UAV Collision Risk as Part of U-space Demand and Capacity Balancing

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Abstract— **The implementation of U-space will facilitate large-scale operations of Unmanned Aerial Vehicles (UAVs) in urban environments. However, the capacity for permitting UAV flights in urban airspace is not unlimited. The DACUS project is developing a concept for balancing capacity and demand for U-space airspace, in line with operational requirements which are unique to the UAV domain. This paper focuses on exploring the role of collision risk between UAVs as part of this process. A collision risk model was developed and tested in a series of experiments as a means of identifying how many UAVs can operate in a given area without exceeding pre-defined risk thresholds. We present the methodology behind this model, and support our claims based on results gathered from some initial experiments. Results provide some initial estimations of airspace capacity values for urban environments, which will be further refined in future experiments.**

Keywords-Unmanned Aircraft Systems Traffic Management; U-space; UTM; urban airspace capacity; UAV collision risk; Demand and Capacity Balancing

I. INTRODUCTION

Establishing U-space, a concept for the collaborative management of UAVs, in urban environments brings with it a series of challenges for managing the overall flow and structure of UAV traffic. The DACUS project (www.dacus-research.eu) set about developing a methodology for defining limits on how many UAVs may access urban airspace and how to manage situations where the demand for airspace is too great. This process can generally be summarized as “Demand and Capacity Balancing” (DCB). DCB is already a well-established element of traditional Air Traffic Flow and Capacity Management (ATFCM) [1]. However, our assessment has found that the differences of operating methods of U-space flight operations to those of air traffic management are significant enough to justify the development of a revised concept specific to UAVs, which will be introduced here.

These differences are elaborated on in chapter II, supported by a series of fundamental principles on which the U-space DCB concept is built. Here we will also explain the necessity to establish a definition of capacity which is better suited to the highly dynamic nature of U-space flight operations. Finally, a general outline of the process for detecting imbalances is introduced. A particular emphasis is placed on the role of UAV collision risk as an indicator driving this process.

The modelling of UAV collision risk for detecting capacity imbalances in U-space DCB is the focus of chapter III. In this chapter, we explain the methodology behind the model which links collision risk and UAV failure rates with the probability of causing harm to third parties. This probability is then used to determine the capacity threshold based on risk.

This model was then tested in a series of simulations, which focused on the effect of Communication, Navigation and Surveillance (CNS) performance, deconfliction service provision and population density on the capacity threshold of a given U-space area. Results of this simulation are presented in chapter IV.

Finally, the discussion section (chapter V) summarizes insights gathered from the simulations of the collision risk model to the overall U-space DCB process, which conclude in a summary of conclusions and definition of next steps in chapter VI.

II. DEMAND AND CAPACITY BALANCING IN U-SPACE

The U-space environment is much more dynamic and multi-facetted than that of traditional air traffic management, as previous research in SESAR has shown. Developing a suitable DCB concept for U-space is a challenge, as it must incorporate much higher quantities of vehicles [2], much smaller operating scales, different approaches to providing Communication, Navigation and Surveillance (CNS) [3], greater levels of information fidelity [4], diverse mission requirements, greater inclusion of societal metrics and shorter timeframes for implementation [5]. A series of principles have been developed to assist in building a DCB concept which covers these requirements.

A. *Key principles of the U-space DCB process*

The fundamental aim of the U-space DCB concept developed in DACUS is to solve capacity overloads whilst allowing UAV operators to execute their planned mission with minimum number of restrictions. Excluding those flying restrictions which will be pre-defined by authorities to facilitate operations in certain urban areas, free-route operations will be prioritized unless additional constraints need to be imposed as a result of the implementation of a DCB measure. If a restrictive DCB measure does become necessary, those which have the least impact on the fulfilment of UAV mission objectives shall be prioritized. As an example for high-density operations, measures may include the organization of UAV flows into separate flight layers depending on their general direction of travel [6], [7].

B. *Defining capacity in U-space*

In order to meet these principles, the DACUS project needed to reevaluate the definition of core components of the DCB process, in particular that of capacity. Given that U-space will be built based on automated services [8], DACUS determined that the definition of "capacity" in U-space should be a function of uncertainty, noise and visual nuisance, safety thresholds, and collision risk - given the proximity of UAV operations to the general public as well as ground infrastructure [9]. Based on this realization, DACUS has developed a process for identifying capacity imbalances by incorporating risk-based and social indicators, and comparing them with U-space demand predictions, as shown in Figure 1. Given the large amount of indicators that this concept encompasses, for this publication, we will focus primarily on the role of collision risk, which is the principal driver of the capacity limit definition. For more information on the other indicators incorporated in this concept please refer to the *DACUS Performance Framework* [10].

C. *Detecting risk-based capacity imbalances*

Figure 1. shows the main processes that lead to the identification of demand and capacity imbalances for urban U-space. The process which involves the identification of collision risk (in green) can be summarized in three high-level steps [11].

It begins with the prediction of demand for a given airspace, by accumulating information about the planned flight trajectory received from the submitted UAV mission plans (Step 1). Prediction accuracy will depend on the overall level of certainty of airspace demand and the level of fidelity provided in the mission plans.

