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Evaluating the Synergy of Conflict Detection and Resolution Services for Constrained Urban Airspace

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ABSTRACT Very-low-level (VLL) urban air operations have been extensively investigated as a solution for mitigating congestion in cities. However, the manner in which the management of such traffic should be performed is still actively investigated. One important component of such a system is the conflict detection and resolution (CD&R), mainly composed of the strategic and tactical CD&R module. While many approaches towards these have been studied, insufficient analysis has been conducted on their compatibility when functioning within a unified, hybrid system. Additionally, their robustness to operational uncertainties such as wind and departure delays is often overlooked. In this work, we investigate the performance of strategic planing methods when combined with tactical CD&R and subjected to a wide range of traffic demand levels and uncertainty conditions. Simulations indicate that the performance of the strategic deconfliction module is highly sensitive to the presence of wind and delay. This decline in performance is partially mitigated by the tactical deconfliction module. Thus, the results suggest that increased use of tactical CD&R could lessen the required level of detail of strategic deconfliction methods, leading to improved compatibility between the two modules.

INDEX TERMS CD&R, strategic, tactical, urban air mobility, U-space, UTM.

I. INTRODUCTION

THE HIGH interest in urban air operations has driven the development of concepts of operations by aviation authorities around the world. The U-space [1], [2], [3] and UTM [4], [5] proposals for the management of urban air traffic in the EU and U.S., respectively, set the foundation for the development of the services required for such operations. A large portion of the U-space/UTM market is driven by operations occurring at low altitudes within very-low-level (VLL) airspace, as noted by the U-space concept of operations [6]. While there is no consensus on how such airspace should be navigated, one promising approach is to fly above the existing street network, ensuring that aircraft make use of public domain while avoiding most urban obstacles (i.e., buildings).

However, to ensure the safety of such operations different from conventional aviation, novel air traffic management services and systems need to be developed. One important component is the conflict detection and resolution (CD&R) service, which aims to maintain a safe separation between aircraft. According to the most current iteration of the U-space concept of operations [6], both pre-departure strategic flight plan optimisation and tactical CD&R are required within high-density constrained very-low-level (VLL) urban airspace. This allows for both a proactive and reactive approach to mitigate and resolve conflicting situations.

The primary focus of U-space operations research in strategic conflict detection and resolution has been on developing pre-departure 4D trajectory planning techniques. These methods aim to model and optimise flight plans for all aircraft within a specified timeframe, with the goal of minimising the likelihood of conflicts occurring. Previous work has demonstrated the viability of this approach for pre-departure strategic deconfliction within VLL constrained urban airspace. Hohmann et al. investigated such methods for both open airspace [7] (i.e., airspace above the majority

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of buildings) and constrained airspace [8] (i.e., aircraft fly within the confines of a network).

Time-based trajectory planning is also often formulated as an optimisation problem, with the aim of ensuring that the separation threshold between aircraft is not breached. Levin and Rey [9] propose a method through which the flow of aircraft through graph links is controlled to maintain separation while ensuring path planning optimality. Berzeiat et al. [10] and Papa et al. [11] developed methods through which a large number of missions can be planned within an airspace network while maintaining operational efficiency. Similarly, Steinberg et al. [12] and Papa et al. [11] propose an algorithm that can plan conflict-free paths for UAVs within urban street networks using space-time graph techniques.

However, a significant gap in the literature exists regarding the examination of these methods under uncertain and dynamic conditions, such as delays and wind. To mitigate their effect, Dubot and Joulia [13] propose the use of protection buffers around drones that scale with the perceived risk level. Thus, strategic planning is performed more conservatively, leading to increased safety but lower operational efficiency. This technique poses further challenges, as highlighted by Joulia and Dubot [14], suggesting that an overreliance on 4D trajectory deconfliction methods could potentially reduce robustness to uncertainties, and emphasises the need for further investigation.

To address this issue, the use of tactical CD&R and dynamic capacity management has been proposed to reactively resolve conflicts resulting from uncertainty-induced flight plan deviations [15], [16], [17]. The design of such a system needs to account for the potential interactions between the different deconfliction modules, and how they are influenced by environmental and dynamic factors. Tactical manoeuvres inherently cause deviations from pre-established flight plans, potentially triggering a domino effect and increasing conflict occurrences. High levels of operational and environmental uncertainties (e.g., wind presence and departure delays) necessitate more frequent tactical adjustments, which might lead to compromising the ability of aircraft to adhere to their original flight plans. Conversely, the use of tactical manoeuvring might allow for lowering the degree of complexity expected from the pre-departure strategic planning module, both increasing the resilience towards uncertainties and the scope and difficulty of the optimisation process.

The aim of the work at hand is to investigate the performance of different approaches to pre-departure strategic planning in various configurations and conditions, and study the impact on their performance of the inclusion of tactical manoeuvring and their robustness against uncertainties. Four levels of optimisation complexity are considered: (1) no strategic planning, (2) altitude allocation, (3) altitude and route allocation, and (4) full 4D trajectory optimisation. Simulations of traffic demand scenarios are created based on predictions of future urban air traffic. Based on these, the effect of the use of tactical manoeuvring and the presence of uncertainties (e.g., wind and departure delay) on the performance of the CD&R service is investigated.

II. CONSTRAINED URBAN AIRSPACE OPERATIONS

To evaluate the performance of strategic planning methods within a hybrid CD&R system and identify areas for improvement, the following considerations about operations in urban airspace environments were considered based on literature and previous research. Firstly, two competing approaches for VLL urban airspace design can be distinguished in literature: open airspace, with geofences used for obstacles such as high buildings and restricted areas (e.g., [18], [19]), and network-based approaches, where aircraft are constrained to flying along a network of established flight paths [20]. While the choice between the two methods is still an ongoing area of research, the latter approach, used in previous work [8], [9], [11], ensures that the risk of collisions of aircraft with immobile obstacles is minimised.

Furthermore, as graph-based airspace is often used to represent and navigate through open airspace [21], the street-based approach can be generalised towards this case as well. The streets in such a network are assumed to be single-lane (i.e., no parallel traffic flows at the same altitude) and uni-directional, as this is proven to increase airspace safety [22]. Furthermore, as vertical manoeuvres are generally undesirable due to their effect on manoeuvring predictability [23], aircraft are allocated a cruising altitude that must be maintained throughout the duration of the flight.

