Conflict Detection and Resolution for Constrained Urban Airspace

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Conflict Detection and Resolution for Constrained Urban Airspace

Conflict Detection and Resolution for Constrained Urban Airspace

Dissertation

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To my wife, Teona, who supported me throughout
this whole journey and beyond.

CONTENTS

SUMMARY

Urban air mobility (UAM) is presented as a potential solution to urban congestion. By utilising aerial vehicles for tasks like parcel delivery, public transport, and surveillance, pressure on traditional ground-based transportation infrastructure can be alleviated. This is particularly important with the rise of e-commerce and the increasing demand for fast and efficient delivery methods. UAM has the potential to revolutionise urban travel, offering faster commutes and enhancing surveillance capabilities for improved traffic management and emergency response.

The U-space concept, developed within the European Union, provides a framework for the safe integration of drones and small unmanned aircraft systems (sUAS) into urban airspace. It focuses on establishing services, regulations, and procedures to manage UAM operations effectively. An important component of this concept is Type Zu airspace, designated for high-density urban operations. This airspace requires strict regulations and safety-critical services like dynamic capacity management, conflict resolution, and continuous monitoring to ensure safe and efficient U-space operations.

Conflict detection and resolution (CD&R) of air traffic is required to ensure the safety of such operations, and VLL urban airspace presents unique challenges compared to conventional air traffic management. Buildings and other obstacles restrict aircraft movement, making manoeuvring and conflict avoidance more difficult. Unpredictable urban wind patterns further complicate flight planning and trajectory prediction. These factors, combined with the inherent complexity of urban environments, necessitate the development of robust CD&R algorithms and rules specifically tailored to the challenges of VLL urban airspace.

The core research objective of this dissertation is to identify and develop effective CD&R algorithms and rules for safe and efficient UAM operations in VLL urban airspace. This involves evaluating the limitations of existing CD&R methods, designing new algorithms that address the specific challenges of urban environments, and defining clear rules and procedures for aircraft navigation and conflict resolution.

Chapter 2 delves into the limitations of current CD&R methods when applied to VLL urban airspace. This constrained environment, characterised by aircraft flying below 150 meters and adhering to street networks due to building obstructions, presents unique challenges that existing methods struggle to address effectively. The chapter examines specific issues such as traffic management at intersections, navigation of non-linear trajectories, and the impact of unpredictable urban wind patterns on flight plans.

To illustrate these challenges, the chapter presents a study utilising a simulated organic street network based on Vienna. This simulation serves as a platform to analyse aircraft behaviour and evaluate the influence of constrained airspace on

both flight efficiency and safety. Through this investigation, the chapter concludes that current CD&R methods and airspace structure designs require significant improvements to adequately address the distinctive challenges posed by constrained urban airspace.

Chapter 3 focuses on enhancing tactical CD&R methods within the context of a decentralised U-space air traffic control system, specifically tailored for topologically organic urban airspace. The chapter proposes several key improvements to address the unique challenges of this environment. These enhancements include avoiding generally vertical manoeuvring, leveraging intent information for more effective conflict detection and resolution, and allowing heading-based manoeuvres in open airspace areas.

To validate these proposed improvements, the chapter presents simulation results that demonstrate the significant increase in airspace safety achieved through the use of intent information and the implementation of suitable prevention procedures. Furthermore, the chapter underscores the potential for further enhancing both safety and efficiency by integrating tactical separation modules with other components of air traffic management systems designed for U-space.

Chapter 4 explores the optimal balance between centralised and decentralised CD&R approaches within a hybrid system designed for constrained VLL urban airspace. This investigation aims to determine the required degree of centralisation for effective U-space CD&R services. The chapter presents a comprehensive study that simulates various levels of tactical and strategic CD&R under different traffic demand scenarios and uncertainty conditions, specifically focusing on the impacts of wind and departure delays.