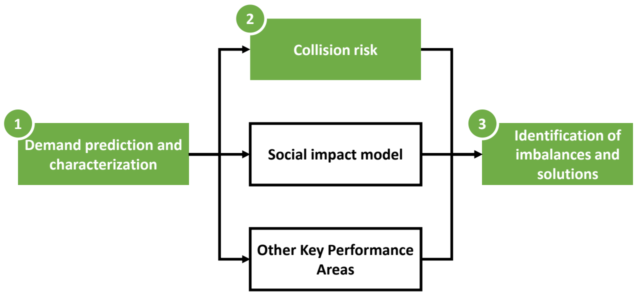

Figure 1. Schematization of the process for detecting U-space capacity imbalances used in DACUS with emphasis on collision risk (in green).

Next, the expected impact on safety is calculated based on the cumulative risk of collision of all operations (Step 2). DACUS defines this indicator as the overall risk of causing fatal incidents or injuries to people in an area [10]. The development of the collision-risk indicator is explained in chapter III.

Finally, the calculated safety impact is measured in comparison with a preset Target Level of Safety (TLS) [12] for the area of operation (Step 3). If the threshold is exceeded, an imbalance between airspace demand and capacity is declared which should be solved through the application of DCB measures. A separation scheme has been developed to support this process [11]. The scheme incorporates pair-wise separation minima between aircraft which depend on several factors such as their performance characteristics, whether the separation is performed by a centralized service or via self-separation, the prevailing airspace structure, as well as other values such as weather or the status of CNS equipment.

The DACUS consortium developed a "Collision Risk Model" which was tested in a series of experiments to understand the effect of different CNS performances and population densities on the maximum acceptable U-space capacity in a given area. The development and testing of these models is further elaborated in the next chapters.

III. METHODS

The operation of UAVs introduces risks both in the air (collision of aircraft with people on board) and on the ground (falling onto people). To ensure safety, a risk assessment process for UAV operations - the Specific Operations Risk Assessment (SORA) concept developed by JARUS [12] –specifies to keep the overall risk below a given Target Level of Safety (TLS). This concept states that the number of fatal injuries to third parties on ground is the best parameter that can embody the equivalence of risk, setting a TLS of 1E-6 fatalities per flight hour. Many other sources as the NATO standard STANAG-AEP4671 [13] follow a similar approach.

With this reference value in mind, a Collision Risk Model can be applied to calculate the probability of midair collisions between drones and the derived fatality risk within a given area. Capacity must be reduced until the total fatality risk of the persisting traffic scenario is below the aforementioned TLS. The Collision Risk Model developed in the DACUS project calculates the ground fatality risk derived from potential collisions between UAVs or from catastrophic failures of individual UAVs. A similar approach has been employed in other studies, e.g. to balance UAV efficiency with the risk of fatality caused by collisions [14]. In our model, we assess potential collisions between UAVs as a factor of the number of vehicles, their performance limitations, the time to react in case of conflict, the capability of detecting a conflict as well as CNS performances. On the other hand, potential for catastrophic failures of the UAV while flying is already identified via its determined "Mean Time Between Failures" (MTBF), and, consequently, is directly proportional to flight time.

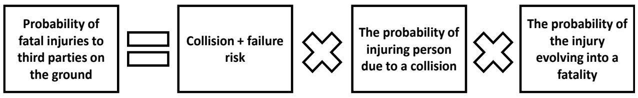

Figure 2. Schematization of the process for calculating the probability of fatal injuries to third parties on the ground.

As starting point to identify potential collisions, the model applies the equations concerning relative velocities and distances between aircraft (as explained further on) from *Annex 1* of the *"Manual on airspace planning methodology for the determination of separation minima*" [15] developed by ICAO. To achieve an estimation of ground fatality risk, a Monte Carlo simulation approach using Python language is applied. A large number of traffic samples are simulated in order to calculate the risk of collision and failures. Once the collisions and failures are calculated, the probability of fatal injuries to third parties on the ground can be determined, considering an inelastic collision between the drones followed by a free fall (parabolic); this fall determines the impacted area on the ground and then, the fatality risk is calculated [20] [21] depending on the population density and how protected people are in the impacted area. Note that we assume the entire vehicle to remain intact after collision. The probability of fatal injuries is determined using a sheltering factor, which quantifies the level of protection that buildings, trees or vehicles offer to people and therefore reduce the probability of serious injuries.

The probability of fatal injuries to third parties on the ground is, therefore, calculated by multiplying the probability of collision and failure with the probability that, if a collision were to occur, the UAV would fall on a person (as a function of population density) and the probability that the injury provokes a fatality (as a function of drone characteristics and sheltering factor). This concept is based on the SORA [12] likelihood of harm estimation and is represented schematically in Figure 2.

Note that collisions between UAVs and manned aircraft were not initially considered in the model to simplify the number of assumptions and variables under consideration, which are mainly those related to the effect of CNS performance, deconfliction service provision and population density.

