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Badea, Calin Andrei; Ellerbroek, Joost; Hoekstra, Jacco

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The Benefits of Using Intent Information in Tactical Conflict Resolution for U-Space/UTM Operations

Calin Andrei Badea, Joost Ellerbroek, and Jacco Hoekstra

***Abstract*— U-space/UTM operations are considered an integral part of the future development of cities, with applications ranging from package delivery to urban air mobility. However, this new complex environment also poses challenges for the conflict detection and resolution (CD&R) process, especially if aircraft will have to navigate above the existing street network due to privacy and obstacle constraints. The research at hand aims to investigate how information about the environment and other aircraft can be used to improve the performance of CD&R methods in constrained urban airspace. For this, three algorithms are developed and tested, each with different levels of information availability: the first solely uses current state information for conflict solving, the second includes additional information about the urban environment within the CD&R process, and the last also incorporates trajectory intent data to solve conflicts. These methods are tested within simulations of urban air traffic scenarios at various demand and wind levels to determine their safety and efficiency performance. Results show the use of street geometry information benefits the resolution process greatly, increasing the safety level while minimally affecting efficiency. Intent information is shown to not be critical for achieving this.**

***Index Terms*— U-space, UTM, CD&R, tactical, urban, air, mobility.**

I. Introduction

URBAN air operations are predicted to play a major role in the future development of cities, with potential applications ranging from package delivery services [1] to urban air mobility [2] and infrastructure surveillance [3]. Such operations require the development of specialised air traffic management systems that can adapt to such highly diverse and dynamic environments.

Urban airspace environments have a high degree of complexity due to the presence of urban obstacles, high terrain variability, and geo-fences [4]. High-level concepts of operations have been developed to set general functioning principles and a framework for both U-space [5], [6], [7] and UTM [8], [9] operations. One of the critical components of such systems is the conflict detection and resolution (CD&R) module, which aims to maintain a safe separation between aircraft.

A highly researched component of the CD&R service is the strategic separation module. This service generally aims to plan the trajectories of aircraft such that conflicts are prevented and resolved well in advance [6]. Literature shows that this method is highly effective at improving urban airspace safety [10], [11], [12]. However, it is generally agreed upon that strategic CD&R needs to be supplemented by a tactical layer, especially when facing operational and environmental uncertainties such as delay, compliance, sudden geofencing, and wind [13].

Many previous studies have implemented state-based CD&R through which aircraft publish and use state information (e.g., position, velocity, heading) to predict and resolve conflicts [14], [15], [16]. In open-airspace operations, where aircraft perform few turning manoeuvres and generally maintain their current state for extended periods of time, this level of information has proven to be sufficient [17]. However, such methods are unsuitable for very-low-level (VLL) constrained airspace. Due to factors such as privacy and the presence of tall buildings, aircraft will have to fly above the existing street network in many cities [18]. Thus, further complexity is induced by the organic nature of street networks in many areas around the world. This makes aircraft trajectories less predictable, which hinders the performance of state-based CD&R algorithms.

One potential solution to this issue is the use of intent information within the CD&R process (i.e., aircraft broadcast their short-term intended trajectory) [19]. While this has the potential to reduce false-positive and false-negative conflict detections, it has several drawbacks. Intent information sharing implies a more complex communication architecture and its standardisation, which can be difficult to implement on a large scale and with such a high end-user diversity. The reliability of such information is also dependent on the ability of aircraft to adhere to the communicated plan, and is also invalidated as soon as a resolution manoeuvre is performed.

Another category of CD&R methods mentioned in literature that might be able to mitigate the aforementioned issues are worst-case methods. They attempt to consider all possible conflicting situations, and calculate a manoeuvre that resolves the most critical one [20]. A study of a comparable algorithm in [21] shows that such algorithms are suitable for use in constrained urban airspace. As aircraft must fly above the existing street network, only a limited number of potential conflicting situations need to be analysed and accounted for.

It is thus clear that, while there is a consensus in literature on the need for tactical CD&R for U-space/UTM operations, there is still much debate on the specifics of how such a system

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The authors are with the Department of Control and Simulation, Faculty of Aerospace Engineering, Delft University of Technology, 2629 HS Delft, The Netherlands (e-mail: c.badea@tudelft.nl).

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should be implemented [22]. Prototype implementations of U-space services, such as [13], suggest keeping the quantity of exchanged information required for tactical CD&R at a minimum. Velocity and altitude commands are generally preferred over trajectory replanning to ensure fast reaction time and increase operational safety. Thus, there is still a need to investigate whether the use of higher levels of detail for flight information increases safety in constrained urban airspace.

The research at hand aims to investigate the level of detail of exchanged information required for tactical conflict detection and resolution in U-space/UTM operations. Three data sources are identified that can be used for such operations: state information (position, velocity, heading), street topology (directionality, geometry), and intended trajectory of other agents. Three CD&R algorithms are developed and tested, each using increasingly complex levels of information about the environment and agents within the system. Fast-time simulations of realistic traffic scenarios are run with varying demand and wind levels using the BlueSky Air Traffic Simulator [23].

II. Methods

The following section presents the design considerations and the tactical conflict detection and resolution methods developed to function with varying levels of information exchange for constrained airspace U-space/UTM operations.

A. Information Sources for Tactical CD&R

As previously mentioned, three sources of information are identified that can be used to improve the performance of conflict detection and resolution methods in constrained urban airspace: current state information (position, velocity, heading), street topology information, and intended trajectory, shown in Figure 1. Using state information only (Figure 1a) implies that the aircraft are not aware of the street geometry and solve conflicts by linearly extrapolating the current state of other aircraft. If agents also have access to information on the street topology, then the path geometry can be taken into account to detect and solve conflicts (Figure 1b). Lastly, if intent information is also exchanged between agents, it can better facilitate the CD&R process (Figure 1c). A conflict detection and resolution algorithm is developed for each of these levels of information, presented further in this work.

B. Tactical Conflict Detection Methods

1) State-Based Conflict Detection: State-based conflict detection and resolution methods are proven to provide robust solutions for cruising aircraft in both open and constrained airspace [14], [20]. They have relatively low information exchange and sensing requirements. The detection is performed by linearly extrapolating the current state of an agent (position, velocity, heading) and determining whether an intrusion event (i.e., distance at closest point of approach is lower than the safety threshold) occurs within a given look-ahead time [16]. A predicted intrusion is then considered a conflict.

