding a good solution to avoid conflicts when departing, since the different IAS makes hard to calculate the point of conflict and the altitude the manned aircraft will get. Regarding arrivals, the solution I am considering is rerouting to maintain traffic and drone separated horizontally.
531005	In between the two landing manned traffic: try to get the priority drone to the south side of the runway, because it was fast enough to proceed in front of the second landing traffic. The other drone was flying to the same corridor, but it would not make it (too slow), so therefore tried to make the corridor just for the priority drone and not for the slower one. Closing the corridor actually meant the faster drone would fly back, so I opened it again and tried to get the slower drone around the corridor by adding extra geofences. Drone in conflict with departure: first block the route so the departure can fly, and once the departure is above the drone it can proceed direct.
531006	During this simulation it is one fixed-wing drone that kept me busy for a while. Not being able to know exactly whether the drone is going to skip a geofenced area with a left or a right turn makes it necessary to over-geofence some additional cells to be sure that the drone is forced to fly a certain corridor. The main problem here is that, horizontal separation can be directly observed/estimated, but vertical separation has to be analyzed on another side of the raster view, complicating the separation of the traffic. An extremely useful thing is to keep the drone as far as possible from the runway threshold because there vertical separation might be easily lost but, in some other areas vertical separation is enough. I have preferred to keep horizontal separation as well considering that just leaving them fly 'below' the other traffic without having WTC interference information, with horizontal separation, if can be provided, we are on the safer side of the ops.

531007	Similar strategy. I protected VFR flights, and didn't pay much attention to drone intentions. I just tried to liberate the areas when possible to allow their operation. I think that in more realistic scenario, The tower controller would not have time to pay attention to drone trajectories, and the geofences areas should be less numerous, so it can be managed with less workload (clicks).
531008	When trying to protect the missed approach paths by activating geofences, it usually involves the fact of ruling out the trajectory of a drone. Instead, a possible 'patch' solution would be to inform the traffics when on final or when joining the VFR circuit using something like 'in the event of MA drones operating 200ft over the terrain right/left hand side'
531009	In this case I 'played' in a more conservative way. Protecting all the manned traffic and penalizing the drones over the other aircraft. It was more comfortable for me because I took less risks.

Table F.12: Experiment Scenario 7 - Please explain your solution strategy during this scenario

Participant	Answer
531001	The main problem in this scenario was to choose a route for the delivery drone that did not interfere with the route of the helicopter. In order to do that I tried to chose the geofences that create a 'good' route for the drone.
531002	Same strategy.
531003	I'm using geofences to 'vector' the drones in my intended general direction, predicting traffic in a few minutes. Not sure if that's what we are aiming for actually.
531004	Trying to avoid conflicts with helicopter when descending, I tried to reroute drones to avoid the helicopter destination point. Regarding the urgent drones, I prefer to change their trajectories to ensure their safety, however I delayed a lot their route time.
531005	Divert the priority drone a bit to make sure the VFR departure to the south could take place. The other priority drone could cross the ILS in front of the landing traffic (route to me did not see the shortest, so by adding geofences I tried to make sure he crossed in the shortest line possible - but did not succeed by adding the fences). And the non-priority drone crossing the helicopter track should cross behind it. Landing spot of the helicopter is a no-go, so will be blocked until he goes airborne again.
531006	Same approach, but just with one difference. It is with quad-copters. They are extremely slow, so they seem to be good candidates for a last-sec-geofencing strategy. Let them fly and, when entering the approach cone, block them as close as possible to that cone to, once free of conflict, cross them as fast as possible. Fixed wing drones behave similarly to a slow PA28, so they can be handled very similarly. It is quad-copters that keep you busy for a long while, since it is not easy to get rid of them fast.
531007	I experimented in this exercise to try and focus on having enough vertical separation, in 2 ways. 1) I didn't block the whole approach area, only the very final one, and the IFR traffic crossed the drone with enough vertical separation (250fr). 2) For the emergency helicopter I liberated the area in between climb and descent, allowing a shorter path for the drone. Considering it was at only 100ft. And the helicopter was flying at 700ft. This is fun but probably not so realistic.
531008	See notes.
531009	The low traffic allowed the simulation to be smooth. For the first time I think I crossed a drone on the ILS area when a traffic was already established, I think I had enough time. For the helicopter also worked smoothly.

Table F.13: Experiment Scenario 8 - Please explain your solution strategy during this scenario

Participant	Answer
531001	The most difficult part here was to give priority to the helicopter, as well as keep short the route for the medical drone, because it was to close to the delivery drone. So, as the speed for the two drones is different, this is one of the things that is not as intuitive as the rest of the exercise.
531002	Many conflicts in different areas at the same time. It was okay.
531003	Multiple situations where closing fences for one drone effected path-finding for another, while it could just continue on it's current path. This problem only occurs when dynamically changing the fences all the time. When the fences are set once, then the path-finding is perfect.
531004	I cleared the critical area for descends, since two drones were affecting the descend of two different traffics. Given the altitude of drones, I just needed to activate the last geofence when approaching to ensure traffics were always higher than drones. In departures, I reroute one drone to be sure departures were able to climb without conflict, once it happened I deactivated geofence again. I activated one more geofence in the end to avoid one low drone affected the last departure. Regarding the helicopter, I activated the geofence in its destination point so no low drones affecting its descend.
531005	Use geofencing to direct drones in a certain direction (especially the north to south crossing non-priority drone). Once he is south of the runway, he is (almost) no conflict anymore. So the priority is set to crossing (otherwise he would be flying on downwind runway 06 a considerable time). Same goes for the slow non-priority drone crossing ILS 06. Since it is only flying 20 knots, it is better to have him cross asap than to let him wait for the VFR flight. VFR flight can be delayed slightly if necessary, but it would be more beneficial in the end. Of course all crossings will take place after the landed KL.
531006	Focusing on 4 areas at a time is always challenging. South of the airport next to the river the flight path between the airport and the landing helipad is pretty short. That makes that no vertical separation can be granted, due to low altitude being reached by the traffic on its departure (no time to go high, due proximity of the landing helipad to the original departure airport).
531007	Same strategy, more traffic in this one, so it can be sometimes confusing for which aircraft you have reserved an area, and if you have done it for two, you can inadvertently free an area that should not be freed.
531008	See notes
531009	I prioritized manned aircraft over drones. I protected the routes of aircraft fencing and protecting them against the drones. When I needed a drone to leave a geofence block I would have preferred to know what the drone would do, especially on fixed wing drones.

F.4. Workload and Situation Awareness

Table F.14: How complex would you consider the traffic mix (drones and manned aircraft) to be, if encountered in real life (1-5)? Any comments on the traffic complexity?

Participant	Answer
531001	4 - I think it will be highly complex situation for a tower ATC in a case of a peak hour in which he has a lot of IFR traffic.
531002	2 - I believe it would not be high. The tools available currently, allow us to prepare in advance to the conflicts which will occur, and help us to discard them or not. This amount of traffic is reasonable and can be controlled. With the adequate training in the management of geofences, which I believe is key.
531003	4 - I was trying to control all the drones simultaneously instead of just 'let them be', blocking airspace to ensure a safe environment for manned traffic.
531004	4 - Different IAS and altitude.

531005	4 - The high taskload scenarios involve a lot of drones, and actually not so much manned traffic. On a 'busy' real day, we would be having a lot more VFR traffic. VFR traffic gives a lot of workload. The combination of VFR traffic and drones will probably give a very complex situation and result in a lot of workload. To reduce the workload, I would probably block(= add geofences) to the final approach and beginning of departure track to not have to deal with any drones there.
531006	4 - No standardized routes for drone traffic makes the things much more complex. To reduce complexity, procedural (geographical, horizontal, vertical) separation has to be implemented where possible. That reduces ops flexibility a little bit, but drastically reduces complexity because flight paths are already separated on their own.
531007	5 - Mixed traffic IFR and VFR already implies increased complexity. Drone integration has to be done with strict procedures and reserved areas, in particular for crossing runway.
531008	5
531009	4 - It really depends on how much control of the drones you have and how defined the procedures are.

Table F.15: How high would you rate your overall workload during the high taskload scenarios (1-5)? Any comments on the workload?

Participant	Answer
531001	4
531002	2 - It was reasonable. Probably going through another sets of scenarios would make it even more reasonable. Now that I have a training in geofence management
531003	4 - Same as above
531004	4 - I find stressing to maintain this complexity along time. The longest the simulation goes, the most stressing it becomes.
531005	3 - Basically at the start of the experiment, you have a 'peak' in workload, where you have to check all the flights and drones, and to see which are conflicting. Then you block any drones crossing the final approach and beginning of departure, until the aircraft has passed by and the drone can continue its way. Knowing where the helicopter will go, you add geofences to the final approach and landing site and then sit back and relax. The workload is pretty high when trying to actively control the drones (which is more fun too). In these experiments, it is okay. But from experience, you always have to be ready for an unusual situation (e.g. emergency, VFR crosser who blocks the frequency for 30 sec). So most likely, the efficiency for drones will go down if the workload increases.
531006	4 - Not having to deal with communication at all reduces complexity. In real life, having to give traffic information to VFR traffic would increase the workload.
531007	5 - It was high but because I was trying to fight with liberating areas and reserving areas, which has consuming my efforts. The scenarios were not of high workload "controller-wise" as there was no traffic separation actions to be performed. That is why combining this activity (reserve and freeing areas) with real controller load can be too much.
531008	4
531009	4 - Geofencing and re-routing drones is a heavy task. In contrast, IFR and VFR traffic are very prediclongtable and maintain the workload to low levels (at least in the simulations)

Table F.16: How high would you rate your overall situation awareness during performance of the task (1-5)? Any comments on the situation awareness?

Participant	Answer
531001	5
531002	5 - I had to play with the zoom. But the number of aircraft made keeping situational awareness possible. Furthermore, the airspace with which we are dealing is not huge, so, you are aware of what is going on every where.
531003	5
531004	3 - Learning with practice, given the different behaviours (IAS, altitude) to be taken into account. In the last one I found much more confident.

531005	4 - Once you have checked all flights and drones, the situational awareness for me was quite high. You have a good idea where they will approximately go. It could be more efficient if you were to see the altitude of the drones (especially when you know when to remove a geofence if the departed traffic is above it), but this would give a lot of clutter on the radar display. Basically this only makes sense for a limited set and time during the experiment, but it would make the initial situation assessment more helpful.
531006	4 - Some things were missing: location of helipads, location of drone op corridors, location of drone landing and departing pads, altitude information on the traffic plots on the raster area made the situational awareness to get reduced.
531007	4 - At some point I didn't realize for which aircraft I had reserved the areas.
531008	4
531009	2 - The predictability of the drones is very low, this requires you to put a lot of attention during the 'shift'. Working with drones at this level in real life has to be exhausting, because you are taking a lot of critical decisions without a clear procedure. Creativity is good for unexpected situations but not as a way of working on a daily basis. Also humans can be very unpredictable and what we think might be good, might not work especially in situations never had before, such as drone management. A training with simulations must be carried out.

F.5. Geofence Size

Table F.17: How do you assess the usefulness of geofences as a tool to perform the tasks given to you? Please provide examples in your answer

Participant	Answer
531001	I think that the use of geofences is a great tool to control drones in the CTR but sometimes I used them just to just stop the drone in the air to give priority to the manned aircraft. Maybe there would be another way to stop them.
531002	It is very useful. Because small size of geofences allow smaller deviation and you can some sort of fine tune the routes which you want the drones to make. Especially when crossing the ILS and avoiding large aircraft.
531003	It is really useful. You just need to find a way that it works for you, managing traffic flows and workload. If there is high workload in manned traffic, you should set some extra-safe fencing, losing efficiency for drones, but that's fine. When your workload drops, you get more time to fine tune the fences in favour of the drone path-finding.
531004	I find them useful since you are able to block a whole area and be aware of this space will be safe of drones while activated. For instance, to allow helicopter descends, geofences are useful to avoid drones entering. Also they allow to predict new conflicts when rerouting, I used them to allow traffics climbing and descending to reach the altitude where no drones could affect.
531005	Geofences work great for active control or block the landing site when the helicopter has to go somewhere. Even for passive control, you would just add some geofences and no drones should/could be flying there. (I on purpose add should be flying, because probably some smart guys will find a way to be able to fly when geofencing is in place)
531006	Totally helpful but those being on top of the runway should have been possible to deactivate. One annoying thing is that there is too much clicking all the time and that some geofences have to be deactivated when the drone has already gone by. Maybe the activation has to be linked to a 'crossed by a drone after a time' event to let them deactivate after a while or, i.e. , mark a zone and deactivate all the geofences in that area. The goal is to reduce the clicking tasks. Graphically a little bit more of contrast might be needed as well, but just a little bit.
531007	Fine but, the size are too small. Approach areas should be a single area (one for approach and one for departure) as IFR traffic would block them completely. Drone crossing runway line should do that always far enough so they should never interfere with IFRs. VFR corridors should also be seleclongtable as a block. But a lower limit could be established so drone operation corridors are possible below.

531008	The fact of having them has been functional, tactical and useful. i.e. you activate and deactivate them to make sure drones paths do not interfere with manned aircraft paths. the different sizes of the geofences (i.e. the ones surrounding the ILS approach) provide more flexibility for a drone to redraw its trajectory without deviating that much.
531009	They work. They allow you to have control of the drones. They work very effectively when acting as a fence (protecting specific areas) rather than using the tool to reroute drones. As an example, protecting the ILS was an easy task.

Table F.18: What size geofence do you think would support you best in performing the tasks given to you and why? (This can be one of the sizes presented to you during the experiment, or your own suggestion)

Participant	Answer
531001	I think that the size of the geofences should not be too small neither to large. If they are large, I think that the reroute will not be as efficient as it should be, and if the size is too small, I think that this will increase the workload of the ATC.
531002	In a mesh style, the closer to the ILS the smaller the better.
531003	I think this was fine.
531004	I found critical areas (last part of approach and departure) as the most restricted ones in terms of size (I had to activate some of them to avoid drones in these areas), so specially these ones could be larger than the experiment. I found the rest of them very handy.
531005	Well, since I did not see the size change during the experiment, I am probably not the right person to ask. Anyway, they should not be too small, because it would be too much clicking to block certain areas.
531006	I preferred the size in the areas far away from the airport. That might make the flight paths longer, but reduces clicking. An exception to that is in the approach area because there, the shape of the geofences helps you remember that there is where final approach happens.
531007	Blocks are okay outside of the areas mentioned above. Similar size as presented.
531008	See notes
531009	Not too big, not too small. I found the size of the fence blocks easy to work with. As the drone fly short routes the blocks had a good size to me.

F.6. Geofence Shape and Layout

Table F.19: How do you asses the usefulness of the shape and layout of geofences to perform the tasks given to you. Please provide examples in your answer

Participant	Answer
531001	I found that the layout of the geofences was chosen in a good way. Maybe it could adapted in a different way, like for the case of the helicopter, in which i had to chose a lot of geofences in order to keep clear all the route.
531002	Smaller geofences and geofences with trapezium like shapes around the ILS help reducing the amount of extra distance the drones have to cover.
531003	The layout was useful (in the runway direction, so in line with the runway).
531004	I found their shape as the most useful to calculate new trajectories when rerouting. I would avoid round shapes since they difficult to evaluate the final behaviour of drone.
531005	The ILS area should be part of the geofencing layout. So basically if you go closer to the aerodrome, the shape should it such as to incorporate the circuit area, departures and approaches and ILS area. Outside the aerodrome, the shape and layout is not so important. You just have to be able to block a certain city for example if the helicopter has to go there.
531006	See above.
531007	As mentioned ILS should be single block. Maybe also VFR circuit areas could be a single block even if these two could overlap. Maybe instead of a grid it would be more useful to freely define areas, basically a circle around AD. and a circle around landing areas for helicopters.
531008	ATZ example (circular shape centered at the aerodrome)

531009	The ILS shape is effective, it protects exactly the areas you want to secure. Otherwise I found the rest of the grid should be regular because, maybe other shapes such as hexagonal could work as well. I had few difficulties when fencing a drone when the purpose was for them to hold positions due to the irregularity of the grid.

Table F.20: What shape and size of geofence do you think would support you best in performing the tasks given to you and why? (This can be one of the sizes presented to you during the experiment, or your own suggestion)

Participant	Answer
531001	I think that square geofences are not bad, but maybe they have to be adapted to the kind of airport (CTR) in which we use them. As I said before, I think that the sizes should be medium size.
531002	Squares, rectangles, trapeziums, four sided shapes I believe are the most intuitive to work with.
531003	Maybe it could be just a bit more efficient with other shapes. I can imagine a honeycomb or something would have smaller effect on deviation around the corners.
531004	They were okay in the experiment, just the minor comment on the critical areas. I found easy to get used to them as they were.
531005	See above.
531006	If clicking can't be reduced, then we have to aim for geofences that take more or less a minute to get crossed to reduce unnecessary blocking/geofencing. I guess that different trials with different geofences have to be made and that is as well a factor that depends on the airport layout, SID/STAR, VFR corridors and traffic mix.
531007	As mentioned, maybe freely place 'circles'. Instead of a grid of squares.
531008	Consider more sided polygons for the mesh (complex?)
531009	Squares were easy to work with. I'll stay with them. The size as well worked fine for me.

Table F.21: There are currently no concrete U-space regulation for separation criteria between drones and manned traffic. How do you assess the separation minima provided to you during the experiment (250 feet vertically, 2000 ft horizontally)?

Participant	Answer
531001	It was nice.
531002	I am not sure about this. Between drones it might be fine. But drone-a/c separation should be according to ICAO rules. 3NM - 5NM. Furthermore, drones might be affected by wake turbulence of aircraft if the move too close to them.
531003	Vertically it's perfect. Manned flight is 500' and above, so drones could fly everywhere at 250' or below. Horizontally there are no rules about it for VFR flights, so I think the 2000' is just constraining now. There is just 1 rule mentioning distance: 600m from buildings/high obstacles. But aircraft - aircraft separation can be as low as 1m, as long as the pilots have each other visual. No idea how to implement this for drones, but I think 2000' is too much. Furthermore: horizontal distance is always measured in NM and measurements (like runway-length) are in meters.
531004	I found them comfortable since drones operate in areas with aircraft in evolution, so specially a 250ft separation vertically is easy to get while climbing and descending. Although maybe vertically separation should be higher to be fully comfortable.

531005	In ATC approach control, the separation minima are 3 NM and 1000 ft. In special VFR conditions in the tower, the minimum separation is 500 ft. Actually, the current transponder are allowed to deviate +/- 300 ft from the indicated value. This means if an aircraft is flying at 1000 ft indicated, it might be flying somewhere between 700 and 1300 ft. I would therefore think the separation minima should be at least 500 ft. Horizontally is much harder to assess. In VFR conditions, we are allowed to give traffic information and the pilot has to apply see and avoid (class C airspace). If two VFR aircraft pass each other within 5 m and they were informed about each other, I actually don't care (as long as they don't hit...). In class G airspace they are mostly not informed at all about other traffic. So if the situation is based on see and avoid, the horizontal distance for me does not have to be specified. Special VFR conditions are going to be real tough though, because we have to separate inside the CTR. So that would be a challenge.
531006	I was aiming at 500ft most of the time to be sure that I kept the 250feet secured. I would say that, for initial drone integration on manned-aircraft airspace, 500ft should be used and, after the first months/years of operation, reduce it as it was the case with IFR traffic years ago. Packing too much drone traffic at a time might increase workload to an unbearable level. 2000ft horizontally is fine. So, 2000ft horizontal + 500ft vertical seems to be okay.
531007	250 ft seems small. 1000ft and 2.5 miles are the smallest radar separations I have seen. Other may be considered safe depending on the tools available. +- 300ft is a typical tolerance of aircraft altimeter.
531008	See notes
531009	The vertical separation should be determined according to drone performances of calculating their altitude, as well as the performance changes resulting from the battery usage (they can degraded the performance during the flight). For initial phases I think a greater separation both vertical and horizontal must be provided.