The process begins by defining the Control Volume where operations will take place, characterizing the population density and sheltering factor on ground. Population density values are obtained from the Socioeconomic Data and Applications Center (SEDAC) [16] and the values of sheltering factor within a given area are obtained from Copernicus [17]. The population density and sheltering factor maps are introduced as inputs to the code. Once the control volume and the overflown area are characterized, random UAV positions and speed vectors are defined. Nominal scenarios are then developed based on trajectories calculated by the UAS and reported to the U-space system. Once nominal trajectories are defined, real positions and speed vectors are estimated considering uncertainties due to navigation errors, randomly chosen following a normal distribution $N(nominal\ position, \sigma)$ to define the real scenarios. Once nominal and real scenarios are defined, trajectories are projected forward in time. Several variables are required to make this projection, which are introduced below:

$x_i(t)$: Nominal random position of UAV "i" in east-west direction

$y_i(t)$: Nominal random position of UAV "i" in north-south direction

$z_i(t)$: Nominal random altitude of UAV "i"

$v_i(t)$: Nominal velocity of UAV "i"

$\theta_i(t)$: Nominal heading in horizontal plane (x,y) of UAV "i"

$\phi_i(t)$: Nominal heading in vertical plane (y,z) of UAV "i". This value is dependent on speed, as aircraft with higher velocities (> 25m/s) are assumed to have almost horizontal trajectories, so $\phi_i(t) < 5°$.

These values are then used to calculate the distance *D* between any UAV pair, as follows:

$$D_{ij}(t) = D_{ij}(t_0) + V_{rel\_ij}^2 t^2 + 2Bt \tag{1}$$

This equation specifies the distance in an instant t between UAV i and j, where:

$$V_{rel\_ij} = \sqrt{v_i^2 + v_j^2 - 2v_i v_j cos\phi_i cos\phi_j \left(\cos(\Delta\theta) + sin\phi_i sin\phi_j\right)} \tag{2}$$

and (3)

$$\begin{aligned} B = {} & \Delta x(t_0)\left(v_i cos\phi_i cos\theta_i - v_j cos\phi_j cos\theta_j\right) \\ & + \Delta y(t_0)\left(v_i cos\phi_i sin\theta_i - v_j cos\phi_j sin\theta_j\right) \\ & + \Delta z(t_0)(v_i sin\phi_i - v_j sin\phi_j) \end{aligned}$$

Real trajectories, with uncertainties in position and time, are used to calculate collisions. Real trajectories are defined following a normal distribution centered in nominal variables and deviation σ, based on CNS performance data (i.e. accuracy) as follows:

$$x_i^* = N(x_i, \sigma_x) \tag{4}$$

$$y_i^* = N\left(y_i, \sigma_y\right) \tag{5}$$

$$z_i^* = N(z_i, \sigma_z) \tag{6}$$

$$\theta_i^* = N(\theta_i, \sigma_\theta) \tag{7}$$

$$\phi_i^* = N(\phi_i, \sigma_\phi) \tag{8}$$

$D_{ij}^*, V_{rel}{}_{ij}^*$ and B_{ij}^* are calculated as described previously but using the variables above. Note that speed is considered the same in both nominal and real scenarios, considering only direction changes.

A collision is considered to occur when:

$$D_{ij}^*(t_{min}) < MARGIN_{COLLISION} \tag{9}$$

Where $(t_{min}: minimum\ time)$ is the instant when distance *D* between UAV "i" and UAV "j" is minimum, and the margin of collision is the distance from which a pair of UAVs are so close that they would collide.

Similarly, a conflict is considered to be declared by the U-space Tactical Conflict Resolution Service when:

$$D_{ij}\left(t_{conflict}\right) = MARGIN_{CONFLICT} \tag{10}$$

Where $(t_{conflict}: conflict\ time)$ is the instant when distance *D* between UAV "i" and UAV "j" is equal to the conflict margin, so a conflict is declared. The margin of conflict is the distance between a pair of UAVs which the U-Space system would start to consider too close and would require an intervention to avoid a potential collision.

Note that this concept is, for the time being, purely distance and time based. More complex conflict detection methods may also include conflict geometries (geovectors) [18], but for sake of simplicity have not been added to this initial concept. Moreover, conflicts are calculated using nominal trajectories as they are the ones tracked by the systems and collision are calculated with real trajectories. Because of that, some conflicts are not collisions and vice versa.

Before defining the outputs, some characteristic times must be presented to explain how the collisions are classified:

- Update time (t_{update}): Update rate of the surveillance system (or "e-Identification" service in U-space terminology [5]).
- Detection and Alert time $(t_{det/alert})$: time required by the U-space Tactical Conflict Resolution service to detect a conflict between two UAVs and provide the alerts to avoid the conflict/collision; assumed as 1s in the experiments. The role of this service within the U-space DCB concept is further defined in [9].
- Manoeuvring time (t_{man}): time required by the UAVs to modify their trajectories attending to the alert, avoiding the conflict/collision; estimated as 4 seconds considering FAA recommendations [19].

$$t_{total} = t_{update} + t_{det/alert} + t_{man} \tag{11}$$

Finally, after calculating conflicts and collisions and considering the times described above, different parameters are obtained:

- Potential collisions: They are those which would occur if there were no tracking and monitoring service in place (i.e. U-space system).
- Avoidable collisions: They are those collisions that can be avoided by the U-space system, i.e. when the time until the collision is long enough to detect and avoid it $(t_{min} > t_{total})$
- Non-avoidable collisions: They are those collisions that can't be avoided by the U-space system, i.e. when the time until the collision is not long enough to detect and avoid it $(t_{min} < t_{total})$
- Non-detected collisions: Collisions that are not detected by the U-space system as conflicts due to the error in position and headings.
- False alerts: Conflicts detected by the U-space system that do not lead to a collision.