The simulation results reveal a critical insight: strategic deconfliction methods are highly sensitive to external factors such as wind and delays. However, the study demonstrates that this vulnerability can be partially mitigated through the implementation of tactical deconfliction measures. Based on these findings, the chapter suggests that increasing the use of tactical CD&R could potentially simplify strategic deconfliction methods, ultimately leading to improved compatibility and synergy between these two modules in the U-space air traffic management system.

Chapter 5 focuses on the potential benefits of incorporating intent information into tactical CD&R systems for constrained urban airspace. Intent information, in this context, refers to aircraft broadcasting their short-term intended trajectories. The chapter presents a comparative analysis of three distinct CD&R algorithms, each utilising different levels of information availability.

The study examines algorithms that use: 1) state information only, 2) state and street topology information, and 3) state, street topology, and intent information. Simulations results reveal a significant finding: the use of street geometry information substantially enhances safety with minimal impact on overall efficiency. Interestingly, the results indicate that, while the use of street topology information is important in improving safety through conservative resolution manoeuvring, the addition of intent information does not provide critical improvements in achieving enhanced safety and efficiency in this specific urban airspace context.

Chapter 6 tackles the issue of over-optimisation in flight planning, which often leads to reduced robustness against uncertainties in urban air mobility systems. To address this challenge, the chapter proposes a CD&R framework designed to mitigate this issue while minimally affecting operational efficiency. This framework combines traffic flow capacity management with the conservative tactical deconfliction method developed in the previous chapter, aiming to enhance both safety and adaptability in uncertain conditions.

A comparative analysis of the proposed framework against two other approaches is performed: 4D trajectory planning and state-based CD&R. These comparisons are conducted through simulations of various urban airspace scenarios. The results indicate that the proposed framework significantly improves both safety and robustness in the face of uncertainties, with notable effectiveness in handling wind variations and departure delays. This outcome suggests that the new framework could offer a more resilient approach to managing the complexities of urban air traffic.

Chapter 7 serves as a comprehensive discussion and conclusion to the dissertation. The chapter provides a comparative analysis, situating the CD&R methods developed in this work within the context of existing literature in the field. Through this comparison, it identifies gaps in current knowledge and suggests promising directions for future research and development in urban air mobility systems. These include leveraging the airspace above street networks more effectively, striking an optimal balance between centralised and decentralised control systems, and developing a unified simulation platform specifically designed for U-space operations. The aim is to reduce the research fragmentation in this domain and enable the advancement towards the deployment of such operations.

SAMENVATTING

Stedelijke mobiliteit door de lucht (urban air mobility, UAM) wordt voorgesteld als een potentiële oplossing voor verstoppingen in het verkeer. Door gebruik te maken van luchtvoertuigen voor taken als pakketbezorging, openbaar vervoer en bewaking kan de druk op de traditionele transportinfrastructuur op de grond worden verlicht. Dit is vooral belangrijk door de opkomst van e-commerce en de toenemende vraag naar snelle en efficiënte bezorgmethoden. UAM heeft de potentie om een revolutie teweeg te brengen in het stedelijk vervoer, door sneller woon-werkverkeer mogelijk te maken en de bewakingsmogelijkheden te verbeteren voor een beter verkeersbeheer en een betere reactie op noodsituaties.

Het U-space concept, ontwikkeld door de Europese Unie, biedt een kader voor de veilige integratie van drones en kleine onbemande vliegtuigsystemen (sUAS) in het stedelijke luchtruim. Het richt zich op het vaststellen van diensten, regels en procedures om onbemande luchtvaartuigen effectief te beheren. Een belangrijk onderdeel van dit concept is Type Zu luchtruim, aangewezen voor stedelijke operaties met hoge dichtheid. Dit luchtruim vereist strikte regelgeving en veiligheidskritische diensten zoals dynamisch capaciteitsbeheer, conflictoplossing en continue monitoring om veilige en efficiënte U-space operaties te garanderen.

