

A SERVICE-ORIENTED COLLABORATIVE INTERFACE WITH AIR TRAFFIC CONTROL FOR INTEGRATED UAS OPERATIONS IN U-SPACE

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Abstract

The rapid growth of Unmanned Aircraft Systems (UAS) is fundamentally changing the low-altitude airspace, and the foreseen introduction of U-space to sustain this growth requires air traffic management systems that can safely operate with many autonomous systems. U-space aims to enable UAS operations to operate safely, efficiently, and securely alongside traditional crewed aviation. The Air Space REsearch Area (AREA U-space) project at the German Aerospace Center (DLR) in Cochstedt is a U-space initiative aimed at enabling the safe integration of UAS into low-level airspace. Launched in 2023, the project is establishing a comprehensive real-world laboratory where all essential U-space system components and digital U-space services are developed and tested under realistic conditions. This paper proposes a digital U-space service, a service-oriented collaborative interface that connects U-space services with Air Traffic Control (ATC) tower controllers to support UAS operations. The U-space system makes it easier for stakeholders to share information in real time and make collaborative decisions by providing standardized services, such as flight authorisation, and dynamic airspace reconfiguration. The interface helps UAS operators stay informed by showing traffic information and enhanced geo-awareness on a single screen. To evaluate the proposed interface, a simulation-based scenario was created to illustrate multiple operations represented by varying operational constraints. The service-oriented collaborative interface with ATC is demonstrated in a pre-flight simulation scenario involving an emergency UAS operation with priority that requires a modification to the airspace structure. A No-Fly Zone (NFZ) was established before the UAS departure, in which two of the three UAS operations intersect with the emergency UAS operation during its validity window and are rejected, and the re-planned routes are authorized, while a third UAS operation whose trajectory crosses the geometry after the zone expires is authorized as filed. This scenario is a step toward demonstrating the interface's ability to handle dynamic airspace reconfiguration, and bringing UAS into controlled airspace will require not only new technology but also a new approach to stakeholder collaboration. The suggested service-oriented collaborative interface is a promising approach to improving coordination between U-space and ATC operations, with the potential to make airspace use safer and more efficient once separation criteria, and human-in-the-loop assessment are established. Future work will incorporate simulation results from the test campaign as well as focus on the human-in-the-loop assessments and compliance with emerging regulatory frameworks to facilitate broad deployment.

1. INTRODUCTION

Uncrewed Aircraft Systems (UAS) have become an established tool for infrastructure inspection, precision agriculture, security and first response missions, medical logistics, parcel delivery, and numerous other use cases. Nearly all of these applications take place in Very Low Level (VLL) airspace below 500 ft [1], where crewed aviation is also present, in particular in the vicinity of airports. Scaling uncrewed operations therefore requires the ability of the air traffic management system to keep crewed and uncrewed operations informed about each other and to change the airspace configuration as and when the operational situation requires it [2]. In Europe, this system is being established, and known as U-space. Commission Implementing Regulation (EU) 2021/664 [4] defines U-space airspace as a volume designated by a member state where UAS operations are only permitted with the support of four mandatory U-space services, namely, network identification, geo-awareness, UAS flight authorisation and traffic information, which are provided by certified U-space Service Providers (USSPs), together with a common information service that makes the relevant data available to all participants in the designated U-space [5]. Together with Regulations (EU) 2021/665 [6] and (EU) 2021/666 [7], this framework has been in force since January 2023. The service levels of the SESAR U-space blueprint [3] place a

collaborative interface with ATC as a service of higher complexity than the baseline. This service allows tower controllers to interact with a representative of a UAS flight, which may be the UAS operator, the aircraft itself in the case of autonomous flight, or the USSP [20], and it is intended to be used whenever a UAS operates near or within a controlled area. The German Aerospace Center (DLR) is implementing a U-space area at its National Experimental Test Center for UAS at Magdeburg-Cochstedt Airport within the Airspace REsearch Area (AREA) U-space project [10], [11]. The project builds on a long line of research on integrating uncrewed aviation into the existing airspace system [2], [34] in particular the blueprint for urban airspace integration [1] and the initial concept of U-space flight rules [19]. The site is an active airport with an Aerodrome Traffic Zone (ATZ) and a permanently established UAS geographical zone, which makes it a suitable environment for evaluating the coexistence of crewed and uncrewed traffic under realistic conditions. Earlier work in the project collected requirements for a tower controller-facing human-machine interface (HMI), adapted DLR's U-FLY ground control station into a tower client, and evaluated it in a live demonstration with the tower controllers of the Magdeburg-Cochstedt Airport [12]. The evaluation confirmed the operational value of a single air traffic picture for crewed and uncrewed aircraft and produced a catalog of improvements suggested by the tower controllers,

particularly the request to create, activate, and deactivate geographical zones of flexible size and validity from the working position. Three limitations were also exposed. Firstly, the interface was largely self-contained: uncrewed traffic signals were received from a hook-on device integrated with an ADS-B transponder, and not via U-space services, so the picture that was presented to the controller may have been different to the picture that was disseminated to the UAS operators. Secondly, all coordination with operators was verbal, which does not scale beyond a small number of simultaneous operations. Thirdly, the evaluation was qualitative and therefore no statement could be made on the timeliness of the coordination or on the safety benefit of the service. The main contributions are the following:

- a service-oriented architecture in which the collaborative interface exchange tower controller generates information for all affected UAS operators through the standardized API interfaces.
- an implementation description of the tower client, covering the geographical zone manager.
- a pre-flight authorisation algorithm that checks every filed flight operation plan against the active geographical zones within their validity window, designed to be extended to a check against already authorised plans, resolved on a first-come, first-served basis.
- pre-flight simulation scenario, for a change of the airspace structure, which is distributed as mission files so that the runs can be replayed.
- quantitative results of the scenario, and a comparison with the non-integrated coordination procedure used in the previous campaign.

2. RELATED WORK

U-space aims to integrate UAS into VLL airspace in a way that is safe, efficient, and scalable, especially in urban and other complex areas with congested scenarios [10]. As UAS operations grow rapidly, ATC systems need support for uncrewed aviation, with high potential through U-space [11]. U-space adds a set of highly automated digital services to manage large volumes of UAS operations safely enabling UAS operators, USSPs, Air Navigation Service Providers (ANSPs), and other stakeholders to work together by moving from human-centered control to data-driven coordination. U-space is an important step towards the future of integrated airspace management. DLR is researching U-space to develop, test, and demonstrate the technology and operational concepts needed to integrate mixed UAS operations into VLL airspace [12]. A major part of this work is setting up a full-scale U-space real-world laboratory at Cochstedt, where DLR implements and develops key U-space services, and studies how they interact with ATC systems in real-world situations [12], [13]. U-space research helps develop prototype technologies and operational processes that enable an automated, scalable, human-centered UAS traffic management system for U-space and future air mobility [18].

2.1. USSP and U-space services

U-space is organized as a set of digital services where the service levels range from foundation services such as registration and geofencing (U1), through initial services such as flight planning and flight authorisation (U2), to advanced services for dense operations including capacity management, conflict identification and resolution support (U3), and finally to complete services with a high degree of automation and integrated interfaces with crewed aviation (U4) [20]. Notably, U-space services do not replace ATC, but provide the information that allows all stakeholders to coordinate reliably with crewed aircraft and other airspace users [12]. In the AREA U-space architecture, the data exchanged between UAS operators and service providers is consolidated by a single Common Information Service Provider (CISP), the mandatory services are supplied by an external USSP [10], and the logical architecture of the platform follows the model-based approach described in [18]. The interfaces of the external USSP follow the System Wide Information Management principles defined in ICAO Doc 10039 [16] and the Eurocontrol yellow profile [17], and are exposed as secure REST endpoints with JSON payloads built around aviation data models, including EUROCAE ED-269 [14] for UAS geographical zones and ASTM F3411 [15] for remote identification. TAB 1. lists the services that the collaborative interface utilizes and the messages it produces. Direction “inbound” denotes information received from the USSP, while “outbound” denotes information produced at the tower position and then distributed by the USSP to all affected UAS operators. The inbound messages correspond to the four mandatory U-space services defined in Regulation (EU) 2021/664 [4], whereas the outbound messages are not part of that mandatory service but are generated by the collaborative interface and distributed through the USSP.

TAB 1. U-space services and messages exchanged with the external USSP

Service or message	Direction	Use in the collaborative interface
Network identification	inbound	Identity, position, height, course, vertical speed and status of every active UAS
Traffic information	inbound	Consolidated crewed and uncrewed air traffic picture
Geo-awareness	inbound	Current set of UAS geographical zones in ED-269 format
Flight authorisation	inbound	Binding authorisation or rejection status issued by the USSP for a filed operation plan, following the platform's zone-check submission
No-fly zone activation	outbound	New restricted volume activation and expiry time, encoded in ED-269 format
No-fly zone modification	outbound	Extension, reduction or early cancellation of an active volume
Zone check result	outbound	Outcome of the platform's check of a filed plan against active geographical zones, submitted to the USSP as the basis for its authorisation decision
Acknowledgement	outbound	Confirmation of receipt and handling of an operation that reached the tower position