To ensure the safety of operations, aircraft operating within VLL urban airspace are expected to maintain a minimum separation distance from other aircraft, analogous to conventional aviation [24]. While the procedure on how this threshold needs to be set is still an area of active research, this research assumes that the protection radius (i.e., separation requirement) is constant.

Lastly, as this study focuses on the cruising phase of missions, the take-off and landing manoeuvres are excluded from the deconfliction process. These flight phases involve a shared resource with limited capacity (the landing pad), which dictates a different set of rules and procedures to ensure safe separation [25], and must thus be treated separately.

III. PRE-DEPARTURE STRATEGIC PLANNING

The following section presents the strategic deconfliction methods used in this work. They are defined as an optimisation problem, of which the goal is to ensure that the required separation threshold is upheld while minimising the total travel time of all missions.

The mathematical model is based on the one presented in [10]. It is adapted to the problem treated in this research: the take-off and landing manoeuvres are excluded from the deconfliction procedure, and a more accurate representation of vehicle dynamics is included. The approach implements a Mixed-Integer Linear Programming (MILP) algorithm that optimises the allocation of flight path, departure time, and flight level for each mission. Flight paths can be selected from a finite set of routes generated for each mission.

A. ASSUMPTIONS

The problem is formulated based on the following assumptions:

1) Aircraft take off and land vertically above their designated origin and destination vertiports.
2) Landing and take-off manoeuvres are not part of the deconfliction model, but count towards the total mission duration.
3) Aircraft do not change altitude during the cruise phase.
4) Aircraft fly at their nominal cruise velocity when not performing turning manoeuvres.
5) Aircraft accelerate and decelerate at a constant rate.
6) Aircraft operate in nominal operational and environmental conditions (i.e., uncertainties are not accounted for in the planning phase).

B. FLIGHT PATH GENERATION AND CONFLICT PRE-DETECTION

The set of paths that can be allocated to each flight contains the shortest time route, as well as alternatives that can be used to resolve conflicts. These alternative routes are generated by selecting random vertices in the graph in proximity to the shortest route, which need to be traversed before reaching the destination.

Considering the aforementioned assumptions, conflicting situations can be identified in advance by analysing the possible paths of all scheduled aircraft. Conflicts are defined as situations in which a loss of separation event is predicted to occur (i.e., the minimum separation distance threshold between two aircraft is breached). Thus, the set of routes that scheduled aircraft could use are analysed for situations in which a loss of separation event is probable, producing a set of conflict pairs. The latter is given as an input parameter for the optimisation problem. This process is more extensively explained in [10].

C. PARAMETERS

The following parameters and sets represent the input data for the optimisation model:

- F: The set of all flights that need to be deconflicted
- $K_f, \forall f \in F$: The set of all routes that can be assigned to flight f
- K: The set of all routes $K = \bigcup_{f \in F} K_f$
- $b_k, \forall k \in K$: The travel time associated with route k
- Y: The set of all available flight levels
- $\delta_f(y), \forall y \in Y, \forall f \in F$: The time required to climb to and descend from flight level y for flight f
- $D_f, \forall f \in F$: The maximum admissible ground delay for flight f
- P: The set of all conflicts
- $k_p^1, k_p^2 \in K, \forall p \in P$: The routes of the first and second aircraft involved in conflict p
- $f_p^1, f_p^2 \in F, \forall p \in P$: The first and second flight of the routes generating conflict p
- $t_p^1, t_p^2, \forall p \in P$: The times at which flights f_p^1 and f_p^2 using routes k_p^1, k_p^2 are predicted to traverse the intersection point of conflict p
- $s_p^{12}, s_p^{21}, \forall p \in P$: The required time separation between f_p^1 and f_p^2 at the intersection point of conflict p.

D. DECISION VARIABLES

The following decision variables are defined:

- $x_k \in \{0, 1\}, \forall k \in K$: 1 if route k is assigned to the corresponding flight, 0 otherwise
- $y_f \in Y, \forall f \in F$: The assigned flight level for flight f
- $d_f \in [0, D_f], \forall f \in F$: The ground delay value assigned to flight f

E. CONSTRAINTS

The following constraint ensures that a singular route is assigned to every flight.

$$\sum_{k \in K_f} x_k = 1, \forall f \in F \tag{1}$$

Due to the definition of the decision variables y_f and $d_f, \forall f \in F$ as discrete, Eq. (1) also ensures that a single flight level and departure delay can be assigned for every flight.

The next set of disjunctive constraints aims to ensure that aircraft are separated at each conflict point by a time interval large enough to prevent an intrusion.

$$\left(t_p^1 + d_{f_p^1}\right) - \left(t_p^2 + d_{f_p^2}\right) + s_p^{12} \leq 0, \forall p \in P \tag{2}$$

OR

$$\left(t_p^2 + d_{f_p^2}\right) - \left(t_p^1 + d_{f_p^1}\right) + s_p^{21} \leq 0, \forall p \in P \tag{3}$$

The constraint (2) ensures separation compliance when flight f_p^1 passes before flight f_p^2 at the intersection point of conflict p, and (3) if the aircraft pass in the inverse order. Furthermore, when these flights are not assigned to the same flight level or when one of their paths (k_p^1 or k_p^2) is not used, the conflict is considered resolved.

F. OBJECTIVE FUNCTION AND OPTIMISATION PROCESS

The objective is to minimise the total travel time, shown in Eq. (4).

$$\text{Minimise} \sum_{f \in F} \left(\delta_f\left(y_f\right) + d_f\right) + \sum_{k \in K} b_k x_k \tag{4}$$

The presented mathematical model is implemented as a Mixed Integer Linear Programming (MILP) problem using the Python programming language, and optimised using the Gurobi Optimiser [26].