A visual representation of the conflict detection method used in this work is presented in Figure 2. The light-shaded area represents the set of relative velocities between the ownship and intruder that would result in an intrusion event, known as the collision cone (CC). It is obtained by scaling the relative position between the aircraft ($\mathbf{x}_{\text{rel}}$) and the protection zone radius (R_{pz}) in function of time (τ) as follows:

$$\text{CC} = \left\{ \mathbf{v} : \|\mathbf{v} - \frac{\mathbf{x}_{\text{rel}}}{\tau}\| \leq \frac{\text{R}_{\text{pz}}}{\tau}, \forall \tau \in (0, \infty) \right\} \tag{1}$$

If the relative velocity between two aircraft ($\mathbf{v}_{\text{rel}}$) is within the bounds of the shaded area, an intrusion event is predicted to occur:

$$\mathbf{v}_{\text{rel}} \in \text{CC} \implies \text{Conflict} \tag{2}$$

The collision cone (CC) is then transposed using the velocity of the intruder ($\mathbf{v}_{\text{intr}}$) to obtain the velocity obstacle (VO) in the ownship frame of reference.

2) Worst-Case Conflict Detection: For street-following airspace concepts, a worst-case CD method has to consider a discrete number of streets that connect two aircraft (as opposed to a continuous area bounded by the performance limits of each vehicle in unconstrained airspace). Compared to intent-based methods, the worst-case CD method presented in this work does not require the communication of intent, but instead relies on knowledge of street topology (which can be assumed to be present already for navigation purposes) and state information. It therefore has the same information exchange (or sensing) requirements as the state-based method. The method is inspired by the principle of defensive driving, where traffic participants are encouraged to take into account all possible actions of others and make decisions accordingly to prevent dangerous situations from occurring.

A visualisation of the functioning principle of the worst-case CD method is presented in Figure 3. The ownship (AC1) is aware of its own intended route, but is only provided with the position and velocity of the potential intruder (AC2). Based on the street topology information, it can then compute all possible paths that the intruder can take, and determine all possible conflict nodes. The ownship can then account for all possible conflicts that might occur in the future, and act accordingly.

A pseudocode representation of the worst-case CD method can be found in Algorithm 1. For each of the possible conflict nodes, the along-path distance and number of turns are computed and communicated to the conflict resolution module.

3) Intent-Based Conflict Detection: An intent-based conflict detection method implies that aircraft broadcast a (short-term) flight plan, which can be used by other agents to improve detection capabilities and safety [24]. The use of intent for CD&R in constrained urban airspace is hypothesised to have the benefit of reducing routing uncertainty and lowering the number of false-positive conflict detections [25]. This method requires a communication framework through which aircraft periodically publish and broadcast their intended short-term path.

The functioning principle of the intent-based conflict detection method in this study uses both the current state and the short-term geometry of the intended route of other airspace

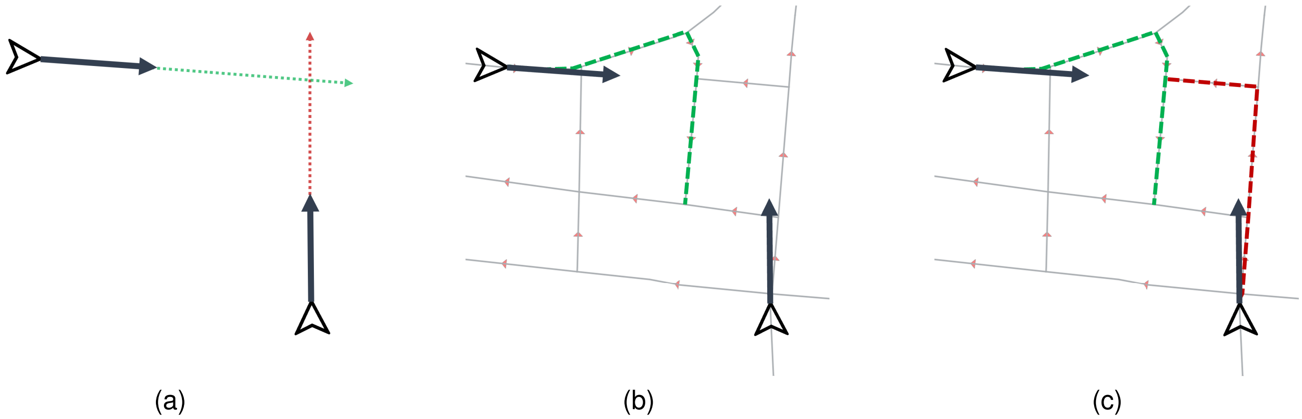

Fig. 1. Information sources for CD&R in constrained airspace: (a) state only; (b) state + street topology; (c) state + street topology + intent.

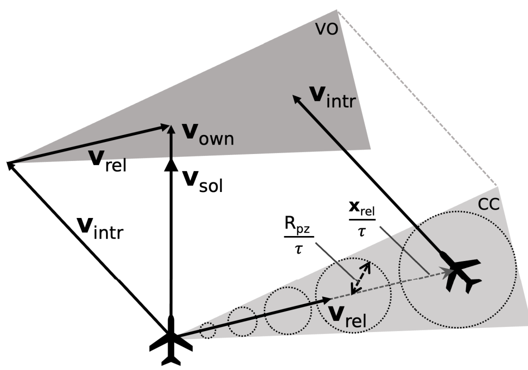

Fig. 2. State-based conflict detection and resolution using velocity obstacles.

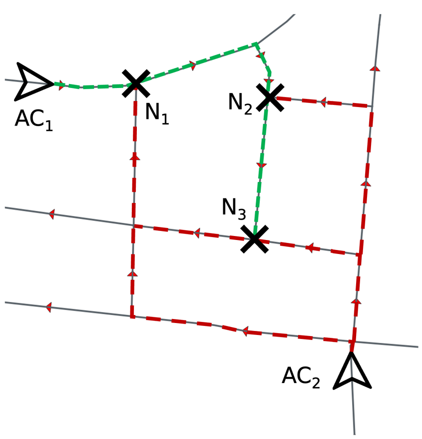

Fig. 3. Functioning principle of the worst-case conflict detection method. The ownship (AC1) accounts for all possible paths that the intruder (AC2) could take, and determines all possible conflict nodes (marked with "x").

users. An aircraft can then determine, based on intent information communicated by other agents, whether its path intersects with others. The intersection (conflict) nodes are evaluated individually in function of set priority and navigation rules. If more than one intersection node is found for one single aircraft pair, meaning that the aircraft are currently on the same path or will be in the future, the most imminent intersection node is considered as the conflict node. A visualisation of the method is described in Figure 4, where two aircraft locate

Algorithm 1 Worst-Case CD Algorithm From the Ownship Point of View

```
pairs = all (ownship, intruder) | distance < max_dist
for all ownship, intruder in pairs do
    Find all reachable nodes for intruder within look-ahead distance max_dist
    Find all common intersection nodes between ownship route and intruder reachable nodes
    if no intersection nodes found then
        continue to next route
    else
        Store pair in conflict_pairs
    end if
    for all intersection nodes do
        Calculate the distance to node
        Determine the number of turns until node
        Store calculated values to node_data_array
    end for
end for
Append conflict pairs that were only detected by state-based detection to conflict_pairs
return conflict_pairs, intersection_nodes, node_data_array
```

a conflicting node within a directional street network using exchanged intent information.