F.7. Traffic

Table F.22: In your opinion, how accurate were the flight profiles of manned aircraft?

Participant	Answer
531001	They were very accurate.
531002	There were fine. The issue with simulation is that aircraft fly too smoothly and they make turns with the exact radius with which they are supposed to do. but they are fine. It is very difficult to realistically simulate the flight of an aircraft.
531003	Very accurate.
531004	I cannot say given my experience.
531005	Even though flight profiles are specified by the charts, it depends on both weather and pilot how the airplane is being flown. Literally, expect the unexpected (especially with VFR pilots). Since the flight profiles were fixed and plotted, you can "steer" the drones actively around them. In real life, this would be a much bigger challenge, because you never know when a pilot will do something... You need to have a bigger separation between manned aircraft and drones.
531006	Better than in real life :) but the feeling of how the traffic turns, evolves and operates is quite good in the sim.
531007	It was great.
531008	Quite accurate.
531009	It was realistic, it took a little bit of time between the fencing and the action of the aircraft. It is similar with planes in real life.

Table F.23: Which of the traffic scenarios presented to you during the experiment do you think provide the largest challenge to tower control and why?

Participant	Answer
531001	The last one. As the traffic increase, the difficult also increase because I have to calculate which is the best route for each of the drone and anticipate to future conflicts that could happen.
531002	The last one. Larger amount of traffic and lots of conflicts in different areas and consecutive conflict. One aircraft affecting several drones. This happening at the same time.
531003	Crossing on final or upwind in an efficient way. Deviation is safe but not efficient. Getting the right balance there is a challenge to tower control.
531004	The last one was the most complex, with more than one departure and arrival at the same time, drones crossing both trajectories and helicopters to be taken into account. The mix was the most complex and tower has to be aware of a larger spectrum of operations.
531005	Any scenario where drones cross the active runway, ILS area and extended center-line are the largest challenge. If done in a passive way, you just add the geofences on the locations where drones should not fly and do your thing. If done in an active way, it will be a lot of adding/removing geofences in these areas.
531006	I think it was 4 and 8 because, when traffic is operating outside of the airport (helipads, hospitals, etc.) workload increases due divided attention to different areas of the screen where, at the same time, traffic does not operate on a so-standardized way as the VFR and IFR ops in the airport itself.
531007	Probably last one. What concerns the tower controller is "his" traffic, and last one had more traffic. Drone ops are secondary.
531008	Scenario 8, because the high amount of drones (fixed wings and quad-copters) as well as because of the manned aircraft flights (VFR, IFR, with an emergency helicopter)
531009	The situation with heavier workload. It is very easy to tell because its all a matter of awareness. The heavier the traffic the more attention is needed and the possibility of making a mistake or having a close call or a loss of separation increases.

Table F.24: Do you think there are any other traffic scenarios not presented during the experiment that would provide a challenge to tower control?

Participant	Answer
531001	Maybe a scenario with aircraft in emergency situations, that requires a lot of priority and a changes of routes for the other IFR traffic.
531002	Nope.
531003	Go-arounds.
531004	I cannot say given my experience.
531005	Any scenario that requires active control and suddenly an emergency or something would occur. I would probably want a button where you immediately block all drones in a certain range of the aerodrome and they would have to land immediately.
531006	Drones doing works that cannot be so easily interrupted. For example: power-line inspections, photography works, aircraft inspection, navigational aids calibration, etc. There, we would be facing a situation pretty similar to IFR/VFR traffic that we had here and that could not be managed during the sim. 'Untouchable' drone might happen as well. Loss of communication from the operator and the drone. Malfunction of the geofencing functionalities of the drone, how do they behave in that case, go-back-home or 'land here'?
531007	Yes, because there was no conflicting manned traffic.
531008	Touch and go, VRF flights orbiting, missed approaches, higher manned aircraft volume.
531009	Sure. Manned traffic doing unexpected things, having emergency situations, communication problems, runway changes, bird strikes, multiple aircraft going around and storms.

F.8. Experiment Interface

Table F.25: Did you consider the "drone endurance indications" as useful elements to complete your task? Please provide examples in your answer.

Participant	Answer
531001	Yes, I considered all the indications. The most useful is the calculated route, and the ellipse, that helps a lot.
531002	Yes definitely and it is important to be aware that drones do not have an eternal battery and consequently an eternal range.
531003	I used the destination-line all the time but didn't use the range-indicators. I just assumed that it would find a new path, and if not it just had to wait for me to open up some routes.
531004	Sincerely I did not take endurance indications into account to avoid conflicts, I tried to maintain drones out of conflict and their range was not the most important value in the decision.
531005	I actually did not pay attention to the drone endurance indication. It either goes where I want it to go, or it does not go anywhere
531006	It helped me understand what to expect from the drone when it some areas where geofenced and helped me choose more selectively the areas to close.
531007	Yes because it gave an indication of the drone intentions when they were loitering. But in real operations you would not have the time to consider this.
531008	See notes.
531009	It provided information, but I honestly thought that if a drone couldn't make it to destination because it had to wait or hold positions nothing would happen. Safety was always a priority. If a drone ran out of battery.

Table F.26: Please score all display elements on how useful they were during the experiment on a scale from 1 (not useful) to 10 (very useful)

Participant	Geofence State	Drone type	Drone priority	Drone route	Endurance regions	Drone info	Endurance marker	Flight strips	Flight labels	Text console
531001	10	4	10	10	10	7	10	7	8	8
531002	10	6	10	9	4	2	8	6	8	6
531003	10	7	8	10	4	9	6	4	9	8
531004	10	10	10	10	7	10	8	10	10	6
531005	10	10	10	10	10	8	10	9	8	7
531006	10	10	10	10	9	7	8	4	4	9
531007	9	3	9	10	8	8	4	3	10	6
531008	10	10	10	10	8	7	8	7	4	3
531009	8	8	10	10	9	7	8	2	2	3

Table F.27: How do you asses the usefulness and clarity of colour in the display? Please provide examples in your answer

Participant	Answer
531001	It was so useful, but I would change the colour of the arrival aircraft in order to distinguish them from the departure aircraft. This will help a lot the ATC.
531002	It was okay. Maybe highlight a little bit more the active geofences. Very slight change. Highlighting aircraft when moving the mouse cursor above the is very useful and the route colour is very useful too.
531003	Colours were fine and clear!

531004	Good idea to represent the urgency in the operation of each drone. Use of green for traffics and geofences was okay, no conflict in this sense.
531005	The red symbol for priority drones helps to spot them easily and know they have a higher priority. The different colors on the screen were clear and distinguishable. The drone vehicle type for me doesn't really matter, it is still a drone. The vehicle type would only be important if I have to look for it in real life, so you know what you are looking for. But since the drones are (for now) quite small, it will be hard to see them anyway.
531006	Background map should be simplified, as it is the case in real life. Labels were too small (on a 27K screen) Flight paths should be a little bit wider for IFR/VFR traffic to be sure that they can be easily distinguished from drone flight paths.
531007	No complains. It was okay
531008	See notes.
531009	It should be more clear when a fence is ON or OFF, in few cases I had difficulties when a drone was inside the block. A bigger difference may help.

Table F.28: Do you have any other remarks?

Participant	Answer
531001	-
531002	Regarding the color scheme, in my case I am used to a set of colours which might help or not the exercise. For instance, we are trained to "ignore" white colours because white colours are traffic that are not going to enter our sectors. Red is bad. The only time you get red is when a two aircraft are going to cross each other at less than 5NM and 1000ft.
531003	Most useful information for tower control is altitude and (for planning purposes) the GS. If you can plot these in the labels, then the flight strips are obsolete.
531004	Keeping the aircraft safe from drones made me reroute drones without taking into account their colour and urgency. So, in the scale of priorities, still safety of manned is higher than urgency of the drone operation.
531005	1) A beep (or something) would be nice if helicopter is starting up (basically highest priority of all). 2) Experiment focuses on active control, but in a more busy situation the focus on drones would quickly shift to passive control(Copy of our books on when to use radar screen on the TWR, to only use the screen for): Flight path monitoring on final approach; Flight path monitoring in the vicinity of an aerodrome; Giving navigational aid to VFR flights.
531006	The similarity of the simulation to real life was impressive. This was no game or simulation in the classical sense at all. The traffic's behaviour was very similar to the real life.
531007	No. Thanks guys!
531008	-
531009	As we discussed, a hold position button, a "LAD", a hold short button, visual aids about how far a IFR traffic was from touchdown so we can decide whether a drone can cross the critical area or not, and also the possibility of crossing the field.

G

Experiment Results

This chapter shows the experiment results for all participants over all scenarios in term of geofence activation times (Section G.1, Figures G.1 through G.8), geofence activation maps (Section G.2, Figures G.9 through G.16) and traffic maps (Section G.3, Figures G.17 through G.32). Note that participant 531009 has been excluded from the results, due to problem with some of their data files.