Conflictdetectie en -oplossing (CD&R) van het luchtverkeer is nodig om de veiligheid van dergelijke operaties te garanderen, en het stedelijk VLL-luchtruim biedt unieke uitdagingen in vergelijking met conventioneel luchtverkeersbeheer. Gebouwen en andere obstakels beperken de bewegingen van vliegtuigen, waardoor manoeuvreren en het vermijden van conflicten moeilijker wordt. Onvoorspelbare stedelijke windpatronen bemoeilijken de vluchtplanning en trajectvoorspelling nog meer. Deze factoren, gecombineerd met de inherente complexiteit van stedelijke omgevingen, vereisen de ontwikkeling van robuuste CD&R-algoritmen en -regels die specifiek zijn afgestemd op de uitdagingen van het VLL stedelijk luchtruim.

De belangrijkste onderzoeksdoelstelling van dit proefschrift is het identificeren en ontwikkelen van effectieve CD&R-algoritmen en -regels voor veilige en efficiënte operaties van onbemande luchtvaartuigen in stedelijk VLL-luchtruim. Dit omvat het evalueren van de beperkingen van bestaande CD&R-methoden, het ontwerpen van nieuwe algoritmen die de specifieke uitdagingen van stedelijke omgevingen aanpakken en het definiëren van duidelijke regels en procedures voor luchtvaartnavigatie en conflictoplossing.

Hoofdstuk 2 gaat in op de beperkingen van de huidige CD&R-methoden wanneer deze worden toegepast op het stedelijke VLL-luchtruim. Deze beperkte omgeving, die wordt gekenmerkt door vliegtuigen die lager dan 150 meter vliegen en zich moeten houden aan straatnetwerken vanwege obstructies van gebouwen, biedt unieke uitdagingen die bestaande methoden maar moeilijk effectief kunnen aanpakken. Het hoofdstuk onderzoekt specifieke problemen zoals verkeersmanagement op kruispunten, navigatie van niet-lineaire trajecten en de invloed van onvoorspelbare stedelijke windpatronen op vliegplannen.

Om deze uitdagingen te illustreren presenteert het hoofdstuk een studie die gebruik maakt van een gesimuleerd organisch stratennetwerk gebaseerd op Wenen. Deze simulatie dient als platform om het gedrag van vliegtuigen te analyseren en de invloed van een beperkt luchtruim op zowel de vluchtefficiëntie als de veiligheid te evalueren. Op basis van dit onderzoek wordt in het hoofdstuk geconcludeerd dat de huidige CD&R-methoden en ontwerpen van luchtruimstructuren aanzienlijk moeten worden verbeterd om adequaat te kunnen reageren op de specifieke uitdagingen van een beperkt stedelijk luchtruim.

Hoofdstuk 3 richt zich op het verbeteren van tactische CD&R methodes binnen de context van een gedecentraliseerd U-space luchtverkeersleidingssysteem, specifiek toegepast op een stedelijk luchtruim met een organische structuur. Het hoofdstuk stelt een aantal belangrijke verbeteringen voor om de unieke uitdagingen van deze omgeving het hoofd te overwinnen. Deze verbeteringen omvatten het minimalizeren van verticale bewegingen, het benutten van intentie-informatie voor effectievere conflictdetectie en -oplossing en het toestaan van koersgebaseerde manoeuvres in open luchtruimgebieden.

Om deze voorgestelde verbeteringen te valideren, presenteert het hoofdstuk simulatieresultaten die aantonen dat de veiligheid in het luchtruim aanzienlijk toeneemt door het gebruik van intentie-informatie en de implementatie van geschikte preventieprocedures. Verder onderstreept het hoofdstuk de potenties voor verdere verbetering van zowel de veiligheid als de efficiëntie door tactische scheidingsmodules te integreren met andere componenten van luchtverkeersbeheersystemen die zijn ontworpen voor het U-space.