G. LEVELS OF STRATEGIC PLANNING

The four levels of strategic planning investigated in this work are obtained by progressively enabling the use of decision variables, and are defined as follows:

- *NONE:* No strategic deconfliction (NONE), aircraft depart at their desired departure time and follow the shortest path. The flight altitude is allocated randomly.
- *ALT:* Only the altitude (ALT) is used as a decision variable (y_f), with (x_k) set as the shortest route and desired departure time ($d_f = 0$) for all flights.
- *RTE:* All decision variables are used to optimise the objective function, including the route (RTE) choice for each flight. However, aircraft are allowed to fly at nominal cruise velocity throughout their whole flight.
- *4DT:* All decision variables are used to optimise the objective function, and aircraft are given strict instructions in the form of required time of arrival (RTA) for each waypoint. Thus, a 4D-trajectory flight plan (4DT) is allocated to each mission.

IV. TACTICAL CONFLICT DETECTION AND RESOLUTION

The role of a tactical resolution algorithm is to solve conflicts reactively through the use of evasive manoeuvres. Such algorithms are often considered to be decentralised, as their formulation enables agents to locally and cooperatively resolve conflicting situations. One of the most established types of tactical CD&R methods is that of state-based algorithms [27]. Conflicts between aircraft are detected by linearly extrapolating their current state (i.e., position, heading, velocity) within a definite look-ahead time, and performing manoeuvres such that the distance at the closest point of approach (CPA) is sufficient.

In the work at hand, a velocity-obstacle based tactical conflict detection and resolution algorithm is employed to investigate the effect of the presence of tactical manoeuvring on the performance of pre-departure strategic planning. Velocity Obstacle methods are widely used in air traffic management research, and are generally shown to improve the overall safety level of U-space operations, also when using speed-based resolution manoeuvres [28], such as employed in this study. However, the use of such manoeuvres induces flight plan deviations, enabling the study of whether these affect the performance of pre-departure strategic planning methods.

A. TACTICAL CONFLICT DETECTION

The tactical CD&R algorithm detects conflicts through the use of velocity obstacle (VO) theory, widely developed and used in previous research [28], [29], [30]. The relative position (x_{rel}) and the protection zone radius (R_{pz}) between the aircraft in the conflict pair are extrapolated in time (τ) to obtain the collision cone (CC) according to Eq. (5).

$$\text{CC} = \left\{ v : \left\| v - \frac{x_{\text{rel}}}{\tau} \right\| \leq \frac{\text{R}_{\text{pz}}}{\tau}, \forall \tau \in (0, \infty) \right\} \tag{5}$$

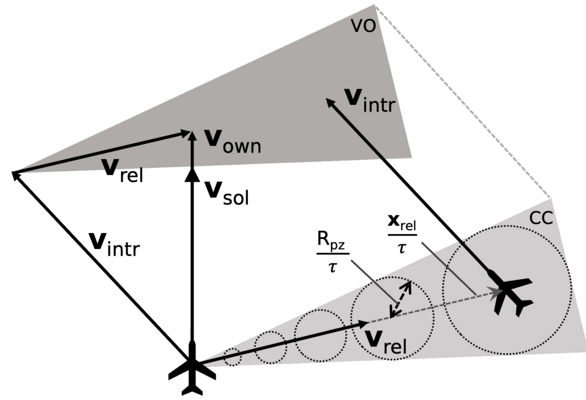

FIGURE 1. State-based conflict detection and resolution using velocity obstacles.

Thus, the collision cone represents the set of all relative velocities (v_{rel}) that would result in an intrusion event. If the current relative velocity vector lies within the bounds of this area, a loss of separation is predicted to occur:

$$v_{\text{rel}} \in \text{CC} \implies \text{Conflict} \tag{6}$$

A visual representation of the relative collision cone is presented in Fig. 1.

B. TACTICAL CONFLICT RESOLUTION

As aircraft in VLL urban airspace are constrained to flying above the existing street network, conflicts cannot be resolved using heading manoeuvres. Furthermore, vertical manoeuvring is shown to affect the safety level negatively [23]. Thus, a velocity obstacle-based conflict resolution method is used [29], modified to only produce speed-based resolution manoeuvres.

The collision cone (CC) in Fig. 1 is translated using the velocity of the intruder (v_{intr}) to obtain the velocity obstacle (VO) in function of the velocity vector of the ownship (v_{own}). As previous research has shown that lower relative velocities increase the safety level [31], the resolution velocity (v_{sol}) is chosen along the direction of the ownship velocity vector (v_{own}) to produce a reduction in velocity that would resolve the conflict.

To ensure that conflict resolution manoeuvres are unambiguous, the state-based CD&R algorithm implements aircraft prioritisation. Thus, an aircraft decides whether it must perform a resolution manoeuvre according to 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.

The speed-based tactical CD&R algorithm is summarised in Algorithm 1.

V. EXPERIMENT

The following section presents the experimental setup used to test the performance of the strategic CD&R methods in

Algorithm 1 State-Based CR Algorithm Using Velocity Obstacles [28]

conflict_pairs = **all** (ownship, intruder) | conflict pair
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

a simulated VLL urban airspace environment. The aim of the experiment is to investigate the compatibility of pre-departure strategic planning and tactical conflict resolution, and their robustness to common operational uncertainties such as wind and departure delay. To achieve this, air traffic scenarios are generated and simulated in a wide range of operational and environmental conditions.

A. HYPOTHESES

The experiment seeks to test the following hypotheses, based on the conclusions of previous studies [21]:

- **H1** Tactical-only CD&R scenarios will perform similarly to strategic-only scenarios in nominal conditions for the ALT and RTE strategies.
- **H2** With the increasing level of strategic CD&R, the safety level will increase in nominal conditions.
- **H3** The safety level will decrease with increasing uncertainty level in non-nominal conditions (i.e., wind and delay).
- **H4** The additional use of tactical CD&R will increase the level of safety in non-nominal conditions.
- **H5** The average mission time will increase with increasing strategic CD&R level.

Hypothesis **H1** is based on the results of previous research [21], which indicated that tactical and strategic CD&R modules perform similarly in nominal conditions within VLL urban airspace.

Hypotheses **H2** and **H3** stem from the presumed effect of operational uncertainties such as wind and departure delay on pre-departure strategic planning. As their presence will result in difficulties for aircraft to follow their nominal trajectory, a deterioration in the safety level compared to nominal conditions is expected. However, in nominal conditions, the strategic optimisation of flight plans is expected to increase safety. Previous research [28] has shown that the use of tactical CD&R is beneficial in non-nominal conditions, when aircraft would not be able to comply with their flight plans, leading to the formulation of Hypothesis **H4**.

