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Towards U-space conflict management services based on 4D protection bubbles

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In order to manage a multitude of drones deployed simultaneously in the same airspace, the European U-space should supplement its initial mandatory services with conflict detection and resolution services. The introduction of virtual 4D protection bubbles around drones could be a key enabler to ensure separation of aircraft, detect potential conflicts and monitor the effect of associated conflict resolutions. Simulations realized with a dense traffic over a city demonstrate the possibility to generate 4D bubbles in the strategic phase through the use of stochastic optimization algorithms. The addition of tactical monitoring tools ensures the resiliency of such 4D bubbles to unexpected events, such as strong winds. If 4D protection bubbles should facilitate the implementation of future strategic and tactical conflict management services, they could also be used to ensure the execution of initial U-space services.

I. Introduction

THE need to safely operate Unmanned Aircraft Systems (UAS), or drones, at Very Low Level (VLL) has led to many technical, operational and regulatory developments in the past decade. Following NASA's initiative on UAS Traffic Management (UTM) [1][2], concepts of operations (CONOPS) have been produced to develop a traffic management framework, in the same way as Air Traffic Management (ATM) for classic aviation. In the US, for example, the Federal Aviation Administration (FAA) has released in 2020 its second version of UTM concept of operations [3].

In Europe, the European Commission launched in 2016 the U-space initiative to address this topic and financed many research and demonstration projects, including the CORUS project (Concept of Operations for EuRopean UTM Systems), which delivered in 2019 the first U-space concept of operations [4][5]. In parallel, a regulatory framework is under construction, both at national level, but also at European level: in 2020, the European Union Aviation Safety Agency (EASA) released its regulatory framework for the U-space [6], paving the way for the regulation [7] implemented by the European Commission in 2021. A new wave of ongoing exploratory, industrial and demonstration projects coordinated by the SESAR Joint Undertaking (SJU) should lead in the near future to a new CONOPS, consolidated with latest regulation and developments.

If some differences remain between these documents [8], they largely agree on how this traffic management can be handled in the short term. As on-board systems required to safely operate in shared U-space airspace [9] may not be mature enough, U-space services should initially rely on current air traffic management techniques such as dynamic segregation and sharing of flight information, including 4D trajectory intentions. UAS operators will be provided a set of services by new actors named U-Space Service Providers (USSPs).

Nevertheless, the management of a high number of drones deployed simultaneously in the same airspace remains a big challenge. Let's take the drone package delivery example: many drones must safely cross each other while avoiding restricted airspaces and other types of air traffic, such as emergency helicopters. Thereby, conflict management services (i.e. conflict detection and conflict resolution services) should be rapidly deployed to handle a traffic of drones in a complex airspace environment like an urban area. It is commonly agreed that conflict management should be largely realized during the strategic phase, through a coordinated process based on flight demands. Nevertheless, unexpected events such as weather phenomena may require tactical updates of initial plans.

We analyzed in [10] the possibility to use 4D contracts to manage a traffic of delivery drones at a city level. We present in this paper an extension of this concept, based on the creation of 4D protection bubbles around drones to enable conflict management whatever the context. After defining the 4D protection bubbles' concept in Section II, we present in Section III the results of simulations realized to assess the efficiency and the resiliency of this concept, taking into account perturbations such as wind effects. Then Section IV describes how these 4D protection bubbles could be

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used to implement U-space services, such as conflict management. Finally Section V summarizes the conclusions, the limits and the perspectives of this study.

II. Managing conflicts with 4D protection bubbles

4D contracts have been introduced in the frame of the European project IFATS [11], aiming at defining a fully automated Air Transport System (ATS). To reach this objective, the way of managing air traffic was completely rethought: during the strategic phase, optimal and conflict-free trajectories are computed in 4D and aircraft commit to accurately fly according to their assigned trajectories. This process creates a “contract” between ground and air segments of the ATS. As long as aircraft respect their contract, there is, by construction, no collision risk. During the tactical phase, if the contract cannot be respected any more, the aircraft is granted an updated one, computed to take into account neighboring traffic. After the IFATS project, this concept of 4D contracts (4DCo) has been refined and assessed through large-scale simulations in the European project 4DCo-GC [12].



Fig. 1 4D bubbles of the 4DCo concept.

The 4DCo concept is based on the use of a set of dynamic (4D) virtual bubbles around the aircraft along its trajectory to ensure safety and reduce the number of contract updates. These are the Safety Bubble and Contract Bubble (Fig. 1) – the Freedom Bubble being a combination of the previous ones. We discussed in [10] on how to use such 4D bubbles to manage small drones flying at VLL (Very Low Level). In the same way as the 4DCo concept, conflict-free bubbles are created in the strategic phase. As long as drones manage to stay within the bubble volume, they are ensured to be appropriately separated from any other aircraft (drone or not) operating in the area. In the following paragraphs, we analyze how such a Contract Bubble could be used to ensure separation between drones, and we call it 4D protection bubble.