G.1. Geofence Activation Times

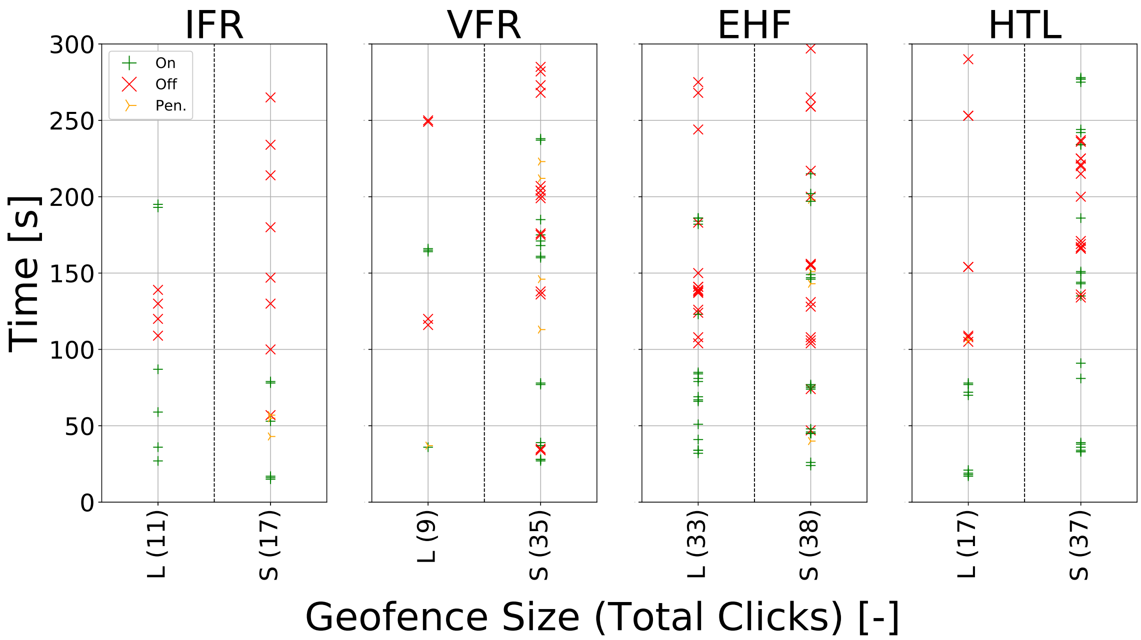


Figure G.1: Geofence interaction times of participant 531001

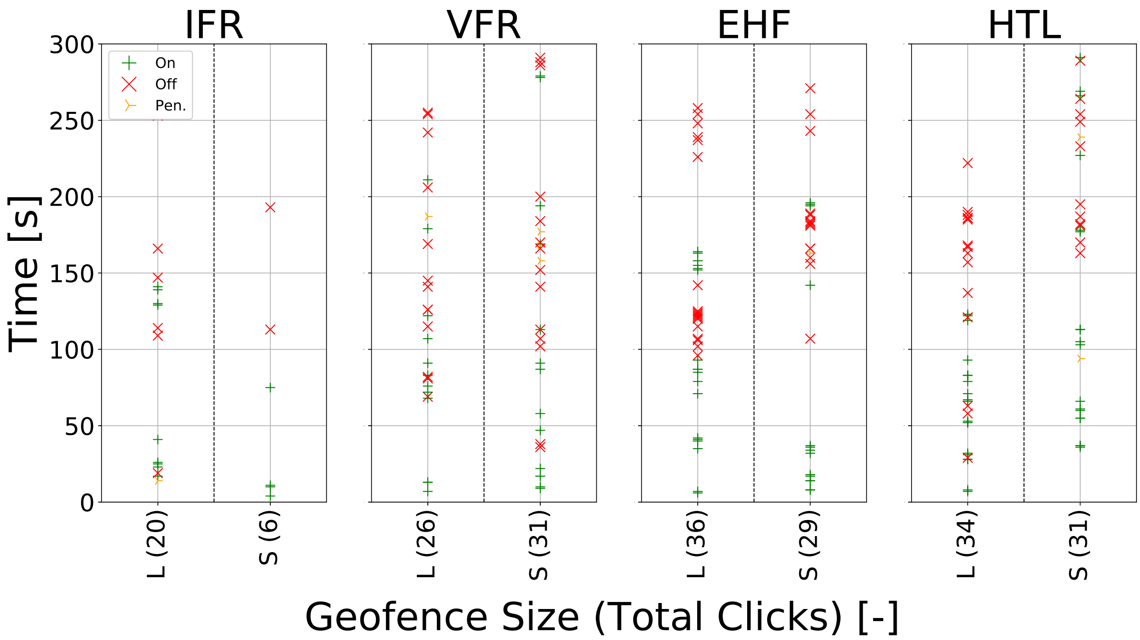


Figure G.2: Geofence interaction times of participant 531002

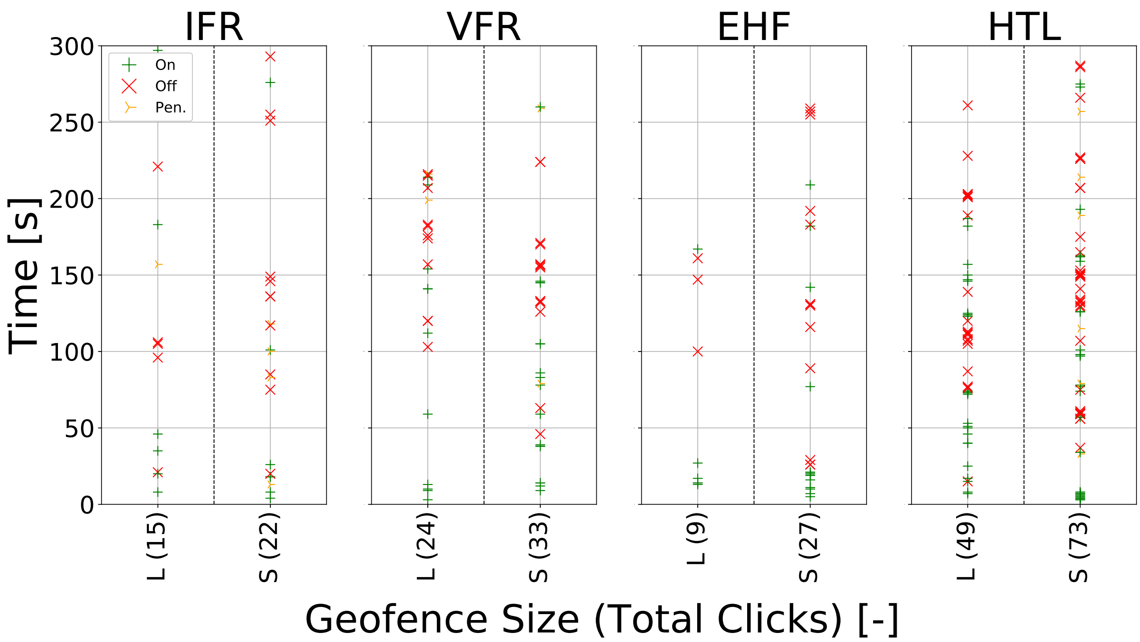


Figure G.3: Geofence interaction times of participant 531003

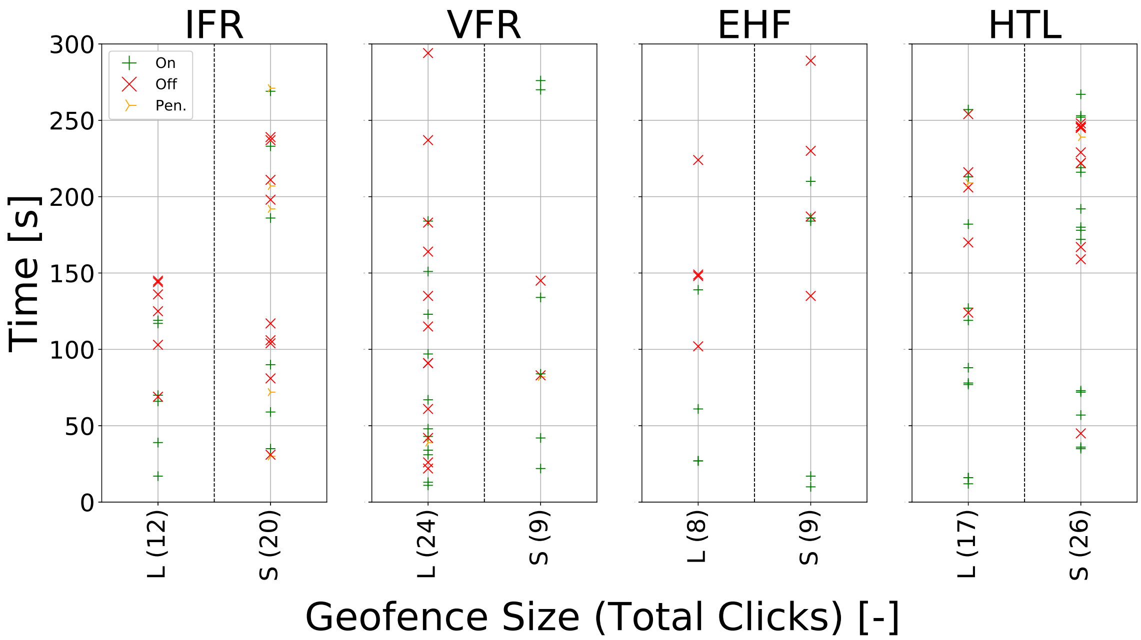


Figure G.4: Geofence interaction times of participant 531004

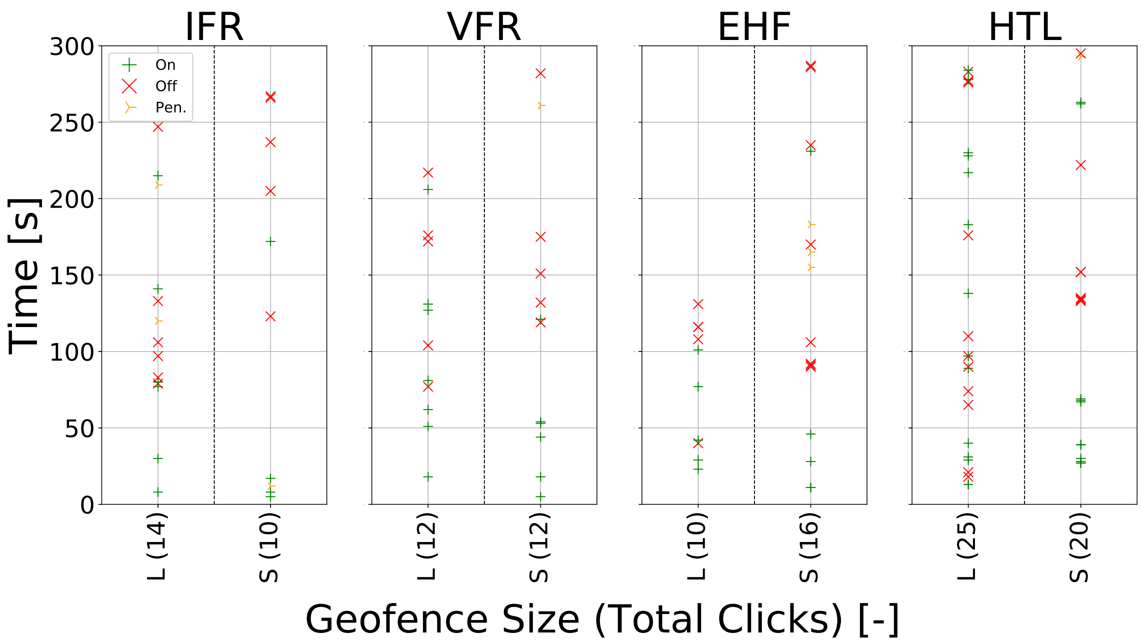


Figure G.5: Geofence interaction times of participant 531005

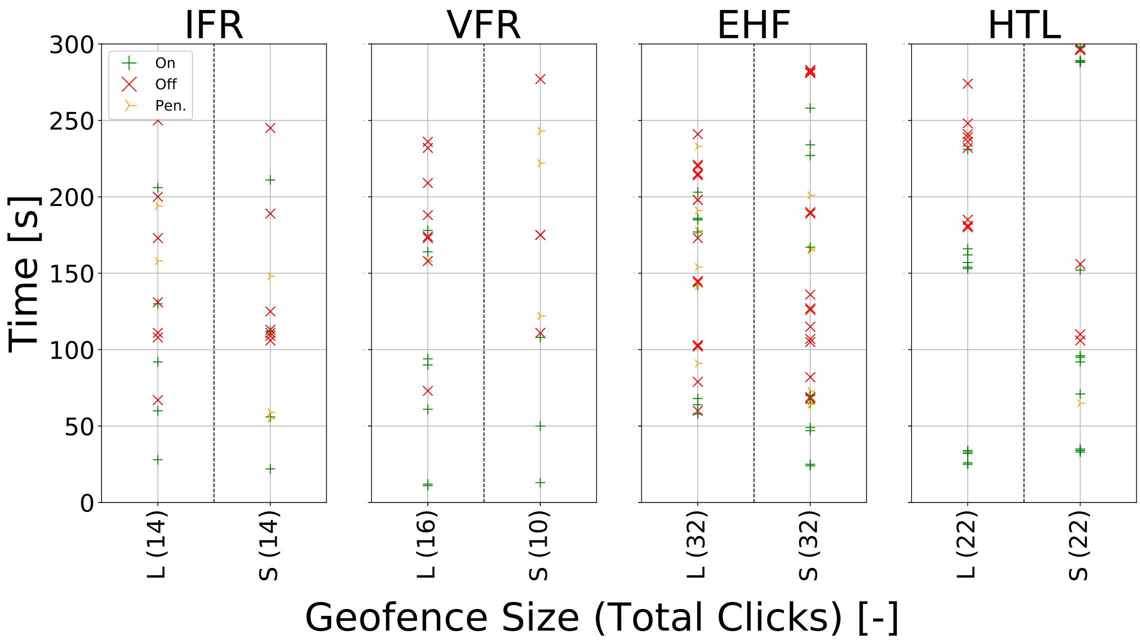


Figure G.6: Geofence interaction times of participant 531006

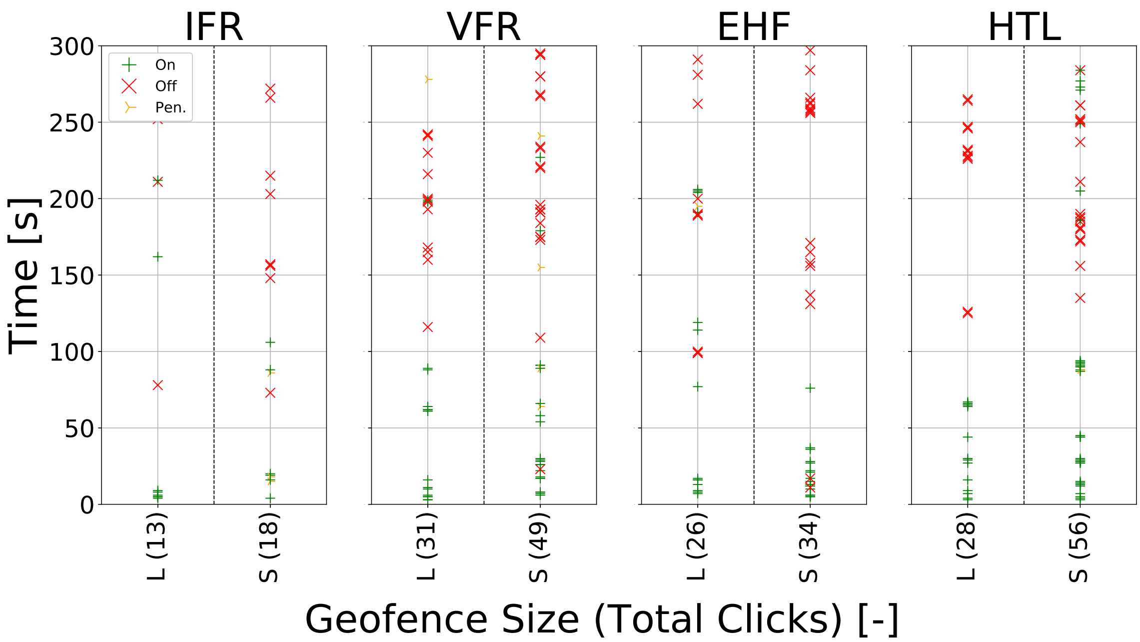


Figure G.7: Geofence interaction times of participant 531007

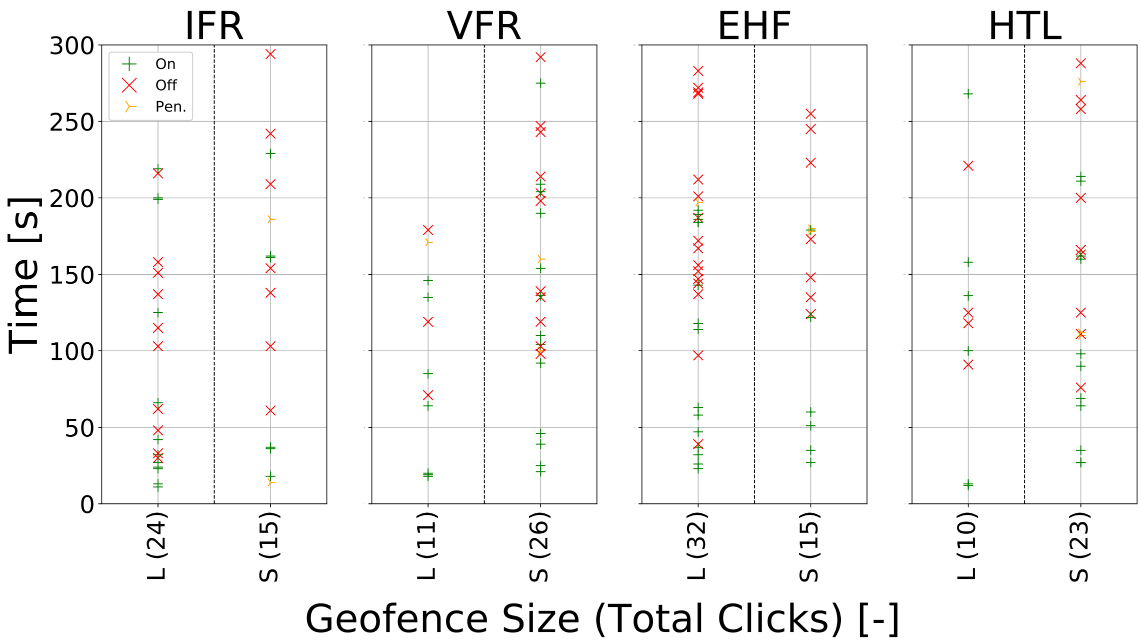


Figure G.8: Geofence interaction times of participant 531008

G.2. Geofence Activation Maps

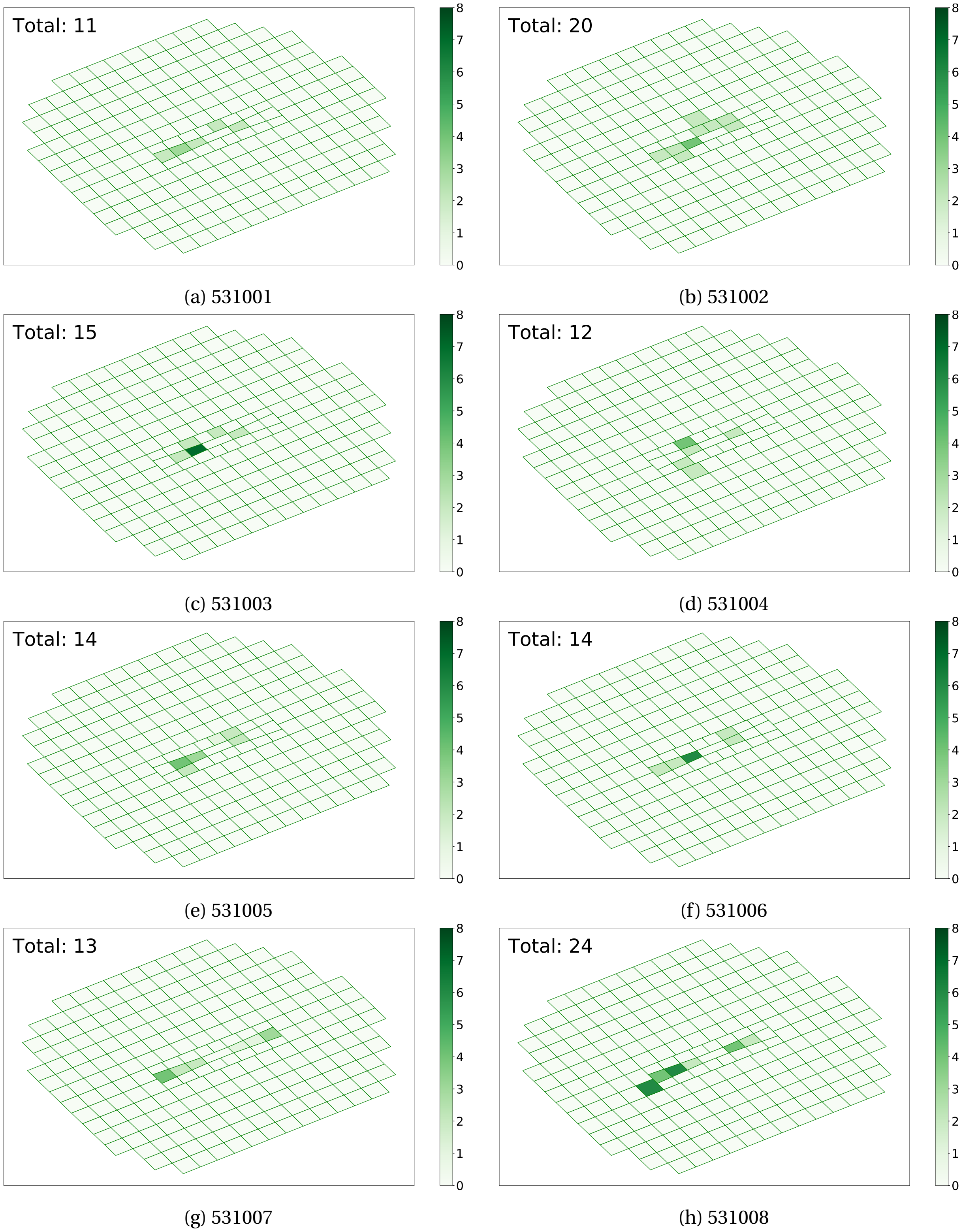
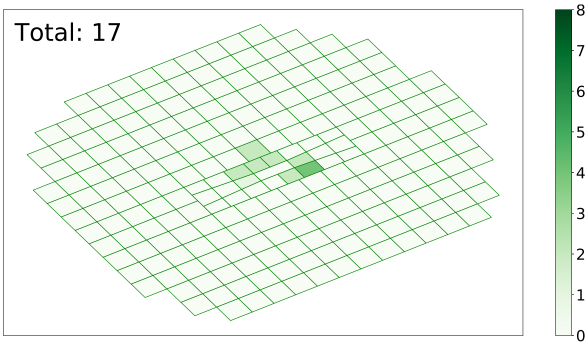
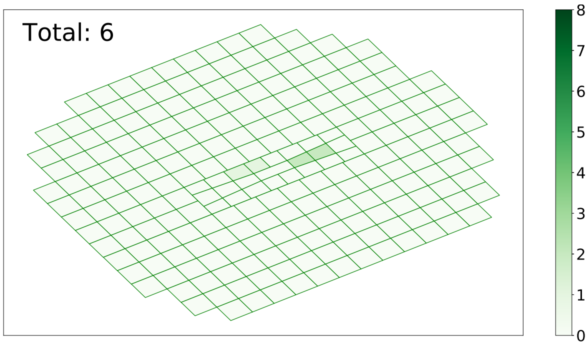


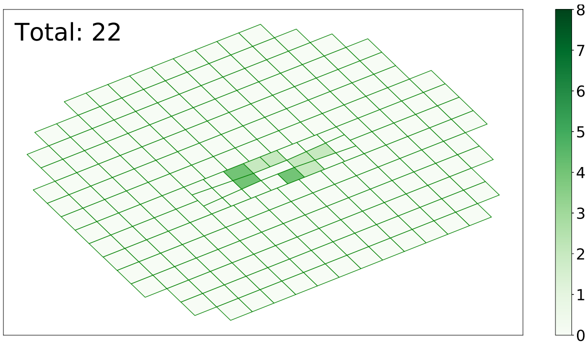
Figure G.9: Geofence activation map for IFR-L