Lastly, hypothesis **H5** captures the assumption that, as the strategic planning will potentially deviate aircraft from their fastest route, the average mission time will increase. This effect is assumed to be lessened by the ability to allocate lower altitude levels to flights.

B. SIMULATION SOFTWARE

The BlueSky Open Air Traffic simulator [32] was used to simulate the urban air traffic environment. This open-source platform was selected due to its widespread adoption in U-space/UTM research ([33], [34], [35]), and because it allows for transparent implementation of custom plugins. For the study at hand, we developed such plugins for the tactical CD&R module, the wind and delay models, and autopilot (source code available publicly: [36]).

Furthermore, previous studies have validated the fidelity of BlueSky simulations compared to real-world urban traffic scenarios [37]. Aircraft dynamics are simulated with a high degree of accuracy, allowing for a better representation of manoeuvres such as turns (i.e., considering turn radius, bank angle, acceleration, etc.). Thus, aircraft trajectories are more difficult to predict using simplified models, which creates a more challenging but realistic simulation environment for testing strategic planning methods.

C. CONSTRAINED URBAN AIRSPACE ENVIRONMENT

The simulation environment is based on the street network within the central districts of Vienna, Austria, presented in Fig. 2. This area was selected due to its diverse topological characteristics: parts of the network are orthogonal in aspect, while others are highly organic, resulting in a wide range of possible manoeuvres and conflicting situations.

The street network was extracted from the OpenStreetMap database [38] using the OSMnx Python library [39]. The obtained graph was then processed further by assigning singular directions to the edges. First, the edges were

FIGURE 2. Constrained airspace structure extracted from the street network of the city centre of Vienna.

grouped into strokes (i.e., groups of consecutive edges that present a smooth street-like geometry) using the COINS algorithm [40]. Then, a genetic algorithm optimisation process was used to assign stroke directions such that the resulting graph is unidirectional, and the minimum required travel distance from every node to every other node is minimised. This optimisation process is more extensively explained in [41]. Lastly, the airspace is divided into 10 cruise altitude layers, each with a thickness of 50 ft (15.24 m).

D. AIR TRAFFIC DEMAND SCENARIOS

High-density air traffic scenarios were generated to test the limits of the proposed deconfliction methods. As parcel deliveries are expected to be the largest source of future VLL urban airspace operations demand [42], the study at hand focuses on point-to-point missions. Thus, for every scenario, 5% of graph nodes were randomly designated as origin vertiports, with all the rest as potential destinations. Then, a demand scenario was generated within a 1.5-hour time window, considered to be a list of flight requests. Each flight was designated a random origin and destination pair.

Three flight demand levels were considered: 120, 180, and 240 aircraft per minute (ac/min). While these are higher than the expected demand in the near future [42], they were chosen to induce the creation of a multitude of conflicting situations. Then, the BlueSky traffic scenario files are generated after the flight requests are optimised for each strategic planning level.

The take-off and landing manoeuvres were not considered for the CD&R process or simulated. Such manoeuvres are highly disruptive for cruising traffic and have different operational procedures and requirements that should be studied separately [43]. However, these were accounted for within the efficiency metrics (i.e., mission travel distance and duration). Furthermore, the aircraft are assumed to cruise at their allocated cruise flight level for the whole duration of their mission, without the possibility of performing vertical manoeuvres. This is proven to increase airspace safety [23], and is an assumption encountered in literature [9].

TABLE 1. DJI Matrice 600 model parameters in BlueSky, based on manufacturer specifications [44].

Maximum horizontal airspeed	18 m/s
Maximum ascent speed	5 m/s
Maximum descent speed	3 m/s
Maximum horizontal acceleration	3.5 m/s^2
Maximum pitch/bank angle	25°

E. AIRCRAFT DYNAMICS AND CHARACTERISTICS

One singular aircraft type was considered within this experiment to better control for the effect of CD&R methods and uncertainties on efficiency and safety metrics. The BlueSky simulator includes a simplified model of the DJI Matrice 600 drone, with characteristics presented in Table 1.

One important consideration regarding the vehicle dynamic simulation is the turning procedure. Within the BlueSky simulator, the turn rate ω and turn radius R are calculated as a function of the gravitational acceleration g, the bank angle ϕ, and the velocity V, as shown in Equation (7) and (8).

$$\omega = \frac{g \tan\phi}{V} \tag{7}$$

$$R = \frac{V^2}{g \tan\phi} \tag{8}$$

By analysing the width of the streets and building characteristics of the selected urban environment (Vienna), a turn radius of 5 metres was determined to prevent collisions with buildings due to turn overshoot and enable aircraft to cruise within the street boundaries. This value will be different for other urban environments, and should thus be determined on a case-by-case basis. By using Equation (8) and the maximum bank angle value of 25° given by the manufacturer for the used aircraft model, a required turning velocity of 4.78 m/s and a turn rate of approximately 55°/s are found.

Thus, to ensure that the turns comply with the required turning velocity, the turning manoeuvre is simulated according to the illustration in Fig. 3. First, a cruising aircraft will initiate a deceleration manoeuvre ahead of a turn (at point 1) such that the required turn velocity is reached. Then, then the turn is performed at constant velocity. Once the aircraft is aligned with the direction of the next waypoint (at point 3), the aircraft will accelerate back to cruise velocity.

Such a manoeuvre is initialised when the turn angle exceeds 25°. For lower values, the aircraft uses the cruise velocity to perform the turn, as the overshoot was determined to be within the limits imposed by the street and building arrangement.

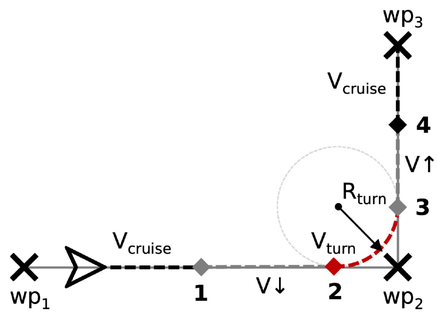

FIGURE 3. Turning manoeuvre as simulated within BlueSky.