A. 4D protection bubbles

For each drone flying in an U-space airspace, a 4D protection bubble is created based on the flight plan submitted by the UAS operator. This virtual bubble is used to verify at each instant that the drone is where it was planned to be (conformance monitoring) or, if it has deviated, that this deviation remains acceptable (i.e. it does not endanger neighboring traffic).

At a given time, this bubble can be represented as a cylinder with a radius (lateral separation) based on drone characteristics (mass, speed, maneuverability, payload, etc.), but also based on environment data (weather, traffic density, etc.). We assume that the radius of each bubble is fixed before take-off and remains the same during the whole flight. The cylinder is not centered on the actual position of the drone, but on an interpolated position calculated from its initial 4D trajectory data (where it is supposed to be).

Only one altitude layer is used, which means a drone cannot fly under or above another one. This assumption is made for two main reasons. First, the risks associated to a sudden altitude change due to wind gusts (which is likely to happen with small drones) are very difficult to assess and could compromise overall safety. In addition, it simplifies the monitoring process of all actors (UAS operators, USSPs, authorities, etc.) and increases their situational self-awareness, thanks to a 2D representation of the traffic. Consequently, 4D bubbles can be seen as high cylinders covering all the vertical space from the ground. In radar-like views, bubbles are hence represented as discs, as illustrated by Fig. 2. We can observe in this example that both drones are not centered in the middle of their bubble, due to the effect of the wind. Nevertheless, as they manage to remain within their bubbles, they are deconflicted by construction.



Fig. 2 4D protection bubbles around drones.

B. Strategic and pre-tactical deconfliction

In the strategic phase, UAS operators share their flight intentions to USSPs. For each individual flight, the UAS operator sends a flight authorization request to its USSP, including especially its 4D trajectory, i.e. the planned 3D trajectory with estimated target times. If several USSPs manage a common U-space airspace, they immediately share the information with each other. Based on the characteristics of the drone (such as its mass and maximum speed) and latest weather prediction data, the USSP determines the radius of the protection bubble and builds a 4D protection bubble (i.e. a set of protection bubbles centered on positions of the 4D trajectory).

At each instant, if the protection bubble conflicts with airspace or traffic constraints provided by Air Navigation Service Providers (ANSPs) or other UAS protection bubbles previously granted by one USSP of the U-space airspace, an operator can analyze the associated risks with a decision support tool based on what-if simulation. If the risk of conflict is too high, a new 4D trajectory is calculated with optimization algorithms and sent to the UAS operator as a counter-proposal. The priority policy is based on a first-come, first-served principle, even if some exceptions remain possible (for state or emergency drones for instance). Once a conflict-free 4D protection bubble has been agreed upon, the USSP delivers a flight authorization to the UAS operator that commits to operate the drone within its protection bubble. At the end of the strategic phase, the USSP is ensured to manage a traffic of very low complexity, with little or no conflicts remaining.

In the pre-tactical phase, just before the UAS take-off, the USSP can simulate the traffic (with latest weather data for instance) and checks if some drones are likely to operate out of their bubble, and if some crossings should be monitored carefully.

C. Tactical monitoring and intervention

In the tactical phase, the UAS operator is responsible to verify that the drone remains within its protection bubble. The operator may use U-space services, such as conformance monitoring, provided by some USSPs. At the same time, the USSP in charge of the conflict management monitors if some conflicts appear and analyzes associated risks.

The main challenge of this phase is to handle uncertainties linked to the strategic planning, such as variation of encountered weather. These uncertainties are likely to cause inaccuracy in the follow-up of the trajectories planned in the strategic phase. As these differences may lead to conflicts, it is of the highest importance to be able to detect and manage them. 4D protection bubbles are hence used both at the aircraft- and supervision-levels to detect potential conflicts. Regarding the aircraft level, geocaging strategies [13] are deployed to ensure that the drone remains within the boundaries of its assigned 4D bubble. However, small drones performance limitations can lead to a risk of bubble excursion. In this case, the UAS operator must immediately inform the USSP supervising this drone and its neighboring traffic. Regarding the supervision level, the detection of air-air risks is done both through UAS direct information and traffic supervision based on the monitoring of 4D bubbles. Depending on the severity of the identified risks, the conflict resolution strategy is different, as described in Table 1.