Hoofdstuk 4 onderzoekt de optimale balans tussen gecentraliseerde en gedecentraliseerde CD&R-benaderingen binnen een hybride systeem dat is ontworpen voor het beperkte stedelijke VLL-luchtruim. Dit onderzoek is gericht op het bepalen van de vereiste mate van centralisatie voor effectieve CD&R-diensten voor U-space. In het hoofdstuk wordt een uitgebreid onderzoek gepresenteerd waarin verschillende niveaus van tactische en strategische CD&R worden gesimuleerd onder verschillende scenario's voor de verkeersvraag en onzekerheidsomstandigheden, waarbij de nadruk ligt op de effecten van wind en vertrekvertragingen.

De simulatieresultaten onthullen een belangrijk inzicht: strategische deconflictmethoden zijn zeer gevoelig voor externe factoren zoals wind en vertragingen. Het onderzoek toont echter aan dat deze kwetsbaarheid gedeeltelijk kan worden verminderd door de implementatie van tactische deconflictiemaatregelen. Op basis van deze bevindingen suggereert het hoofdstuk dat een groter gebruik van tactische CD&R de strategische deconflictmethoden zou kunnen vereenvoudigen, wat uiteindelijk leidt tot een betere compatibiliteit en samenwerking tussen deze twee modules in het luchtverkeersbeheersysteem voor de U-space.

Hoofdstuk 5 richt zich op de potentiële voordelen van het gebruiken van intentie-informatie in tactische CD&R-systemen voor beperkt stedelijk luchtruim. Intentie-informatie verwijst in deze context naar vliegtuigen die hun geplande trajecten op korte termijn bekendmaken. Het hoofdstuk bevat een vergelijkende analyse van drie verschillende CD&R-algoritmen, die elk gebruikmaken van verschillende niveaus van informatiebeschikbaarheid.

De studie onderzoekt algoritmen die gebruik maken van: 1) alleen informatie over de huidige situatie, 2) informatie over de huidige situatie en de topologie van de straat, en 3) informatie over de huidige situatie, topologie van de straat en de intentie van andere vliegtuigen. Simulatieresultaten onthullen een significante bevinding: het gebruik van straatgeometrie-informatie verbetert de veiligheid aanzienlijk met minimale gevolgen voor de algehele efficiëntie. Interessant genoeg geven de resultaten aan dat, terwijl het gebruik van informatie over de topologie van de straat belangrijk is voor het verbeteren van de veiligheid door middel van manoeuvreren met conservatieve resolutie, de toevoeging van intentie-informatie geen kritieke verbeteringen oplevert voor het bereiken van verbeterde veiligheid en efficiëntie in deze specifieke stedelijke luchtruimcontext.

Hoofdstuk 6 behandelt het probleem van overoptimalisatie in de vluchtplanning, wat vaak leidt tot verminderde robuustheid tegen onzekerheden in stedelijke luchtmobiliteitssystemen. Om dit probleem aan te pakken, wordt in dit hoofdstuk een kader voor CD&R voorgesteld dat is ontworpen om dit probleem te beperken terwijl de operationele efficiëntie minimaal wordt aangetast. Dit kader combineert capaciteitsbeheer van verkeersstromen met de conservatieve tactische deconflictmethode die in het vorige hoofdstuk is ontwikkeld, met als doel zowel de veiligheid als het aanpassingsvermogen onder onzekere omstandigheden te verbeteren.

Een vergelijkende analyse van het voorgestelde kader met twee andere benaderingen wordt uitgevoerd: 4D trajectplanning en toestandsgebaseerde CD&R. Deze vergelijkingen worden uitgevoerd door middel van simulaties van verschillende scenario's voor het stedelijk luchtruim. De resultaten geven aan dat het voorgestelde kader zowel de veiligheid als de robuustheid met betrekking tot onzekerheden aanzienlijk verbetert, met een opmerkelijke effectiviteit in het omgaan met windvariaties en vertrekvertragingen. Dit resultaat suggereert dat het nieuwe kader een veerkrachtigere aanpak kan bieden voor het beheren van de complexiteit van het stedelijk luchtverkeer.