Then, the collision risk is multiplied by the mean number of fatalities per collision to obtain the fatality risk due to drone collisions (CR), as explained above. Additionally, the ground risk derived from a sudden failure (FR) of the drone across its entire path, causing a parabolic free fall, is calculated as well, following the same principles. Finally, the total ground risk due to collisions (CR) and drone failures (FR) is obtained for each simulation.

$$GR_{total} = CR + FR \tag{12}$$

As explained, this total ground fatality risk is compared with the TLS using the equation depicted in Figure 2. to determine whether the number of UAVs considered in the scenario can operate safely or not; in the latter case, the number of UAVs in the scenario will be reduced until the risk is below the TLS, being this figure the maximum acceptable capacity for that airspace volume. Results will show how these elements affect the maximum acceptable capacity.

IV. RESULTS

As stated above, the objective of the experiments conducted in this study is to be able to estimate the capacity of an airspace depending on different factors such as CNS performances and the maximum admissible fatality risk of the overflown ground area. This section will outline the experiment setup and main results.

A. General experiment setup

A series of simulations have been carried out considering different setups in terms of CNS performances, conflict margin and number of aircraft. Each of these factors have an impact on the risk of collision, which, depending on the area overflown, will determine the fatality risk, as well as on the detection rate.

The proposed setups combine different factors in order to analyze the impact of each one of them on the overall fatality risk. The objectives of these setups are to evaluate:

- The impact on the collision risk when a U-space Tactical Conflict Resolution Service is deployed.
- The effect of the positioning update rate on the ability to detect and prevent collisions.
- The impact of the navigation accuracy on the conflict detection rate and, therefore, on the remaining collision risk.
- Finally, to identify the fatality risk in different urban environments for the same collision risk.

The last objective is particularly crucial for defining capacity. Given that the collision risk depends on the number of drones, comparing the collision risk with a predefined TLS, the maximum capacity can be calculated in different urban environments.

All the scenarios have been tested considering only small multirotor UAS of 1,5 m size and speeds up to 25 m/s with the same performance characteristics. Moreover, a series of independent variables were introduced. The values and ranges considered in these variables are presented below:

1) Deconfliction service: In order to test the effect of deploying a U-space Tactical Conflict Resolution Service, two possible situations are considered. The first situation is one in which no deconfliction actions – either by U-space or onboard systems - are provided (reference scenario). In the second scenario, a U-space Tactical Conflict Resolution Service is considered, which would detect pairs of drones in risk of collision, once they converge closer than a predefined conflict margin.

2) CNS performances: Two fundamental aspects for detecting potential collisions are considered. The first is the accuracy of the navigation system, which considers a position error following a normal distribution. The second is the update rate, i.e. how often the position of the UAV is reported (see TABLE I.).

3) Conflict margin: For the experiments, three different conflict margins are considered to evaluate the impact on detected collisions (see TABLE II.).

4) Overflown area: Regarding overflown areas, cities with different population density and sheltering factor are considered to evaluate the fatality risk of overflying them in several situations with different collision risks (see TABLE III.).

B. Description of the scenarios/Scenario setup

By combining these factors in different scenarios, the collision and fatality risks, as well as the detection rate can be estimated and the influence of each factor can be analyzed. Hereafter, these scenarios are described in detail.

1) Scenario 1.- Collision Risk reduction with U-space Tactical Conflict Resolution service

This scenario compares the total collision risk with and without U-space services. For that, and considering the effect of the update rate, the collision risk in both cases is analyzed (TABLE IV.). Note that, for an airspace without U-space services, all the potential collisions are assumed to occur, so the update rate has no effect. However, flying in U-space environment, it will have an impact. In this scenario, it is assumed that all avoidable collisions are detected by the system.

As expected, results for scenario 1 show a much lower collision risk for an environment with U-space deconfliction in place than without in all cases, by a factor of ten (see TABLE V.); the collision risk is constant without U-space system (no effect of the update rate, beyond slight variations which would disappear with a larger number of simulations), but it increases with the update rate when there is U-space in place (as expected). Out of the scenarios which provide deconfliction, as expected, the ones with the highest update rate provide for the lowest collision risk overall.

TABLE I. OVERVIEW OF CNS PERFORMANCE-RELATED VARIABLES: NAVIAGITON ACCURACY AND UPDATE RATES.