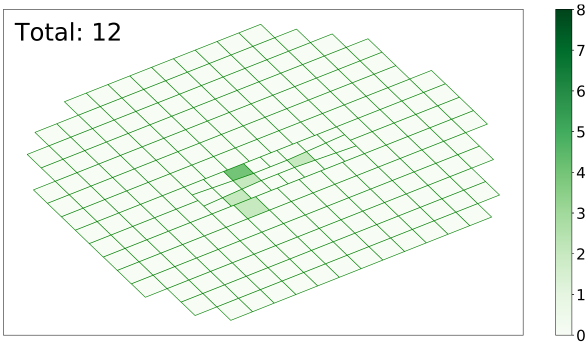
(a) 531001



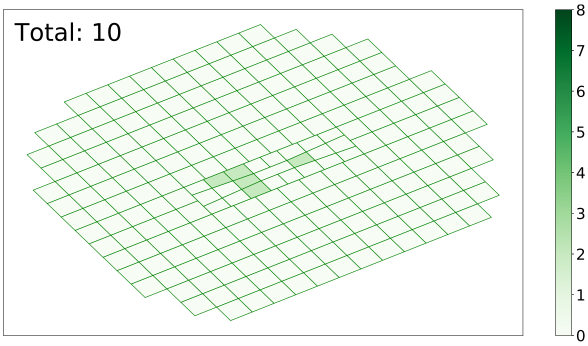
(b) 531002



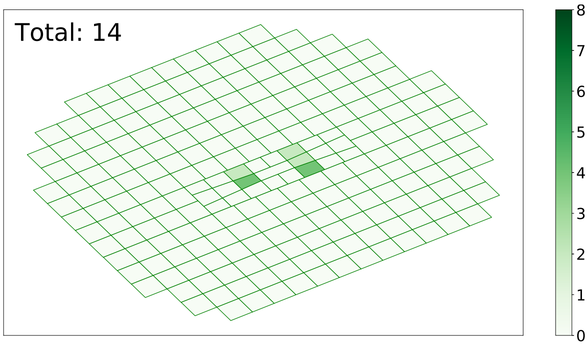
(c) 531003



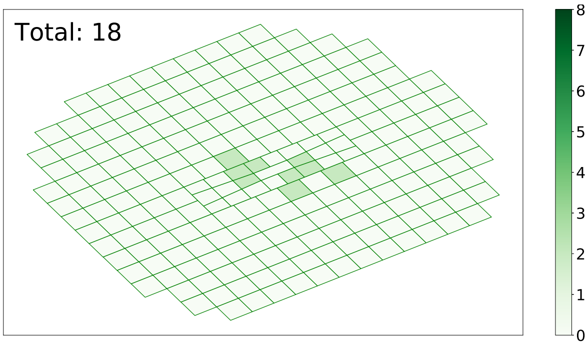
(d) 531004



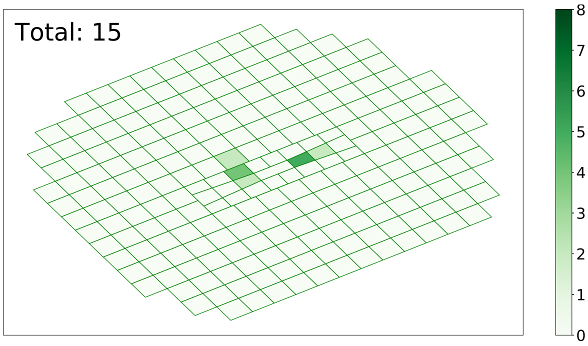
(e) 531005



(f) 531006

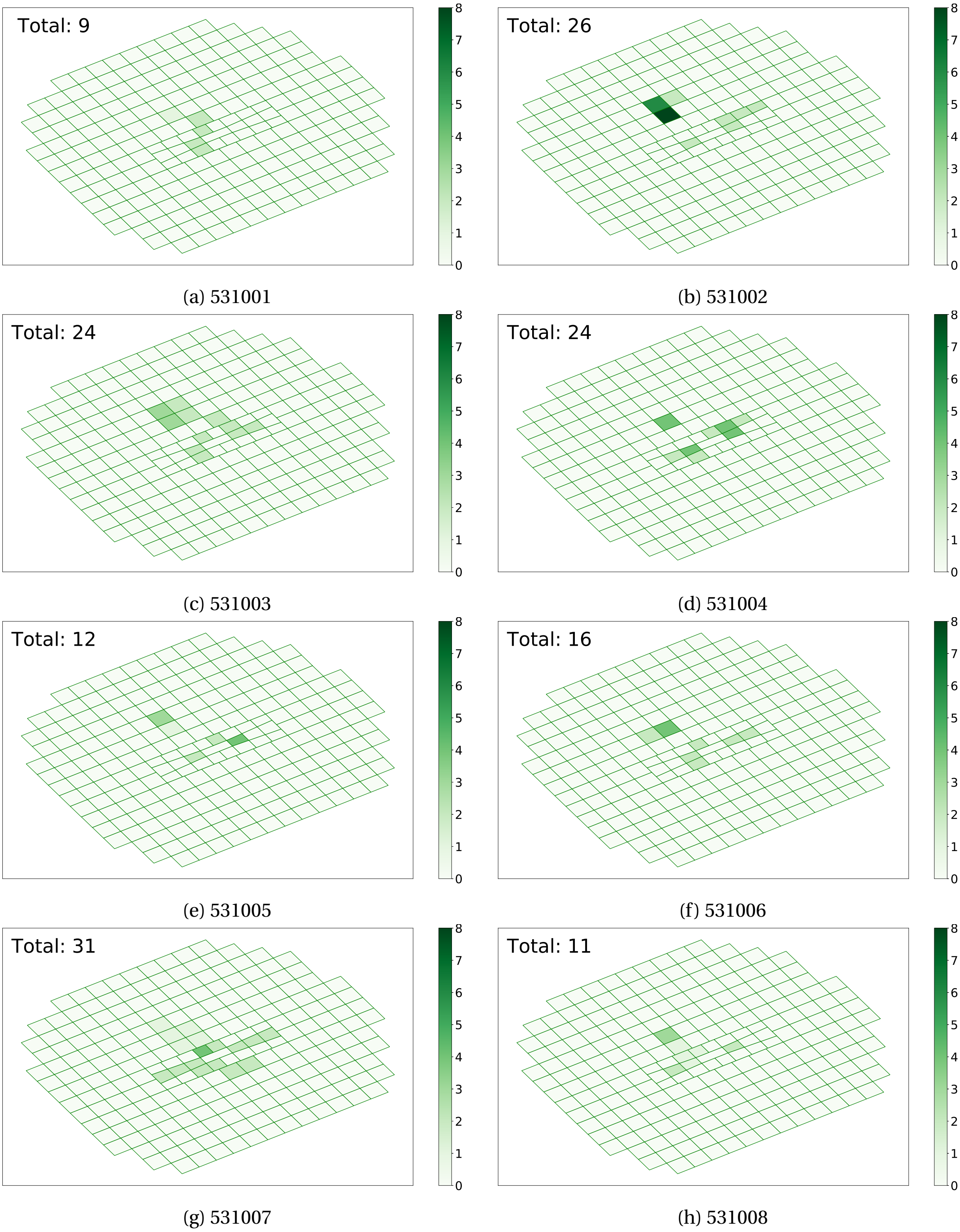


(g) 531007



(h) 531008

Figure G.10: Geofence activation map for VFR-L



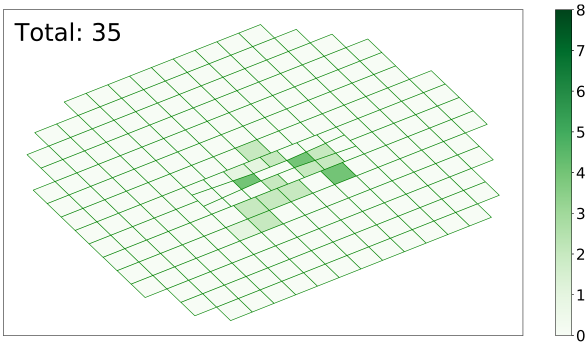
(a) 531001 (b) 531002

(c) 531003 (d) 531004

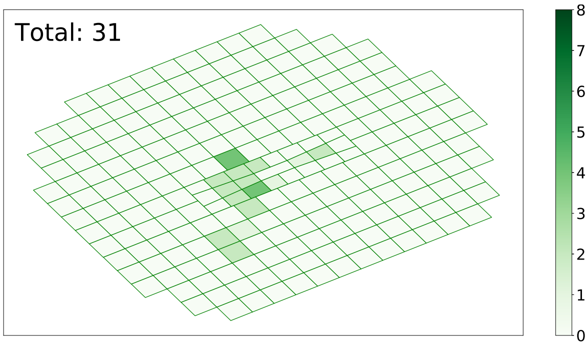
(e) 531005 (f) 531006

(g) 531007 (h) 531008

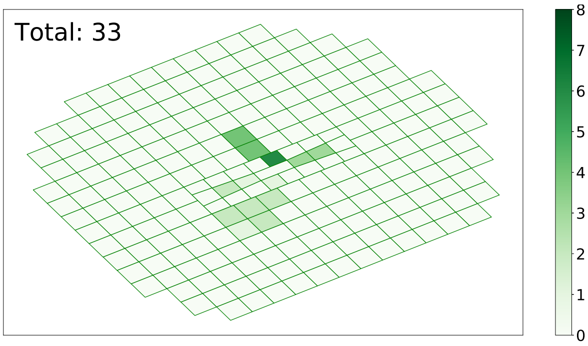
Figure G.11: Geofence activation map for EHF-L



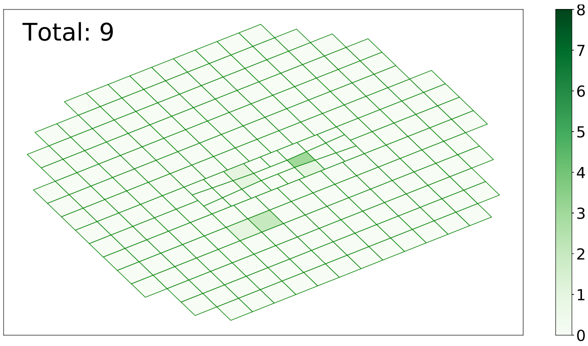
(a) 531001



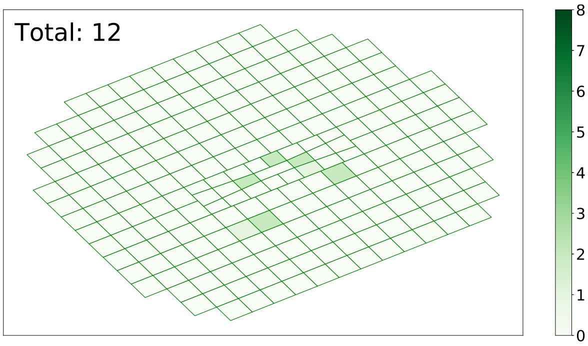
(b) 531002



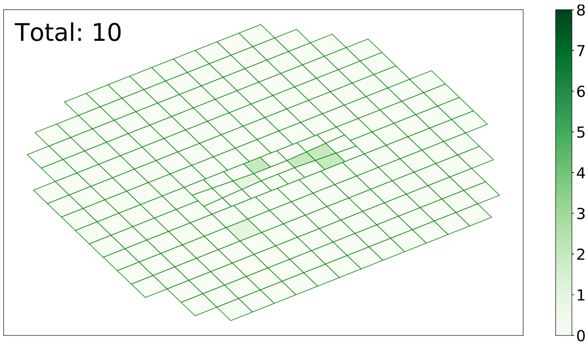
(c) 531003



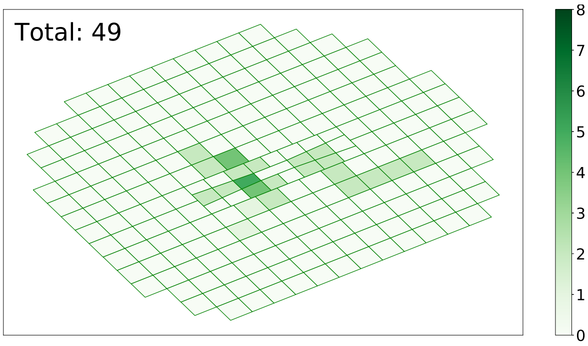
(d) 531004



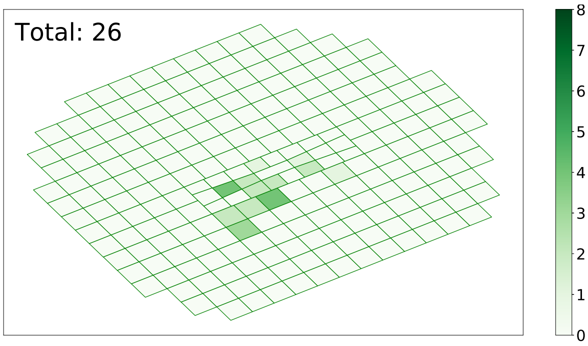
(e) 531005



(f) 531006

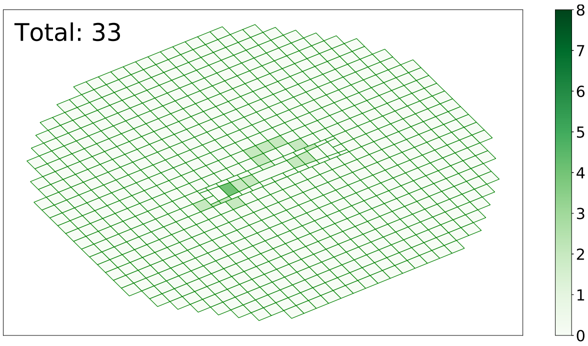


(g) 531007

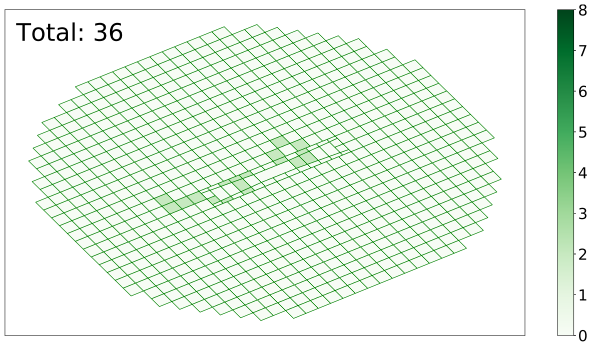


(h) 531008

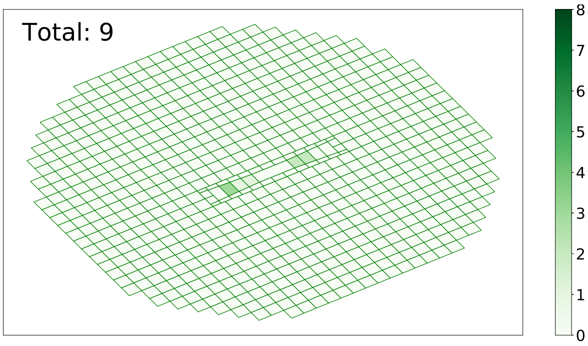
Figure G.12: Geofence activation map for HTL-L



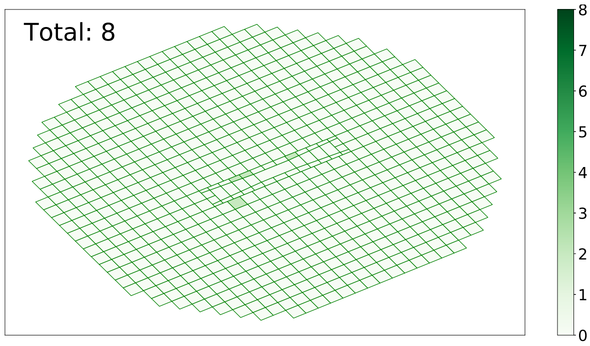
(a) 531001



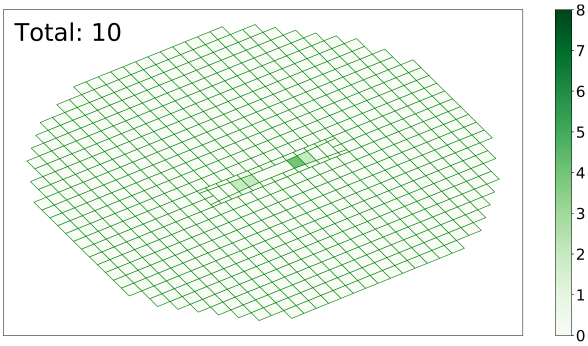
(b) 531002



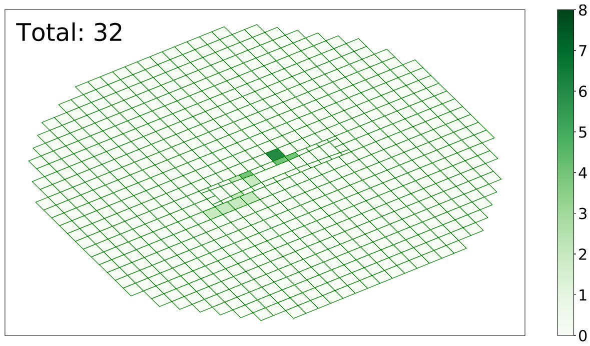
(c) 531003



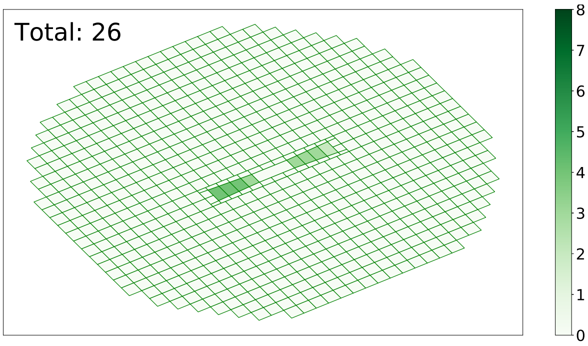
(d) 531004



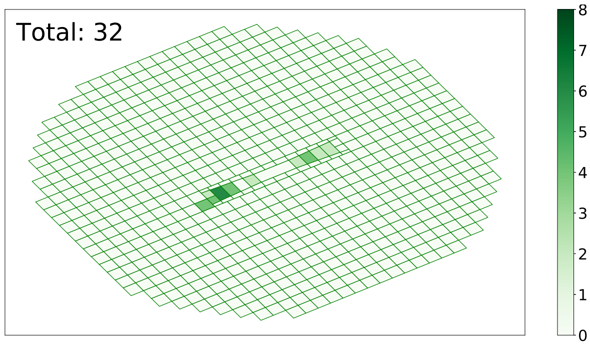
(e) 531005



(f) 531006

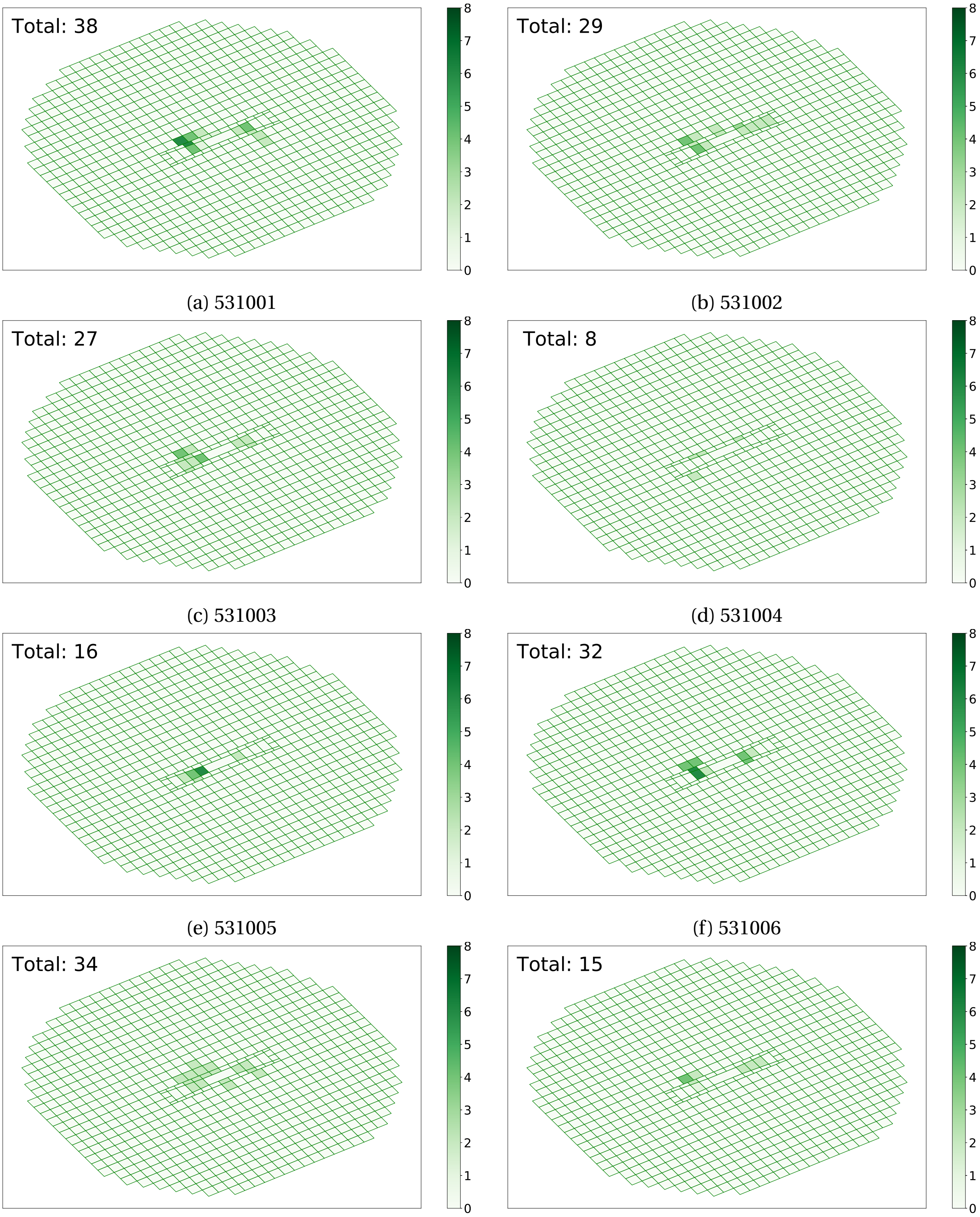


(g) 531007



(h) 531008

Figure G.13: Geofence activation map for IFR-S



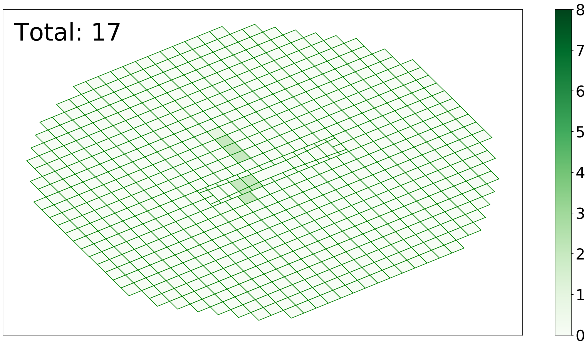
(a) 531001 (b) 531002

(c) 531003 (d) 531004

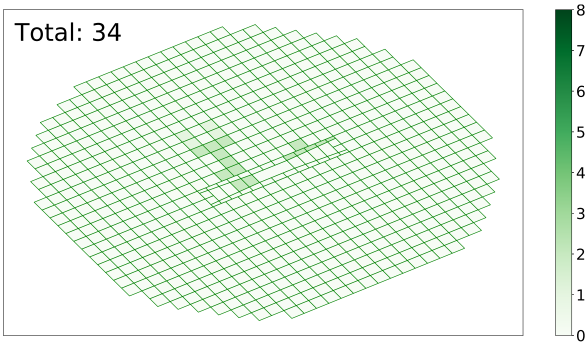
(e) 531005 (f) 531006

(g) 531007 (h) 531008

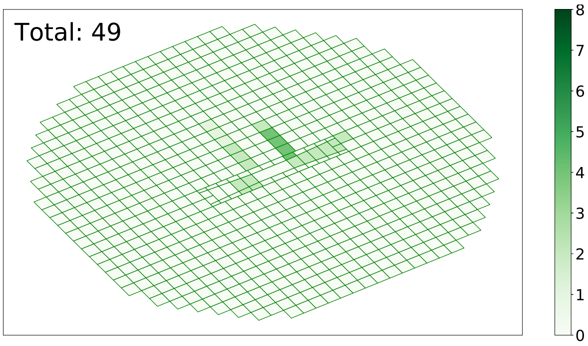
Figure G.14: Geofence activation map for VFR-S