Hoofdstuk 7 dient als een uitgebreide discussie en conclusie van het proefschrift. Het hoofdstuk biedt een vergelijkende analyse, waarin de CD&R-methoden die in dit werk zijn ontwikkeld, worden geplaatst in de context van bestaande literatuur op dit gebied. Door deze vergelijking worden gaten in de huidige kennis geïdentificeerd en veelbelovende richtingen voorgesteld voor toekomstig onderzoek en ontwikkeling in stedelijke luchtmobiliteitssystemen. Deze omvatten het effectiever benutten van het luchtruim boven straatnetwerken, het vinden van een optimale balans tussen gecentraliseerde en gedecentraliseerde regelsystemen en het ontwikkelen van een uniform simulatieplatform dat specifiek is ontworpen voor U-space operaties. Het doel is om de versnippering van het onderzoek op dit gebied te verminderen en de ontwikkeling van dergelijke operaties mogelijk te maken.

1

INTRODUCTION

Urban mobility is progressively becoming a great challenge as the level of urbanisation is globally increasing, leading to congestion. Many are thus looking towards very-low-level (VLL) urban airspace operations as a way to lower the pressure on existing land-based infrastructure. How suitable are current air traffic management methods for this new airspace environment? How should such operations be performed in a safe and efficient manner?

The dissertation at hand investigates and proposes an operational framework for conflict detection and resolution between aircraft within VLL airspace. This chapter provides an overview of current work in this domain, and presents the methodology and structure for the rest of this research project.

1.1. THE FUTURE OF URBAN AIRSPACE OPERATIONS

Urban air mobility is emerging as a potential contributor to alleviating congestion and improving the efficiency of cities. Current methods of transportation are often insufficient for dealing with the increasing level of urbanisation, and upgrading existing infrastructure can prove costly. The implementation of urban air operations could alleviate the pressure exerted on current urban mobility methods. The concept entails that small aerial vehicles can perform a wide variety of tasks currently undertaken by ground vehicles, adding another dimension to the transportation of goods and people. By enabling the automation of operations, it promises to improve the financial attractiveness and energy efficiency of urban mobility.

One of the largest prospective markets for urban air operations is parcel deliveries. The European E-Commerce Report [1] shows that the proportion of internet shoppers is on the rise within the European Union, with more types of products being sold using this medium every year. This is producing a rise in the demand for the delivery of goods, with alternative methods (i.e., electric bicycles) already being used to reduce congestion. Thus, the demand for parcel delivery using small unmanned aerial systems (sUAS) is predicted to reach the order of tens of thousands of daily missions in large urban areas [2, 3] by the year 2050.

Other applications for small and medium-sized aerial vehicles within urban environments are public and private transport [4], emergency medical operations [5], and surveillance missions [6]. With advances in electric aircraft technology [7, 8], the use of electric vertical take-off and landing vehicles (eVTOL) for taxi services in cities is being increasingly considered as a decongestion measure. Moreover, the use of drones for infrastructure inspection is a growing field [9], promising to reduce costs and improve the maintenance of ground-based transportation networks.

The growing range of potential applications indicates that the use of sUAS in urban environments will gain traction and increase with the continuing innovations in electronic component miniaturisation and battery technology. However, the predicted traffic volumes pose challenges for conventional air traffic management frameworks, in which human controllers must issue commands to aircraft. Within the European Union, the U-space operational framework is therefore being developed, with the aim of creating a set of regulatory and operational rules for the safe implementation of urban airspace operations.

In the U-space concept of operations developed through the CORUS project [10], urban airspace is designated as “Type Zu” airspace, as shown in Figure 1.1. This type of airspace seeks to enable high density operations. It will therefore be highly regulated and safety-critical mandatory services will have to be provided, such as dynamic capacity management, strategic and tactical conflict resolution, weather information, and permanent global monitoring.