F. WIND MODEL

Wind in urban environments can greatly affect strategic planning in U-space/UTM operations by hindering aircraft from closely following their allocated flight plan [45]. This paper uses a simplified model to represent the effects of local wind. A global rooftop wind magnitude and direction is selected and projected onto the average bearing of each street (i.e., stroke as explained in Section V-C) within the street network according to Equation (9).

$$\mathrm{mag}_{street} = \mathrm{mag}_{roof} \cos\left(\Delta_{bearing}\right) \tag{9}$$

Then, the direction of the wind within each street is determined by the difference in bearing between the street and the global wind direction. As streets are unidirectional, wind will either slow aircraft down or speed them up. Wind perpendicular to the direction of flight is not considered. Thus, the final effect of the wind on the ground speed of an aircraft is given by Equation (11).

$$\mathrm{dir}_{street} = \begin{cases} 1, & \text{if } \Delta_{bearing} < 90^\circ \\ -1, & \text{otherwise} \end{cases} \tag{10}$$

$$\Delta_{gs} = \mathrm{mag}_{street} \times \mathrm{dir}_{street} \tag{11}$$

Throughout the span of a single traffic scenario, the wind magnitude and direction is kept constant along every street. Thus, as aircraft must travel along several streets to reach their destination, they will experience a wide range of wind magnitudes and directions.

Lastly, the aircraft will attempt to fly their nominal cruise airspeed throughout all scenarios except the 4DT strategic planning cases. For the latter, the aircraft will attempt to follow the RTA commands within the limit of their speed performance envelope.

G. DELAY MODEL

In this study, the presence of departure delay is used to investigate the robustness of pre-departure strategic planning to imperfect planning adherence, and whether tactical CD&R can mitigate the negative effects.

In literature, aircraft departure delay has often been modelled as an exponential distribution [46]. In this work, two parameters govern the effect of the delay model on operations: the average delay magnitude, and the probability of a mission to experience departure delay. Thus, if a mission is determined to be delayed, a random value will be extracted from an exponential distribution (λ = average delay magnitude^{-1}) and applied as departure delay, limited to a maximum of 5 minutes.

H. INDEPENDENT VARIABLES

To test the hypotheses presented in Section V-A, the experiment considers the following independent variables:

1) Tactical CR method
   No tactical CR, and state-based tactical CR
2) Strategic CD&R method
   NONE, ALT, RTE, 4DT
3) Flight demand level
   120, 180, and 240 aircraft per minute (ac/min)
4) Rooftop wind magnitude
   2, 4, and 6 m/s
5) Rooftop wind direction
   0°, 90°, 180°, 270°
6) Average delay magnitude
   10, 30, and 60 seconds
7) Probability of a flight being delayed
   10%, 30%, and 50%

The experiment is divided into three parts: nominal, wind, and delay conditions. The tactical and strategic CD&R levels serve as independent variables throughout all parts. In the wind experiments, the traffic demand level is set at 180 aircraft per minute, and the wind magnitude and direction are varied. Similarly, the delay magnitude and probability serve as independent variables within the delay experiments, with the traffic demand level kept constant (180 ac/min). Each experiment condition is repeated five times with different random seed values. Thus, 960 traffic scenarios were simulated: 120 scenarios with nominal conditions, 480 scenarios with simulated wind, and 360 scenarios with a non-zero departure delay probability.

I. DEPENDENT MEASURES

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

1) Total number of intrusion events
   An intrusion occurs if the distance between two aircraft is lower than the minimum separation limit, set at 32 metres [21], [28].
2) Average distance at closest point of approach (CPA)
   The average minimum distance between two aircraft during an intrusion event. This metric captures the severity of the separation limit violation.
3) Average mission duration
   This metric is used to quantify efficiency in this work, and includes both horizontal and vertical travel time for each mission.

TABLE 2. Experiment controlled variables.

Parameter name	Value
Tactical CD&R look-ahead time	10 s
Target cruise airspeed	15 m/s
Minimum separation threshold	32 m
CD&R module update interval	1 s
Simulation update interval	0.1 s
Wind & delay conditions: demand level	180 ac/m

J. CONTROLLED PARAMETERS

The parameters presented in Table 2 were kept constant throughout most experiment conditions. For the wind and departure delay conditions, the mission demand level was set to 180 aircraft per minute (ac/m).

VI. RESULTS

The following section presents the results of the urban traffic scenario simulations. The first section focuses on the nominal condition scenarios, where wind and delay were not present. Then, the wind and delay scenarios are presented.

A. NOMINAL SCENARIOS

The overall safety level within the airspace can be observed from the number of intrusion events that occurred throughout a scenario. Fig. 4 presents the results for the nominal scenarios, which indicate that the best performance was achieved when using state-based tactical CR in combination with strategic 4D trajectory planning (4DT). The greatest relative decrease in the number of intrusion events was obtained through the use of the ALT strategic planning strategy (i.e., altitude allocation and shortest route), compared to no strategic pre-planning.

An interesting observation of the intrusion results is that the use of departure delay and assigned route as decision variables is only effective if aircraft actively adapt their velocities to follow the RTA commands. Otherwise, most of the increase in safety is attributed to the altitude allocation strategy, as the ALT and RTE CD&R strategies performed similarly in all conditions. However, the constant and frequent need to adjust velocity might be detrimental to operations, as this would lead to higher energy consumption and decreased traffic predictability.

The effect of including the tactical CD&R module can be seen in Fig. 5 in terms of intrusion severity. Fig. 4 already shows that the use of state-based CR lowers the number of intrusions in all cases, Fig. 5 shows that it also decreases the severity of the remaining conflicts. Only in the 4DT case, a similar performance in terms of intrusion severity is already achieved solely by the strategic planning method.

This effect is further illustrated in the histogram presented in Fig. 6. When comparing the NONE, ALT, and RTE cases, the presence of state-based tactical CD&R shifts the distance at CPA towards higher values. Thus, fewer high-severity intrusions remain. For the 4DT case, the magnitude of this shift is lower, but nevertheless still present as some of the most severe intrusions are mitigated. These results suggest that the use of tactical manoeuvring can indeed produce a net positive effect on airspace safety in combination with strategic planning methods.