A pseudocode representation for the intent-based conflict detection algorithm is presented in Algorithm 2. The algorithm includes the computation of parameters that serve to estimate the time of arrival at the intersection node for each aircraft: the distance to the intersection node and the number of turning manoeuvres that the aircraft must perform ahead of the intersection node (aircraft slow down for turns). These are needed by the conflict resolution algorithm presented later in this work.

C. Tactical Conflict Resolution Methods

1) State-Based Conflict Resolution: The state-based conflict detection method is used in combination with a velocity-obstacle resolution algorithm [26], as the lack of access to street topology information limits the effectiveness

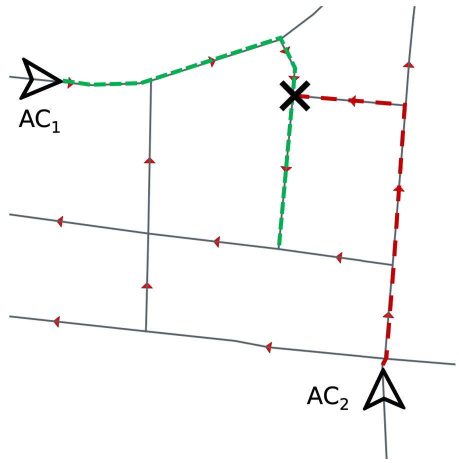

Fig. 4. Functioning principle of the intent-based conflict detection method. The ownship (AC1) is aware of the intended route of the intruder (AC2), and locates the conflict node (marked with “x”).

Algorithm 2 Intent CD Algorithm From the Ownship Point of View

pairs = **all** (ownship, intruder) | distance < max_dist
for all ownship, intruder *in* pairs **do**
Obtain intruder *last reported intended* path
Find all common intersection nodes *between* ownship *and* intruder *routes*
if *no* intersection nodes *found* **then**
continue *to next* pair
else
Store pair *in* conflict_pairs
end if
for all intersection nodes **do**
Calculate the distance *to* node
Determine the number of turns *until* node
Store calculated values to node_data_array
end for
end for
Append conflict pairs that were only detected by state-based detection to conflict_pairs
return conflict_pairs, intersection_nodes, node_data_array

of halting manoeuvres (used within the other CR methods presented in this work). Furthermore, this combination has been studied in previous work ([19], [25], [27], [28]), and is thus used to obtain baseline safety and efficiency data.

As the aircraft fly within constrained airspace, they must follow the street direction, and thus can only solve conflicts through adjustments in speed, as shown in Figure 2. The collision cone (CC) obtained during the detection process is transposed using the velocity of the intruder ($\mathbf{v}_{\mathrm{intr}}$) to the frame of reference of the ownship to obtain the velocity obstacle (VO). A solution ($\mathbf{v}_{\mathrm{sol}}$) can be chosen along the direction of the ownship velocity ($\mathbf{v}_{\mathrm{own}}$) to solve the conflict.

In the study at hand, aircraft always resolve conflicts by slowing down, as a reduction in relative velocity is shown in literature to increase safety [29]. Due to the nature of the allocated airspace, aircraft cannot solve conflicts cooperatively as in previously proposed CD&R algorithms (e.g., [30], [31]), as aircraft must unilaterally slow down for turns to reduce overshoot. Thus, in order to determine which aircraft must perform a manoeuvre, the resolution algorithm is augmented with priority logic, as shown in Algorithm 3. Priority is determined based on the following rules:

1) An aircraft has priority if it is positioned in front of another aircraft.
2) An aircraft has priority if it is closer to the intersection point of their extrapolated paths than the other aircraft.

Algorithm 3 State-Based CR Algorithm Used in This Work

conflict_pairs = **all** (ownship, intruder) | state-based conflict
for all ownship, intruder *in* conflict_pairs **do**
if *loss of separation* **then**
if intruder *is in front* **or** *closer to path intersection* **then**
{intruder has priority, ownship halts}
return Halt
else
{ownship has priority, continue cruise}
return None
end if
else if intruder *is behind* **then**
{ownship has priority, continue cruise}
return None
else if intruder *is in front* **then**
{intruder has priority}
return Match intruder speed
else if ownship *closer to path intersection* **then**
{ownship has priority, continue cruise}
return None
else
{intruder has priority, ownship solves conflict}
return Lower speed VO command
end if
end for
{Aircraft are issued cruise speed commands if they have priority over all intruders.}
for all aircraft **do**
if aircraft *has priority in all involved conflicts* **then**
return Cruise speed command
end if
end for

2) Worst-Case and Intent Conflict Resolution Method: The conflict resolution method presented in this section makes use of the information provided by either the intent-based or the worst-case conflict detection methods to resolve conflicts with other aircraft.

First, the resolution algorithm determines which agent within a conflict pair has priority, similarly to the aforementioned rules of the state-based conflict resolution method, as follows:

1) If the aircraft are flying on the same route, the one in front has priority;
2) Otherwise, the aircraft with the shortest estimated time of arrival at the intersection node has priority.

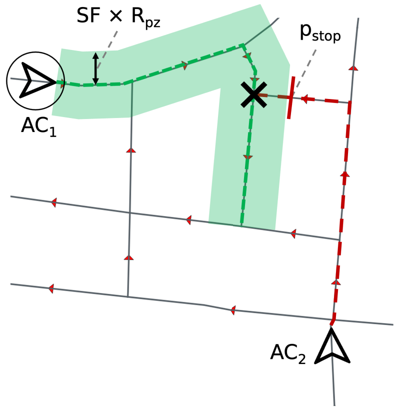

Fig. 5. Functioning principle of the conflict resolution method used with the worst-case and intent CD methods. The protection radius of the ownship (AC1) is shown as a circle. The route of the higher priority aircraft is buffered by the protection radius scaled with a safety factor ($SF \times R_{pz}$) to determine the location of the stopping point p_{stop}.