2.2. Collaborative interface with ATC

Several European projects have investigated the interface between U-space and ATC. PODIUM examined a collaborative interface between UAS operators and ATC and demonstrated improved situational awareness for both sides, particularly for pre-tactical planning and dynamic airspace reconfiguration, while identifying the need for further work on real-time communication and alerting [21]. ENSURE developed and validated a collaborative interface with a focus on emergency and reconfiguration scenarios, and its trials covered crewed aircraft in distress, command and control link loss in controlled airspace, and UAS emergencies near airports [22]. The AURA project introduced the concept of shared airspace between ATC and U-space, along with a dynamic airspace reconfiguration role, and demonstrated the exchange of operational plans, telemetry, no-fly zones, conflict alerts, and reconfiguration signals with real ATC systems through SWIM-based data exchange [23]. Within DLR, complementary work has addressed the effect of UAS contingencies on ATC operations in shared airspace [27], the interaction between ATC and UAS operators and its automation potential [26], and drone contingencies during runway inspection [25].

In this work, the interface is deployed at the tower controller working position as a separate display at Magdeburg-Cochstedt Airport. The tower controller can change the airspace configuration and immediately see which UAS operations are affected and which UAS operators have acknowledged the change. The NFZ is published before the UAS operation, if a plan is rejected, the UAS operator receives the reason so they can replan on a different route or at a different time and resubmit, and the tower controller sees the replacement flight plan at the working position. The collaborative interface does not replace the USSP flight authorisation service. Under Regulation (EU) 2021/664 [4], the USSP provides the flight authorisation service, and the U-space consumes the authorisation status of every UAS operation plan as inbound information. The tower controller's contribution is the airspace constraint; the controller creates and publishes a dynamic geographical zone, against which the filed flight plans are evaluated. This evaluation is performed by the collaborative interface itself, which submits the outcome to the USSP as the basis for the USSP's binding authorisation or rejection decision (TAB 1, Fig. 1) the tower controller does not issue that decision directly.

2.3. Test environment at Magdeburg-Cochstedt Airport

Magdeburg-Cochstedt Airport also serves as Germany's National Experimental Test Center for UAS. The airport has an asphalt runway and a grass runway, is open during weekdays, and accepts aircraft with a maximum take-off mass of up to 14 t [30]. The test center has a permanently established UAS geographical zone under Article 15(2) of Implementing Regulation (EU) 2019/947 [8], which was developed jointly by the German Civil Aviation Authority (LBA) and DLR [29]. Its definition, including the safe flight areas within the airport boundary, the altitude limits [31], [32], and the associated risk mitigation measures, is delivered to the platform as a structured reference dataset encoded in ED-269 format [14], [15]. The associated

airspace risk assessment follows the EASA guidance, whose applicability to this site was examined in [28].

3. SERVICE-ORIENTED ARCHITECTURE AND REQUIREMENTS

3.1. Architecture overview

Fig. 1 shows the external data exchange between the USSP and the AREA U-space platform. The USSP provides the four mandatory services, namely network identification, traffic information, geo-awareness and flight authorisation. The four mandatory U-space services (inbound) are utilized by the platform, and the no-fly zone activations, controller instructions, flight plan decisions and acknowledgments produced at the tower working position (outbound) are returned to the same technical infrastructure.

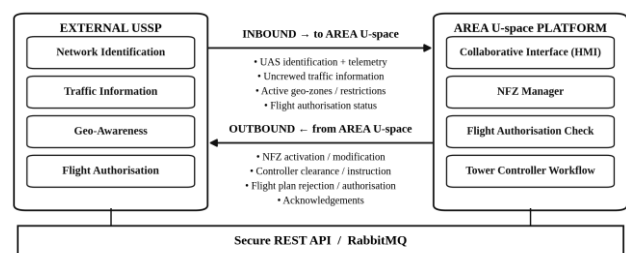


Fig. 1. External data exchange between the external USSP and the AREA U-space platform.

On the platform side, the collaborative interface consumes inbound information and presents it to the tower, whereas for dynamic geographical zones, the pre-flight authorisation check and the tower controller workflow combine to produce the outbound messages. Both directions use the same transport, so that a message created at the tower position reaches the operators over the same path on which the services are received [13]. Two complementary transports are used; request and response interactions use a secure REST application programming interface (API) with JSON payloads. This applies to retrieving the current set of geographical zones, submitting a new zone object, filing an operation plan, and querying its authorisation status. State and event distribution uses a RabbitMQ message broker, on which the platform publishes position reports, zone objects and flight plan decisions and to which the operators subscribe.

