Limitations of Conflict Prevention and Resolution in Constrained Very Low-Level Urban Airspace

Badea, C.; Morfin Veytia, A.; Ribeiro, M.J.; Doole, M.M.; Ellerbroek, J.; Hoekstra, J.M.

Publication date
2021

Document Version
Final published version

Published in
11th SESAR Innovation Days

Citation (APA)
Badea, C., Morfin Veytia, A., Ribeiro, M. J., Doole, M. M., Ellerbroek, J., & Hoekstra, J. M. (2021). Limitations of Conflict Prevention and Resolution in Constrained Very Low-Level Urban Airspace. In *11th SESAR Innovation Days*

Limitations of Conflict Prevention and Resolution in Constrained Very Low-Level Urban Airspace

Călin Andrei Badea & Andres Morfin Veytia, Marta Ribeiro, Malik Doole,
Joost Ellerbroek, and Jacco Hoekstra
Control and Simulation, Faculty of Aerospace Engineering
Delft University of Technology, The Netherlands

***Abstract*—Road traffic delay and urban overcrowding are increasing rapidly all over the world. As a result, several companies have proposed the use of small unmanned aerial vehicles (sUAVs) as an alternative to road-based transportation. These small autonomous drones are expected to operate within a thin airspace band (Very Low Level) in high traffic densities in constrained urban environments. This presents a challenge for ensuring the safe separation and efficient routing of drone flights. Current research has made modest progress towards finding solutions for conflict detection and prevention in highly dense and constrained environments (e.g., in-between buildings). In this paper, the state of the art of urban airspace design and conflict prevention and resolution research are discussed, and their applications to constrained environments. Additionally, fast-time high-fidelity simulations of high-density traffic scenarios are used along a non-orthogonal city layout to identify bottlenecks in the performance of speed-based conflict resolution in a multi-layered airspace structure. Results show that the current airspace structure and conflict detection and resolution concepts need to be refined to further reduce conflicts and intrusions that occur in constrained environments. First, additional measures must be adapted to further prevent conflicts during turning and merging. Second, conflict resolution manoeuvres must account for speed limits resulting in turn radii which do not cross physical boundaries. Finally, conflict detection needs to consider the topology of the streets to prevent false-positive conflicts and to prepare in advance for conflicts resulting from heading changes in non-linear streets.**

***Keywords*—Conflict Detection and Resolution (CD&R), Velocity Obstacle (VO), U-Space, Unmanned Traffic Management (UTM), BlueSky ATC Simulator, Urban Airspace**

I. Introduction

Urban air mobility is attracting the interest of commercial operators and investors as a potential decongesting solution for high-density cities. One industry that has the potential to greatly benefit from the introduction of unmanned aerial systems (UAS) is the parcel delivery domain. A recent study predicted the demand for urban drone-enabled parcel delivery for Germany and the United Kingdom to be in the order of several billion missions per year [1]. Therefore, the further development of concepts of operations for very low level urban airspace is needed.

Several proposed urban airspace concepts of operations suggest that drones should fly above buildings as much as possible [2]–[4]. However, this might not always be desirable (noise and privacy issues in formerly undisturbed areas) or even feasible in most cities (e.g., in cities with large high-rise areas such as New York). In such cases, aircraft would be constrained to flying above the existing street network. This introduces several challenges for conflict prevention and resolution not present in open airspace. Amongst these are the restrictions of heading manoeuvres, non-linear trajectories, and traffic flow intersections.

There have been studies that focused on constrained airspace [5]–[7]. However, these largely studied orthogonal street networks. In comparison, organically developed street networks entail traffic patterns and situations that result in a high degree of uncertainty and variation in the required navigation manoeuvres, such as intersections with an odd number of entry and exit points, which create merging and diverging traffic flows. This area of urban air navigation requires more research.

In this study, an organic street network is investigated to get a broader picture of the limitations imposed by a constrained environment, with emphasis on the issues with current airspace structure design and conflict resolution techniques. Using an open source Air Traffic Control Simulator [8], fast-time simulations of a highly constrained urban environment are performed to analyse the behaviour of aircraft and determine the influence of operating in constrained airspace on flight efficiency and safety. Recommendations for future research in the urban airspace structure and conflict resolution domains are made based on the results.

This paper is structured as follows: Section II provides the motivations for the work. Section III provides information about the urban airspace environment, and the conflict prevention and resolution techniques. Section IV describes the design and procedure used for the simulations. Sections V and VI present the experimental results and discussion, respectively. Lastly, Section VII presents the conclusions and future research recommendations.

II. Motivation

This work investigates the challenges of operating in constrained airspace. We identify four main challenges that are unique to constrained airspace in comparison with other airspace types: (i) the challenge of coping with traffic at intersections, (ii) the imposed directions of travel by the street network, (iii) the limitations of state-based conflict detection, and (iv) the turn dynamics. The following paragraphs will go more into detail about each challenge. Previous works [6], [7] in constrained airspace have dealt with some of these challenges. However, they assumed a maximum number of traffic flows entering/exiting each intersection, and a fixed turning speed/radius respecting the distance between buildings at all intersections. This work does not make these assumptions.