Navigation accuracy	**Description**
GPS L1	Deviations: $\sigma_x, \sigma_y = 1.633$m, $\sigma_z = 2.55$m
GPS+SBAS	Deviations: $\sigma_x, \sigma_y = 1.02$m, $\sigma_z = 1.1$m

Communications update rate	**Description**
1 s	High, one update every second
3 s	Medium, one update every 3 seconds
5 s	Low, one update every 5 seconds

TABLE II. OVERVIEW OF THE THREE DIFFERENT CONFLICT MARGINS TESTED IN THE EXPERIMENTS.

Conflict margin	**Description**
3 m	Conflict is declared when the distance between two UAVs is less or equal to 3 m
5 m	Conflict is declared when the distance between two UAVs is less or equal to 5 m
10 m	Conflict is declared when the distance between two UAVs is less or equal to 10 m

TABLE III. OVERVIEW OF THE TWO INDEPENDENT VARIABLES CONCERNING THE OPERATING ENVIRONMENT.

Environment	**Population Density (inh/km2)**	**Sheltering factor**
Madrid City Centre	12000	High
Toulouse City Centre	5500	High
Toulouse Outskirts - Industrial	5500	Very High
Toledo Outskirts	900	Low
Toulouse Outskirts - Residential	900	High
Toledo City Centre	600	High
Toledo Rural	50	Very Low

TABLE IV. OVERVIEW OF INDEPENDENT VARIABLES USED TO SET-UP THE INDIVIDUAL SCENARIOS.

Scenario 1 setup	
Number of aircraft	20 aircraft/km^2
U-space deconfliction	YES/NO
CNS: Update rate	1 s/3 s/5 s
CNS: position accuracy	GPS+SBAS
Scenario 2 setup	
Number of aircraft	20 aircraft/km^2
U-space deconfliction	YES
CNS: Update rate	1 s
CNS: position accuracy	GPS L1/ GPS+SBAS
Conflict margin	3 m/ 5 m/ 10 m
Scenario 3 setup	
Number of aircraft	20 aircraft/km^2
U-space deconfliction	YES
CNS: Update rate	1 s
CNS: position accuracy	GPS L1/ GPS+SBAS
Environment	Toulouse, Madrid, Toledo

TABLE V. Collision risk (Collisions/Flight Hour) results for 20 UAVs/km^2 and GPS+ SBAS scenario.

Update Rate	Without U-space system (Potential collisions)	With U-space (Non-avoidable collisions)
1 s	3.41E-02	2.86E-03
3 s	3.44E-02	4.68E-03
5 s	3.40E-02	7.60E-03

TABLE VI. Collision risk (Collisions/Flight Hour) results for 20 UAVs/km^2 and 1s update rate.

Conflict margin	GPS L1	GPS+SBAS
3 m	2.33E-02	1.21E-02
5 m	1.32E-02	3.78E-03
10 m	3.93E-03	3.83E-03

TABLE VII. Percentage of undetected collisions for the 20 UAVs/km^2 scenario.

Conflict margin	GPS L1	GPS+SBAS
3 m	63%	24%
5 m	26%	2%
10 m	2%	1%

TABLE VIII. False conflicts per flight hour.

Conflict margin	GPS L1	GPS+SBAS
3 m	0.122985401	0.107963504
5 m	0.353832117	0.336255474
10 m	1.46589781	1.46749635

TABLE IX. Fatality risk (Fatalities/Flight Hour) results for different environments, UAV densities and position accuracies.

Environment	GPS L1 1s/5m		
	7 UAS/km2	14 UAS/km2	21 UAS/km2
Madrid City Centre	5.98E-06	1.50E-05	2.87E-05
Toulouse City Centre	2.68E-06	6.69E-06	1.28E-05
Toulouse Outskirts - Industrial	2.24E-06	5.61E-06	1.08E-05
Toledo Outskirts	7.88E-07	1.97E-06	3.78E-06
Toulouse Outskirts - Residential	4.41E-07	1.10E-06	2.11E-06
Toledo City Centre	3.66E-07	9.16E-07	1.76E-06
Toledo Rural	1.09E-07	2.71E-07	5.21E-07

Environment	GPS SBAS 1s/5m		
	7 UAS/km2	14 UAS/km2	21 UAS/km2
Madrid City Centre	2.66E-06	6.98E-06	8.20E-06
Toulouse City Centre	1.19E-06	3.12E-06	3.67E-06
Toulouse Outskirts - Industrial	9.96E-07	2.62E-06	3.08E-06
Toledo Outskirts	3.50E-07	9.19E-07	1.08E-06
Toulouse Outskirts - Residential	1.96E-07	5.14E-07	6.04E-07
Toledo City Centre	1.63E-07	4.27E-07	5.02E-07
Toledo Rural	4.82E-08	1.27E-07	1.49E-07

TABLE IX. (continued).