3.2. Requirements for the controller working position

The platform's system requirements are extracted from the acceptable means of compliance and guidance material to Regulation (EU) 2021/664 [5] and from the German national strategy on the establishment of U-spaces [33]. The general requirements identified in the earlier study remain valid and are grouped into usability and stability, safety and security, reliability and accessibility, interoperability and efficiency, and compliance with standards and regulations [12]. Three requirements from the controller interviews are particularly important for the present work. Controllers do not need to control UAS directly; their role is to monitor and ensure separation, so uncrewed aircraft shall be represented by a distinct, easily identifiable symbol. The essential data

elements for each operation are altitude, speed, call sign, and maximum take-off mass, with the vehicle type as a desirable addition. Finally, the tower controller must allow geographical zones and no-fly zones of flexible size and validity to be activated and deactivated [12]. TAB 2. summaries the information and data elements of the resulting working position for ATC controllers.

TAB 2. Information and Data Elements of the Collaborative Interface

Display area	Data elements	Source
Map display	Orthographic map of the area, current vehicle position, planned route and trajectory, active geographical zones, protected volumes, control zones and restricted areas	Traffic information, geo-awareness, navigation database
Vehicle box	Call sign, altitude, ground speed, vertical speed, vehicle type	Network identification,
Vehicle list	Number of vehicles, call sign, operator identifier, flight status, authorisation status	Network identification, flight authorisation
Zone panel	Zone identifier, geometry, lower and upper limit, activation and expiry time, status	Geo-awareness, no-fly zone manager

The interface shows, for every zone it distributes, which operation plans are affected and which operators have acknowledged the zone, because a zone that is not received is not a mitigation. The interface checks every filed UAS operation against the active geographical zones before the operation starts, and it returns the reason in case of a rejection so the UAS operator can replan the flight accordingly. Elements printed in the vehicle box and the vehicle list extend the set derived from the controller interviews reported in [12]. Each external interface is bound to a documented standard, which keeps the integration verifiable and replaceable and aligns the platform with the

wider U-space ecosystem [13]. TAB 3. lists the regulations, standards and protocols used.

TAB 3. Regulations, Standards and Protocols Used by the Interface

Standard or regulation	Used for
Implementing Regulation (EU) 2021/664 [4]	Regulatory framework of the mandatory U-space services and the role of the USSP
Implementing Regulation (EU) 2019/947 [8]	Operational rules and the framework for establishing a geographical zone
Delegated Regulation (EU) 2019/945 [9]	Product requirements for the UAS operated in the area
EUROCAE ED-269 [14]	Data model for UAS geographical zones exchanged with the USSP
ASTM F3411 [15]	Remote identification supported by the network identification service
ICAO Doc 10039 [16], Eurocontrol yellow profile [17]	SWIM principles and technical infrastructure profile
Secure REST application programming interface	Request and response exchange of operation plans, zones and authorisation status
RabbitMQ message broker	Distribution of telemetry, zone objects and flight plan decisions

4. IMPLEMENTATION OF THE COLLABORATIVE INTERFACE

The collaborative interface is implemented as a dedicated configuration of DLR's U-FLY human-machine interface, also used as a ground control station for supervising and guiding multiple highly automated UAS [24], and adapted to the tower position in earlier work [12]. The working position for controllers is installed on a separate computer in the tower of Magdeburg-Cochstedt Airport and is operated on a touch display. Fig. 2 shows the schematic layout of the HMI, the operation list with all known operations and their authorisation state, the panel used to create, publish, modify and cancel dynamic geographical zones, and the traffic situation display, on which each operation is drawn as a symbol with an associated vehicle box. The dynamic airspace reconfiguration function shows the control zones