While there are cities around the globe that do have parts with a grid-like structure (e.g., New York, Barcelona), many others have a more organic infrastructure sprawl, especially in Europe (e.g., Amsterdam, Rome, Vienna). This produces a larger variation in the topological properties of intersections. Fig. 1 shows examples of these intersections in Vienna. The investigation of these kinds of intersections helps in analysing the limitations of currently proposed conflict prevention and resolution methods in constrained airspace.

The Metropolis project [4] proposed a layered airspace design for lowering the number of conflicts, by separating traffic with different travel directions into different flight levels. The available airspace is segmented vertically, with each layer setting an allowable heading range. Aircraft choose a layer based on their origin-destination heading. The heading alignment in each layer reduces the relative speed between aircraft cruising at the same altitude. However, this concept is not as efficient in a constrained urban airspace, where aircraft are constantly forced to adapt their heading to the topology of the streets or adapt their altitude. As a result, aircraft may violate the heading limitations of the current layer, thus cancelling the benefit of the alignment effect.

Moreover, aircraft cannot use heading deviations to resolve conflicts due to the presence of the surrounding urban infrastructure without changing altitude. Allowing heading variations would require knowledge on the width of every street. However, (near-) head-on conflicts are practically impossible to resolve without heading variation. As aircraft may encounter such conflicts at intersections, these may rapidly become conflict hot-spots.

In open airspace, aircraft try to maintain a straight path, since it is usually the fastest route to their destination. In these cases, state-based conflict detection is a viable and preferable method due to its fast computational speed and limited data sharing needed between aircraft. However, in constrained urban airspace, this is no longer feasible, as aircraft will have to change headings constantly in order to avoid static obstacles. Thus state-based conflict detection can potentially consider false-positive conflicts, or only detect conflicts after a heading change without enough time for aircraft to defend against.

Additionally, aircraft are required to slow down prior to a turn to ensure that turns are not overshot. However, in non-orthogonal organic street networks, turn sharpness and edge lengths vary. Thus, aircraft will have to adopt different turning speeds in different areas of the environment, introducing speed heterogeneity. The latter is recognised as a causal factor for increased complexity in air traffic operations.

Current research has yet to address all of these challenges. It has either tried to avoid them (e.g., flying above the tallest buildings) or limit them (e.g., assuming orthogonal street-networks, fixed turning radius). However, in organic cities this may not always be possible. For this reason, we explore these challenges in detail by simulating drone operations in the city of Vienna.

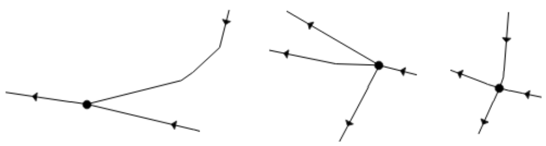


Figure 1. Examples of intersections in the city of Vienna: (a) merging intersection, (b) diverging intersection, and (c) classical four-way intersection.

III. Methods

A. Iterative speed-based conflict resolution

As previously described, due to the assumption that aircraft will only use streets to navigate dense urban airspace, aircraft are restricted in heading-based movement. Thus, most conventional conflict resolution methods are not appropriate in this situation, as most make use of heading manoeuvres to solve conflicts [9].

In this paper, an iterative speed-based conflict resolution algorithm is used, based on principles used in [10]–[12]. The latter makes use of trimmed velocity obstacles, as shown in Fig. 2, as they extend the available solution space for conflict resolution. Thus, solutions with a time to closest point of approach that is past the conflict look-ahead time are discarded. The resulting minimum relative velocity change solution $\mathbf{u}$ is then projected on the velocity vectors of each aircraft, resulting in a speed-only velocity vector change. As the velocity change is only a projection of $\mathbf{u}$, it is not a guaranteed solution. However, a viable solution is found through further iterations, moving the relative velocity outside the velocity obstacle.

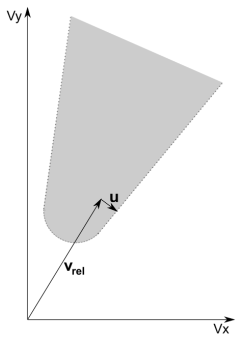


Figure 2. Trimmed velocity obstacle in relative velocity ($\mathbf{v_{rel}}$) space, with minimum velocity change solution ($\mathbf{u}$).

B. Conflict prevention by airspace structure design

The Metropolis project [4] showed that an effective airspace structure can have beneficial effects on safety and capacity, by reducing conflict probability [13]. With the Layers concept, the available airspace is divided into several cruising layers (segmentation), in which the allowable heading range is limited for each layer (alignment). These two policies were then formalised as geovectoring [14]. Two recent studies applied this strategy to a constrained airspace [6], [7], but only for largely orthogonal street networks with low bearing entropy values of 2.65 and 1.63 (a value of 1 means that the street network is perfectly orthogonal), placing them in the top 30% percentile of organisation from the cities ranked in [15]. In the current work, the street network is not orthogonal and has a bearing entropy of 3.10, ranking in the lower 40% percentile.

Two airspace structuring concepts were tested within the chosen street network. The first is a simple structure where all drones are restricted to an altitude 25 ft above the minimum flight level. The second structure, presented in Fig. 3, is similar to those from [6] and [7]. The difference is that it is difficult to ensure vertical segregation of North/South and East/West streets. Fig.1 (a) shows how a street with an initial South bearing progressively bears West. Therefore, individual streets are first assigned to a group of continuous streets and then allocated a cruising height based on the overall bearing of the group. For this reason, North and South bearing streets generally contain the cruising layer at 25 ft, while East and West bearing streets have it at 75 ft. Both of them share a turn layer at 50 ft.