Environment	GPS L1 1s/10m		
	7 UAS/km2	14 UAS/km2	21 UAS/km2
Madrid City Centre	2.66E-06	6.31E-06	8.64E-06
Toulouse City Centre	1.19E-06	2.82E-06	3.86E-06
Toulouse Outskirts - Industrial	9.97E-07	2.37E-06	3.24E-06
Toledo Outskirts	3.50E-07	8.31E-07	1.14E-06
Toulouse Outskirts - Residential	1.96E-07	4.65E-07	6.37E-07
Toledo City Centre	1.63E-07	3.87E-07	5.29E-07
Toledo Rural	4.82E-08	1.15E-07	1.57E-07

Environment	GPS SBAS 1s/10m		
	7 UAS/km2	14 UAS/km2	21 UAS/km2
Madrid City Centre	2.56E-06	5.15E-06	7.88E-06
Toulouse City Centre	1.14E-06	2.30E-06	3.52E-06
Toulouse Outskirts - Industrial	9.60E-07	1.93E-06	2.96E-06
Toledo Outskirts	3.37E-07	6.78E-07	1.04E-06
Toulouse Outskirts - Residential	1.89E-07	3.80E-07	5.80E-07
Toledo City Centre	1.57E-07	3.15E-07	4.82E-07
Toledo Rural	4.64E-08	9.35E-08	1.43E-07

2) Scenario 2.- Impact of Navigation accuracy on the Conflict detection rate and the remaining collision risk.

After having established that providing U-space deconfliction with an update rate of one per second yields the lowest overall collision risk, the impact of navigation accuracy on the ability to detect conflicts was tested. Given that the position reported by the drone will differ its real position, part of the avoidable collisions will not be prevented if the U-space service is not able to detect them. The remaining collision risk will be calculated from the sum of the unavoidable collisions and the non-detected avoidable collisions. This means that the navigation accuracy has no effect in the number of potential collisions, but it determines the ability to detect avoidable collisions. Moreover, different conflict margins are also introduced into the assessment (see TABLE IV. , scenario 2).

Results show a clear reduction of collision risk for SBAS augmented GPS at lower conflict margins (see TABLE VI.). The lowest overall collision risk was found to be situated between the 5 and 10-meter conflict margin for the GPS+SBAS case. As the margin of conflict increases, the improvement introduced by SBAS is attenuated since most of the conflicts are detected even with the highest error (GPS L1). In the case of the conflict margin, for GPS L1, the greater the conflict margin, the lower the collision risk (more potential collisions detected). With GPS+SBAS, the effect is similar, but given that results for 5 m and 10 m conflict margins were equivalent, the smaller margin is enough to detect most of the potential collisions.

TABLE VII. and TABLE VIII. show that, as the margin of conflict increases, the percentage of undetected collisions drastically decreases, but the number of false conflicts per flight hour raises exponentially. Therefore, it is necessary to find a trade-off between ability to detect conflicts and efficiency.

Based on the results obtained, this could be GPS + SBAS with a margin of conflict of 5m, whereas in cases of drones equipped only with GPS L1, a conflict margin of 10 m would be required, causing therefore many more false conflicts.

3) Scenario 3-Fatality risk and maximum capacity in different overflown cities with and without UTM system.

The results presented so far do not depend on the population density since they only consider the risk of collision. However, to set the fatality risk, and subsequently the maximum capacity of an airspace, the population density and sheltering factor of the overflown area must be considered (TABLE IV. , scenario 3).

Moreover, U-space system performance will have an impact on the fatality on the ground and a better performance will allow increasing airspace capacity while maintaining acceptable risk levels. This is shown in TABLE IX. , which presents the fatality risk for the different environments considered, for 5m and 10 m conflict margins and GPS L1 and GPS+SBAS accuracy ranges. The highest performing scenario (GPS+SBAS 1s/5m) is also depicted graphically in Figure 3. Results show that for the methodology applied in this study, the established target level of safety can only be reasonably achieved in low population density environments, lower vehicle densities and high update rates and navigation accuracies.

V. DISCUSSION

Results from the experiments show that providing tactical deconfliction has a large, positive influence on the overall collision risk. When providing deconfliction services, the positioning report update rate has a great impact on the ability to prevent conflicts, which worsens as this rate increases. The potential number of collisions was found not to depend on the navigation and positioning accuracy in a free flight environment; however, it did affect the ability to detect conflicts. A lower dispersion between real and calculated positions implied a larger number of potential conflicts detected (and potentially avoided) per conflict margin. In this sense, the paper has shown that positioning based on SBAS augmented GPS allow for a lower overall collision risk than GPS alone, in particular within the 5 to 10-meter conflict margin range.

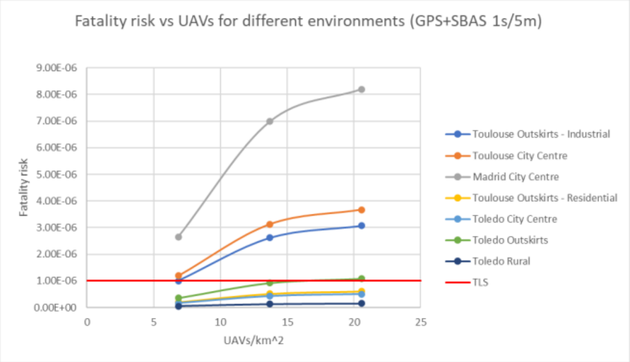

Figure 3. Overview of the fatality risk cause by increasing numbers of UAVs in all environments for the GPS+SBAS 1s/5m scenario.