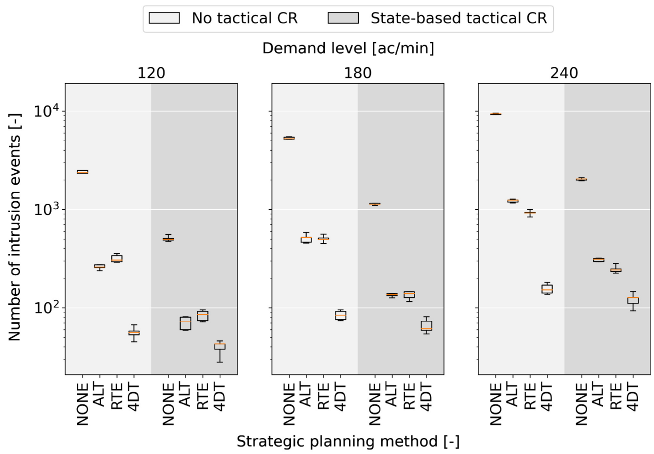

FIGURE 4. The number of intrusion events in function of demand level and CD&R configuration.

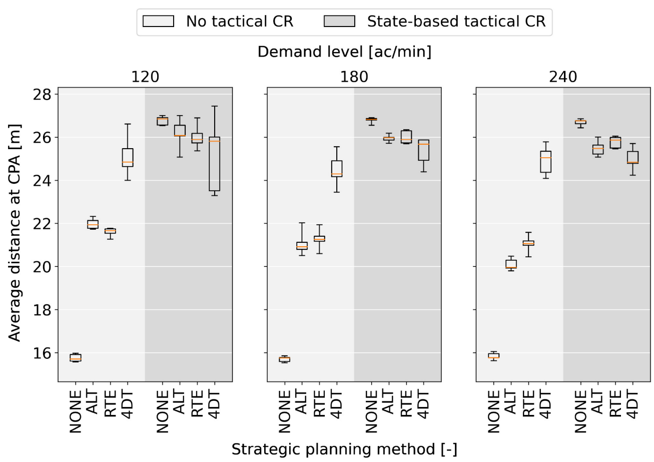

FIGURE 5. Average distance at CPA in function of demand level and CD&R configuration.

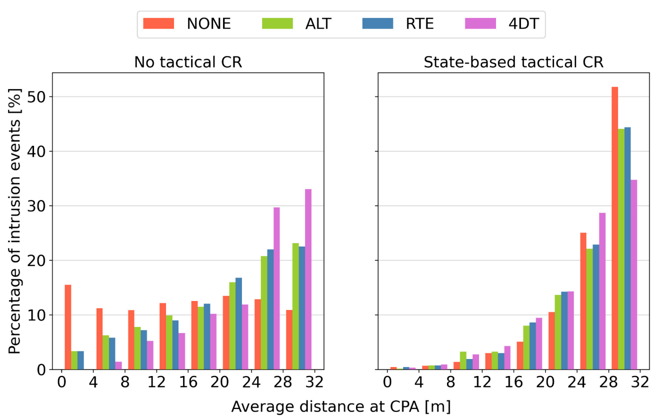

FIGURE 6. Histogram of the average distance at CPA in function of tactical and strategic CD&R configuration, with a 4m bin size.

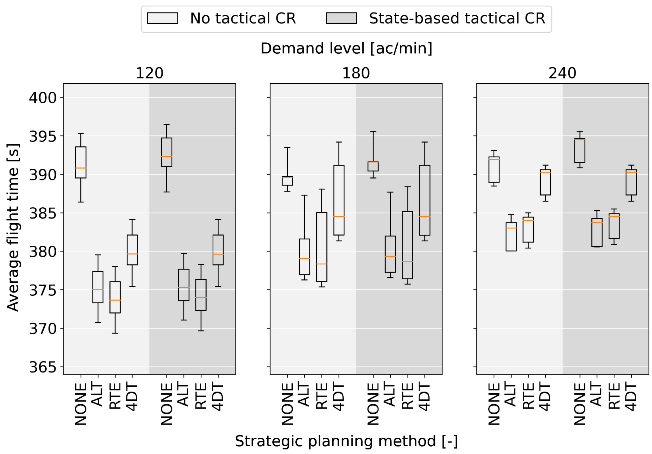

FIGURE 7. Average mission duration in function of demand level and CD&R configuration.

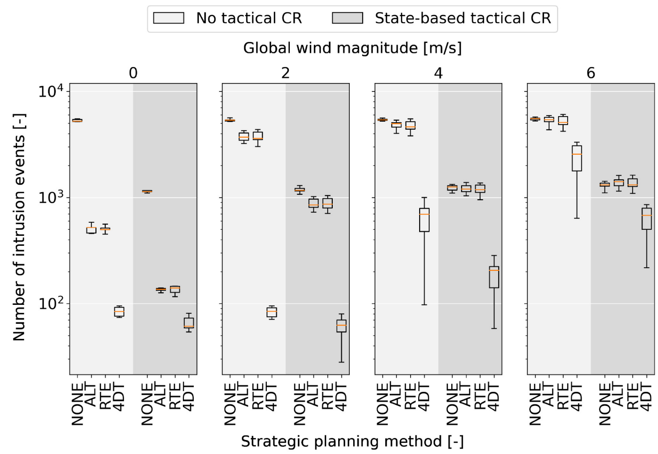

FIGURE 8. The number of intrusion events for wind scenarios in function of wind magnitude and CD&R configuration, averaged over all wind directions.

Another interesting observation from Figures 5 and 6 is that the NONE strategy in combination with tactical CD&R resulted in the lowest average distance at CPA, and thus the highest intrusion severity level. However, this can be attributed to the presence of low-severity conflicts that were solved in other cases using strategic planning. This highlights one of the benefits of the use of pre-departure CD&R: although tactical intervention is still necessary due to planning inaccuracies, the severity of the remaining conflicts in nominal conditions is low and are thus more easily resolved.

The operational efficiency performance of the different CD&R strategies can be observed in the average flight time values, presented in Fig. 7. Overall, the altitude allocation (ALT) strategy has a great effect on efficiency, as the need for vertical travel is lessened compared to the NONE case. Furthermore, the 4DT case experiences a slight increase in flight duration compared to the RTE strategy. This suggests that the optimisation model underestimates aircraft travel times. Overall, the efficiency metrics for nominal conditions show the benefits of using optimisation methods for pre-departure strategic planning, as they can greatly improve operational efficiency.