The speed limit at cruising layers for both concepts is 30 kts. In the event of a turn larger than 20°, aircraft must decelerate to 10 kts in both concepts, the same method used in [6] and [7]. All heading turns are performed in the turn layer, which is expected to be (mostly) depleted of traffic. Aircraft then move to a cruising layer once the turn is finished.

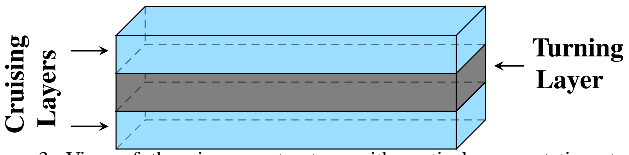


Figure 3. View of the airspace structure with vertical segmentation: two cruising layers with a turning layer in between. Airspace structure without vertical segmentation contains only one cruising layer.

IV. Experimental Design and Procedure

A. Simulation software

Experimental results were obtained through fast-time simulations using BlueSky, an open air traffic simulator [8]. This tool has an Airborne Separation Assurance System (ASAS) to which different conflict detection and resolution (CD&R) implementations can be added; therefore, allowing for all CD&R to be tested under the same scenarios and conditions.

B. Aircraft models

Only certain types of aircraft will likely be able to operate in constrained airspace. Aircraft with hovering capabilities are more suitable for navigating constrained urban environments. Thus, a DJI Matrice 600 Pro hexacopter drone model was used for the simulations. Specifications are shown in Table I.

C. Independent variables

The experiment uses three independent variables:

1) **Traffic density**: Low, medium, and high traffic densities are employed. The traffic levels were selected based on [6], and are shown in Table II.

TABLE I. DJI Matrice 600 model specifications.

DJI Matrice 600	
Max horizontal speed	18 m/s
Min horizontal speed	0 m/s
Max vertical speed	5 m/s
Min vertical speed	0 m/s
Max take-off mass	15 kg
Max acceleration/deceleration	3.5 m/s^2

TABLE II. Number of aircraft concurrently in-flight for each traffic density.

	Average (rounded)	Peak
Low density (L)	3	5
Medium density (M)	5	8
High density (H)	7	11

2) **Conflict resolution**: The iterative speed-based conflict resolution (CR) method is compared with a baseline situation with no CR.
3) **Conflict prevention by airspace structure**: A layered airspace is compared with a baseline situation where all aircraft travel at the same altitude.

Thus, the experiment is performed on 12 flight conditions, as presented in Table III. Each condition was simulated using 10 mission scenarios, each approximately one hour in length, resulting in a total of 120 simulations.

TABLE III. Experiment conditions. **None** corresponds to a situation without conflict resolution where aircraft all travel at the same altitude.

		Conflict Prevention and Resolution Method			
		None (N)	**Layered Airspace (A)**	**Conflict Resolution (CR)**	**Layers + CR (CRA)**
Traffic Density	**Low (L)**	N_L	A_L	CR_L	CRA_L
	Medium (M)	N_M	A_M	CR_M	CRA_M
	High (H)	N_H	A_H	CR_H	CRA_H

D. Conflict prevention: urban airspace structure

A 4.4 km^2 area in the city of Vienna was selected for the experiment, due to the presence of a combination of grid-like and organic street patterns. In the simulation, the city layout is represented as a multi-directed graph, with streets and intersections represented by edges and nodes, respectively. Street data was obtained from OpenStreetMap (OSM) using OSMnx [16]. Simplifications were made to the street graph for ease-of-use. These are (i) removing slip roads, (ii) removing dead-ends, (iii) merging parallel roads in close proximity, (iv) removing other redundant connections between nodes. Moreover, all roads were forced to be one-way as that has been shown to reduce the conflict probability [6].

In one-way, grid-like street networks, deciding the directionality and vertical segmentation of the streets is trivial [6]. However, this is not the case for organic street networks, as intersection topology may vary, as shown in Fig. 1. Although the street network in Fig. 4 contains some grid-like attributes vertically, the strategy for vertical segmentation and directionality is not immediately discernible. This is handled with the following steps:

Figure 4. Street layout of the experimental area with traffic flow directions.

Step 1: Extract the natural continuity using the Continuity in Street Networks (COINS) algorithm [17]. COINS groups all streets into different strokes to ensure continuity over intersections. For example, in Fig 1 (a) the street in the top right merges with the one in the bottom right. However, it is not immediately clear which street continues left after the intersection. Here, COINS calculates all interior angles at the intersection and group the two streets with the angle closest to $180°$. Note that groups with $90°$ turns were split manually.

Step 2: Calculate the bearing of each group from start to end node, dividing them into two separate groups: North/South and East/West bound. This enables the use of the vertical segmentation method portrayed in Fig. 3 to the street layout in Fig. 4.

Step 3: Employ a genetic algorithm to decide the directions of the strokes, to ensure that the street network is well-connected. A well-connected network implies that most intersections are reachable from any other intersection. However, in a non-orthogonal street network, perfect connectivity is difficult to achieve. Thus, evolutionary optimisation was used to ensure a high connectivity level in the street network.