The paper has also shown that a reduced conflict margin, e.g. 3-meters, has the drawback of an increased collision risk among vehicles. On the other hand, shifting to a more conservative 10-meter margin would have a strong impact on the numbers of false conflicts. From our results, it seems that the sweet-spot between UAV position accuracy and false conflict detection is at a conflict margin of 5 meters.

When applied to operating environments with varying population densities and shelter factors, the resulting fatality risk values show that the described target level of safety of 1E-06 can be achieved under certain conditions. If U-space deconfliction services are in place, vehicle communications are updated every second, a conflict margin of 5-10 meters is defined and the UAVs are equipped with GPS+SBAS, it would be possible to allow up to 7 UAVs per square km into the city centre of a city with the population density of Toulouse (around 5500 inhabitants per square km), with a very high sheltering factor. This value can be increased up to 21 UAVs per square km for flight operations smaller and lower population density cities like Toledo and even further in a rural setting (60 inhabitants per square km and very low sheltering factor).

However, with the current setup, no combination of the variables tested in scenario 3 would permit high density UAV operations in very large cities, given that the fatality risk is substantially above the permissible TLS. Further research is required to fine-tune some of these metrics and especially assess which other measures need to be included in the algorithm to reduce the overall risk of conflict, such as the ones introduced in the DACUS separation scheme [11]; in particular, on board collision avoidance systems should reduce the risk of collision for those which cannot be avoided by the U-space services, allowing greater drone densities, especially in large cities. It must be noted that the model developed does not consider a previous strategic deconfliction for the trajectories, assuming only tactical deconfliction; this is one of the reasons for those limited capacity figures obtained. In addition, no pre-defined airspace structures were defined in our scenarios.

The issue of increasing capacity to facilitate UAV flight operations within higher density areas is one that the DACUS DCB concept is aiming to resolve. The proposed DCB process involves a service for resolving conflicts among flight plans at strategic level [9]. Only allowing previously deconflicted UAV missions to take place in urban airspace has the potential to greatly reduce the amount of conflicts and increase the overall capacity level. As part of a series of on-going experiments, DACUS will analyze the conflict resolution process among flight plans at strategic level to meet this end.

A limitation of this study is that only a single type of UAV was modelled. Further work would need to incorporate a more complex traffic mix of different UAV performances and airspace structures, as well as include passenger-carrying vehicles. We would assume that incorporating a larger traffic mix would increase the conflict margin beyond 5m. The collision risk model could also be improved in future studies by incorporating the probability midair collisions between general aviation and unmanned aircraft [22], as well as more refined risk modelling methods from other relevant studies (see [23] - [28]).

Other elements which would require further investigation include the consideration of pilot response times to pending conflicts among remotely piloted UAVs, separation standards for the areas of operation, effects of wind and precipitation in urban environments on UAV performance, U-space system performance, as well as the inclusion of additional risk mitigation techniques, such as parachutes.

VI. CONCLUSIONS

This paper elaborated on the challenges for defining a suitable capacity value for managing U-space UAV flight operations in and urban environment. It was found that U-space would need to balance airspace demand and capacity based on as diverse set of metrics, the most important of which is collision risk between UAVs. We applied a methodology which incorporates collision risk to define the overall capacity of urban U-space airspace. The methodology was tested in a series of experiments. Results showed that allowing up to 7 UAVs per square km with up to 5500 inhabitants within the same area would meet industry specified target safety levels. It was however not possible to meet these goals for environments with higher population densities, which would require additional traffic measures such as flight plan deconfliction and airspace structuring. The impact of such measures will be addressed in ongoing studies of the DACUS project.

REFERENCES

[1] EUROCONTROL Network Manager. ATFCM Operations Manual. EUROCONTROL. Ed. 24. Online: https://www.eurocontrol.int/sites/default/files/2021-03/eurocontrol-atfcm-operations-manual-25-26032021.pdf [Accessed on 07-10-2021], 2021.

[2] SESAR Joint Undertaking. European Drones Outlook Study, Unlocking the value for Europe. Online: https://op.europa.eu/en/publication-detail/-/publication/93d90664-28b3-11e7-ab65-01aa75ed71a1/language-en [Accessed on 15-09-2021], 2016.

[3] TERRA Consortium. D5.2, Architecture & Integration of Systems Description. SESAR Joint Undertaking. Ed. 2. 2020.

[4] IMPETUS Consortium. D2.1, Drone Information Users' Requirements. SESAR Joint Undertaking. 2018.

[5] CORUS Consortium. U-space Concept of Operations. SESAR Joint Undertaking. Online: https://www.sesarju.eu/node/3411 [Accessed on 15-09-2021], 2019.