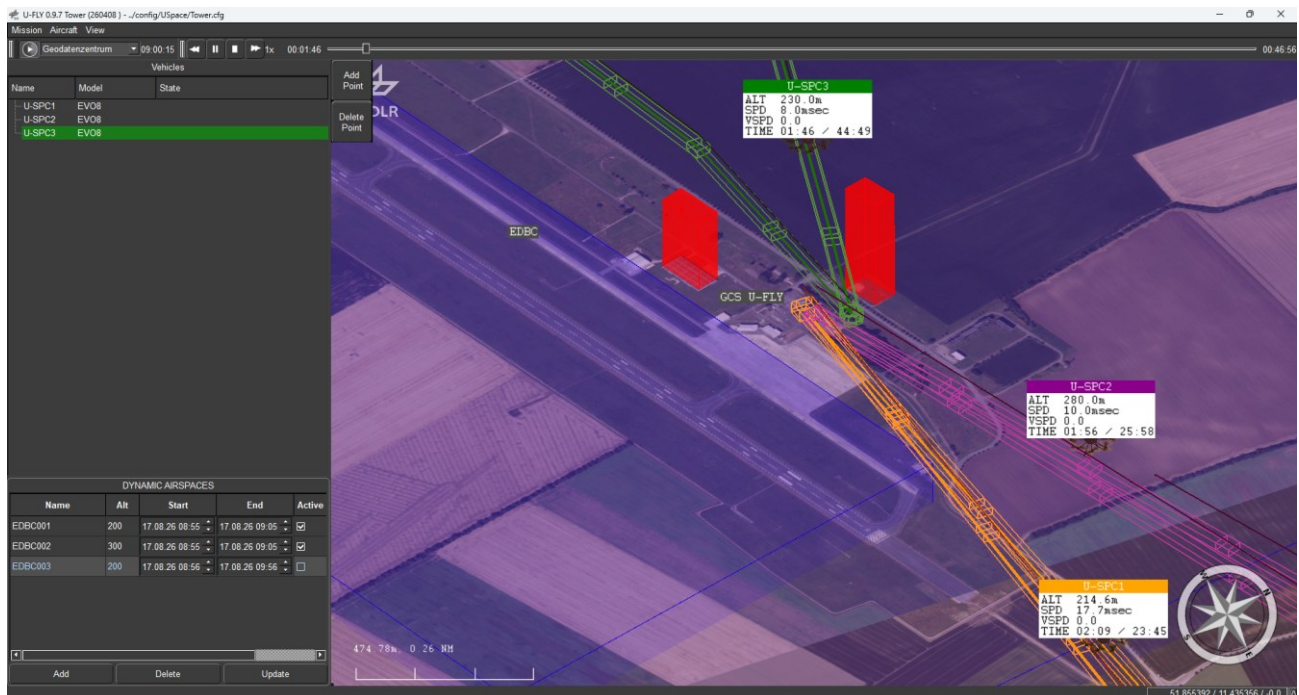


Fig. 2. Schematic layout of the collaborative interface at the tower working position, with the operation list, the geographical zone manager and the traffic situation display.

and restricted areas of the national navigation database together with the active geographical zones received from the geo-awareness service. Air traffic reaches the tower controller's working position through the USSP's network identification and traffic information services. Each label carries the aircraft identifier, geographical position, height above the surface or the take-off point, heading vertical speed, and the time at which the position was determined [13].

4.1. Geographical zone manager

The zone manager divides the zone into two types: reference zones, such as the permanently fixed geographical zone of the test center, are loaded from the ED-269 reference data set and cannot be modified from the work position. Whilst the other type, dynamic zones, are defined by the controller by drawing a polygon on the situation display and entering the lower and upper altitude limits and the activation and expiry time. The zone is encoded as an ED-269 [14] object, published through the message broker, and distributed by the USSP to all registered operators in the U-space airspace. Since the zone has a validity window, an operation plan whose trajectory falls outside the geometry during that window is unaffected, avoiding superfluous rejections. Fig. 3 shows the message sequence for a change of the airspace structure caused by an UAS operation. The controller is notified of the operation and creates and publishes the zone. Any plans filed after that are checked against the new airspace structure, and the operator receives either an authorisation or a rejection with a reason, allowing the plan to be refiled before departure.

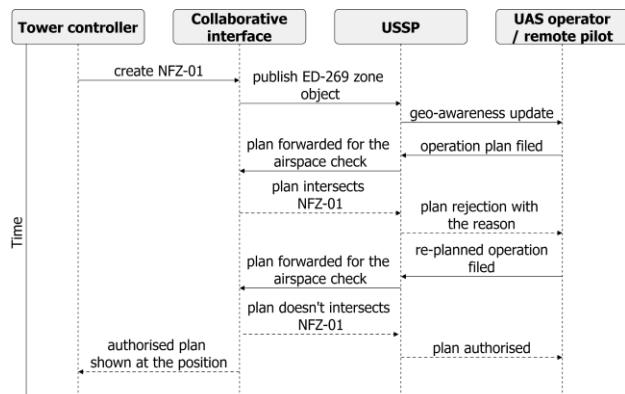


Fig. 3. Message sequence of a pre-flight change of the airspace structure.

4.2. Pre-flight authorisation algorithm

Every operation plan filed for the U-space airspace follows the procedure shown in Fig 4. The collaborative interface retrieves the geographical zones active during the period in which the operation would take place and checks the filed flight plan against them. The result of this check is submitted to the USSP, which issues the binding authorisation or rejection and returns it to the platform and the operator. A plan whose four-dimensional trajectory enters an active zone within its validity window is rejected by the USSP, which returns the reason to the UAS operator, so that the operator can re-plan on a different route or at a different time and file the UAS operation again. A plan that passes the check is authorised by the USSP, published to the operator and displayed at the tower working position.

The authorisation therefore remains with the USSP, as required by Regulation (EU) 2021/664 [4]; and the tower controller contribution is the airspace constraint against which the plan is evaluated and the visibility of the decision at the working position. Because the check is made before departure, a plan that would infringe the protected volume is stopped while the aircraft is still on the ground, and the operator knows the reason for the plan rejection.