Table 1 Resolution strategy according to risk severity

Risk severity	Example situation	Strategy
Low risk	4D bubble excursion without any impact on other flights, close drones with diverging directions, etc.	An updated trajectory is recomputed, not leading to any avoidance maneuver
Moderate risk	Potential conflict in a low density traffic	A simple, potentially pre-computed, avoidance maneuver (e.g. heading modification) is sent to both conflicting drones; When the conflict is cleared, both drones fly back to their initial flight plans.
High risk	Potential conflict in a high density traffic	In this case, several drones may be implied. A complex trajectories/bubbles computation must be dynamically performed by the USSP, at the level of a cluster of aircraft [14]. For instance, an iterative geometric approach to minimize jointly the trajectory deviation and processing time while resolving local conflicts is presented in [15].

III. Evaluation of the 4D protection bubbles concept

In this Section, we describe the methodology and the initial results of a set of simulations performed to assess the resiliency and efficiency of the 4D protection bubbles concept. We consider the following use case: the management of a high number of drones flying between a set of warehouses to deliver packages at the level of a large city (Toulouse - France).

A. Strategic and pre-tactical simulations

For the simulations, we built a scenario with a large number of drones deployed in an urban environment in the same time slot (about 50 flights per hour). All drones use the same cruise level, as specified in Section II.A and have a constant cruise speed. Each drone is flying over the city, from a warehouse to another, with a requested take-off time assigned randomly. In theory, it can cross another drone flying on the same route (between same warehouses), but also on another route (between one or two different warehouses). This scenario leads to a high number of potential conflicts; this is done on purpose to test the performance of the system.

As soon as a new request is received, a 4D trajectory is built from initial flight intentions data: take-off time, cruise speed, start and arrival locations. An initial 4D protection bubble is created along the trajectory with a default radius of 500 m. Then we check if the new 4D bubble intersects with airspace constraints (e.g. airport proximity or emergency helicopters' corridors) or other drones' protection bubbles. If this is the case, we compute an alternate 4D trajectory/bubble.

Based on the assumption that most of the flight intentions are known, we developed an algorithm to simultaneously deconflict all 4D protection bubbles by adjusting UAS take-off times. Concretely, each drone is assigned a delay to minimize the number of intersections with other drones' bubbles. This algorithm is based on a stochastic optimization, the objective functions being the number of bubbles' intersections and the delay put on flights. This optimization could be simplified, thanks to additional trajectory adjustments, such as the modification of the cruise speed, or the use of hovering capability to yield the way. We do not present in this paper the results of these algorithms.

We described in [10] such a mono-objective optimization based on the Simulated Annealing [16]. Successive iterations allow to minimize the weighted sum of remaining conflicts (in seconds) and all delays affected (also in seconds). The algorithm iterates until all conflicts are resolved. However, this process requires a large computation time and it is more realistic to limit the maximum number of iterations and to analyze individually the remaining conflicts. This closes the strategic phase of the deconfliction.

Fig. 3 illustrates the result of this optimization phase with a zoom on a district of the city. At a given time, two couples of bubbles were supposed to intersect based on their initial flight demand (upper figure). After the optimization,



Fig. 3 Conflict-free trajectories (bottom) generated to minimize bubbles' intersections (top)

thanks to the take-off time shift, the same bubbles are conflict-free.

The strategic traffic deconfliction is done with the following assumptions:

- 5 waves of 10 drones (every 5 minutes)
- single flight level (2D)
- constant speed for all drones
- no wind

The pre-tactical phase can then be modelled: a fast-time simulation is performed in order to assess the effect of the wind uncertainties on this organized traffic.

A strong wind scenario was considered. The drones behavior was limited to reaching the arrival target, without trying to counterbalance the wind effect on their trajectories.