The genetic algorithm is initialised with a random distribution of stroke directions and searches for a directionality combination that yields the lowest cost. The latter is the distance it takes to get from all intersections to all other intersections. If a path cannot be found, a $100\,\text{km}$ penalty is added to the cost. The selected directionality of strokes is illustrated with the arrows in Fig. 4. It was applied to both the structures with and without vertical segmentation.

E. State-based conflict detection

State-based conflict detection was employed to identify potential minimum separation violations. Detection is achieved by linearly extrapolating the current position of the drone along its velocity vector, within a look-ahead time. The vertical and horizontal separation margins are set to $25\,\text{ft}$ and $105\,\text{ft}$, respectively. The values are obtained from the signal-in-space performance requirements from Table 3.7.2.4-1 of [18]. In order to limit the number of false-positive detection events (detected conflicts that cannot result in an intrusion due to airspace topology), a look-ahead time of $10s$ was chosen, as it means that drones only need to look-ahead about $150m$ when cruising.

F. Missions

Building data from the government of Vienna [19] was processed to create a database of geofences. Routes are pre-planned with shortest path algorithm from [16] to follow the street-network and avoid collision with geofences.

All flights originate outside the simulation area and have destinations at intersections of the street-graph. All missions are at least $1\,\text{km}$ in length. Origins and destinations are allocated randomly. Aircraft are removed from the simulation once they reach their destination.

G. Simulation time

Dependent variables were measured throughout the entire simulation in all scenarios. Each scenario ran until all aircraft reached their destinations. This was approximately $60\,\text{min}$.

H. Dependent measures

The dependent measures are placed into two categories: safety and efficiency. They are as follows:

- Number of pairwise conflicts (safety)
- Location of aircraft in conflict (safety)
- Number of losses of minimum separation (safety)
- Number of geofence intrusions (safety)
- Total track distance (efficiency)
- Total track time (efficiency)

A loss of separation, or intrusion, occurs when the minimum vertical and horizontal separation minimums are infringed. A conflict is a predicted intrusion within the look-ahead time. All aircraft routes were pre-planned to avoid buildings. However, due to a uniform turn strategy (decelerating to a speed of $10kts$ regardless of turn geometry) and conflict resolution interference with navigation, is it still possible for aircraft to breach geofences. It should be noted that no obstacle avoidance algorithm for buildings was used, aircraft return to their pre-determined path after a breach. In reality, this would be needed, but the results were not affected here because it does not affect conflict resolution between aircraft.

V. Experimental Results

The following chapter presents the experimental results. Figs. 5, 7, 8, 9 and 10 show box-plot representations. Each of these contain three subplots, one for each traffic density.

The conflict prevention and resolution method is shown in the horizontal axis (**N**, **A**, **CR**, **CRA**, see Table II), and the dependent variable of interest is presented on the vertical axis.

Fig. 6 shows the conflict pair heat-map of each conflict prevention and resolution method ((**N**, **A**, **CR**, **CRA**). Note that aggregated values for the three traffic densities are shown.

A. Safety

Fig. 5 shows that the number of pairwise conflicts increase for all conditions as the traffic density increases. This was expected because higher density leads to a higher chance that a conflict will be encountered. Additionally, it was seen that vertical segmentation reduces the number of conflicts (**A**, **CRA**) as opposed to without segmentation (**N**, **CR**). This was also expected, as the same traffic is split over different layers, and thus the traffic density per layer is decreased. Furthermore, due to the iterative nature of the conflict resolution algorithm, the number of detected conflicts is substantially higher in the **CR** condition. If, as a result of following the street below, one of the involved aircraft needs to adjust their heading, the conflict solution might become invalid. As a result, the same conflict pair can be counted more than once for the conflict metric.

This is also the case for back-to-back conflicts. The solution found by the CR method (see Fig. 2) guarantees that no conflict will occur within the lookahead time, but not necessarily that the conflict is resolved permanently. The conflict may just have been postponed to after the lookahead time. Due to this, back-to-back conflicts require iteration to reach the conflict solving solution (velocity matching), and thus may be counted more than once. However, a notable observation is that the number of conflicts in the **A** and **CRA** cases are similar, which points towards the fact that many of the conflicts detected in the **CRA** condition were prevented through the use of layered airspace.

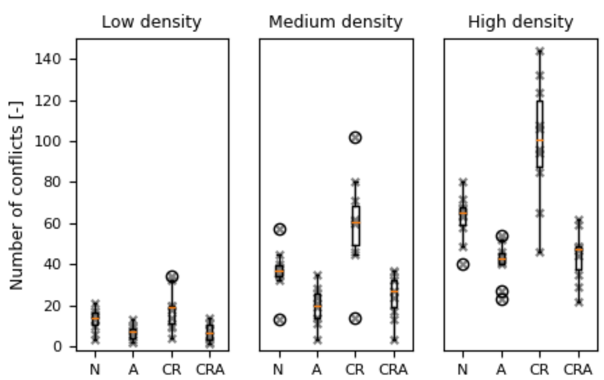


Figure 5. Number of conflicts for each traffic density, conflict prevention, and resolution method. × = measurement point, ○ = outlier.