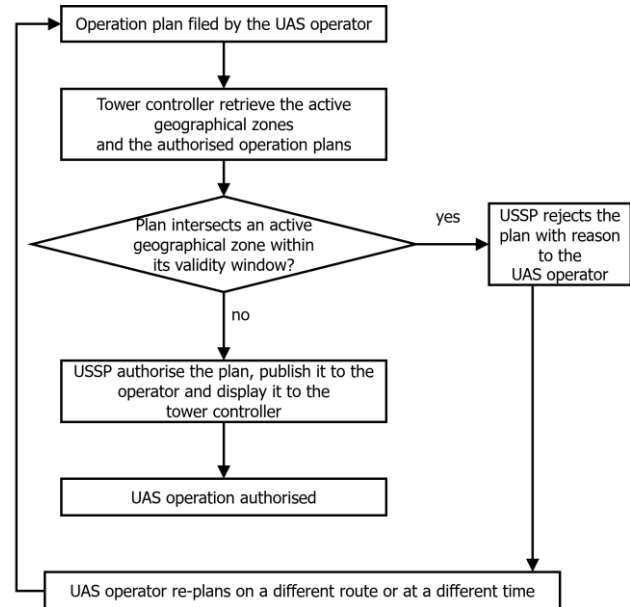


Fig. 4. Algorithm flow of the pre-flight check against active geographical zones.

5. SIMULATION-BASED TESTING

5.1. Simulation environment

Each UAS operation is described in a mission file using the following characteristics: call sign, vehicle type, display color, cruise altitude and cruise speed, start time, and a route of waypoints with geographic position and altitude. The file therefore defines a four-dimensional trajectory for every operation, which is exactly the information that the pre-flight authorisation algorithm requires. The reference airspace is supplied by the ED-269 dataset of the test center, and the tower controller creates the scenario's dynamic zone before the UAS operation starts. Two UAS mission files were produced for this study for the rejected flights, and each rejected and re-planned operation includes two routes. The route that was authorised, which is the route that is flown during the replay, and the originally filed route, which is stored as an inactive route so that the rejected plan and the authorised plan can be compared directly in the same mission file. The scenario is designed to exercise the pre-flight authorisation algorithm checks for geographical zones. Their properties are summarized in TAB 4. The traffic samples are deliberately small, so that every decision of a mission run remains traceable and every reported value can be attributed to an individual operation plan.

TAB 4. Definition of the test scenario

Property	Value
Objective	Pre-flight change of the airspace structure for a priority operation
Simulated period	10:00:00 to 10:16:00

Ordinary operation plans	3
Priority operation	1 emergency UAS operation
Cruise altitude	205 to 300 m MSL (25 to 120 m AGL)
Cruise speed	8 to 25 m/s
Airspace structure	NFZ-01 published at 09:50:00, corridor of 5.7 km by 0.8 km, GND to 400 m AGL, valid 10:06:00 to 10:12:00
Functions exercised	Geo-awareness, zone publication, airspace check of the filed operation plans

5.2. Test scenario

An emergency UAS operation is announced at 09:45:00. It is planned to depart from the apron of the test center, transit to the east along the axis of the runway and continue to its destination south-east of the airport, and it is granted priority over the other UAS operations. In order to protect that UAS operation, the tower controller creates the no-fly zone NFZ-01 and publishes it at 09:50:00, that is, before any uncrewed operation departs. NFZ-01 is designed to be valid from 10:06:00 to 10:12:00. Fig 5a and Fig. 5b show the filed and the authorised routes together with the protected volume NFZ-01.

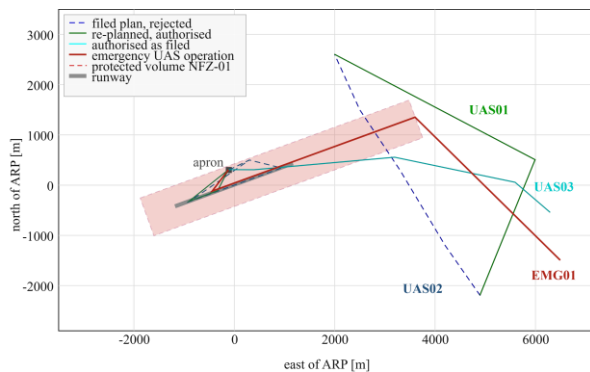


Fig. 5a. Schematic test Scenario for the emergency UAS operation.