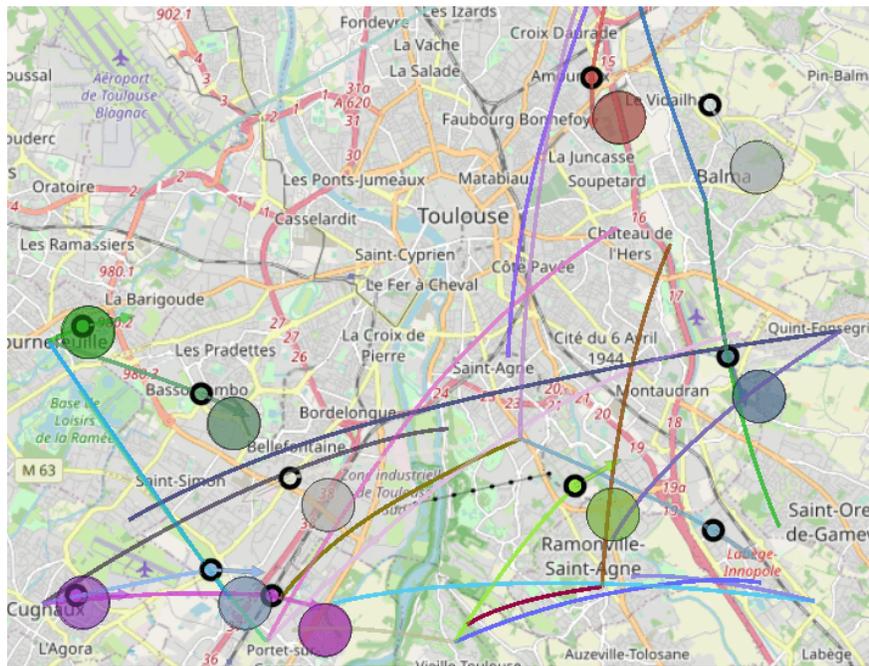


Fig. 4 Traffic snapshot of pre-tactical simulation.

Table 2 Separation losses due to wind

Separation losses	5
Duration (s)	51
	33
	27
	24
	21
Longest (s)	51
Shortest (s)	21
Cumulative time (s)	176
	2 min 56 s

As expected, the wind effect forced many of the drones to operate out of their assigned protection bubble, as illustrated by Fig. 4. However, even in such a worst-case scenario, the number of conflicts remained quite low, illustrating the great benefit of starting with a well organized and deconflicted traffic planning. Some simulation results are provided in Table 2.

B. Tactical simulations

In order to complete the assessment of the proposed concept in terms of feasibility and performance, the tactical phase must be modelled and simulated. To this end, parametric simulations were performed to evaluate the impact of several wind situations (no wind, moderate and strong wind) on various traffic scenarios (number and complexity of conflicts).

These simulations required the development of several models and tools:

- Drone performance model: it consists of the main characteristics of the drone, such as the speed and acceleration ranges, maximum altitude, rate of climb and descent, weight, battery time, etc. This model accounts for protection bubbles; the geocaging function can be disabled if needed.
- Traffic simulator: an adaptation of an in-house traffic simulator (initially developed for simulation of conventional commercial traffic), to enable the handling of 4D contracts.
- Supervision model: its role is to monitor the positions of the drones and detect when minimum distance thresholds are violated. This model represents the USSP.
- Wind model: it consists of the computation of wind fields (wind force on 3 axes: eastward, northward and upward), based on Meteo France weather data.
- User interface: to visualize the flights and interact with the simulation.

Table 3 Separation losses due to wind. Left: geocaging off, right: geocaging on

	Geocaging OFF	Geocaging ON
Separation losses	5	4
Duration (s)	51	45
	33	24
	27	6
	24	6
	21	
Longest (s)	51	45
Shortest (s)	21	6
Cumulative time (s)	176	81
	2 min 56 s	1 min 21 s

Tactical simulations can be run in batch or interactive modes.

1. Batch simulations

The former is much faster and is suited to parametric simulation or optimization in the loop. However, it does not enable the user to interact with the simulation. This mode was used to measure the performance of the system when the geocaging function was enabled. Table 3 compares the results of Table 2 with the exact same simulation inputs but with an active geocaging function.

This table enables to conclude that the strategic deconfliction phase is of primary importance: even in the case of a traffic with a high risk of conflict, with a strong wind making most of the flights deviate from their initial flight plans, almost no separation loss occur. The situation is even better (even not perfect) when using a basic geocaging capability.

In addition, the threshold used to determine a loss of separation (500 m) is very conservative, especially regarding the considered type of aircraft (small drones at VLL).

So we can consider that the use of 4D protection bubbles for drone parcel delivery as a viable concept, at least from a safety perspective.

2. Interactive simulation

However, this needs to be further investigated. To this end, other simulations, with Man-In-The-Loop, have been performed. A specific User Interface has been developed in order to enable the monitoring of the situation and the interaction with the flights. The simulation is run a little faster than real-time to speed the process up. The supervision model constantly monitors the separation distances between all the drones, in order to detect conflict risks.

In case a loss of separation is detected:

- the simulation stops;
- the conflicting drones are highlighted in order for the user to immediately spot the situation to be resolved;
- a control panel is displayed, enabling the user to send control orders to the conflicting drones. As the simulator is still under development, the available maneuvers are currently limited to hovering (for a certain period of time) and heading change.