B. WIND SCENARIOS

The following section presents the results for the scenarios in which wind was present. All scenarios were simulated at a demand level of 180 aircraft per minute at different global wind magnitudes. The results were also averaged for all wind directions to mitigate the effect of the street network topology on the results.

The data on the number of intrusions, presented in Fig. 8, shows that the use of tactical CD&R partially mitigates the effect of wind for high uncertainty situations. An important observation is that, since uncertainties are not accounted for, the strategic planning is greatly affected by any level of wind, as can be seen for the ALT and RTE cases for a wind level of 2 m/s. In these cases, aircraft sought to maintain a constant cruise airspeed, thus incurring non-nominal ground speeds. This induces significant flight plan deviations, leading to a large degradation in performance for the lower complexity planning methods.

For the 4DT case, aircraft were able to compensate for the low wind levels, with difficulties only appearing for higher wind levels that pushed the required compensation past the velocity performance limits of the aircraft. This result highlights the importance of using velocity control to ensure flight plan compliance. However, this strategy is detrimental at higher uncertainties, as drones need to fly at higher velocities to maintain flight plan compliance, making conflicts more difficult to solve due to the large difference in relative velocity between agents [47].

The effectiveness of the tactical CD&R module against the presence of wind can be seen in Fig. 9. For all the strategic planning strategies, stronger global wind magnitudes lead to an increase in intrusion severity. On the other hand, the average intrusion severity is maintained throughout all conditions when state-based CR is used. Thus, while the use of strategic planning lowers the intrusion severity metric in nominal conditions, the presence of wind produces the opposite effect, especially visible in the 4DT case, as aircraft cruise at higher speeds.

C. DELAY SCENARIOS

Similarly to the wind scenarios, the traffic demand level was set at 180 aircraft per minute for all departure delay conditions. Furthermore, as the variation of the average departure delay and departure delay probability affected the output in similar proportions, this section presents the results when the departure delay probability is set to 10%. The results for the other experimental conditions can be found in the public code and data repository of this work [36].

As the occurrence of a departure delay alters the flight plan significantly, the increase in the number of intrusion

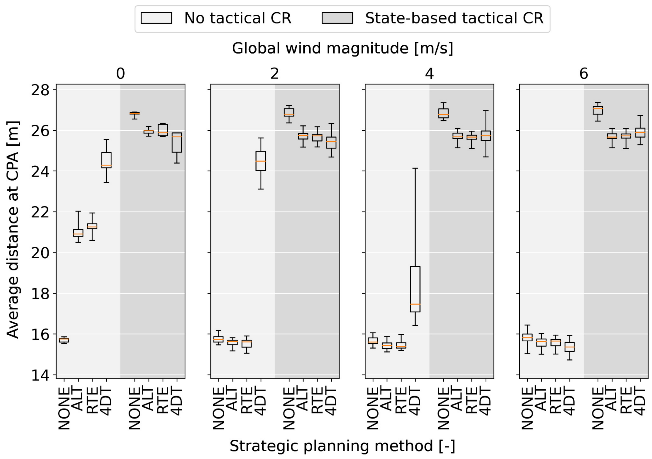

FIGURE 9. Average distance at CPA for wind scenarios in function of wind magnitude and CD&R configuration, averaged over all wind directions.

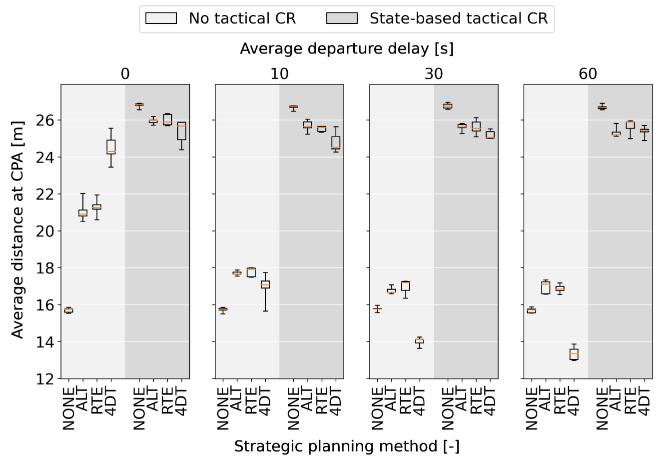

FIGURE 11. Average distance at CPA for departure delay scenarios; 10% delay probability.

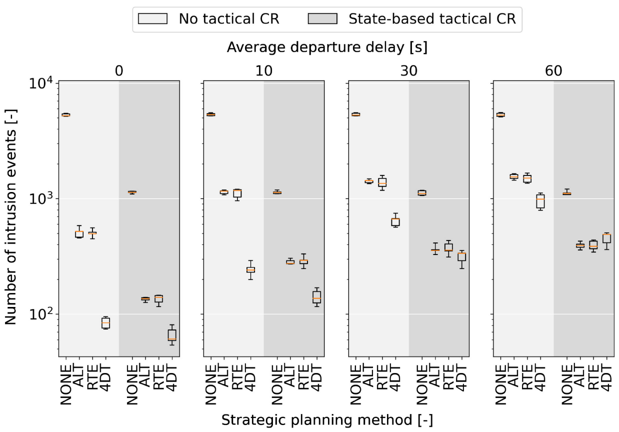

FIGURE 10. The number of intrusion events for departure delay scenarios, 10% delay probability.

events seen in Fig. 10 is according to expectations. The strategic planning is affected by any amount of delay, as the aircraft that cannot follow their flight plans will produce a high number of conflicts with compliant aircraft. This result highlights the effects of over-optimising flight plans and lowering the safety margins for efficiency gains. Unlike the effect of wind, where aircraft are both slowed down and sped up, departure delay acts unidirectionally, producing a large negative effect on the safety level even at low uncertainty levels. However, the presence of tactical CD&R partially helps with mitigating the negative effects on safety.