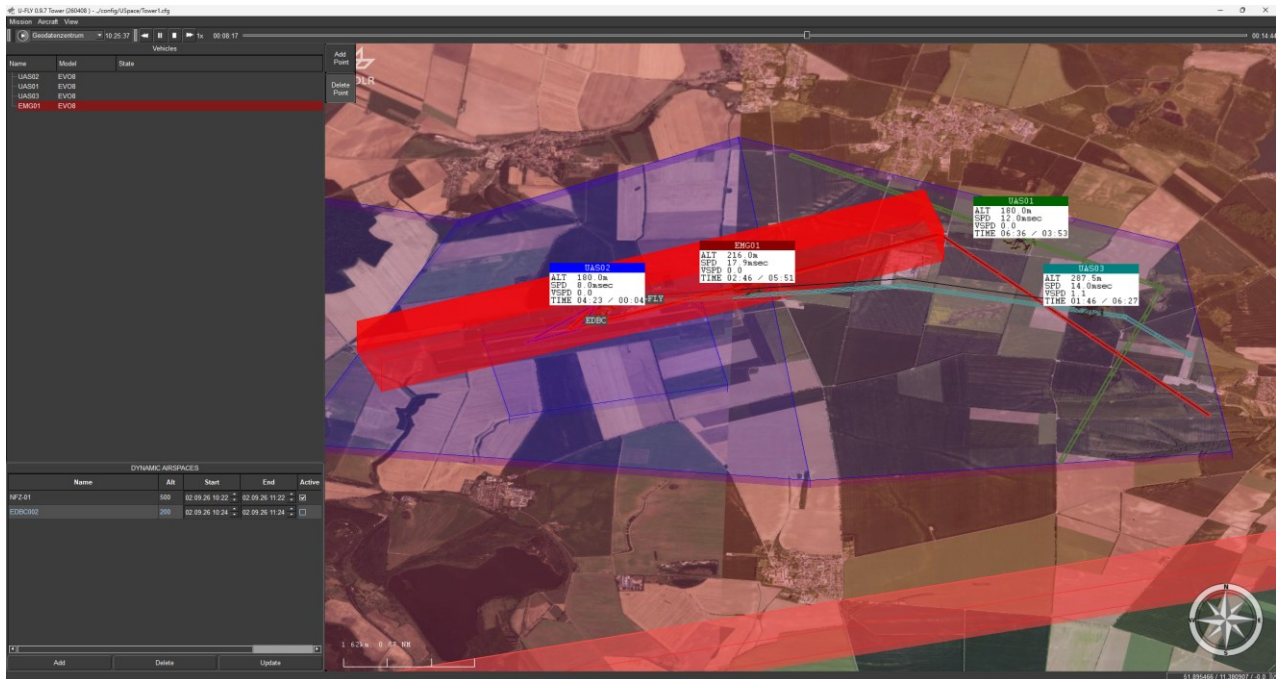


Fig. 5b. Filed UAS operation plans, the routes that were finally authorised, the emergency UAS operation (EMG01) and the protected volume NFZ-01.

The emergency UAS operation departs at 10:06:30, climbs to 260 m MSL (about 80 m above ground level), and flies at a ground speed of 25 m/s, arriving at 10:09:44. Three uncrewed UAS operation plans are filed afterward. UAS01 is a runway and apron surface inspection at 205 m MSL, which is about 25 m above ground level, and therefore follows the runway axis for most of its mission. UAS02 is a cross-airspace transit at 260 m MSL that crosses the runway 25 m from the south-east to the north-west. UAS03 flies the return leg of the medical corridor from the east and crosses the same centerline late in the runway.

6. RESULTS AND DISCUSSION

6.1. Scenario: pre-flight change of the airspace structure

Of the three filed operation flight plans, two intersect the published protected volume NFZ-01 while it is valid and were therefore rejected. The flight plan of UAS01 would have spent 322 s inside the volume during the validity window, because its mission is flown along the runway axis. The flight plan of UAS02 would have crossed the corridor at 10:07:26 and would have remained inside for 69 s. The third flight plan, UAS03, intersects the geometry of the corridor at 10:12:21, that is, after the zone has expired, and was authorised as filed consequently. For UAS03, using only the geometry would have produced an unnecessary rejection and an unnecessary re-planning for an operation that never shares the volume with the emergency operation. Both operators re-planned and re-filed before departure, and both re-planned routes were authorised. None of the authorised plans spend any time inside the volume during its validity window. UAS02 was re-planned around the eastern end of the corridor, which extended its route by 1.8 km and its flight time by 151 s. UAS01 could not be re-planned on a different route, the operation was therefore shortened to the runway and scheduled to be

completed at 10:05:20, before the zone becomes active. TAB 5 summarises the decision on each plan, and Fig 6. shows the time that the filed and the authorised plans spend inside the volume.