The user can then send the chosen control orders to the simulator and they are applied to the flights. When the supervision model detects that the distance between the drones is above the separation threshold, their original flight plan is sent back to them so they can resume their mission. Fig. 5 illustrates the detection of a conflict between two drones (in red, on the left). Default maneuvers (heading change) are suggested to solve this local conflict.

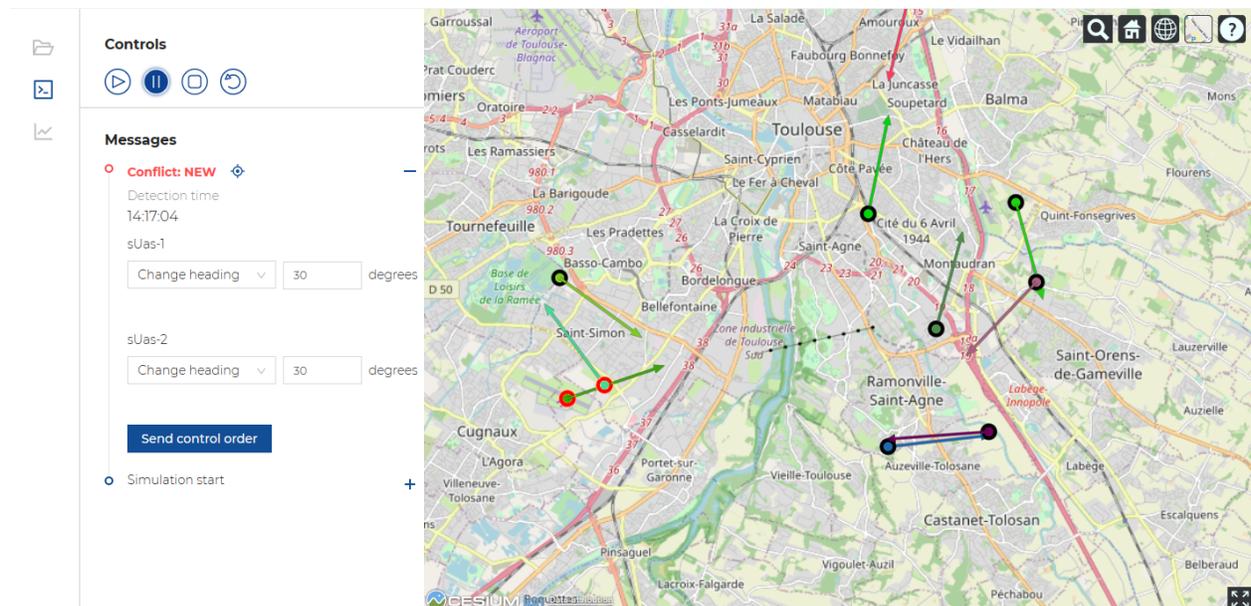


Fig. 5 Supervision tool to visualize tactical separation losses and suggest maneuvers.

These simulations with Human-In-The-Loop enabled to roughly assess the difficulty to manage the proposed type of traffic. The conclusion is that, thanks to the strategic planning phase, the task is pretty simple: the number of conflicts is low and the drones ability to perform hovering flight gives a safe bet in the more complex situations. This can lead to the conclusion that the proposed concept is promising enough to considering using it in an operational U-Space.

IV. 4D protection bubbles in U-space services

In this Section, we discuss how 4D protection bubbles could be used to implement U-space services. Many services have been identified in CORUS CONOPS [4][5]. They are mapped to four U-space levels, going from U-space foundation services (U1), such as geo-awareness, to U-space full services (U4), offering high levels of automation to all UAS operations [17]. The European U-space regulation [7] identifies four initial mandatory services:

- network identification;
- UAS flight authorization;
- geo-awareness;
- traffic information.

In order to be qualified as U-space Service Provider, the interested entity needs to demonstrate its capability of providing at least these four services. Nevertheless, for each U-space airspace, European member states can require additional services, such as weather information or conformance monitoring. EASA explains in [6] that additional U-space services, such as tactical de-confliction, should be added in the regulation as soon as these services become mature (and required). It is hence likely that many other services identified in European CONOPS, including conflict management services, will be soon listed as optional or mandatory services to manage more and more complex scenarios.