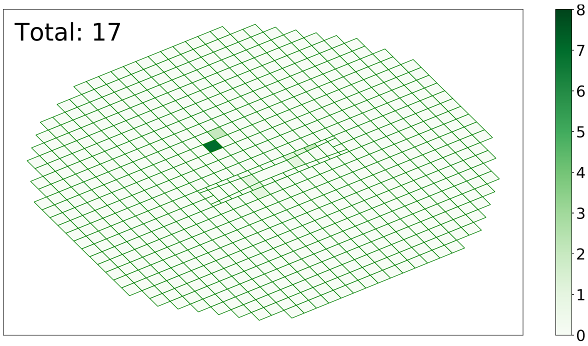
(a) 531001



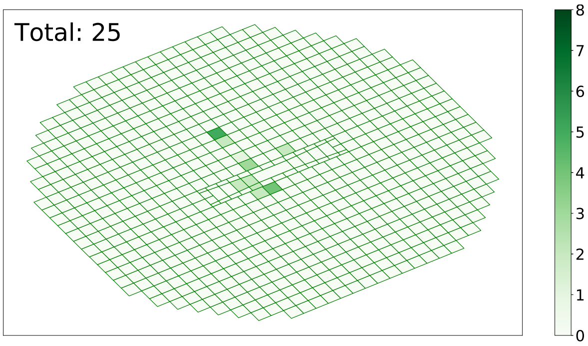
(b) 531002



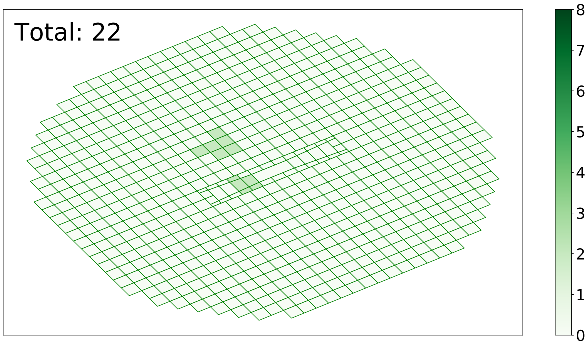
(c) 531003



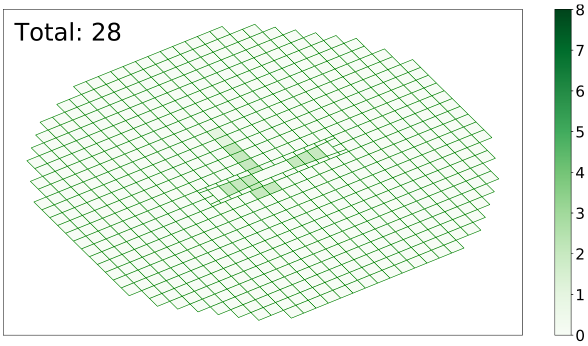
(d) 531004



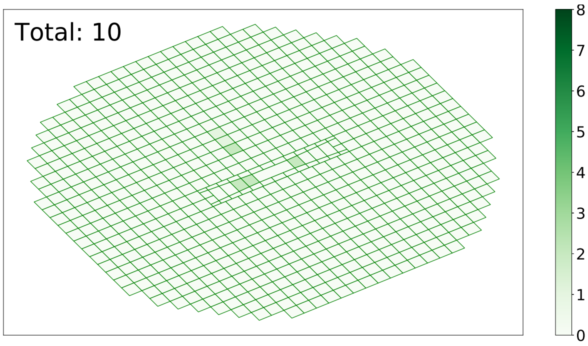
(e) 531005



(f) 531006

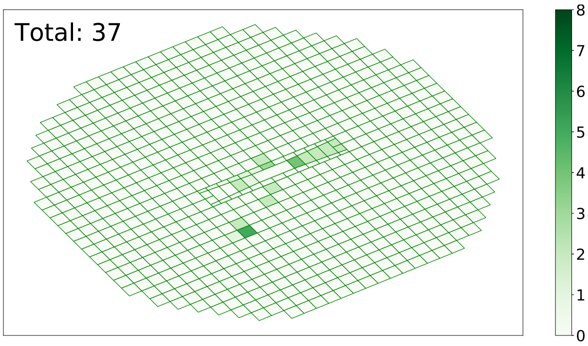


(g) 531007

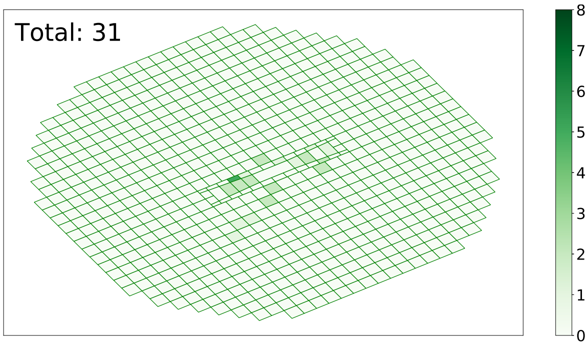


(h) 531008

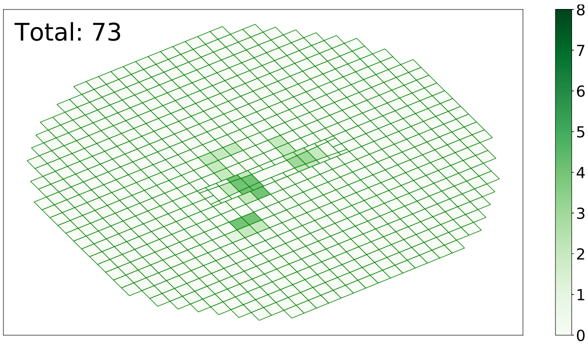
Figure G.15: Geofence activation map for EHF-S



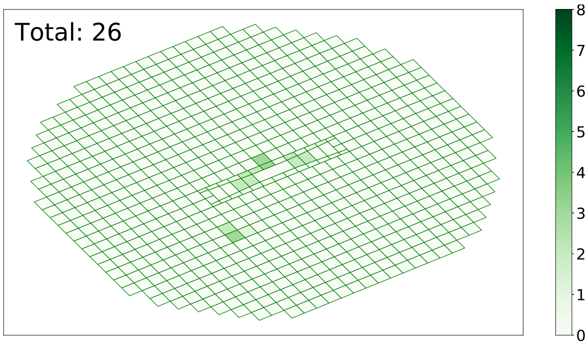
(a) 531001



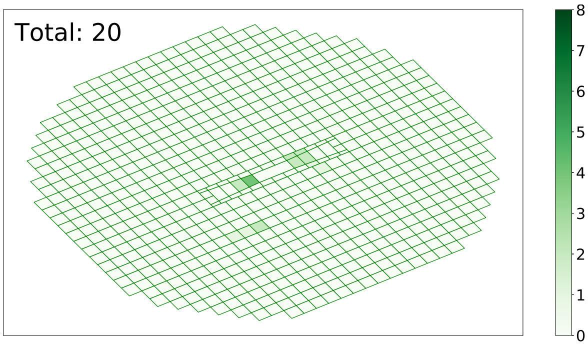
(b) 531002



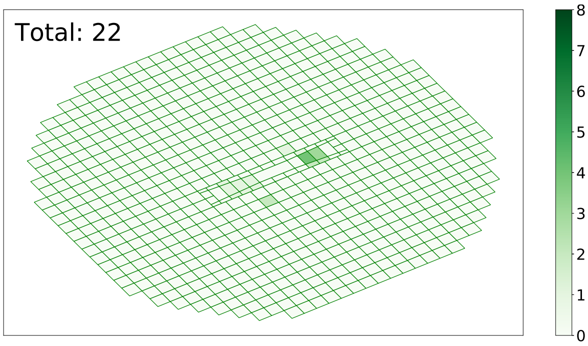
(c) 531003



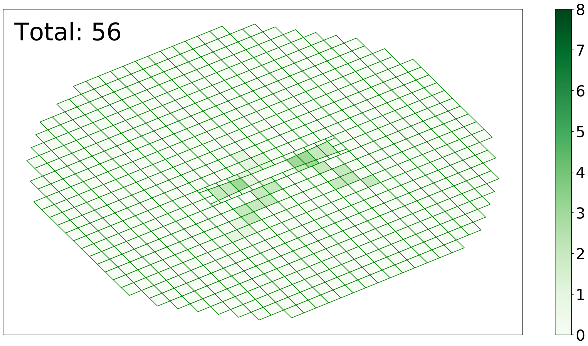
(d) 531004



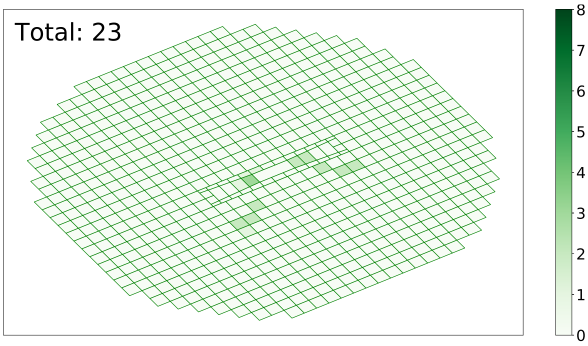
(e) 531005



(f) 531006



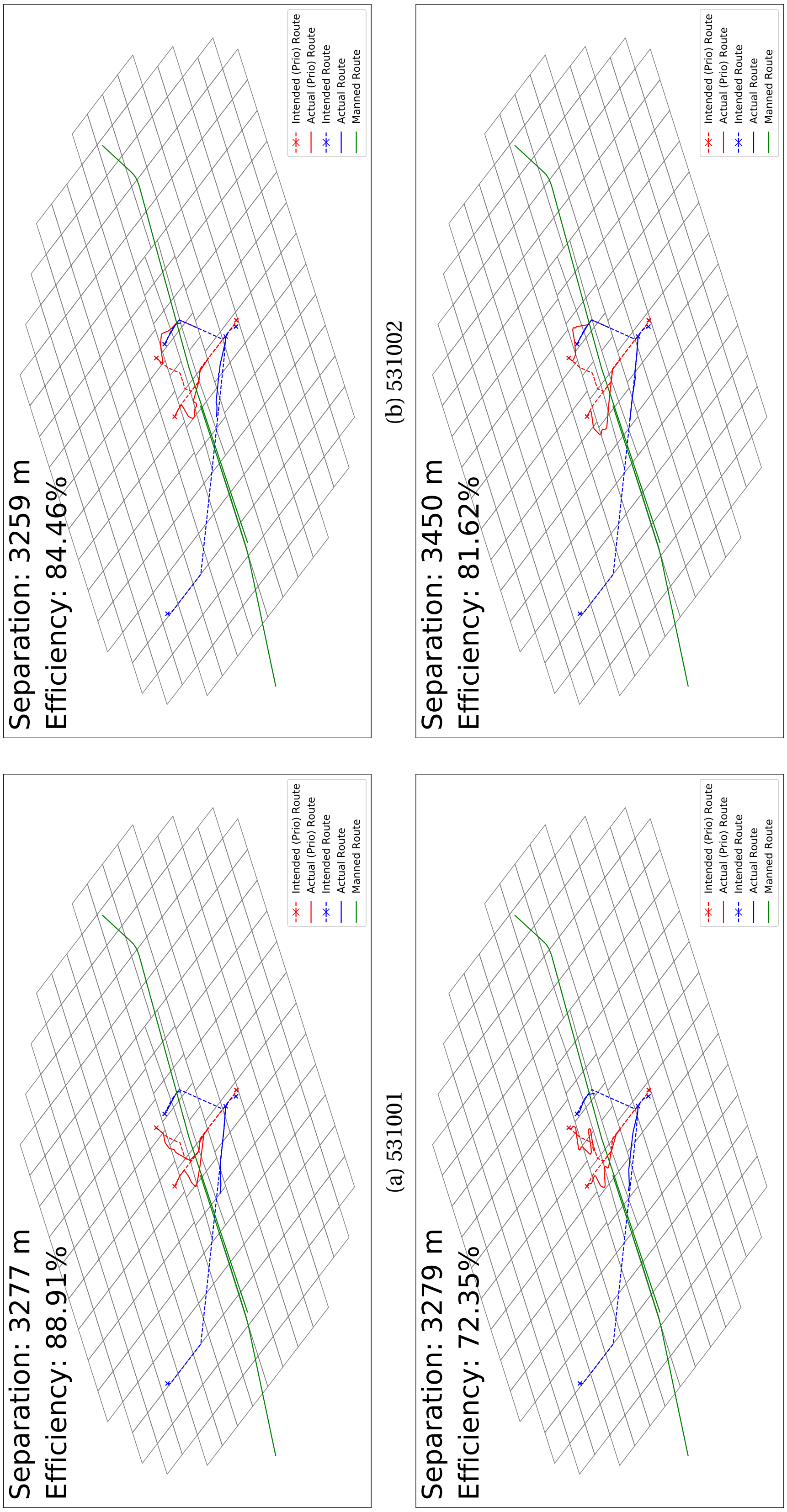
(g) 531007



(h) 531008

Figure G.16: Geofence activation map for HTL-S

G.3. Traffic Maps



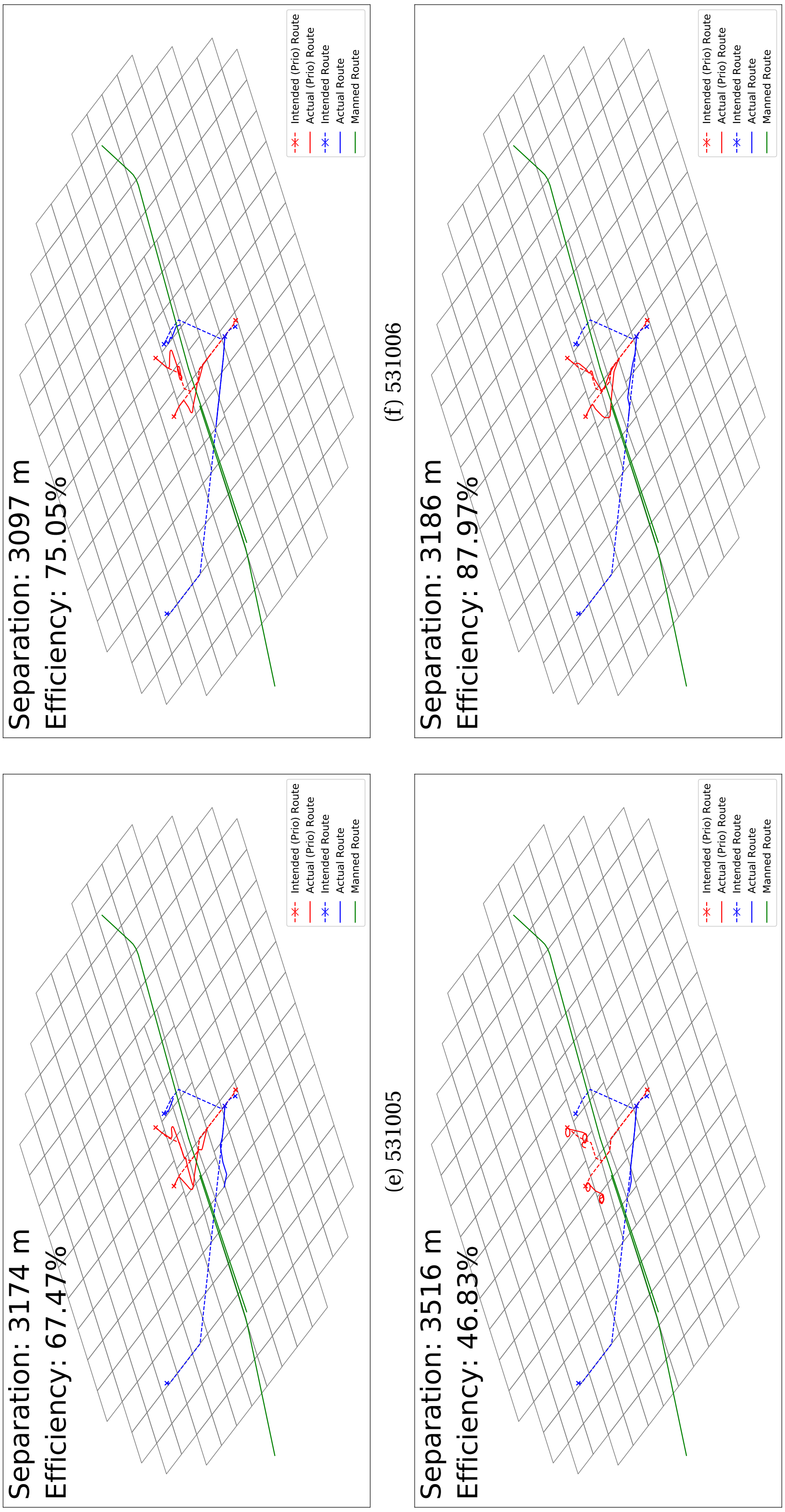
(a) 531001

(b) 531002

(c) 531003

(d) 531004

Figure G.17: Traffic patterns for IFR-L



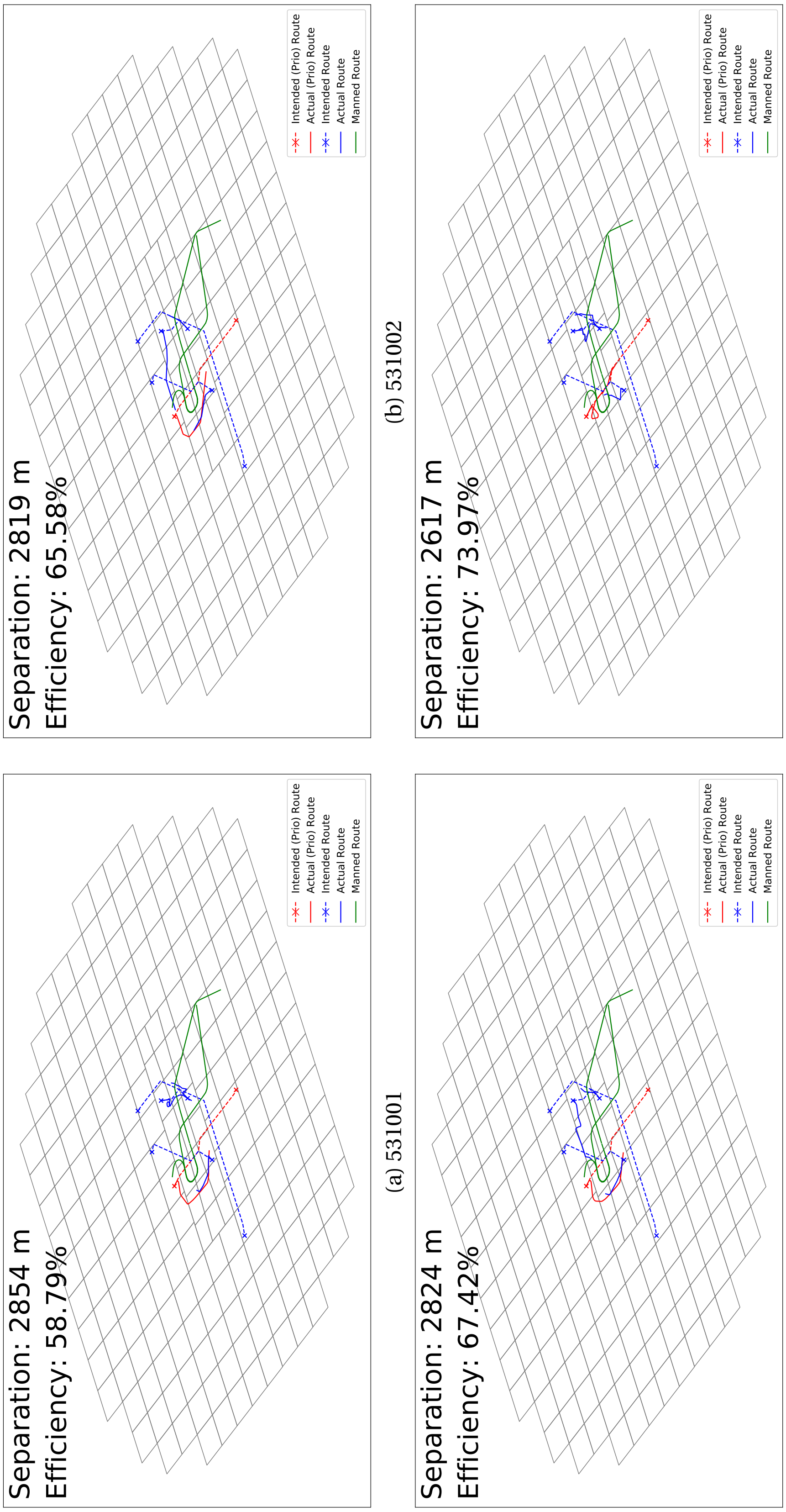
(e) 531005

(f) 531006

(g) 531007

(h) 531008

Figure G.18: Traffic patterns for IFR-L (continued)