The resolution manoeuvre depends on the type of conflict: if the aircraft are along the same path segment, the one further along the path has priority and the other must match its speed, thus ensuring safe separation. If the aircraft are not on the same route and will cross paths at a node, the one that is estimated to reach the node last will need to unilaterally manoeuvre and reduce its speed.

The conflict resolution process, an example of which is described in Figure 5, involves determining the position at which the aircraft of lower priority must stop in order to not interfere with higher priority aircraft traversing the intersection. This is done by buffering the geometry of the path leading to the node by the radius of the protection zone (R_{pz}) scaled with a safety factor (SF). After this location is found, the low-priority aircraft can continue cruising normally until it is within stopping distance of the stopping point. It then initialises a halting manoeuvre, and waits until the intersection is cleared. This method thus improves the capability of the CD&R module to maintain a safe separation between aircraft in cases where street geometries are highly organic and variable.

The pseudocode representation of this conflict resolution method is presented in Algorithm 4. The logic accounts for the existence of multiple intersection nodes, each with its own solution, to ensure compatibility with both the intent and worst-case CD methods. Thus, the most conservative solution (the one that produces the lowest speed) is always chosen, as it solves the most imminent conflict.

If this set of rules and algorithm would be applied to the situation described in Figure 3 from the perspective of the ownship, with both aircraft having the same cruise velocity, the following logic is applied:

- **Node 1:** As the ownship (AC1) will reach the node first, it has priority over the intruder (AC2), and thus the solution is to continue cruising;
- **Node 2:** The ownship (AC1) is still estimated to reach the node faster, and thus has higher priority;
- **Node 3:** The intruder (AC2) is estimated to reach the node faster, and thus has priority over the ownship (AC1).

Algorithm 4 CR Algorithm Used in Combination With Intent-Based or Worst-Case CD From the Ownship Point of View

```
for all ownship, intruder in conflict_pairs do
    if state-based only conflict then
        Apply state-based Algorithm 3
    else if intruder is behind and on same route then
        {ownship has priority, continue cruise}
        return None
    else if intruder is in front and on same route then
        {intruder has priority}
        return Match intruder speed
    else
        {Create empty list of potential solutions}
        solutions = []
        for all nodes in intersection_nodes do
            Estimate time to reach node for both aircraft in
            function of cruise velocity, distance, number of turns
            Calculate the position of the stopping point for this
            node
            if ownship will reach node faster then
                {ownship continues cruising}
                store None in solutions
            else if close to stopping point then
                store Halt in solutions
            else
                {not yet close to stopping point}
                store None in solutions
            end if
        end for
        Select the most conservative solution (slowest) as the
        main solution.
    end if
end for
```

Given these solutions and following the logic presented in Algorithm 4, the resolution action for both aircraft at this point in time is to continue cruising, with the consideration that the intruder (AC2) is aware of the need to resolve for Nodes 1 and 2, and the ownship (AC1) is aware it needs to resolve for Node 3. As the aircraft continue cruising, the route uncertainty is lessened, and the situation presented in Figure 5 occurs, where the intruder (AC2) must stop ahead of the conflict node to resolve the conflict.

III. Experiment

A. Hypotheses

The CD&R methods presented in this work are developed to study data exchange requirements for future U-Space/UTM operations, and the impact of using knowledge of the street topology within the CD&R process on the efficiency and safety of such operations. Overall, we hypothesise that the worst-case and intent methods outperform the state-based method in terms of safety and efficiency for nominal no-wind conditions, as conflicts are detected more time in advance due to the use of street topology information, which the latter does not have access to in this study. Furthermore, due to the determination and use of safe stopping locations, the severity of intrusion events when using the intent and worst-case methods is hypothesised to be lower.

With increasing wind level, the performance of the state-based algorithm is hypothesised to be minimally affected, as the resolution velocity is iterated upon and adapted to wind conditions for every update step, and the simplicity of the prediction method makes it robust to changes in velocities. On the other hand, the worst-case and intent methods are hypothesised to be affected by the presence of wind, as the uncertainty in the future velocities of aircraft deteriorates the accuracy of the future state estimations. This poses problems in unambiguously establishing priority, and thus makes conflicts more difficult to solve.

To avoid confounding factors, the worst-case and intent CD&R methods are kept at a low complexity level. This means that the detection method is mainly spacial (i.e., detection of intersecting trajectories with only rudimentary time estimation), and the resolution manoeuvres are highly conservative (e.g., halt, velocity matching). Thus, it is expected that, compared to the state-based method, the average mission duration is higher when the worst-case or intent CD&R methods are used. Moreover, the worst-case conflict detection is more conservative and intentionally has a high false-positive detection rate. We hypothesise that this increases the average mission duration compared to the intent-based conflict detection method.

B. Simulation Environment

A simulation environment is used to test the hypotheses presented in Section III-A, based on the layout of the city centre of Vienna, shown in Figure 6, extracted and converted into graph format using OpenStreetMap [32] data and the OSMnx Python package [33]. This area is selected due to its high population density. Aircraft must follow the centre axis of the streets when cruising to avoid collision with buildings.

The street graph is simplified by reducing redundant geometrical information and the number of features (e.g., nodes very close to each other were merged). The streets are then assigned a single direction of travel to ensure that head-on conflicts are minimised. For this, the graph edges are grouped into continuous strokes (streets) using the COINS algorithm [34]. Then a genetic algorithm is used to set the directionality of each street with the objective of minimising the total distance from each node to all other nodes of the graph. The method used is more extensively explained in [35].

The BlueSky Open Air Traffic simulator [23] is used for this experiment, as it is capable of simulating urban air operations, and allows the open-source implementation of the proposed algorithms. The code as well as the results of the simulations can be found at [36].

C. Navigation in Constrained Very-Low-Level Urban Airspace

The present work implements navigation principles and rules from literature that have been proven to increase efficiency and safety within constrained urban airspace, and are as follows:

Fig. 6. Constrained airspace structure extracted from the street network of the city centre of Vienna.

1) All streets have a singular direction of travel (one-way). This reduces the probability of head-on conflicts occurring and increases safety [37].
2) Aircraft do not perform vertical manoeuvres during the cruising phase. Changes in altitude have been shown to produce a destabilising effect on the airspace [25], [27].
3) Aircraft must follow the centre axis of streets to avoid interference with urban obstacles (e.g., buildings).