[6] Sunil, E., et al.. Metropolis: Relating Airspace Structure and Capacity for Extreme Traffic Densities. Eleventh UAS/Europe Air Traffic Management Research and Develioment Seminar (ATM2015). Online: http://atmseminar.org/seminarContent/seminar11/papers/498_Sunil_0126150624-Final-Paper-4-30-15.pdf [Accessed on 23-09-2021], 2015.

[7] Labib, N., et al. A Multilayer Low-Altitude Airspace Model for UAV Traffic Management. 9th ACM Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications (DIVANet 2020). Miami Beach. FL. Online: https://dl-acm-org.tudelft.idm.oclc.org/doi/pdf/10.1145/3345838.3355998 [Accessed on 23-09-2021], 2019.

[8] European Commission. Commission Implementing Regulation (EU) 2021/664, On a regulatory framework for the U-space. European Commission, Directorate-General for Mobility and Transport. Online: http://data.europa.eu/eli/reg_impl/2021/664/oj [Accessed on 15-09-2021], 2021.

[9] DACUS Consortium. D1.1, Drone DCB concept and process. SESAR Joint Undertaking. Online: https://dacus-research.eu/wp-content/uploads/2021/03/DACUS-D1.1-Drone-DCB-concept-and-process_01.00.00.pdf [Accessed on 15-09-2021], 2021.

[10] DACUS Consortium. D5.3, Performance Framework. SESAR Joint Undertaking. 2021.

[11] DACUS Consortium. D5.2, Separation Management Process Definition. SESAR Joint Undertaking. Ed.3. 2021.

[12] JARUS. JARUS guidelines on Specific Operations Risk Assessment (SORA). Joint Authorities for Rulemaking of Unmanned Systems. Ed. 2. Online: http://jarus-rpas.org/sites/jarus-rpas.org/files/jar_doc_06_jarus_sora_v2.0.pdf [Accessed on 15-09-2021], 2019.

[13] NATO. STANAG AEP-4671, Unmanned Aircraft Systems Airworthiness Requirements (USAR), Ed.B. V.1. April 2019.

[14] Sedov, L., Polishchuk, V., Bulusu, V., Ground risk vs. Efficiency in Urban Drone Operations. Fourteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2021). Online: http://www.atmseminar.org/seminarContent/seminar14/papers/ATM_Seminar_2021_paper_1.pdf [Accessed on 23-09-2021], 2021.

[15] ICAO. Doc 9689-AN/953, Manual on Airspace Planning Methodology for the Determination of Separation Minima. International Civil Aviation Organization. Ed.1. Online: https://www.icao.int/Meetings/anconf12/Document%20Archive/9689_cons_en.pdf [Accessed on 23-09-2021], 1998.

[16] Socioeconomic Data and Applications Center (SEDAC). Online: https://sedac.ciesin.columbia.edu/ [Accessed on 15-09-2021].

[17] Copernicus. Online: https://www.copernicus.eu/en [Accessed on 15-09-2021].

[18] Hoekstra, J., et al. Geovectoring: Reducing Traffic Complexity to Increase the Capacity of UAV airspace. International Conference for Research in Air Transportation (ICRAT), 2018.

[19] FAA AC 90-48D - Pilots' Role in Collision Avoidance.

[20] K. Dalamagkidis, K. P. Valavanis and L. A. Piegl, "Evaluating the risk of unmanned aircraft ground impacts," 2008 16th Mediterranean Conference on Control and Automation, 2008, pp. 709-716, doi: 10.1109/MED.2008.4602249.

[21] S. Primatesta, A. Rizzo, A.La Cour-Harbo "Ground risk map for Unmanned Aircraft in urban environments" J Intell Robot Syst (May 2019), 10.1007/s10846-019-01015-z.

[22] A. La Cour-Harbo, H. Schioler, Probability of low-altitude midair collision between general aviation and unmanned aircraft, Risk Analysis, Vol. 39 (2019), pp. 2499-2513.

[23] R. Melnyk, D. Schrage, V. Volovoi and H. Jimenez, "A third-party casualty risk model for unmanned aircraft system operations," Reliability Engineering & System Safety, Vol. 124 (2014), pp. 105-116.

[24] S. Bertrand, N. Raballand, F. Viguier, F. Muller, Ground risk assessment for long-range inspection missions of railways by UA's, Proc. 2017 Int. Conf. on Unmanned Aircraft Systems, Miami, FL.

[25] E. Ancel, F. Capristan, J. Foster and R. Condotta, Real-time risk assessment framework for unmanned aircraft system (UAS) traffic management (UTM), 17th AIAA ATIO Conf., 2017, AIAA-2017-3273.

[26] A. La Cour-Harbo, Quantifying risk of ground impact fatalities for small unmanned aircraft, J. of Intelligent and Robotic Systems, Vol. 93 (2019), pp. 367-384.

[27] S.H. Kim, Third-Party Risk Analysis of Small Unmanned Aircraft Systems Operations, J. of Aerospace Information Systems, Vol. 17 (2020), pp. 24-35.

[28] H.A.P. Blom, C. Jiang, Safety risk posed to persons on the ground by commercial UAS-based services - Learning from airports and hazardous installations, 14th USA/Europe Air Traffic Management Research and Development Seminar (ATM2021)