U1	Foundation	<ul style="list-style-type: none"> ▶ Registration ▶ Registration assistance ▶ e-identification ▶ Geo-awareness ▶ Drone aeronautical information management 		
U2	Initial	<table style="width: 100%; border: none;"> <tbody> <tr> <td style="vertical-align: top;"> <ul style="list-style-type: none"> ▶ Tracking (Position report submission) ▶ Surveillance data exchange ▶ Geo-fence provision (includes dynamic geo-fencing) ▶ Operation plan preparation /optimisation ▶ Operation plan processing ▶ Risk analysis assistance ▶ Strategic Conflict Resolution ▶ Emergency Management ▶ Incident/ Accident reporting </td> <td style="vertical-align: top;"> <ul style="list-style-type: none"> ▶ Citizen reporting service ▶ Monitoring ▶ Traffic information ▶ Navigation infrastructure monitoring ▶ Communication infrastructure monitoring ▶ Legal recording ▶ Digital logbook ▶ Weather information ▶ Procedural interface with ATC </td> </tr> </tbody> </table>	<ul style="list-style-type: none"> ▶ Tracking (Position report submission) ▶ Surveillance data exchange ▶ Geo-fence provision (includes dynamic geo-fencing) ▶ Operation plan preparation /optimisation ▶ Operation plan processing ▶ Risk analysis assistance ▶ Strategic Conflict Resolution ▶ Emergency Management ▶ Incident/ Accident reporting 	<ul style="list-style-type: none"> ▶ Citizen reporting service ▶ Monitoring ▶ Traffic information ▶ Navigation infrastructure monitoring ▶ Communication infrastructure monitoring ▶ Legal recording ▶ Digital logbook ▶ Weather information ▶ Procedural interface with ATC
<ul style="list-style-type: none"> ▶ Tracking (Position report submission) ▶ Surveillance data exchange ▶ Geo-fence provision (includes dynamic geo-fencing) ▶ Operation plan preparation /optimisation ▶ Operation plan processing ▶ Risk analysis assistance ▶ Strategic Conflict Resolution ▶ Emergency Management ▶ Incident/ Accident reporting 	<ul style="list-style-type: none"> ▶ Citizen reporting service ▶ Monitoring ▶ Traffic information ▶ Navigation infrastructure monitoring ▶ Communication infrastructure monitoring ▶ Legal recording ▶ Digital logbook ▶ Weather information ▶ Procedural interface with ATC 			
U3	Enhance	<table style="width: 100%; border: none;"> <tbody> <tr> <td style="vertical-align: top;"> <ul style="list-style-type: none"> ▶ Dynamic Capacity Management ▶ Tactical Conflict Resolution ▶ Geospatial information service ▶ Population density map </td> <td style="vertical-align: top;"> <ul style="list-style-type: none"> ▶ Electromagnetic interference information ▶ Navigation coverage information ▶ Communication coverage information ▶ Collaborative interface with ATC </td> </tr> </tbody> </table>	<ul style="list-style-type: none"> ▶ Dynamic Capacity Management ▶ Tactical Conflict Resolution ▶ Geospatial information service ▶ Population density map 	<ul style="list-style-type: none"> ▶ Electromagnetic interference information ▶ Navigation coverage information ▶ Communication coverage information ▶ Collaborative interface with ATC
<ul style="list-style-type: none"> ▶ Dynamic Capacity Management ▶ Tactical Conflict Resolution ▶ Geospatial information service ▶ Population density map 	<ul style="list-style-type: none"> ▶ Electromagnetic interference information ▶ Navigation coverage information ▶ Communication coverage information ▶ Collaborative interface with ATC 			
U4	Full	<ul style="list-style-type: none"> ▶ Integrated interfaces with manned aviation ▶ Additional new servicesw 		

Fig. 6 SESAR U-space service levels [17].

A. Using 4D protection bubbles in initial U-space services

This section describes how the concept of 4D protection bubbles can be mapped to the initial mandatory U-Space services listed previously.

1. UAS flight authorization service

In the strategic phase, UAS operators shall submit their flight intentions through UAS flight authorization services. Before each individual flight, the UAS operator submits an UAS flight authorization request to its USSP. Annex IV

of U-space regulation [7] details the information that shall be included in this request, such as the identification and registration of the UAS, the type of flight, or the category of operation (ex: specific). A 4D trajectory must also be shared, i.e. the flight plan of the UAS with associated target times. The USSP accepts the flight authorization if the flight is free of intersection in space and time with any other notified UAS flight authorization. If it is unable to grant such an authorization, it may propose an alternative to the UAS operator. As described in Section II.B, 4D protection bubbles could be used to rapidly detect potential conflicts between the requested 4D trajectory and previous UAS flight authorizations. In case of intersection, the USSP should analyze whether the UAS flight authorization could be granted or if another 4D trajectory should be computed. When a flight authorization is issued, the USSP shall indicate the allowed flight authorization deviation thresholds. The 4D protection bubble radius could be used to specify and illustrate such threshold.