D. Air Traffic Scenarios

The air traffic scenarios used in this experiment sought to create realistic U-space operational situations while also providing a controlled environment to test the proposed CD&R algorithms. This study focuses on urban point-to-point missions (e.g., parcel deliveries), as these are predicted to be the majority of urban airspace operations [38]. The scenario generation process started by randomly designating 5% of the nodes as mission origins, and the remaining as potential destination points. Then, all shortest routes between the origin and destination nodes are computed using the Dijkstra algorithm, and the route coordinates are cached in separate files per origin-destination pair.

As the study at hand focuses on the cruising phase of U-space operations, the take-off and landing phases of the missions are not considered or simulated. Such operations have different requirements and procedures, and should be studied separately [39]. Furthermore, as previously mentioned, vertical manoeuvres are not during the cruise phase, as these have a major negative effect on airspace safety [25]. Thus, the traffic scenarios generated for this experiment only consider one urban airspace layer (i.e., all aircraft cruise at the same altitude), with the mention that several such layers can be stacked to produce a complete airspace structure.

The proposed CD&R algorithms are tested at a wide range of traffic demand levels, defined in function of the number of aircraft concurrently in flight. Initially, the required number of flights is spawned into the simulation environment by

TABLE I
CHARACTERISTICS OF THE DJI MATRICE 600 DRONE MODEL INCLUDED IN BLUESKY, BASED ON MANUFACTURER SPECIFICATIONS [40]

Maximum horizontal speed	18 m/s
Preferred cruise speed	10 m/s
Maximum horizontal acceleration	3.5 m/s^2
Maximum bank angle	25°
Maximum wind resistance	8 m/s

randomly selecting missions from the aforementioned database of cached routes. Then, the set level of concurrent in-flight aircraft is maintained by spawning a new random mission whenever another has ended. Thus, over the course of the whole experiment run, the global traffic density is kept constant. Each experiment condition runs for two hours and is repeated five times with different random seed values.

E. Aircraft Model and Characteristics

Homogeneous traffic scenarios are used for this study to best isolate the difference in performance of the CD&R methods. A simplified model of the DJI Matrice 600 drone, included with BlueSky, is used to simulate vehicle dynamics, with some of its characteristics presented in Table I.

As generated mission paths would include sharp turns, an aircraft would risk overshooting and deviating from the path. Thus, all turns require aircraft to adjust their velocity such that the turn radius would not exceed 5 metres. The latter value is determined by analysing the distances between buildings in Vienna using the model sourced from [41].

F. Wind Model

A simplified wind model is used within the simulated urban environment to test the robustness of the proposed CD&R methods to uncertainties. The goal of the inclusion of wind is to induce variability in the cruising velocities of agents throughout the duration of their missions. This affects the accuracy of the future state prediction calculations of all conflict detection methods. It should be noted that, in safety-critical situations such as conflict resolution and turning manoeuvres, the aircraft are issued ground-speed commands. The aircraft are assumed to attempt to comply with these ground-speed commands in all tested wind conditions.

The model is generated by assigning a wind magnitude and direction along each street (i.e., groups of edges produced by the COINS algorithm [34]). First, the average bearing of each street is computed. As the streets are directional, the average bearing is determined in function of its directionality. Then, the absolute difference in bearing ($\Delta_{bearing}$) is calculated with respect to the rooftop wind direction. The rooftop wind magnitude and direction are used to determine the street wind values, as follows:

$$\text{mag}_{street} = \text{mag}_{roof} \cos(\Delta_{bearing}) \tag{3}$$

$$\text{dir}_{street} = \begin{cases} 1, & \text{if } \Delta_{bearing} < 90 \\ -1, & \text{otherwise} \end{cases} \tag{4}$$

Thus, the effect on the cruising ground speed (Δ_{gs}) of an aircraft flying along a street is computed using Equation 5.

$$\Delta_{gs} = \text{mag}_{street} \times \text{dir}_{street} \tag{5}$$

The wind direction and magnitudes for each street are kept constant throughout the duration of a scenario, which is a simplification of reality. However, these are assumed to be unknown to the agents, as urban wind patterns cannot be reliably predicted [42]. Thus, as aircraft must traverse several streets in order to reach their destination, the cruise ground speed will vary over the duration of a mission. Furthermore, street intersections will be particularly affected in terms of velocity variability, increasing the level of uncertainty for conflicts at such locations.

G. Independent Variables

The independent variables studied within the experiment are as follows:

1) Conflict detection and resolution method
   - Four experiment conditions: State-based CD&R, Worst-case CD&R, Intent CD&R and no CD&R.
2) Number of aircraft concurrently in flight
   - From 100 to 600 in increments of 50 for a total of 11 experiment conditions. Based on the scaled traffic densities of previous work [14], [38].
3) Rooftop wind magnitude
   - From 0 m/s to 8 m/s in increments of 2 m/s for a total of 5 experiment conditions.
4) Rooftop wind direction
   - Four experiment conditions, one for each cardinal direction (0°, 90°, 180°, 270°)

Each experiment condition is repeated five times with different random seed values. For the wind experiments, the number of aircraft concurrently in flight is set at a fixed value of 300. Thus, there are 220 traffic scenarios without wind with varying CD&R method and traffic density, and 320 traffic scenarios with varying CD&R method, wind magnitude, and wind direction.

H. Dependent Measures

The dependent measures recorded during the experiment are focused on the efficiency and safety of the operations within the simulated U-space environment, and are as follows:

1) Average mission duration
   - Used to quantify efficiency over the whole span of one experiment condition (one traffic scenario), and reflects the level of disruptiveness of the CD&R methods.
2) Total number of detected conflicts
   - The total number of unique aircraft pairs that are added to the "conflict_pairs" list in Algorithms 3, 2, and 1.
3) Total number of intrusion events

TABLE II
CONTROL VARIABLES USED THROUGHOUT ALL EXPERIMENT CONDITIONS

Name	Value
Street structure and geometry	-
Street directionality	-
CD look-ahead time	10 s
CD minimum look-ahead distance	100 m
CD maximum look-ahead distance	300 m
CD&R module update interval	0.5 s
Flight altitude	100 ft
Target cruise velocity (true air speed)	10 m/s
Minimum separation threshold	32 m

- Within the present study, the minimum separation limit between two aircraft was set as 32 metres, used in previous studies on U-space operations [14], [25].

4) Average distance at closest point of approach (CPA)
- This value is computed by logging the smallest distance between two aircraft during intrusion events, and is used to quantify the intrusion severity.

I. Control Variables

Table II presents the control variables used across the experiment conditions. For the experimental conditions involving non-zero wind magnitudes, the number of concurrent airborne aircraft is set as a control variable, fixed at 300.