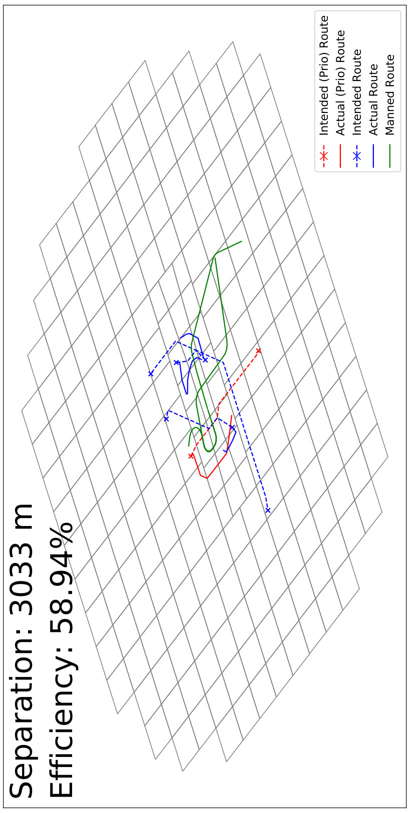
(a) 531001

(b) 531002

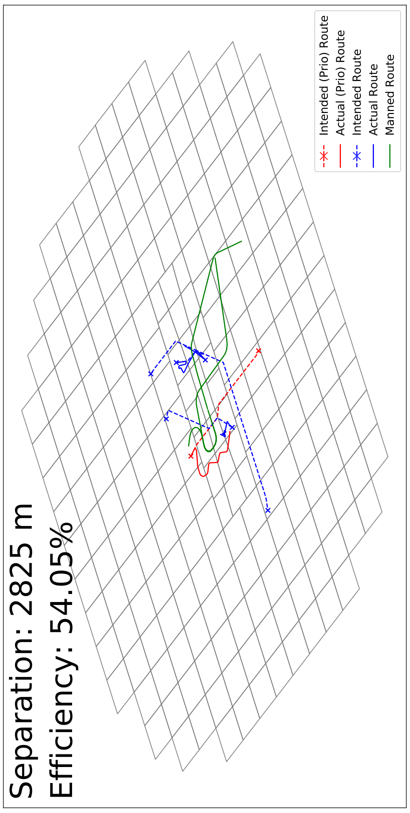
(c) 531003

(d) 531004

Figure G.19: Traffic patterns for VFR-L



(e) 531005



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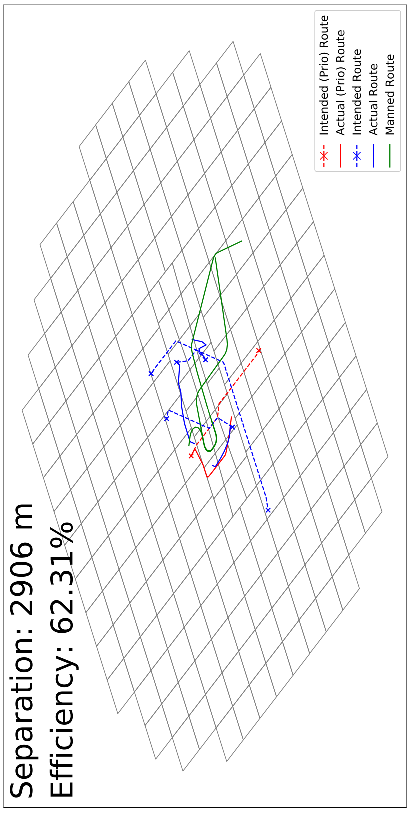

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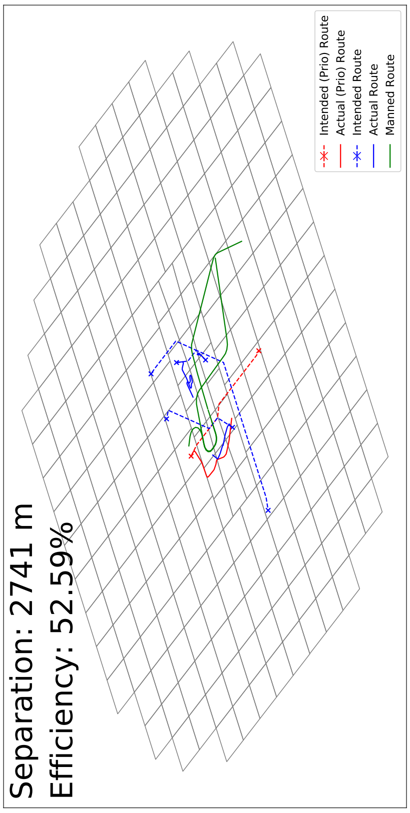

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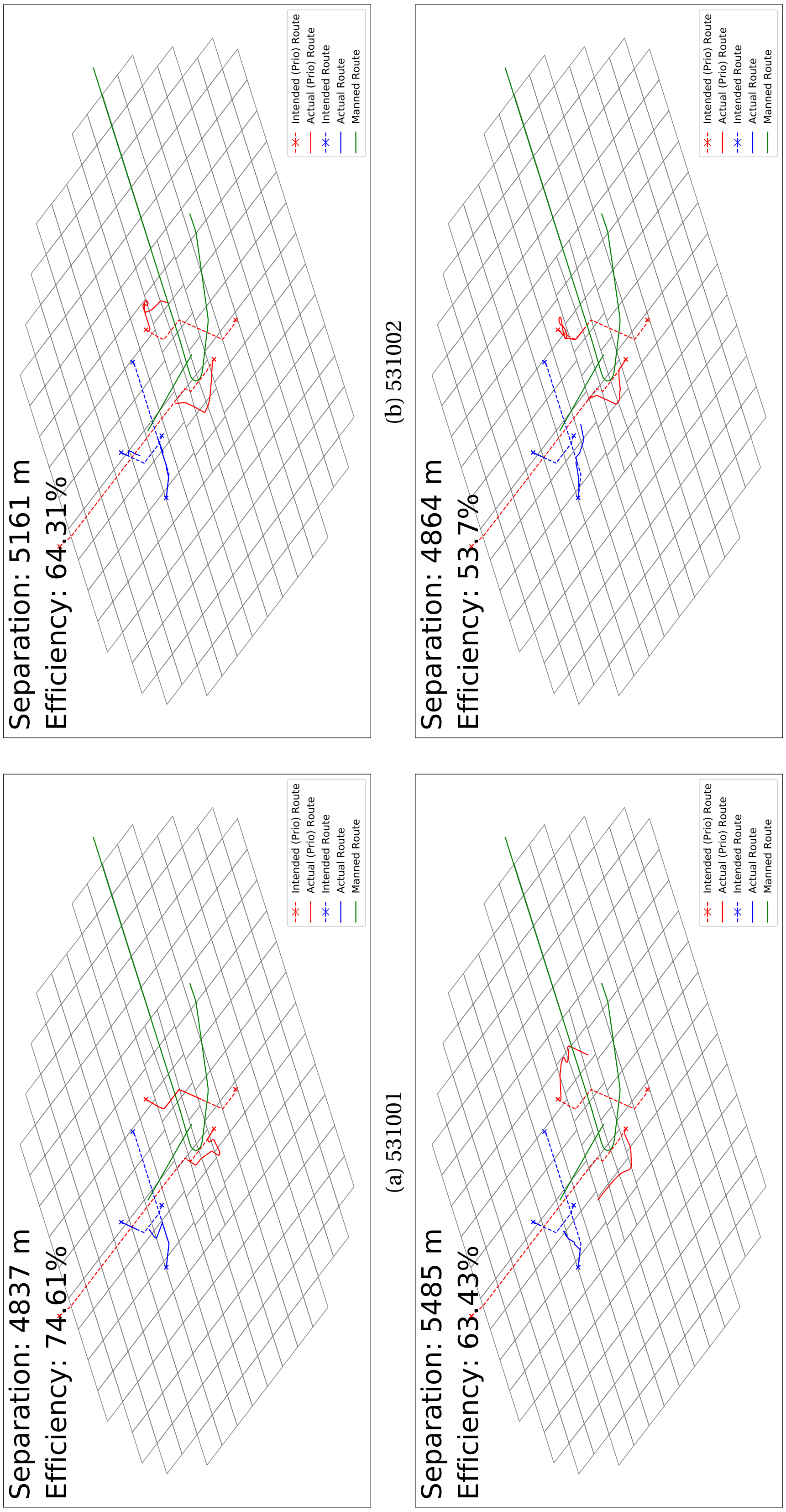
Figure G.20: Traffic patterns for VFR-L (continued)



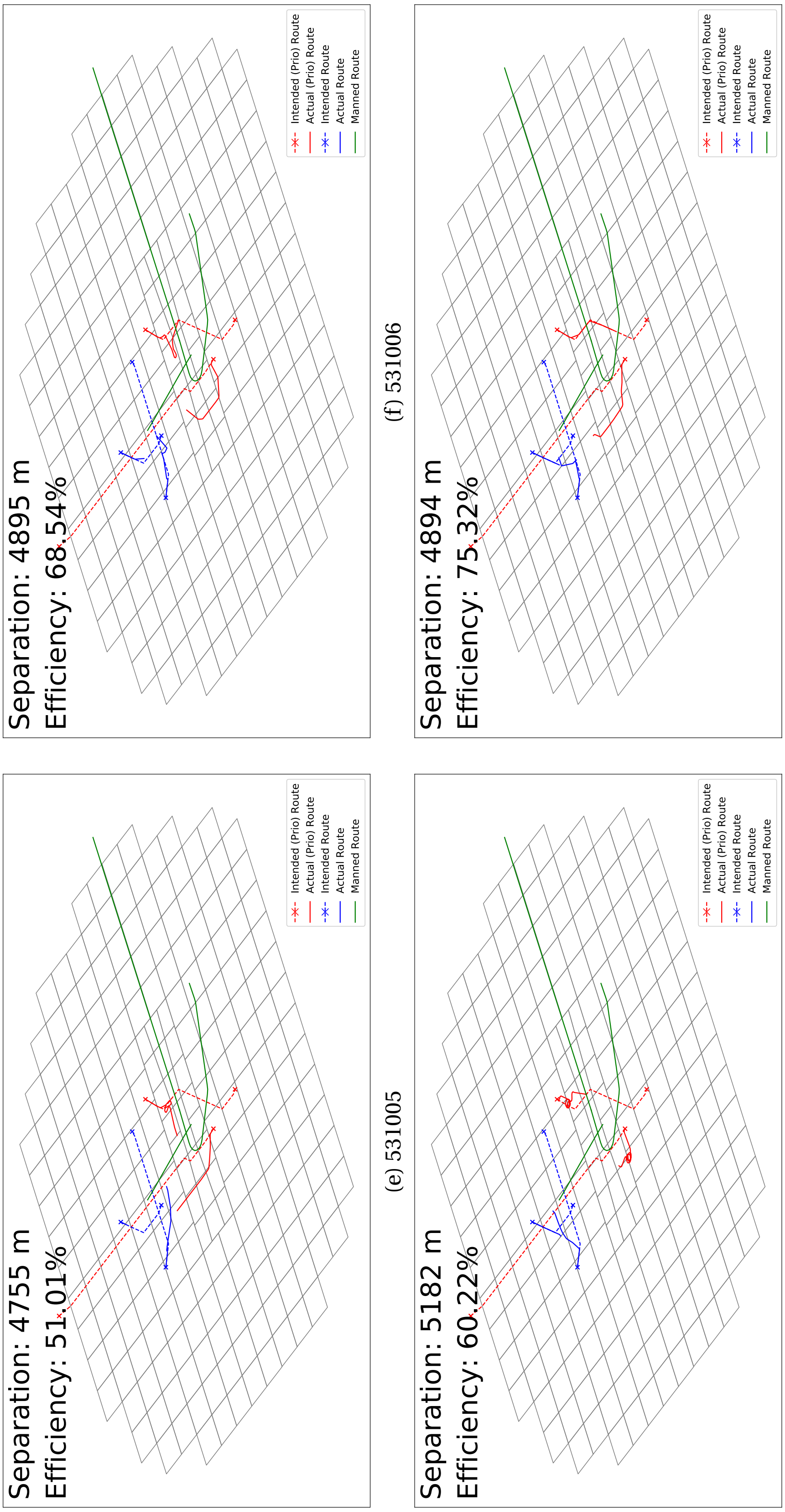
(a) 531001

(b) 531002

(c) 531003

(d) 531004

Figure G.21: Traffic patterns for EHF-L



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(g) 531007

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Figure G.22: Traffic patterns for EHF-L (continued)

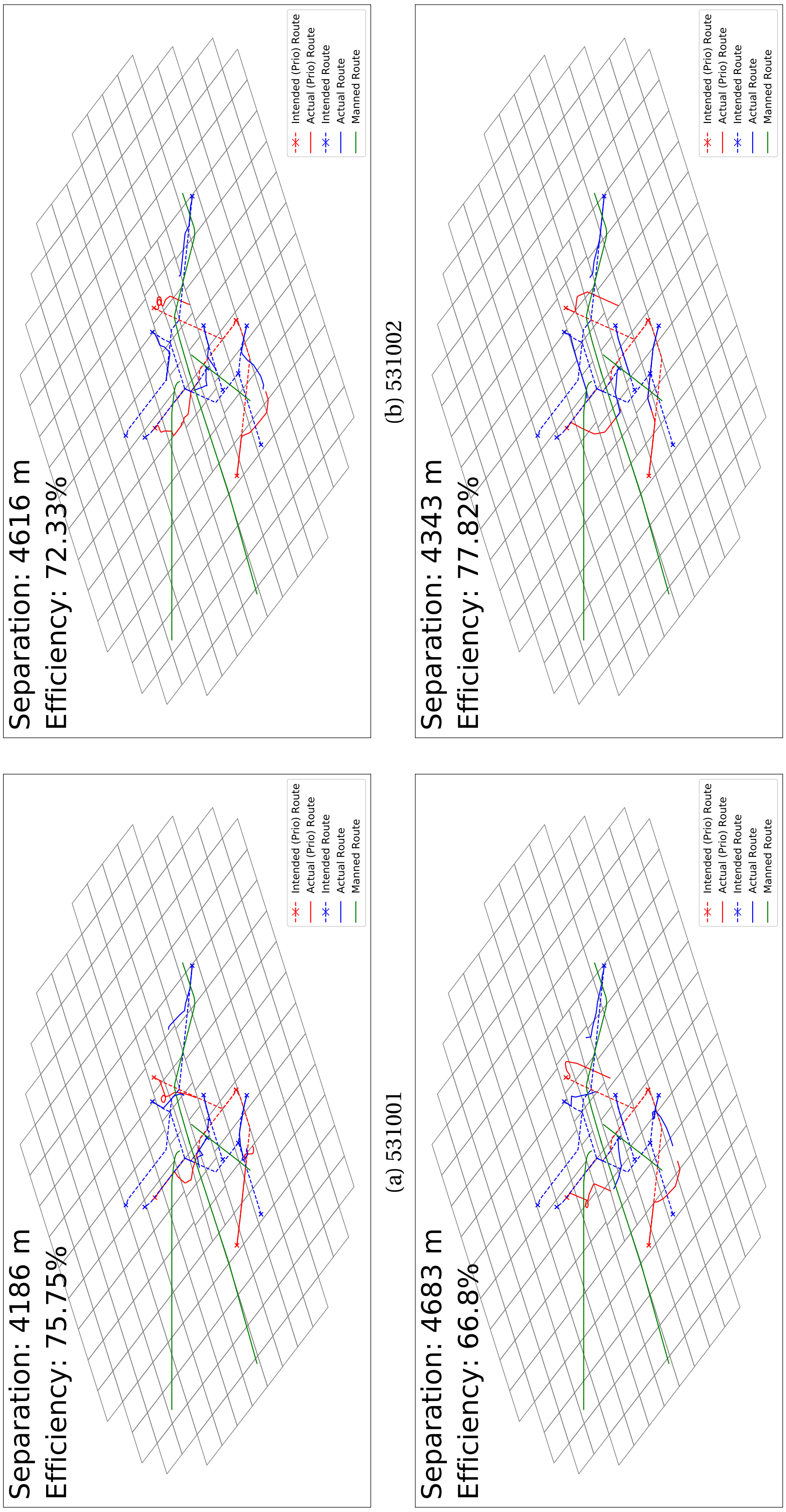

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Figure G.23: Traffic patterns for HTL-L

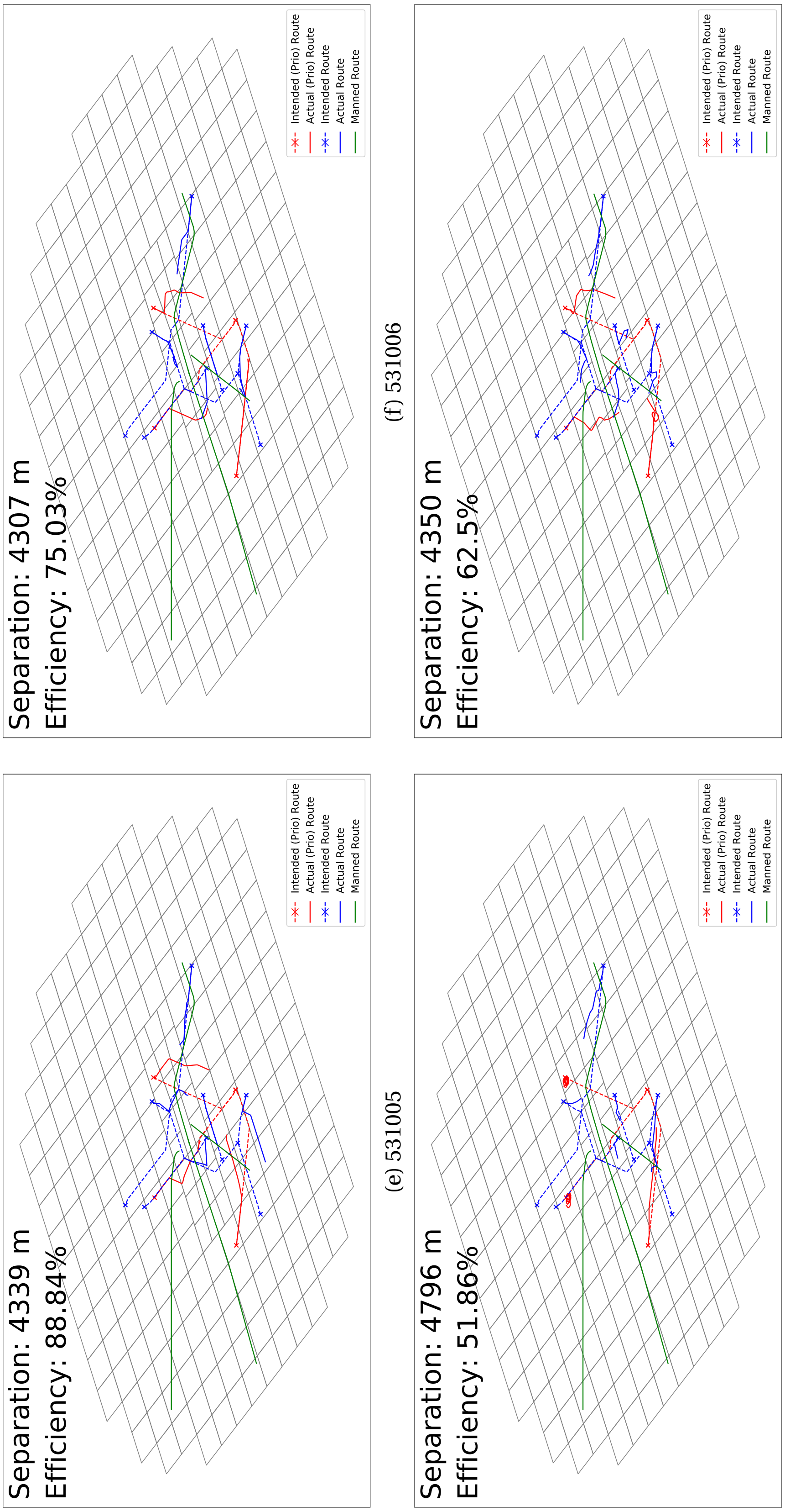

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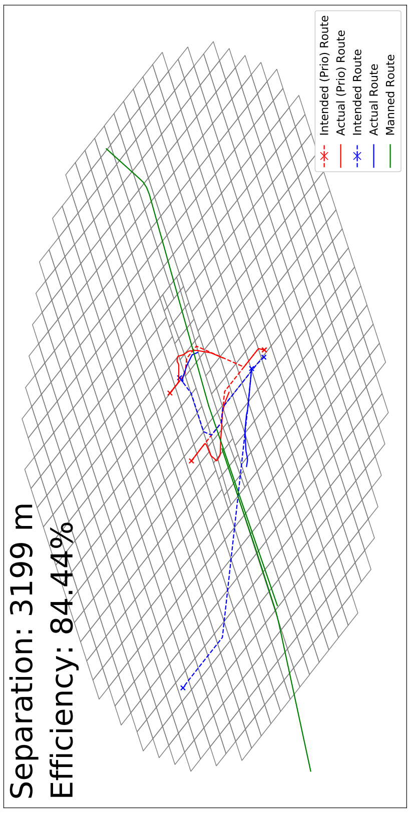
Figure G.24: Traffic patterns for HTL-L (continued)