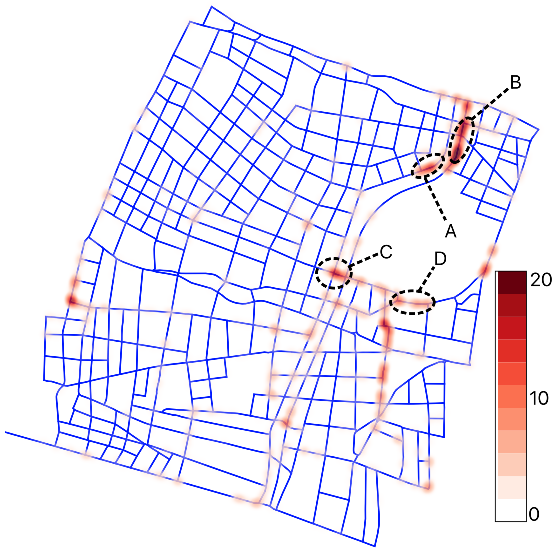
More observations can be made when analysing the locations of the conflict pairs within the street network. Fig. 6 shows the heat map of conflict pair locations in the street network with clusters of interests marked out. The trends observed in Fig. 5 are visible on the map. Clusters A and B are in false-positive conflicts with each other because the state-based conflict detection method linearly extrapolates the location of all drones with a 10 second look-ahead time. Thus, aircraft on these two parallel streets appear to be in conflict even though they will not intersect if they follow their planned paths. When comparing the intensity of clusters A and B when no vertical layering is applied in the airspace (Figs. 6a and 6c) with the opposite case (Figs. 6b and 6d), it can be observed that the vertical airspace structure helped mitigate the false-positive conflicts. This is because aircraft in the area of cluster B had a higher chance of being in a different cruise or turn layer than aircraft in the area of cluster A. While this solution is specific to this topology, it shows that such situations can occur in highly organic street networks and can be mitigated through airspace design.

Cluster C shows conflicts at an intersection. Again comparing situations with vertical airspace structure (Figs. 6a and 6c) to cases without it (Figs. 6b and 6d), shows that vertical segmentation reduces the number of conflict pairs at this intersection. However, it does not avoid all conflicts; when a North/South aircraft and an East/West aircraft turn at this intersection they will both ascend or descend to the same layer leading to a conflict.

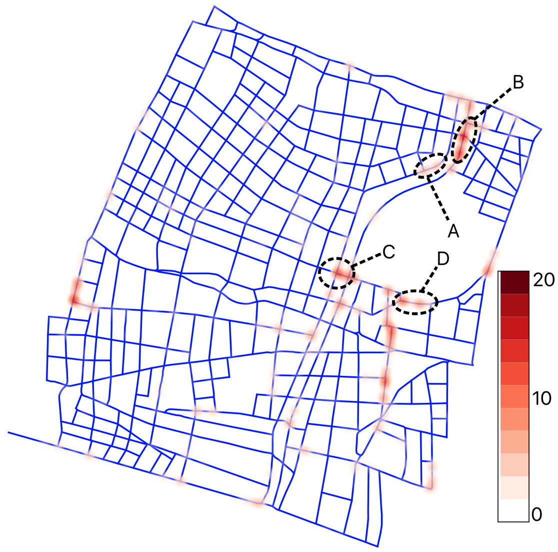
Cluster D shows aircraft in conflict at a diverging intersection. The heat maps do not show a great difference in the number of conflicts at that location between experimental conditions. This is because, as shown in Fig. 4, both streets that meet at this intersection are in the E/W layer category, thus at the same height. Due to the turning rules, drones coming from the right must move to a turning layer to continue in any of the streets at that intersection. Therefore, false conflicts are still detected ahead of the turning manoeuvre even if aircraft continue along different streets after passing the intersection.

However, looking at conflicts does not give a complete picture of the situation. Although **CR** and **CRA** create more conflicts than their counterparts in **N** and **A**, they prevent more losses of separation overall (Fig. 7). This gap becomes more evident as the traffic density decreases. When looking at **CR** and **CRA**, it is seen that vertical segmentation had minimal effect on the number of losses of separation at high and low densities. This implies that most conflicts that were not solved by the conflict resolution algorithm occurred when aircraft were turning. If airspace is not layered, aircraft that slow down to turn will produce back-to-back conflicts with aircraft coming from behind. When aircraft are in the same layer, losses of separation are more likely to occur. As the conflict resolution algorithm did not account for turn manoeuvring and back-to-back conflicts, these situations were not solved.

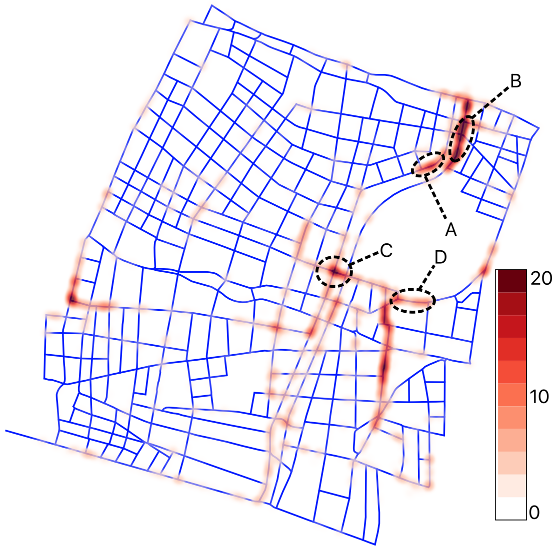
The number of geofence breaches is another measure of safety, but it is also a measure of the compatibility of the used conflict resolution methods with the task of following a pre-determined path through constrained airspace. Due to the lack of obstacle avoidance measures, breaches can occur when two aircraft select resolution velocities such that the conflict between them is solved, but do not account for the reduction in velocity needed in case a sharp turn follows. Since drones are travelling in constrained airspace, the maximum turn angle