IV. RESULTS

A. Safety

The following section presents the results of the safety metrics obtained from simulating the no-wind traffic scenarios. Figure 7 shows the average number of conflicts that each CD method detected within each scenario. The worst-case CD&R method detected more unique conflict pairs than the others. This trend is expected, as the worst-case method considers all possible conflict situations. Furthermore, the intent method detected more conflicts than the state-based method for all traffic levels as a result of the ability to use trajectory information to find conflicts that would otherwise be overlooked if state linear extrapolation is used.

The average number of intrusion events for each scenario is presented in Figure 8. The difference in this metric between the state-based and the urban environment-aware methods is significant across the whole range of traffic demand levels. Results also show that the intent and worst-case CD&R methods consistently performed similarly in mitigating conflicts.

Figure 9 presents the intrusion prevention rate for each set of algorithms relative to the traffic scenarios that were simulated without the CD&R module enabled. Results indicate that all methods can resolve at least 70% of the conflicts. However, it is clear that the urban environment-aware methods perform better, and experience a relatively small degradation in performance across the traffic demand level spectrum.

On the other hand, the performance of the state-based CD&R method deteriorates with increasing number of concurrently airborne aircraft. The incidence of multi-aircraft conflicts increases, which saturates the solution space for velocity obstacle methods and thus limits the number of possible solutions.

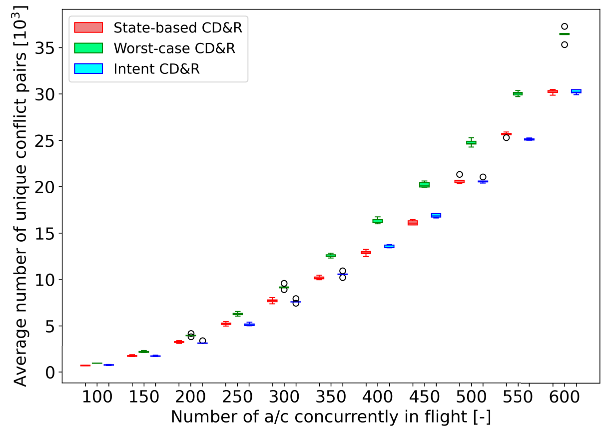

Fig. 7. Average number of unique conflict pairs detected by each method in function of traffic demand level for no-wind scenarios with conflict resolution enabled.

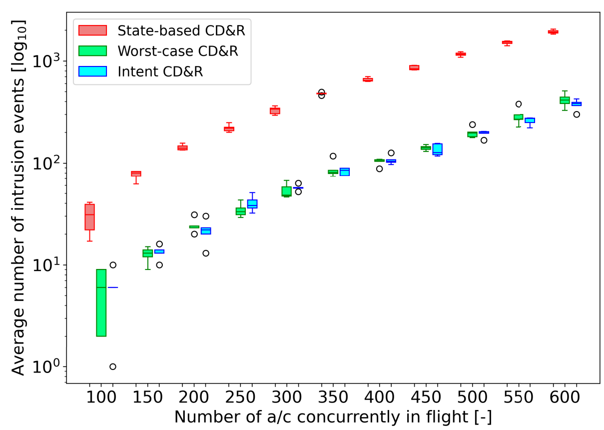

Fig. 8. Average number of intrusions detected by each method in function of traffic demand level for no-wind scenarios with conflict resolution enabled.

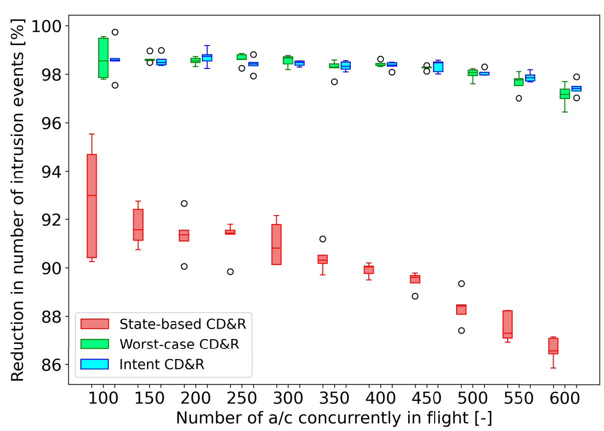

Fig. 9. Percentage reduction in the number of intrusion events from the use of CD&R compared to traffic scenarios with no CD&R enabled.

The last safety metric considered in this work is the average distance at the closest point of approach, presented in Figure 10. While the results at low traffic demand levels have a relatively high variance and are inconclusive, a clear trend can be observed at the high end of the range. This result is

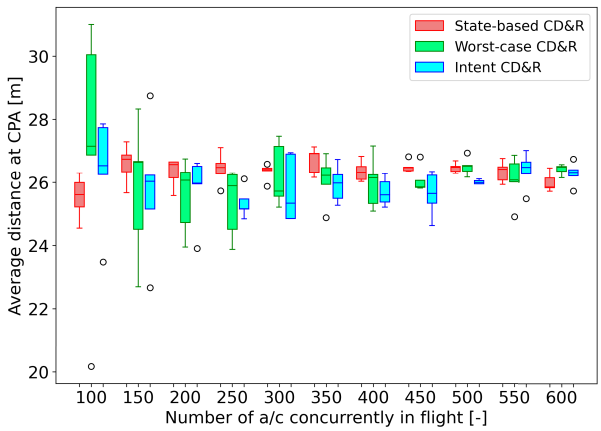

Fig. 10. Average distance at CPA during intrusion events in function of traffic demand level for no-wind scenarios with conflict resolution enabled.

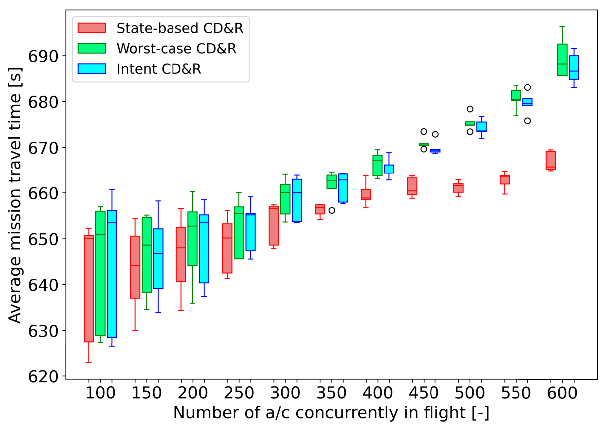

Fig. 11. Average mission travel time for each method in function of traffic demand level for no-wind scenarios with conflict resolution enabled.

expected, as the intent and worst-case CD&R methods are better able to maintain separation through the use of the street geometry information, while the state-based method does not have access to such data, and is thus affected by deviations from the predicted linear trajectory.