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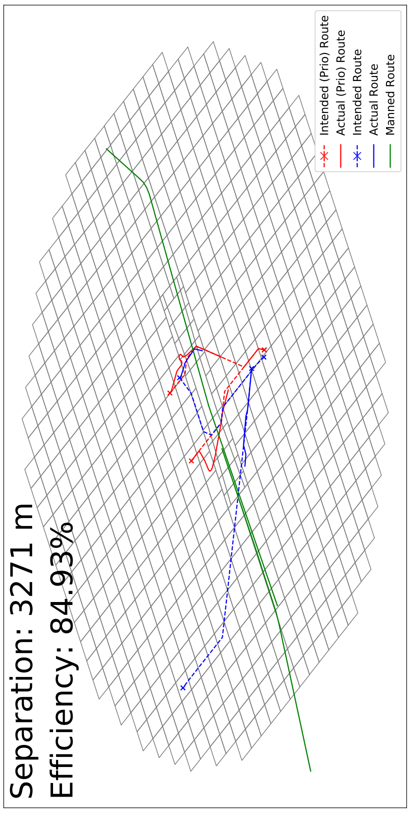

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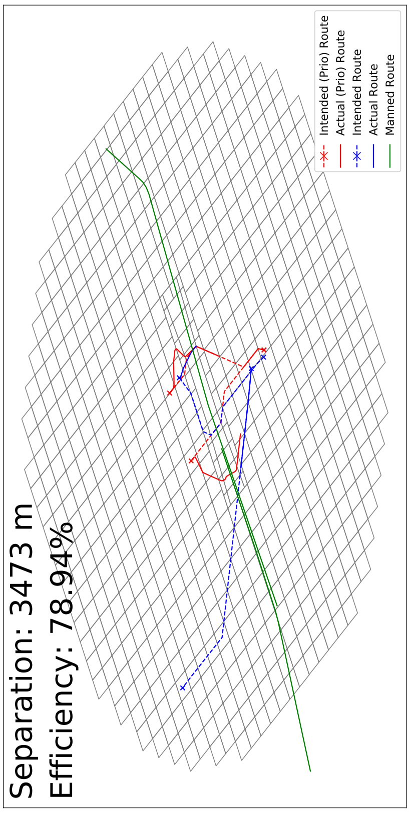

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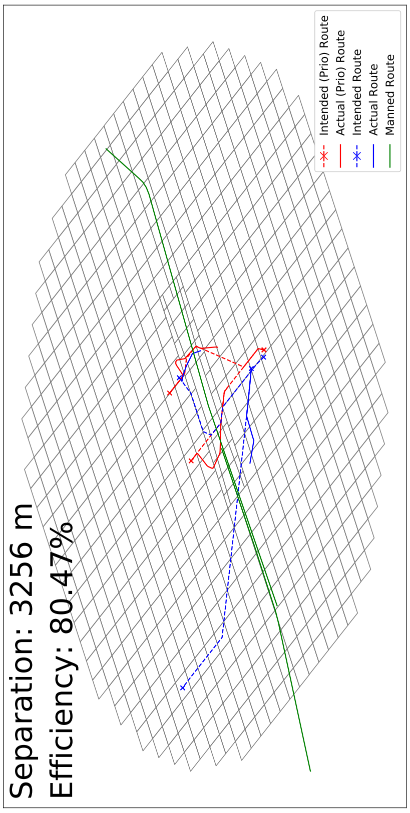

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Figure G.25: Traffic patterns for IFR-S

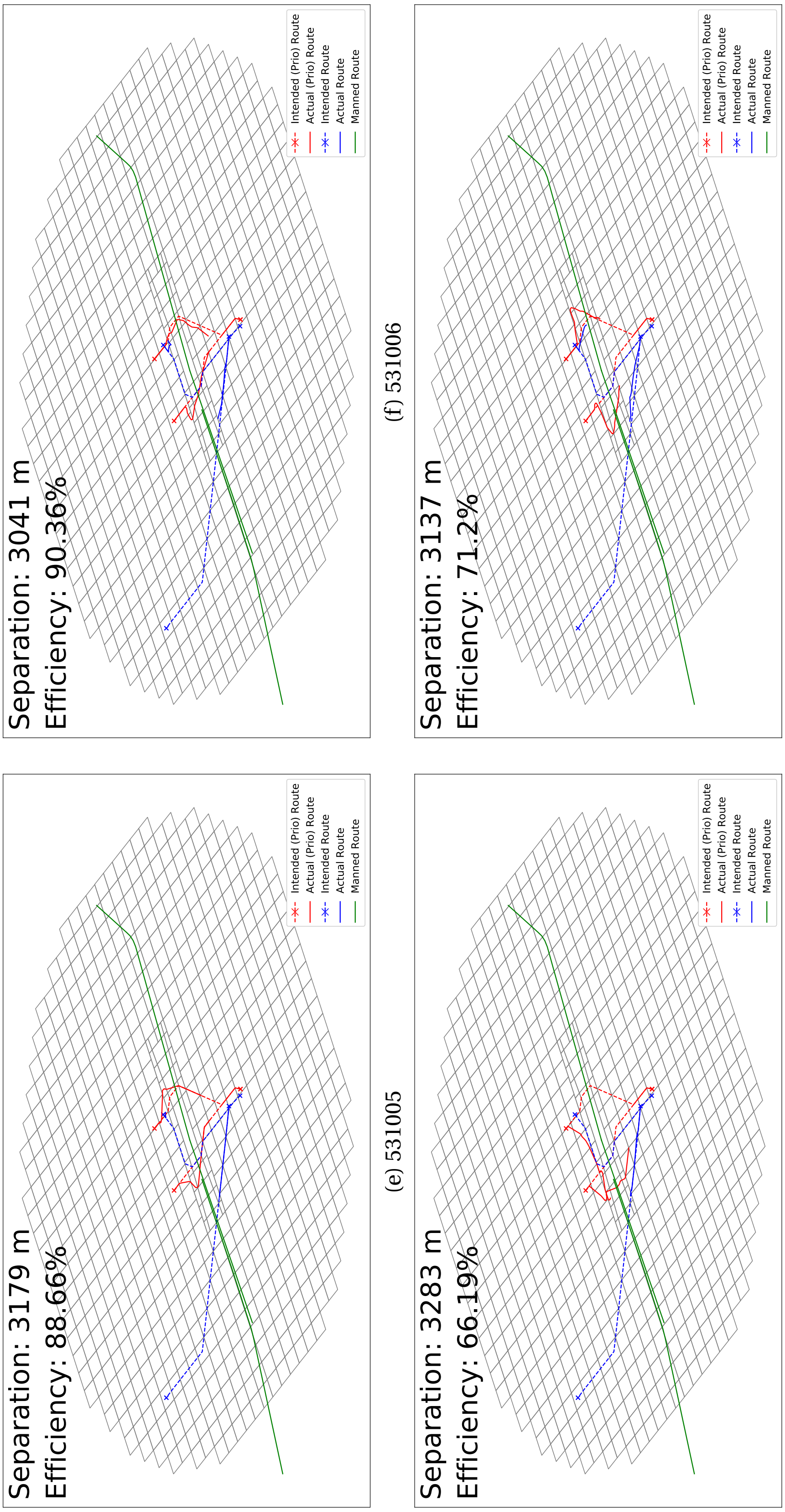

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Figure G.26: Traffic patterns for IFR-S (continued)

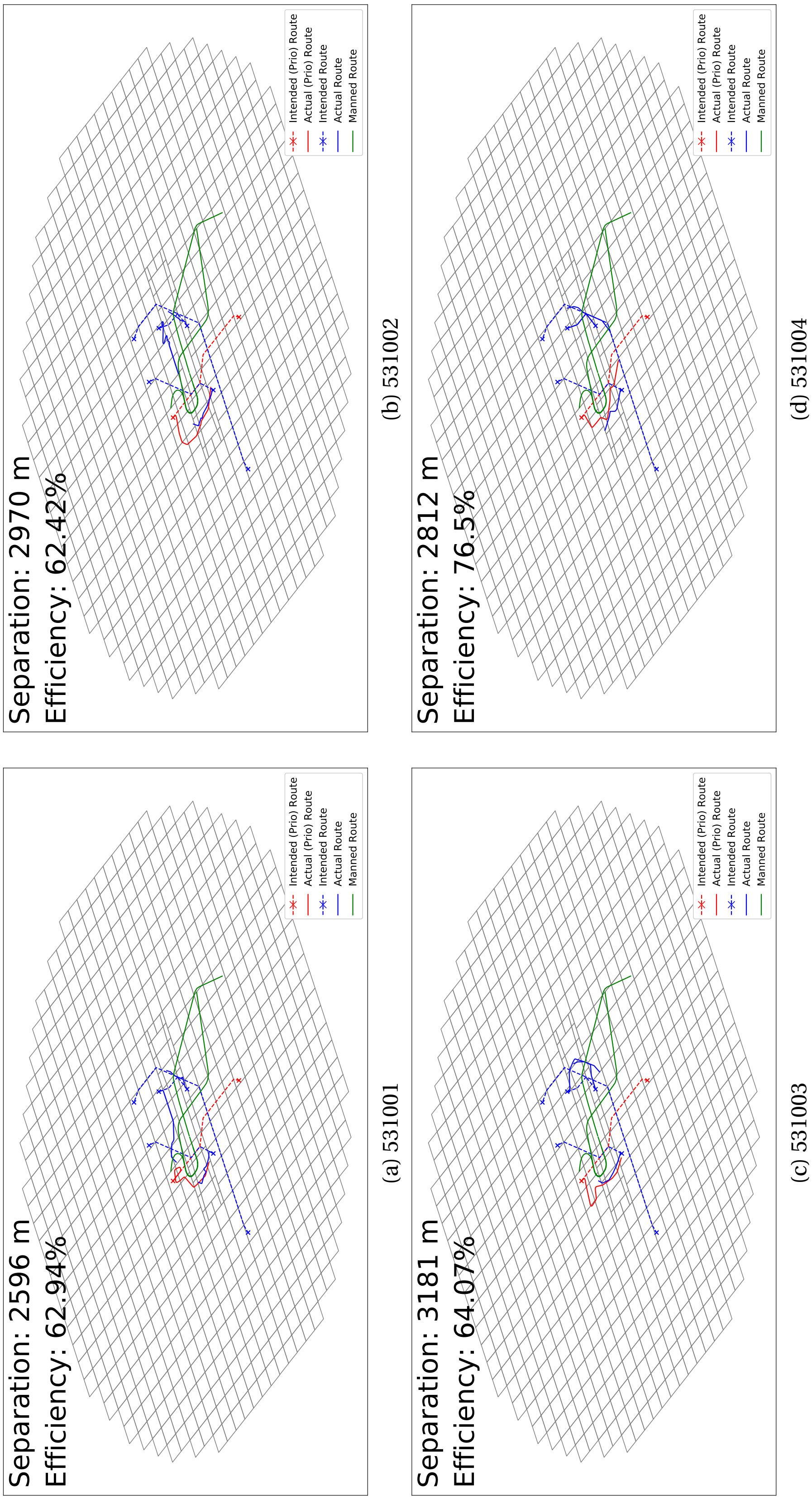

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Figure G.27: Traffic patterns for VFR-S

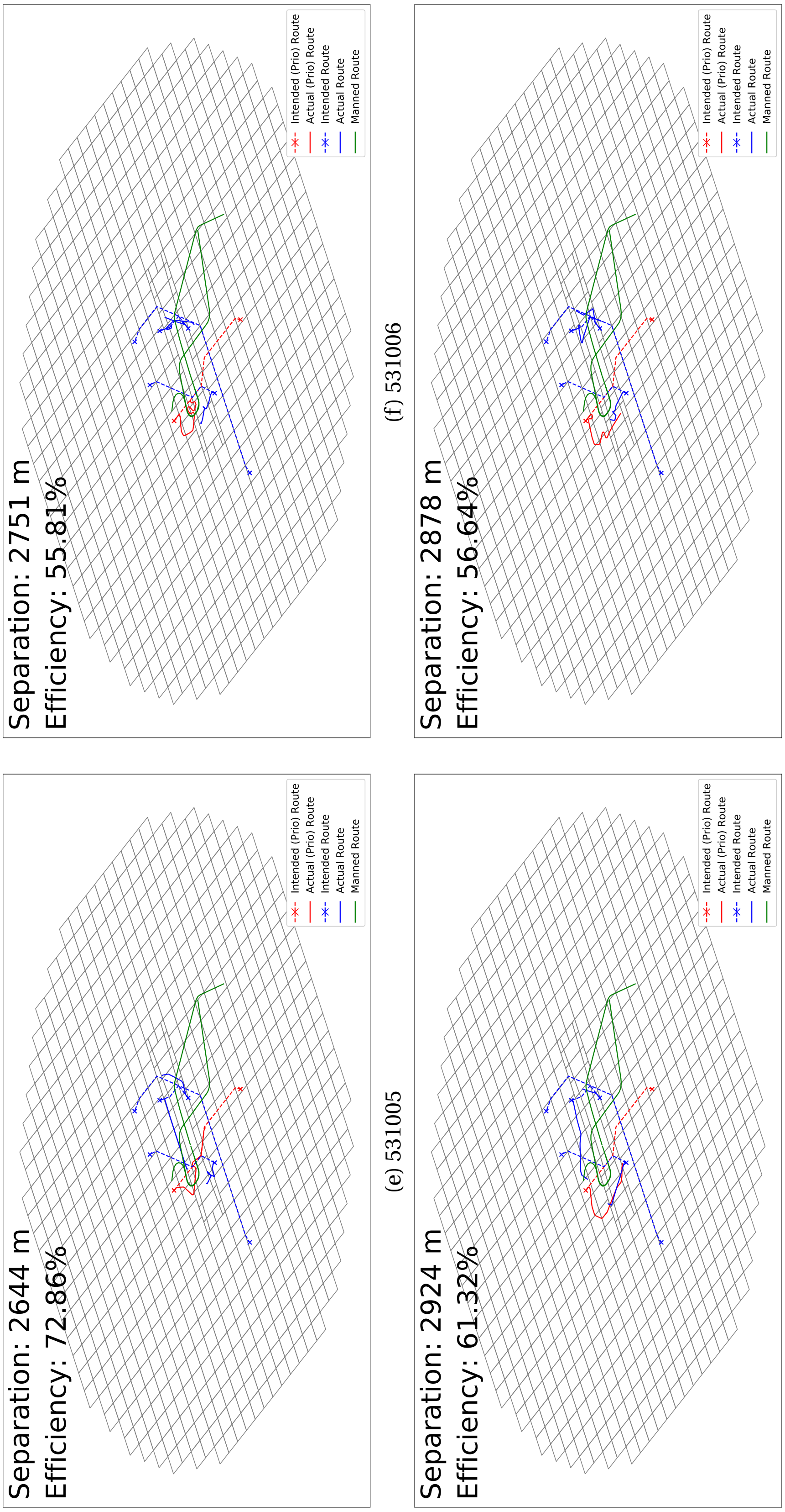

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Figure G.28: Traffic patterns for VFR-S (continued)

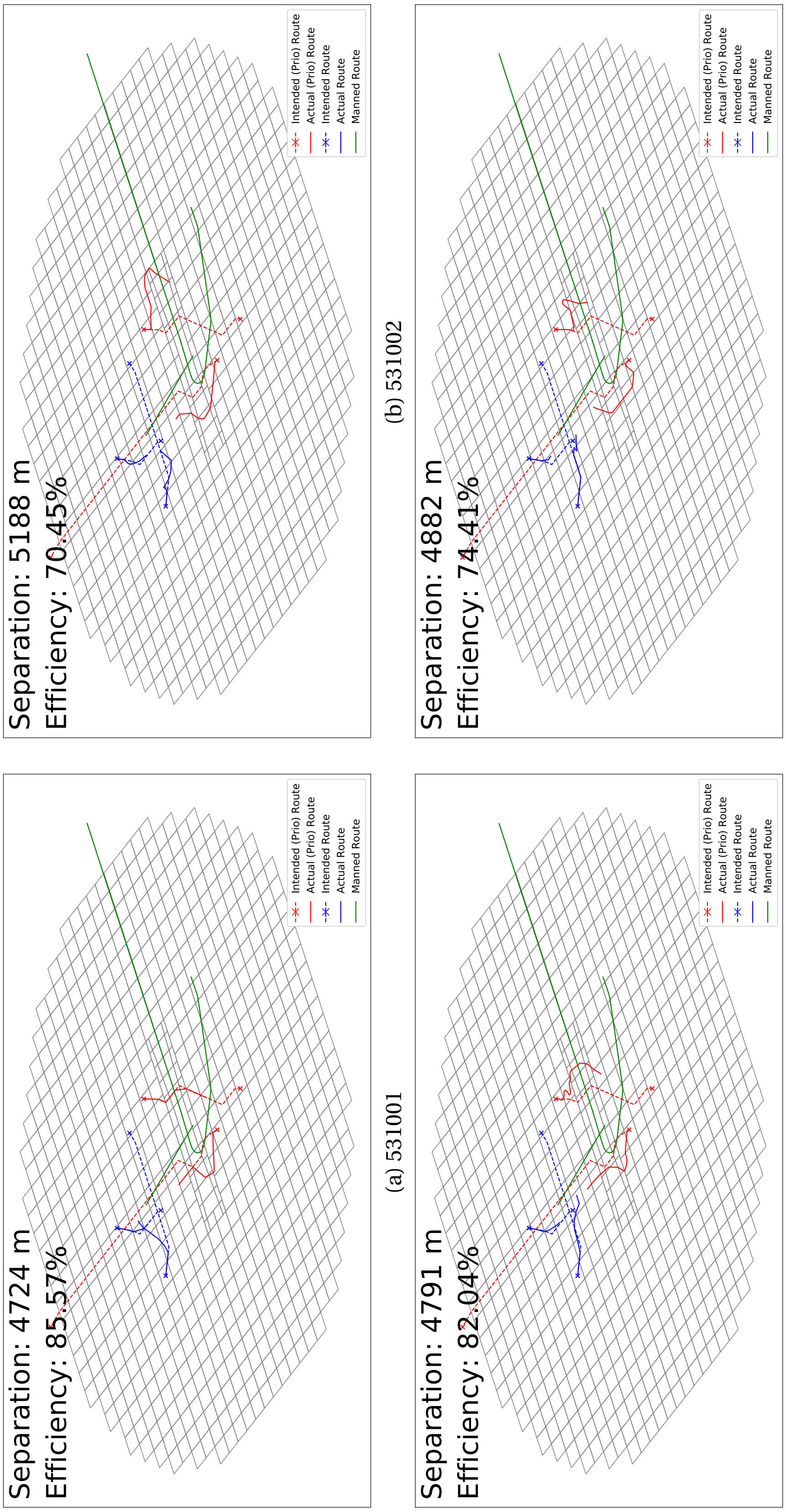

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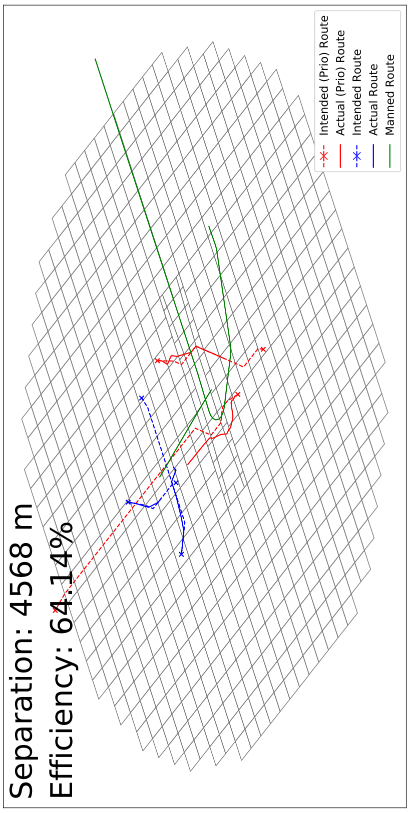
Figure G.29: Traffic patterns for EHF-S