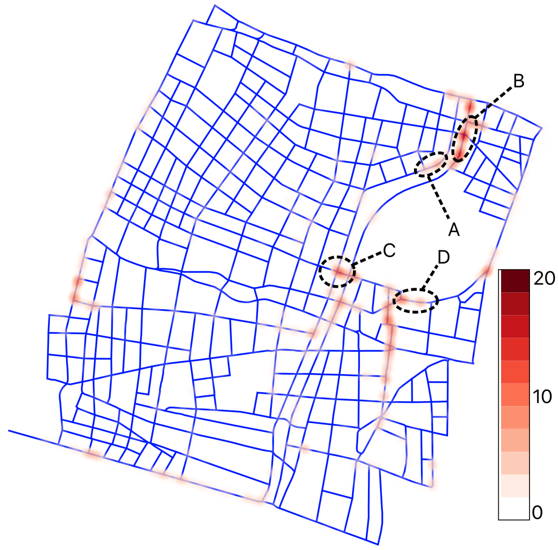
(a) With no vertical airspace structure and no CR (**N**).



(b) With vertical airspace structure and no CR (**A**).



(c) With no vertical airspace structure and CR (**CR**).



(d) With vertical airspace structure and CR (**CRA**).

Figure 6. Heat map of number of conflict pairs.

that does not result in a geofence breach varies according to the layout of the streets. In Fig. 8, it is seen that performing no conflict resolution (**N**, **A**) led to fewer geofence breaches as opposed to conditions with conflict resolution enabled (**CR**, **CRA**). There is no difference when comparing between **N** and **A** because the horizontal speed in both is similar, thus the number of geofence breaches is equal.

However, this is not the case when comparing between conditions with conflict resolution (**CR**, **CRA**). The number of geofence intrusions decreased when adding vertical segmentation. The effect also becomes more visible as the traffic density increases. This is because vertical segmentation reduces the number of conflicts, thus drones perform fewer resolution manoeuvres that may lead to geofence breaches. Lastly, the safety metrics also confirm that using a constant turn speed for all intersections in an organic street layout will lead to geofence breaches, as some intersections require a greater reduction in speed, as seen per the number of breaches in the **N** condition. In practical terms, this means that the turning speed should be adjusted during the planning of a flight.

B. *Efficiency*

The average travelled distance (Fig. 9) is a measure of efficiency. At all traffic densities it is clear that the conditions with vertical segmentation (**A**, **CRA**) travel more distance than those without vertical segmentation (**N**, **CR**). This was expected due to the vertical travel component in this airspace structure. Despite the fact that a speed-only resolution method is applied, conflict resolution also produces an increase in flight distance. When correlated to the recorded number of

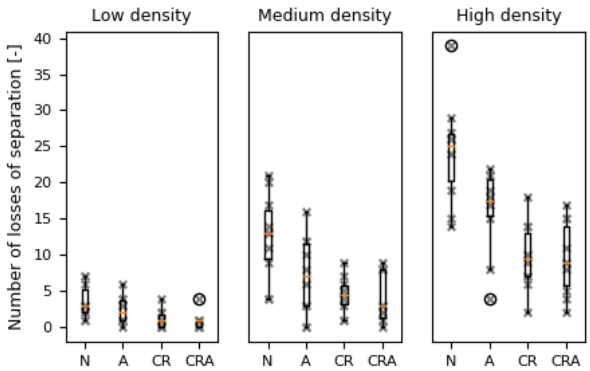


Figure 7. Number of losses of separation for each traffic density, conflict prevention, and resolution method. × = measurement point, ○ = outlier.

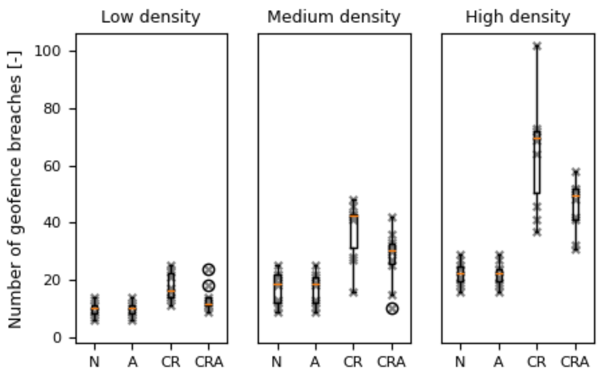


Figure 8. Number of geofence breaches for each traffic density, conflict prevention, and resolution method.

geofence breaches (Fig. 8), the explanation for this is that aircraft in conflict were forced to maintain their conflict resolving speeds until the conflict was resolved, or delayed past the look-ahead time, thus often overshooting turns where a turn speed of 10 kts would have normally been enforced.