B. Mission Efficiency

As aircraft cannot modify the route during cruising, the only efficiency metric considered in this work is the average mission travel time, presented in Figure 11. At low traffic demand levels, all CD&R methods perform similarly, with relatively small differences from one level to another.

A divergence in this trend is observed starting at a level of 450 concurrent airborne aircraft. While the state-based CD&R scenarios show a relatively constant level, the average mission time in case of the worst-case and intent methods increases. This effect is likely caused by the high prevalence of halting commands issued to aircraft with increasing number of conflicts. In the highest traffic demand level case, the intent and worst-case methods delay aircraft by an average of 30 seconds (approximately 5% of the nominal mission time) when compared to the state-based method.

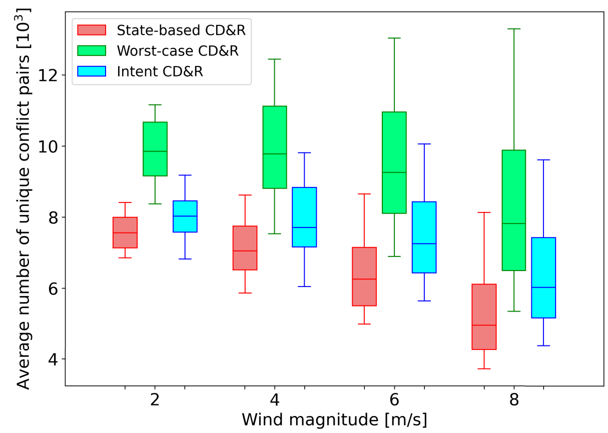

Fig. 12. Number of conflicts for varying wind magnitudes with 300 aircraft concurrently in flight, averaged over all tested wind directions (0°, 90°, 180°, 270°).

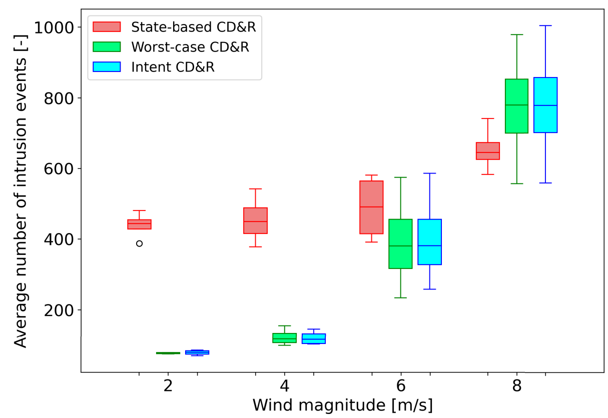

Fig. 13. Number of intrusion events for varying wind magnitudes with 300 aircraft concurrently in flight, averaged over all tested wind directions (0°, 90°, 180°, 270°).

C. Wind Traffic Scenarios

The following section presents the safety and efficiency results of the wind-inclusive simulations. Figure 12 shows the number of unique conflicts detected by each method in function of rooftop wind level. All methods experience higher variance with increasing wind, a direct effect of the increased uncertainty level. The decrease in the number of conflicts at higher wind velocities is due to the lower aircraft throughput as a result of the use of slow-down resolution manoeuvres.

The effect of the higher uncertainty levels greatly affects the average number of intrusion events for the worst-case and intent methods, presented in Figure 13. For the lower wind magnitudes, the intent and worst-case methods still outperform the state-based method. However, at high wind levels, the latter performs best. This confirms findings of previous studies, which found that state-based methods are highly robust towards uncertainties [14].

The intent and worst-case methods heavily rely on velocity matching when aircraft are determined to follow the same route. This resolution strategy is more difficult to implement when the wind level differs for each street. For example, if an aircraft performs a turn manoeuvre onto a street with

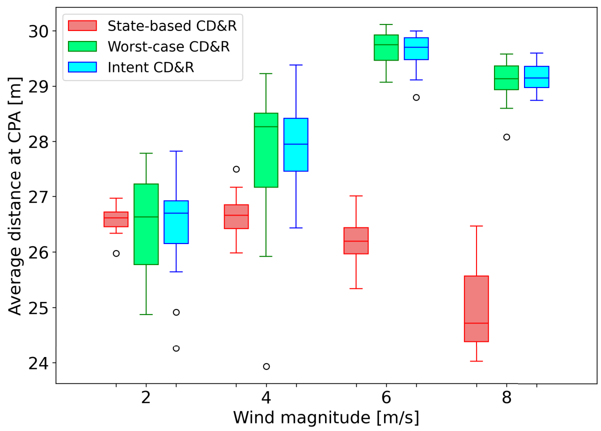

Fig. 14. Average minimum distance during intrusion events for varying wind magnitudes with 300 aircraft concurrently in flight, averaged over all tested wind directions (0°, 90°, 180°, 270°).

different wind conditions, it cruises with a different velocity compared to aircraft closely following it. Thus, the trailing aircraft is forced to match the ground speed of the aircraft in front, which leads to higher relative velocities with respect to other nearby aircraft. Furthermore, as wind information is not available for use in conflict detection, the future cruising velocities of aircraft are difficult to account for.

However, while the intent and worst-case CD&R methods have lower performance in preventing intrusions, the severity of these events is not negatively affected by the presence of wind, as seen in Figure 14. This shows that the inclusion of street geometry information within the detection process increases the safety level in high-uncertainty conditions.

V. Discussion

The results presented in this work show that the use of street geometry information within the conflict detection and resolution process greatly improves the safety of operations in constrained airspace. Contrary to our expectations, the increase in safety did not produce a large increase in mission travel time (approximately 5%), despite the use of halt manoeuvres and high caution level of the worst-case CD&R algorithm.

Results also show that the performance of the intent and worst-case methods experienced a lower degree of deterioration with increasing traffic density when compared to the state-based method. As the number of aircraft increases, the occurrence of multi-aircraft conflicts is more prevalent. These are better handled through the use of street geometry information, as the aircraft are more aware of the possible actions and states of other agents in proximity.

No significant differences can be observed in the efficiency performance indicators between the intent and the worst-case CD&R methods. In most cases, the false-positive conflicts considered by the worst-case conflict detection algorithm would be resolved without any action as aircraft further advance along their routes. As an action would only be taken for the most immediate conflict, and only shortly ahead of the intersection node, the resolution manoeuvres are similar for both methods. Computing the worst-case scenario does not require additional information from other aircraft.