2. Geo-awareness service

The geo-awareness service is used to provide UAS operators with airspace constraints linked to geographical zones or temporary restrictions. In the strategic phase, the use of 4D protection bubbles could assist the USSP and the UAS operator in identifying risky parts of the trajectory, too close to an airport for instance. In the tactical phase, the USSP must inform the UAS operator when a new airspace constraint, such as a dynamic geofence for emergency helicopter, conflicts with the initial 4D trajectory/bubble agreed in the UAS flight authorization. Once again, protection bubbles can be used to rapidly compute the intersections between airspaces, whatever their type: cylindrical bubbles, cuboid corridors etc.

3. Traffic information service

The USSP shall also provide UAS operators with traffic information services, i.e. information on any other conspicuous air traffic, in proximity to the position or intended route of the UAS flight. The automatic detection of potential intersection of 4D protection bubbles in the short term could assist the operator by triggering alerts that could lead, after analysis, to a traffic information. It has to be noted that the size of bubbles (radius) could be configured to get warnings before the real intersection of 4D protections bubbles. The UAS operator could also get a lot of information on the neighboring traffic (position, speed, heading) by visualising 4D protection bubbles. The USSP should also inform the neighboring traffic when one of the UAS does not behave as agreed in its flight authorization. Bubbles should be used to rapidly visualize whether an UAS deviates from its trajectory: when a drone is about to exit its protection bubble, both USSP and UAS operator should react. Such activity can be linked to the conformance monitoring service, identified in Article 13 of the regulation [7] as a candidate mandatory service. When flight authorization deviation thresholds are violated (i.e. when the drone leaves its 4D bubbles), the UAS operator and all other UAS operators in the vicinity should be immediately alerted.

B. Towards U-space conflict management services

In both CONOPS and regulatory documents, the need to implement conflict management services has been identified to address operations in dense and complex airspace environment. Conflict management refers to the process of preventing aircraft to operate too close to each other, i.e. with a separation distance below an agreed separation standard. This process can be divided into two tasks:

- the detection of a conflict: the identification of two aircraft operating (or about to operate) too closely;
- the resolution of the conflict: actions leading to go back to an adequate separation.

Each conflict resolution service relies on a conflict detection that can be performed by other U-space services.

The conflict management process should be addressed as a continuous process from strategic to tactical phase. Initially, some operations will be enabled through the sole implementation of strategic conflict management, as showed by U2 service level in Fig. 6. Nevertheless some complex operations in dense areas with unexpected events will require a tactical conflict management service, as listed in U3.

4D protection bubbles are perfectly suited to enable such a conflict management service. As described in previous Section, UAS trajectories are deconflicted by construction with the UAS flight authorization service. The 4D trajectory agreed between the UAS operator and the USSP hence guarantees that the drone is separated from all other authorized traffic as long as it remains within its bubble. The radius of the bubbles can be tailored to ensure a given separation between all aircraft: the greater the risks linked to uncertainties (probability of operations out of bubbles), the larger the bubble. The majority of potential future conflicts can then be avoided thanks to the strategic phase.

In the pre-tactical and tactical phases, the intersection of bubbles can be rapidly computed to detect potential conflicts with what-if simulations. [15] explains how a 4D grid representation enables an optimized detection of potential conflicts. Depending on the severity of the identified risks, several conflict resolutions can be performed, as described in Section II.C. For instance an avoidance maneuver is sent to both aircraft, modifying their 4D bubbles temporarily.

V. Conclusion

In order to manage a complex traffic of drones in an urban environment, we developed a concept of operations based on 4D protection bubbles to manage potential conflicts between drones. From initial 4D trajectories submitted in flight authorization requests, conflict-free bubbles are calculated to keep each drone separated from any other traffic and any restricted airspace. In the tactical phase, UAS operators and USSPs monitor that drones remain within their protection bubbles, even when they face unexpected events such as strong winds. If not, a tactical conflict resolution can be performed, based on these 4D bubbles.

We assessed the resiliency of this concept with a set of simulations. First we generated deconflicted 4D bubbles from requested flight plans with stochastic optimization algorithms. Then we run simulations based on drones models, wind models and ad hoc algorithms to detect intersections between bubbles and solve latest conflicts. These simulations demonstrated the possibility to generate such realistic 4D bubbles for a dense traffic at the level of a large city. Nevertheless further simulations would be necessary to check if such algorithms could manage higher traffic with various shapes and sizes of bubbles. Besides, more sophisticated avoidance maneuvers should be added to our model to manage tactical conflict resolution, such as IMPETUS technical solution, based on potential field theory [18].