The second considered efficiency metric is the average flight time, presented in Fig. 10 for each concept, and each traffic density condition. It can be seen that in the conditions without conflict resolution (**N**, **A**), the travel time is not affected by the vertical airspace structure. This is because the

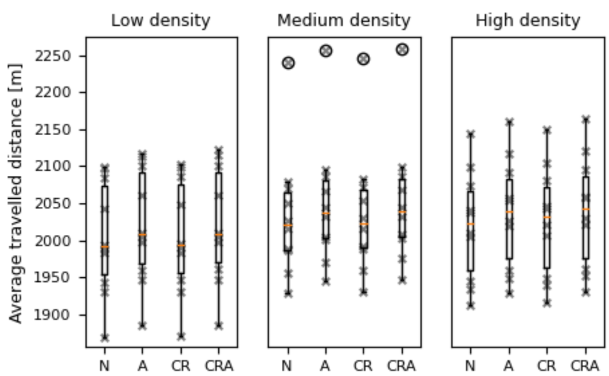


Figure 9. Average flight distance per aircraft travelled for each traffic density, conflict prevention, and resolution method.

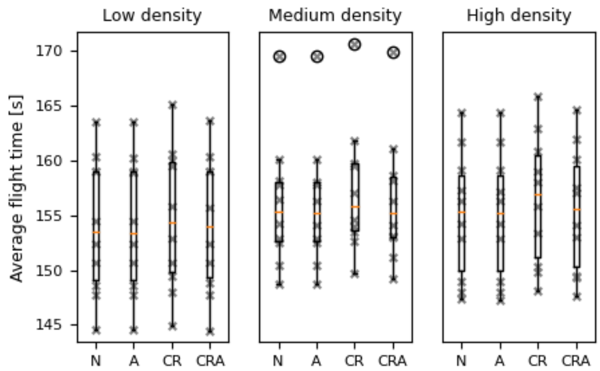


Figure 10. Average mission flight time per aircraft for each traffic density and conflict prevention and resolution method.

horizontal speed of the drones (turn and cruise speed) is the same in both cases, and is not influenced by the presence of vertical manoeuvring. Employing the use of conflict resolution increased flight time, as aircraft slow down to solve conflicts. This difference increases as the traffic density increases: more aircraft result in more conflicts. However, adding a layered airspace structure reduces the number the conflicts.

VI. Discussion

The results illustrate several areas where the current knowledge in constrained airspace is lacking and requires further development. Firstly, state-based conflict detection that linearly extrapolates state of the aircraft for a certain look-ahead time is unsuitable in constrained airspace without adaptations, as it results in false-positive conflicts. For example, when looking at clusters A and B in Fig. 6, the streets do not intersect, thus a conflict should not occur between aircraft following them. Previous research [6], [7] with orthogonal street networks also has similar issues when linearly extrapolating. Even though it aligns with the street orientation during cruising, it does not work when performing a turn or when changing altitudes. This illustrates the need for an improved way to implement conflict detection (e.g., by using intent information or predictive airborne separation assurance systems [10]) and conflict recovery (i.e., recovery should not produce more immediate conflicts). Velocity obstacles can also be used to avoid turning into a conflict, thus preventing otherwise missed conflicts due to the lack of exchanging intent information [20].

Another knowledge gap is highlighted by horizontal traffic merging and diverging situations. This is seen in cluster D of Figs. 6b and 6d. In previous research [6], [7], the design of the vertical airspace layer structure was straightforward. In orthogonal networks the N/S and E/W (or similar divisions), layers are vertically segmented and cruising aircraft will not intersect. However, due to the organic nature of the street network in cluster D, this is impossible to avoid. As seen in Fig. 4, there are several intersections where streets of the same layer heights would meet with a cardinal division of street heights. It is not efficient to add unique layer heights for these streets as that would quickly saturate the airspace.

From the results, it was not evident that the use of vertical segmentation led to fewer losses of separation when also having conflict resolution (Fig. 7). However, this may be dependent on the airspace structure used for this particular work, and thus requires more investigation involving a diverse set of urban street layouts. Furthermore, other vertical segmentation combinations with a different number of vertical layers should be explored to find the ideal configuration. Moreover, vertical layers can also be used for vertical conflict resolution.

Finally, although routes are pre-planned such that they do not intersect buildings, breaches occurred due to turn dynamics and conflict resolution manoeuvres. Previous research in constrained airspace [6], [7] assumed that all turns may be handled using a fixed turning speed/radius. However, in non-orthogonal street networks, intersections have greater topological variation, and thus a dynamic turn method is required. Furthermore, from Fig. 8, it is clear that conflict resolution manoeuvres lead to more geofence breaches. Aircraft must take static obstacles into account when resolving conflicts, as well as the required manoeuvring speed in case of a turn.

VII. Conclusion

This paper highlighted the current limitations of having effective conflict resolution and airspace management in constrained airspace. Results showed that vertical segmentation of the airspace, as well as the use of an iterative, speed-based conflict resolution algorithm led to fewer conflicts and losses of minimum separation. However, not all conflicts encountered in the simulations were resolved through the separate use of conflict prevention, resolution, or a combination of both. Further research is needed into a comprehensive conflict prevention and resolution strategy to be employed in highly constrained and topologically organic urban airspaces.