Thus, the results indicate that intent information is not required to achieve a high improvement in the safety level within constrained airspace, as the discrete nature of the airspace deems worst-case CD&R methods sufficient. Intent information might still be beneficial when considering vertical manoeuvres, as the altitude dimension is not discretised and would pose problems for worst-case methods. However, the development and standardisation of an intent information exchange framework is a complex undertaking, and its necessity should thus be further investigated.

The results also show that the performance of the worst-case and intent method deteriorate with increasing wind level. The variability and uncertainty in the velocities of aircraft affected the stability of the detection and resolution algorithms. For the lower wind magnitudes, the intent and worst-case methods still outperform the state-based method, showing robustness towards low degrees of uncertainty. However, the differences lessen with increasing uncertainty, indicating that the worst-case and intent CD&R methods are more sensitive to position and velocity inaccuracy. This would lead to lower performance levels in realistic operating conditions, especially if more complex intent information (4D trajectories) are used.

Another observation highlighted by the results of the simulations is the negative effect of the uncertainty and variability in cruising velocity on the predictability and stability of the airspace. The variance in both the number of conflicts and the average mission travel time increased with higher rooftop wind level, which also affected the ability of all CD&R methods to resolve conflicts. This shows how sensitive U-space operations are to environmental factors such as wind, and should be an important point of focus for future research in this domain.

The performance of all tested CD&R methods in high wind conditions could be improved through the use of live-wind data and wind models to improve state estimations as well as future state predictions. For example, using small aircraft to record live-wind data has been proposed and studied [42], [43], as well as urban wind models produced through computational fluid dynamics simulations [44], [45]. The further development and scaling of these methods for use across large urban areas is important for future U-space operations.

Overall, the results indicate that a high safety level for air traffic operations in constrained urban airspace can be achieved without requiring the development and standardisation of a more complex information exchange framework. Due to the discrete topology of this environment, where aircraft are restricted to flying above the existing street network, worst-case conflict detection and resolution methods can be used with minimal impact on mission efficiency. However, this study also finds that U-space/UTM operations are highly susceptible to uncertainties such as wind. This shows the necessity of the development of an urban airspace meteorological service that would provide information with which worst-case CD&R methods can better account for conflicting situations.

VI. Conclusion

A. Main Findings

The study at hand sought to investigate the use of varying degrees of information exchange levels for tactical conflict detection and resolution (CD&R) in constrained U-space/UTM operations. Three CD&R methods were developed and tested within an urban environment based on the topology of the centre of Vienna. The first method (state-based) only requires current state information, and uses velocity obstacles to compute resolution manoeuvres. The intent CD&R method uses state, intent, and street network information to resolve conflicts. The third method attempts to account for all possible conflict situations and resolve for the most immediate one, and thus does not require the exchange of intent information.

Traffic scenarios were simulated across a wide range of demand levels and wind magnitudes to measure the performance of the three CD&R methods. Results indicate that the use of street network information can greatly benefit operational safety, with minimal impact on efficiency metrics. Furthermore, while the use of intent information has a positive effect on the conflict detection process by filtering false-positive alerts, it is shown that similar performance can be achieved through the use of defensive CD&R principles (i.e., accounting for all possible conflicts and always resolving for the most immediate threat). Thus, results show that, within the well-defined street network of a city, intent information is not necessary for achieving a high safely level.

Another noteworthy finding is the effect of wind on urban airspace operations. The urban-environment aware methods are highly sensitive to increasing uncertainly level, affecting their ability to unambiguously determine priority and resolution manoeuvres for aircraft pairs. As previous studies have shown, the safety level of the state-based method was robust to the presence of wind, as the iterative nature of the algorithm makes it highly adaptable to uncertainties.

The research presented in this article shows that increasing the level of information used within the CD&R process is a worthwhile effort for the safety of U-space operations. Knowledge on the network topology is the most important factor for improving the tactical conflict detection and resolution process, especially for highly organic street networks. However, the augmentation of information exchange frameworks to include intent information is shown to not be of critical importance, thus eliminating the need for the development and standardisation of such a system.

B. Recommendations for Future Research

One of the limitations of this study is the use of a simplified wind model, which does not consider the effect of wind variation in time commonly encountered in urban environments. Studies that include a more realistic representation of wind in urban environments are critical for the further development of CD&R methods. Future research should also focus on the development and improvement of urban wind prediction methods and their integration with tactical CD&R algorithms. Furthermore, aircraft communication and sensing capabilities are not included in this analysis. The performance of the investigated CD&R algorithms is susceptible to factors such as transmission frequency, integrity, and information reliability. The adaptation of the algorithms to account for such disruptions is essential towards a practical implementation.

The traffic scenarios simulated within this study are mostly representative of low-altitude point-to-point delivery operations, as these are predicted to be the largest component of a U-space/UTM system [38]. However, other types of missions (e.g., monitoring, surveying, infrastructure inspection) have different operational characteristics and trajectory planning requirements. Thus, future research should account for these types of operations, and ensure that tactical CD&R algorithms are able to handle a wide variety of conflicting situations.

Lastly, the take-off and landing phases of missions were not included in the simulations. Such manoeuvres have the potential to disrupt cruising aircraft, and would require a different set of rules and operational framework such that the interference with cruising aircraft is minimised. Thus, future research on tactical CD&R methods for constrained urban airspace should account for the presence of such operations.

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Calin Andrei Badea received the B.Sc. and M.Sc. degrees in aerospace engineering with a specialization in control and simulations from TU Delft, where he is currently pursuing the Ph.D. degree with the Department of Control and Operations, Faculty of Aerospace Engineering. His research focuses on the development of tactical deconfliction methods for very-low-level high density urban air traffic operations.

Joost Ellerbroek received the M.Sc. and Ph.D. degrees from TU Delft, in 2007 and 2013, respectively. He is currently an Assistant Professor with the CNS/ATM Chair, Faculty of Aerospace Engineering, TU Delft. His current interests include urban airspace design for drones, topics of airspace complexity and capacity analysis, analysis of future ATM concepts and new approach procedures, separation algorithms for UAS, and several other ASAS-related studies.

Jacco Hoekstra received the M.Sc. and Ph.D. degrees in air traffic management from TU Delft. After obtaining the pilot's license in 1990 and a brief excursion in telecommunications, he started working with the National Aerospace Laboratory (NLR). He was the Head of the NLR Air Transport Operations Division. He was the Dean for two terms. He is currently the Head of the CNS/ATM Chair. He is also a Full Professor with the Faculty of Aerospace Engineering, TU Delft.