4D bubbles could be rapidly used to facilitate the implementation of U-space initial mandatory services, such as UAS flight authorization service. They could also be a key enabler to develop new U-space services in next U-space service levels, such as conformance monitoring service. Finally, the management of conflicts, i.e. the strategic or tactical conflict detection and resolution should be built upon this concept. Nevertheless further research will be needed to fine-tune this concept based on latest regulation evolutions, U-space CONOPS updates and new elements brought by SESAR exploratory research projects. For instance, the BUBBLES project aims at defining the building basic blocks for a U-space separation management service [19].

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References

- [1] Kopardekar, P., Rios, J., Prevot, T., Johnson, M., Jung, J., and Robinson, J. E., "Unmanned aircraft system traffic management (UTM) concept of operations," *AIAA aviation forum*, 2016.
- [2] Prevot, T., Rios, J., Kopardekar, P., Robinson III, J. E., Johnson, M., and Jung, J., "UAS traffic management (UTM) concept of operations to safely enable low altitude flight operations," *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016, p. 3292.
- [3] "Unmanned Aircraft System (UAS) Traffic Management(UTM) Concept of Operations v2.0," FAA, 2020.
- [4] "CORUS U-space Concept of Operations 03.00.02," SESAR Joint Undertaking, 2019.
- [5] Barrado, C., Boyero, M., Brucculeri, L., Ferrara, G., Hately, A., Hullah, P., Martin-Marrero, D., Pastor, E., Rushton, A. P., and Volkert, A., "U-space concept of operations: A key enabler for opening airspace to emerging low-altitude operations," *Aerospace*, Vol. 7, No. 3, 2020, p. 24.
- [6] "High-level regulatory framework for the U-space," EASA, 2020.
- [7] "Commission implementing regulation (EU) 2021//664 of 22 April 2021 on a regulatory framework for the U-space," *Official Journal of the European Union*, 2021.
- [8] Lieb, J., and Volkert, A., "Unmanned Aircraft Systems Traffic Management: A comparison on the FAA UTM and the European CORUS ConOps based on U-space," *2020 AIAA/IEEE 39th Digital Avionics Systems Conference (DASC)*, IEEE, 2020, pp. 1–6.

- [9] Geister, R., Peinecke, N., Sundqvist, B.-G., Del Core, G., Timmerman, B., Boer, J.-F., Zimra, D., Steinbuch, Y., Batzdorfer, S., Grevtsov, N., Neeman, E., and Petrov, N., "On-Board System Concept for Drones in the European U-space," *2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC)*, 2019, pp. 1–6. <https://doi.org/10.1109/DASC43569.2019.9081661>.
- [10] Joulia, A., Dubot, T., and Bedouet, J., "Towards a 4D traffic management of small UAS operating at very low level," ICAS, 30th Congress of the International Council of the Aeronautical Sciences, 2016.
- [11] Le Tallec, C., and Joulia, A., "IFATS: 4D contracts in 4D airspace," *AIAA Infotech@ Aerospace 2007 Conference and Exhibit*, 2007, p. 2778.
- [12] Joulia, A., Riviere, T., and Le Tallec, C., "Impact of aircraft guidance and navigation on 4D contracts generation and execution-example of the 4DCo-GC project," *AIAA Guidance, Navigation, and Control (GNC) Conference*, 2013, p. 4890.
- [13] Hoekstra, J. M., Ellerbroek, J., Sunil, E., and Maas, J., "Geovectoring: reducing traffic complexity to increase the capacity of uav airspace," *International Conference for Research in Air Transportation, Barcelona, Spain*, 2018.
- [14] Dubot, T., Joulia, A., and Bedouet, J., "Managing the 2035 air traffic through clustered self-separation out of 4D protection bubbles," 2nd place winner of the NASA Tournament Lab "Sky for All" challenge, 2016.
- [15] Acevedo, J. J., Capitán, C., Capitán, J., Castaño, A. R., and Ollero, A., "A Geometrical Approach based on 4D Grids for Conflict Management of Multiple UAVs operating in U-space," *2020 International Conference on Unmanned Aircraft Systems (ICUAS)*, IEEE, 2020, pp. 263–270.
- [16] Aarts, E. H., Korst, J. H., and Van Laarhoven, P. J., "4. Simulated annealing," *Local search in combinatorial optimization*, Princeton University Press, 2018, pp. 91–120.
- [17] "U-space - Supporting safe and secure drone operations in Europe," SESAR Joint Undertaking, 2020.
- [18] Escalonilla, P. S., Janisch, D., Forster, C., Büddefeld, M., and Teomitz, H. E., "Towards a continuous Demand and Capacity Balancing process for U-space," 2020.
- [19] "BUBBLES Guidelines to implement separation minima and methods 01.00.00," SESAR Joint Undertaking, 2021.