This work also illustrated some key knowledge gaps. Namely, that state-based conflict detection is not reliable when dealing with variable-heading streets, as they may cause false-positive conflicts between drones with non-intersecting routes. Additionally, strategies for dealing with merging and diverging streets need to be developed by exploring different vertical segmentation configurations. Finally, turning rules also need to be handled in a more refined approach in organic networks.

Due to the surrounding buildings in constrained airspace, it is vital for conflict resolution to incorporate the presence of obstacles into the resolution loop. One potential research direction could be the creation of compound algorithms that perform different actions depending on the situation. Another option could be the use of artificial intelligence for conflict resolution, as such methods are known to be suitable for environments with a high degree of variability.

Acknowledgements

This research has received funding from the SESAR Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 892928 (Metropolis II). The authors would like to thank Niki Patrinopoulou and Ioannis Daramouskas, from the University of Patras, for their contribution to the procurement and processing of the street network data.

References

[1] M. Doole, J. Ellerbroek, and J. Hoekstra, "Estimation of traffic density from drone-based delivery in very low level urban airspace," *Journal of Air Transport Management*, vol. 88, p. 101862, 2020.
[2] CORUS consortium, "U-space Concept of Operations," SESAR Joint Undertaking, Vol 2., Edition 03.00.02, 2019.
[3] E. Sunil, J. Ellerbroek, J. Hoekstra, A. Vidosavljevic, M. Arntzen, F. Bussink, and D. Nieuwenhuisen, "Analysis of Airspace Structure and Capacity for Decentralized Separation Using Fast-Time Simulations," *Journal of Guidance, Control, and Dynamics*, vol. 40, no. 1, pp. 38–51, 2017.
[4] E. Sunil, J. Hoekstra, J. Ellerbroek, F. Bussink, D. Nieuwenhuisen, A. Vidosavljevic, and S. Kern, "Metropolis: Relating Airspace Structure and Capacity for Extreme Traffic Densities," in *ATM seminar 2015, 11th USA/EUROPE Air Traffic Management R&D Seminar*, 2015.
[5] D.-S. Jang, C. A. Ippolito, S. Sankararaman, and V. Stepanyan, "Concepts of Airspace Structures and System Analysis for UAS Traffic flows for Urban Areas," in *AIAA Information Systems-AIAA Infotech @ Aerospace*, 2017.
[6] M. Doole, J. Ellerbroek, V. L. Knoop, and J. Hoekstra, "Constrained Urban Airspace Design for Large-Scale Drone-Based Delivery Traffic," *Aerospace*, vol. 8, no. 2, 2021.
[7] M. Ribeiro, J. Ellerbroek, and J. Hoekstra, "Velocity obstacle based conflict avoidance in urban environment with variable speed limit," *Aerospace*, vol. 8, 2021.
[8] J. Hoekstra and J. Ellerbroek, "Bluesky ATC simulator project: an open data and open source approach," in *Conference: International Conference for Research on Air Transportation*, 2016.
[9] M. Ribeiro, J. Ellerbroek, and J. Hoekstra, "Review of Conflict Resolution Methods for Manned and Unmanned Aviation," *Aerospace*, vol. 7, 2020.
[10] J. Hoekstra, R. N. H. W. van Gent, and R. C. J. Ruigrok, "Designing for safety: the 'free flight' air traffic management concept," *Reliability Engineering & System Safety*, vol. 75, no. 2, pp. 215–232, 2002.
[11] J. Ellerbroek, "Airborne Conflict Resolution in Three Dimensions," 2013.
[12] J. van den Berg, S. J. Guy, M. Lin, and D. Manocha, "Reciprocal n-Body Collision Avoidance," in *Robotics Research*, ser. Springer Tracts in Advanced Robotics. Berlin, Heidelberg: Springer, 2011, pp. 3–19.
[13] J. Hoekstra, J. Maas, M. Tra, and E. Sunil, "How do layered airspace design parameters affect airspace capacity and safety?" in *7th International Conference on Research in Air Transportation*, 06 2016.
[14] J. Hoekstra, J. Ellerbroek, E. Sunil, and J. B. Maas, "Geovectoring: Reducing Traffic Complexity to Increase the Capacity of UAV airspace," *2018 International Conference on Research in Air Transportation*, 2018.
[15] G. Boeing, "Urban spatial order: street network orientation, configuration, and entropy," *Applied Network Science*, vol. 4, no. 1, pp. 1–19, 2019.
[16] ——, "Osmnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks," *Computers Environment and Urban Systems*, vol. 65, pp. 126–139, 2017.
[17] P. Tripathy, P. Rao, K. Balakrishnan, and T. Malladi, "An open-source tool to extract natural continuity and hierarchy of urban street networks," *Environment and Planning B: Urban Analytics and City Science*, 2020.
[18] International Civil Aviation Organisation, *Annex 10 - Aeronautical Telecommunications - Volume I - Radio Navigational Aids*, 7th ed. ICAO, 2018.
[19] Baukörpermodell (LOD0.4) Wien. Accessed 2021-05-20. [Online]. Available: https://www.data.gv.at/katalog/dataset/76c2e577-268f-4a93-bccd-7d5b43b14efd
[20] J. Hoekstra and F. Bussink, "Free flight: how low can you go? [ATC]," in *Proceedings. The 21st Digital Avionics Systems Conference*, vol. 1, Oct. 2002, pp. 1B1–1B1.