This effect can also be seen in the results for the average distance at CPA, shown in Fig. 11. While the intrusion severity for the cases with no tactical CD&R increases with higher delay, the use of state-based CR helps with maintaining a higher safety level by increasing the average distance at CPA. However, as a result of the over-optimisation of flight plans and the attempt of agents to re-enter a state of compliance by using high cruise velocities, the highest intrusion severity level is experienced by the 4DT strategy when tactical CD&R manoeuvring is not used.

VII. DISCUSSION

The results presented in the previous section indicate that the use of both pre-departure strategic planning and tactical conflict detection and resolution is beneficial for airspace safety in all tested situations. In nominal conditions, any level of strategic optimisation of flight plans resolves the majority of intrusions, while many of the remaining conflicts are resolved on a tactical level. Furthermore, the random allocation of flight level (NONE) in combination with the state-based algorithm was outperformed by other CD&R configurations that include higher levels of strategic planning in nominal conditions. Thus, Hypothesis **H1** is rejected, as the strategic optimisation model was improved compared to previous implementations in [10], [21].

A surprising result can be observed when comparing the ALT and RTE strategic planning strategies, which performed similarly across all simulated scenarios. This occurred due to the ability of the optimiser to resolve the majority of potential loss of separation events through the use of the altitude allocation decision variable. Thus, the optimised flight plans for most missions use the shortest path and nominal departure time, resulting in similar results.

This shows the importance of the use of and compliance with 4D flight planning in VLL constrained urban airspace. As the MILP model relies on estimating the time at which aircraft will reach each node in their trajectories, inaccuracies will be present due to modelling assumptions and uncertainties. These inaccuracies need to be compensated for through the use of RTA commands. Thus, hypothesis **H2** is partially accepted, as a higher strategic planning level did not always lead to a higher safety level.

In the case of the non-nominal condition scenarios, the observations confirm hypotheses **H3** and **H4**. The presence of wind or departure delay resulted in aircraft deviating from their nominal flight plans. Thus, with no tactical intervention, the overall safety level deteriorated. However, the use of state-based tactical CD&R was able to partially mitigate the negative effects of the presence of uncertainties.

A notable result is that, even for the lowest departure delay magnitude and probability (i.e., 10% probability of experiencing an average of 10 seconds of delay), the number of intrusions greatly increased for all levels of strategic planning. More importantly, aircraft in the 4DT case were unable to safely compensate for the delay by using higher cruise velocities. This confirms the conclusions of Joulia and Dubot [14], as robustness towards uncertainties deteriorated with increased focus on routing optimality. Thus, future U-space/UTM research should reconsider the use of optimality-focused pre-departure strategic optimisation methods (e.g., [9], [10]), and attempt to either incorporate the effect of uncertainties within the tactical and strategic CD&R modules, or investigate safety-oriented approaches.

Lastly, the use of strategic altitude allocation had a beneficial effect on the average mission duration in nominal conditions, as the spare capacity at lower flight levels was leveraged to produce shorter take-off and landing manoeuvres. Furthermore, against the expectations captured within Hypothesis **H5**, alternative trajectories that deviated from the shortest path were not required in most cases to optimise the nominal condition traffic scenarios used in this work.

Overall, the experimental results suggest that the development of strategic conflict detection and resolution methods needs to focus on improved compatibility and resilience against the effects of flight plan deviations due to tactical manoeuvring or uncertainties. The presence of wind and departure delay greatly reduced the benefits of pre-departure flight plan optimisation. Such uncertainties are often encountered in air traffic operations, and their consideration is thus of critical importance for the future development of the strategic deconfliction module.

Another important outcome is that the use of tactical manoeuvring produced a net positive effect on overall safety, despite the use of an algorithm originally designed for use in open airspace. Although tactical intervention did induce flight plan deviations, it helped with maintaining separation between agents and resolving conflicts. Thus, future research should focus on developing a tactical CD&R framework that improves compatibility with pre-departure strategic methods and improving their resilience towards uncertainties.

VIII. CONCLUSION

The aim of the work at hand was to investigate the performance of tactical and strategic conflict detection and resolution (CD&R) methods in various operational and environmental situations within very-low-level (VLL) airspace. Two approaches prevalent in literature are tested within traffic scenario simulations at varying demand and uncertainty levels, with the purpose of gaining a more in-depth understanding of the strengths and shortcomings of each individual module and their combined use.

Results show that, in nominal conditions, pre-departure strategic planning can resolve most of the predicted loss of separation events, while tactical CD&R assists with the conflicts remaining due to prediction inaccuracies. However, the strategically deconflicted flight plans are highly sensitive to uncertainties, such as situations with high-magnitude wind or departure delay. In such situations, tactical CD&R could the required short-term reactivity required to overcome many conflicts resulting from trajectory non-compliance. Furthermore, the use of the state-based method proved to increase the overall safety level in all situations (nominal and non-nominal), thus presenting a high degree of compatibility with pre-departure strategic methods.

Therefore, future research should focus on the mitigation of the negative effects of operational uncertainty within tactical and strategic CD&R. Current strategies for this involve heavily sacrificing capacity through the use of buffered minimum separation requirements (e.g., [48]), and in-depth investigations on other approaches are generally lacking in literature. A promising method through which this could be achieved is the development of more suitable tactical CD&R modules that can offload part of the deconfliction responsibility from the pre-departure strategic planner. In this way, more conflicts could be resolved locally and reactively, reducing the impact of uncertainty when large look-ahead time horizons are used.

While the results of the study at hand offer valuable directions for future development of urban air traffic management systems, it is important to acknowledge and consider its limitations. The simulated air traffic scenarios are representative of future demand estimations, but are specific to a particular urban airspace design and mission set for the city of Vienna. Additionally, the study focused on a single tactical CD&R algorithm and employed a single simulation platform. However, both the conflict detection and resolution method and the simulation platform are representative of other work in the field or validated for urban airspace operations respectively, and thus serve as a robust foundation for comparison and recommendations.

Lastly, this study uses simplified vehicle, wind, and delay models to better isolate the performance of the CD&R methods and reduce confounding factors. While these implementations are sufficient for studying the effect of such disruptions on the general safety and efficiency levels of urban air traffic, a more accurate representation of urban hyperlocal wind effects, together with the simulation of a wider variety of vehicles and more realistic operational conditions can further reveal factors that need to be accounted for within the design of a U-space/UTM conflict detection and resolution framework.

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