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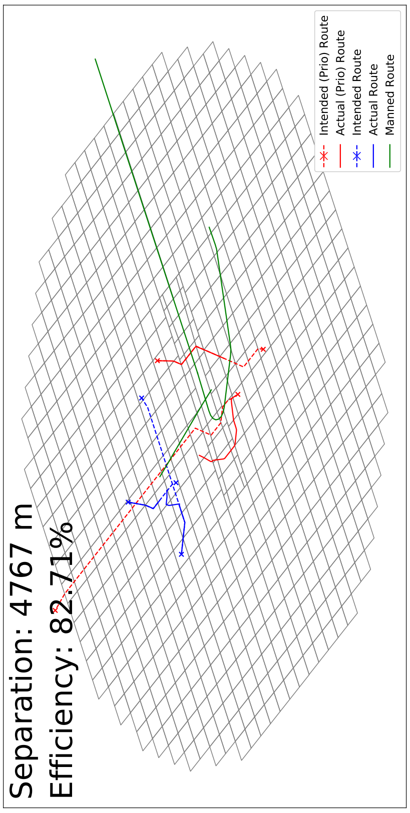

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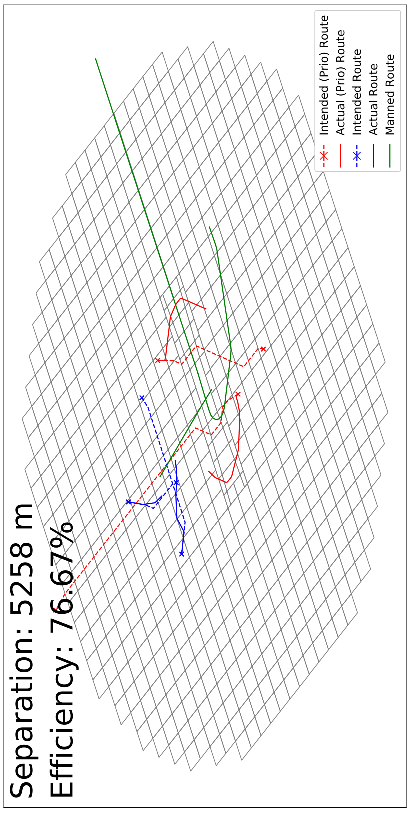

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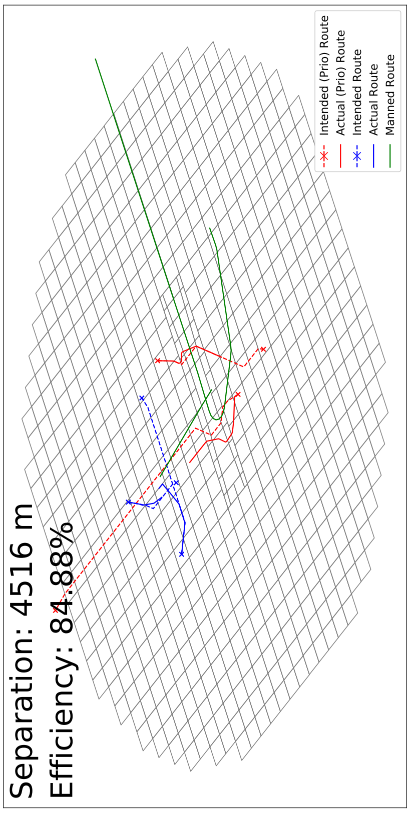

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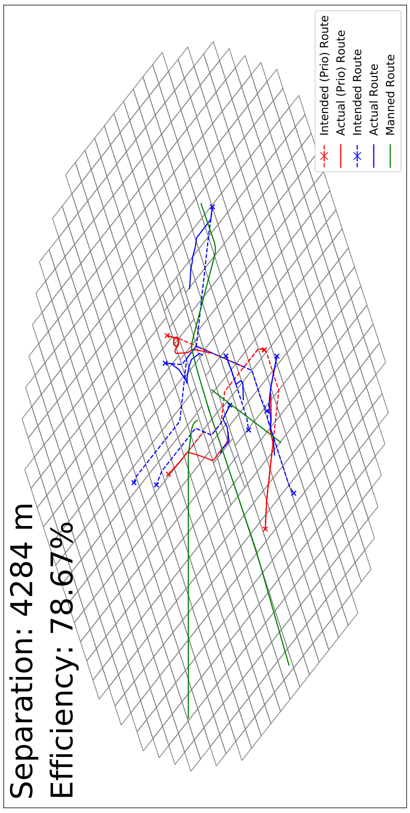
Figure G.30: Traffic patterns for EHF-S (continued)



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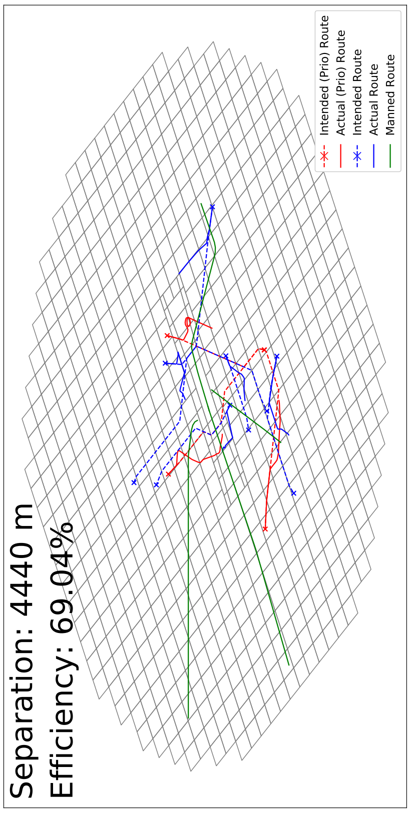

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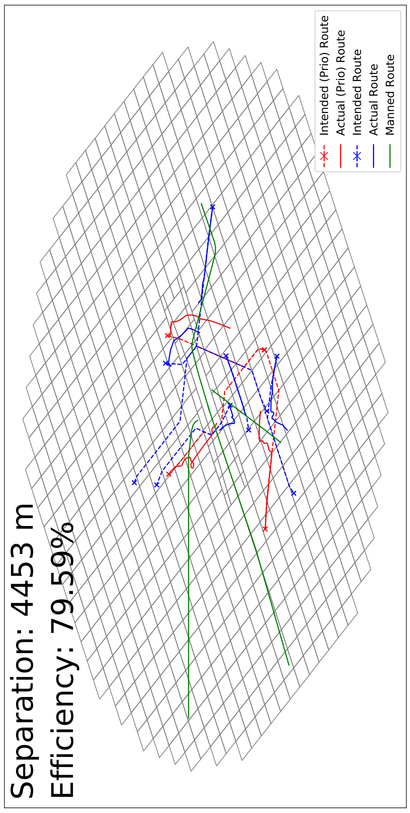

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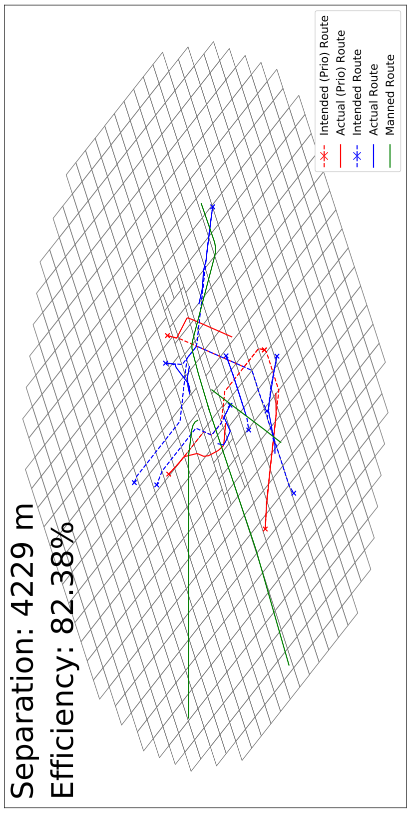
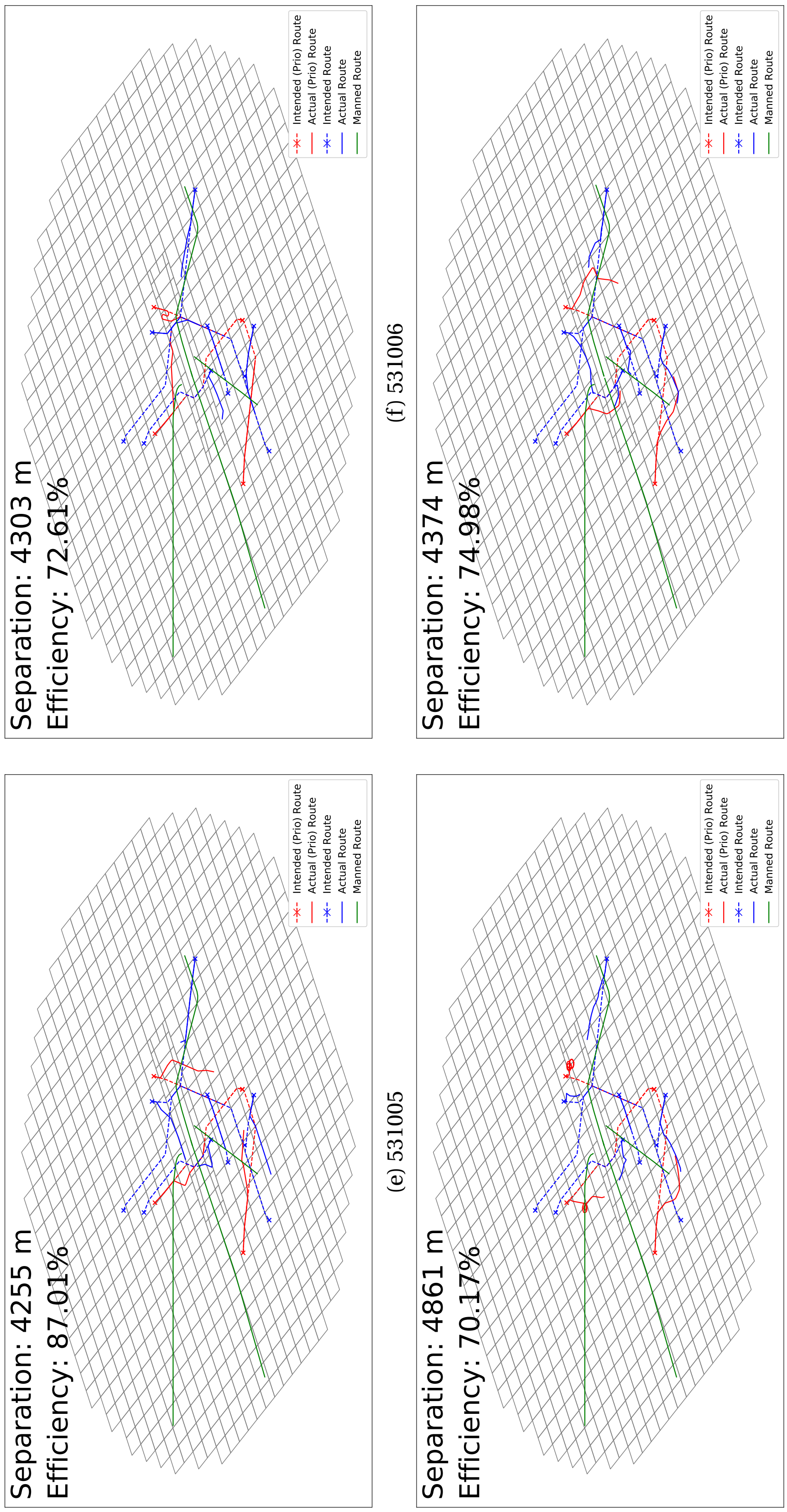


(d) 531004

Figure G.31: Traffic patterns for HTL-S



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(f) 531006

(g) 531007

(h) 531008

Figure G.32: Traffic patterns for HTL-S (continued)

H

Conclusions and Recommendations

This chapter elaborates on the recommendations and conclusions presented in the thesis paper. First, Sections H.1, H.2 and H.3 discuss the recommendations and conclusions for the design of the simulation, interface and experiment, respectively. Afterwards, considerations for future work are presented in Section H.4.

H.1. Simulation Design

The current simulation of the Rotterdam traffic area was developed in Javascript using the Google Maps API. The simulation was generally considered to be accurate by the experiment participants, but some improvements can be made.

The most significant improvement to the simulation environment could be the inclusion of the temporal aspect of geofences. Currently, UAVs re-route around any active geofences that occur along their entire intended route. They do not consider the time it will take them to reach a certain geofence or the duration of the geofence activation. First, this sometimes leads to unrealistic behaviour, because a UAV is unlikely to divert immediately because of a geofence that it will reach in 20 minutes. Moreover, it leads to inefficient UAV operations, as the most efficient solution is often shortly loitering until the geofence restriction is lifted, upon which the UAV can continue the direct route. Implementing these temporal aspects of geofences will greatly increase the fidelity of the simulation environment, while also improving the judgement of task performance.

A second major improvement could be the inclusion of more diverse UAV operations. The current simulation environment only considers point-to-point UAV operations, re-routing them to their destination by the shortest way possible. From a U-space perspective, the fidelity of the simulation could be greatly improved by implementing UAV operations involving surveillance, inspection, tracking, etc. First of all, this forms an interesting combination with the aforementioned temporal aspect of geofences, as some of these operations cannot re-route and will have to wait for the geofence restrictions to be lifted or will have to simply abort their mission. Moreover, it stresses the importance of UAV mission type, as is emphasised by U-space and reflected in the abstraction hierarchy. A broader range of UAV operations will make the operator considered the mission type (next to the priority) in predicting UAV behaviour and in geofence activation.

Finally, there are some minor improvements that could be made to increase the fidelity of the simulation, but are of significantly lower priority than the previous points. First, some participants remarked that the behaviour of (manned) flights is 'too good', in the sense that real-life operations always contain a degree of uncertainty and small imperfections. An example of this is the perfect turn behaviour currently encountered in the simulation. However, a high fidelity traffic simulation is not the aim of the research and it should be considered if the effort required for implementing this is not too large for the reward. Next, some participants remarked they would have liked the addition of sound, either in the form of incoming voice messages or a beep indicating an incoming text message. Finally, the simulation currently runs client side, which can lead to performance problems on weaker machines. A possible solution is to run the simulation server-side and only send visual updates to the client side every five seconds.

H.2. Interface Design

The interface that was designed in this research can be considered a conceptual design for a decision support interface for tower controller dealing with UAV operation. Due to its conceptual nature, various improvements can be made to the interface design.

The addition of the endurance regions to the interface received mixed responses. Some participants considered them useful in anticipating the UAV's behaviour, while other participants mainly used the outer endurance region as an indication of the UAVs locomotion space. Two participants even indicated they rarely used the endurance indications, focusing on safety. As the outer endurance region (visualising the locomotion constraint), was generally considered more useful than the inner endurance region, it should be investigated if there is substitute for the latter that better supports the operator in their behaviour. A first suggestion is to visualise the uncertainty in the UAV's intended route. However, this would also require a more detailed simulation of weather effects and navigational failures. A second suggestion is to implement what-if probing, visualising the most likely route of a UAV upon activating a certain geofence (possibly including delay time). This can aid the operator in anticipating UAV behaviour and in effectively activating geofences. Next, it could be investigated if only visualising the outer endurance region is considered more useful than having a secondary visualisation. Finally, a visualisation not including the outer range region could be considered.

A second improvement concerns a combination of simulation and interface, and is related to the argument made in Section H.1 regarding the temporal aspect of geofences. Several participants indicated they would have liked a feature that allowed them to instruct a UAV to loiter at its current position. This would allow the operator to shortly activate a geofence, without imposing a re-route to a certain UAV. Once the geofence is deactivated, the UAV can proceed. This allows the operator to deal with the temporal aspect of geofence activation of short duration, even when close to a UAV, without severely impacting the route efficiency.

Finally, Some participants noted that the contrast between the 'on' and 'off state' was not always immediately discernible. A slightly higher contrast between the two should be considered. Additionally, there were some discrepancies between elements of the designed interface and those the participants were familiar with from their day-to-day work environment. However, as not all participants were from the same country, this effect is difficult to account for.

H.3. Experiment Design

The experiment performed in this research was the first remote human-in-the-loop experiment within this research group. The setup was generally found effective. Only minor problems occurred with video communication and the web-server running the simulation, none of which significantly impeded the experiment. Moreover, the remote setup allowed participants from other countries (in this case Spain) to take part in the experiment, increasing the sample group size. It should be noted, however, that this setup was currently used for a first evaluation of a conceptual interface design. In case (detailed) workload and situational awareness measurements are required, a remote experiment is not recommended, as there is little control over the participants' apparatus and working environment.

Although the interface itself was considered easy to understand, most participants indicated they needed time beyond the training scenarios to get accustomed to the UAV behaviour and capabilities. Participants remarked they needed to adapt to the surprisingly low speeds of the UAVs and how to best incorporate this into their usual control strategy. Second, they needed time to adjust to the concept and functioning of the geofences in combination with the UAV capabilities. These finding stresses the general lack of training in tower control regarding UAV operations and should be taken into consideration in future research.

Although the high task load scenario was generally considered to lead to high work load, the UAV density in the simulation was relatively low compared to the expected levels. The fact that the current low density lead to high workload can be contributed to the fact that most participants currently opted for a very active control strategy, as they only had active control over the UAVs. Future research should investigate the effect on workload and situational awareness of UAV density and the type of control exerted on the traffic.

H.4. Future Work

As was indicated in the thesis paper and the sections above, there are several suggestions available for further research. Most prominently, several participants indicated they considered high priority UAV operations of higher importance than regular VFR flights. Consequently, they would have preferred to slightly extend the track of a VFR flight in the traffic circuit to let a high-priority UAV pass as efficiently as possible. This prompts interest for investigating the control behaviour of tower controller in this simulation environment, when having control over both UAV and manned traffic. This is further emphasised by the findings in Section H.3, regarding the effect of UAV/manned traffic control on workload. Therefore, the most prominent suggestion for future work is to investigate the effect of control over both UAV and manned traffic on control strategy, task performance and (possibly) workload.

A second important consideration is that of the geofence configuration. Participants generally preferred the larger geofences, as these allowed them to obtain traffic safety more easily. However, some participants remarked that smaller geofences over the ILS did allow for more precise control, once safety was obtained. Moreover, the geofences adapted to the ILS were considered useful in providing traffic safety for ILS flights. It should therefore be considered if the geofence configuration can be tailored better to the desires of the operator, rather than simply imposing a grid. First, custom geofences could also be placed over the VFR traffic circuit. Second, designated crossing points/corridors could be provided over the runway and across the ILS. This makes the UAV traffic flow more orderly, guarantees perpendicular crossings and combines large areas for safety with detailed control over UAV traffic flow. Finally, it could be considered to allow for group activation of geofences, or to incorporate the creation of custom geofence by the operator.

To summarise, the most important suggestion for future work is to investigate the effect of control of both UAV and manned traffic on control strategy, task performance and workload, while using geofence tailored to support the operator's control behaviour. From the previous sections there are several suggestions that stand out and compliment this main suggestion. First, the temporal aspect of geofences is important to consider in future iterations. Next, a broader range of UAV operations could be considered, resulting in different types of UAV behaviour. Additionally, the interface could be supplemented by information regarding UAV route uncertainty or what-if probing. Finally, the effect of UAV density combined with the type of control (manned, UAV, both) on workload could be investigated.

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