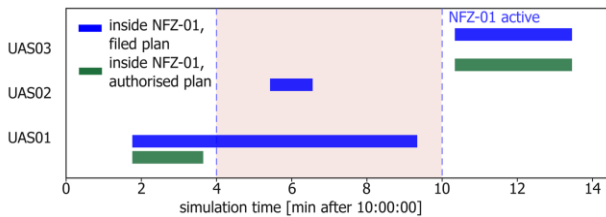


Fig. 6. Scenario: time spent inside the protected volume by the filed and by the finally authorised UAS operation plans. The shaded band is the validity window of NFZ-01.

TAB 5. Scenario: Decision on the filed operation plans

Call sign	Filed	Decision	Remedy and effect
UAS01	09:52:00	rejected, plan inside NFZ-01 during the validity window	Inspection shortened to the the runway and completed at 10:05:20
UAS02	09:53:00	rejected, plan inside NFZ-01 during the validity window	Re-planned around the eastern end of the corridor
UAS03	09:54:00	authorised as filed	Trajectory intersects the corridor geometry at 10:12:21, after the expiry of the zone

The safety effect is visible in the separation from the emergency UAS operation. Both the emergency aircraft and UAS01 would have been on the runway axis, with the emergency aircraft overtaking the inspection at a closing speed of 17 m/s. In physical terms, this is a near collision over the runway in the absence of airspace reconfiguration. The authorised plan of UAS01 has landed 70 s before the emergency operation departs, so the two do not overlap in time. Because the check is made before departure, the NFZ-01 does not depend on the reaction time of a UAS operator or of a tower controller during the flight.

6.2. Comparison with the non-integrated procedure

TAB 6 summarizes the performance indicators for the test scenario, along with the analytical reference. In the non-integrated procedure, no check of the filed flight plans against the airspace structure was performed. A change of the airspace structure had to be communicated verbally to the UAS operator in turn, which is estimated at 60 s to 80 s for two operations. It is derived from the coordination procedure in the earlier demonstration campaign [12], in which a single verbal instruction exchange was observed to take 30-40 s, and the exchanges are sequential. More importantly, the verbal procedure reaches UAS operators only after they are already flying, so a UAS operation whose route conflicts with the NFZ must be re-routed in the air; in the integrated procedure, the same operation is stopped before it starts. Two further differences are qualitative rather than numerical. In the integrated procedure, the rejection carries a machine-readable reason, so the UAS operator knows whether the flight plan failed against a zone or against another flight plan and can re-plan accordingly.

TAB 6. Summary of the Performance Indicators

Indicator	Value
Filed plans checked against the airspace structure	3 of 3
Plans correctly rejected	2
Unnecessary rejections avoided by the validity window	1
Time spent inside NFZ-01 by the authorised plans	0 s
Time that the filed plans would have spent inside NFZ-01	322 s and 69 s

7. CONCLUSION AND FUTURE WORK

This paper presents a service-oriented collaborative interface with air traffic control, developed as a digital U-space service in DLR's AREA U-space project. In contrast to the earlier self-contained prototype, the tower controller utilises the four mandatory U-space services from an external U-space service provider through documented interfaces and distributes controller-generated information to every affected UAS operator. A secure REST API carries the request and response exchanges, and every controller action and every flight plan decision is monitored. On this basis, a pre-flight authorisation algorithm checks each filed operation plan against the geographical zones active during the operation period and returns the reason for rejection so the UAS operator can replan before the operations start. The interface was evaluated in a pre-flight simulation scenario in which the airspace structure was changed to protect an emergency UAS operation that had been granted priority. The protected volume NFZ01 was published at 09:50:00 for a validity window from 10:06:00 until 10:12:00, before any UAS operations. Of the three filed operation plans, two intersected the volume NFZ01 during its validity and were rejected. At the same time, the third was correctly authorised as filed, because its trajectory crosses the corridor after the zone has expired. Both rejected flight plans were re-planned and re-filed before departure, and none of the authorised plans spend any time inside the volume NFZ01 while it is valid. The safety effect is visible in the separation from the emergency UAS operation; the UAS01 flight plan, flown without the change to the airspace structure, would have been overtaken over the runway, whereas the authorized plan for the same operation lands before the emergency operation departs.

Future work will establish the separation minimum against which a filed flight plan is compared with already authorised plans, as it must follow the airspace risk assessment for the designated airspace. Human-in-the-loop exercises with the tower controllers of Magdeburg-Cochstedt Airport are planned to measure the workload and situational awareness associated with creating and publishing a zone, and to replace the analytical coordination reference with measured coordination times. The scenario will be flown with real UAS to measure the latency of NFZ creation, flight-plan decisions, and the acknowledgment path. The geometry of the protected volume NFZ will also be extended to follow the priority route rather than a fixed corridor. This will be combined with emergency operations and conformance monitoring during the flight, so pre-operation establishment is complemented by a response when a UAS operation does not follow its authorised plan.

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