Within Type Zu volumes, a large volume of aircraft operations in cities would occur in very-low-level (VLL) urban airspace, defined in the U-space concept of operations [11] as airspace below an altitude of 150 metres. One major challenge is that many cities around the world have high-density areas with building heights exceeding this level, some examples of which are presented in Figure 1.2. In such areas, it might be required that aircraft have to follow the existing street network to avoid collisions with buildings [12]. In literature, this kind of VLL urban airspace, within which aircraft can fly between buildings, is referred to as constrained airspace.

1.2. CONFLICT DETECTION AND RESOLUTION

One of the most safety-critical tasks within both conventional and U-space air traffic management is the timely detection and resolution of conflicting situations between aircraft or drones. To reduce the risk of collisions, aircraft must maintain a minimum separation distance between each other, called the protection zone (PZ). Conflicts are defined as situations with conditions that, if left unmitigated, lead to a breach of the protection zone, and called a loss of separation (LOS) or intrusion event. An example of such a situation is shown in Figure 1.3.

Conflict detection and resolution (CD&R) methods aim to detect and resolve conflicts in a procedural, rule-based manner through the use of evasive manoeuvres and route optimisation. These can generally be divided into two categories [13]: tactical CD&R methods, which are made to resolve conflicts

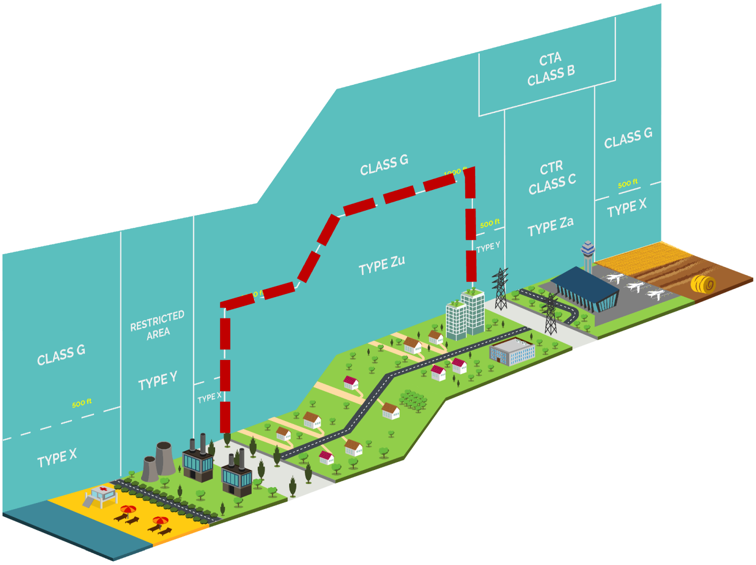

Figure 1.1: Airspace classification according to the U-space concept of operations, with highlighted Type Zu airspace. Image courtesy of the CORUS consortium [10].

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[1] Imagery ©2024 Google, NOAA, TerraMetrics, Landsat / Copernicus, Airbus, CNES / Airbus, Maxar Technologies, Sanborn, U.S. Geological Survey, USDA/FPAC/GEO, Map data ©2024 Google

reactively within a short time horizon, and strategic CD&R methods, which act on a longer timescale, and seek to optimise entire flight plans to avoid conflicts in the long term.

Tactical conflict detection and resolution

Tactical conflict detection and resolution (CD&R) algorithms for air traffic control (ATC) environments have been extensively studied within the aviation domain [14]. Such algorithms are hypothesised to increase airspace capacity while maintaining a high level of safety [15], but have faced regulatory and practical difficulties in their path to large-scale implementation within conventional aviation ATC systems [16]. However, with the emergence of urban airspace operations, the use of automated tactical CD&R algorithms will be necessary to

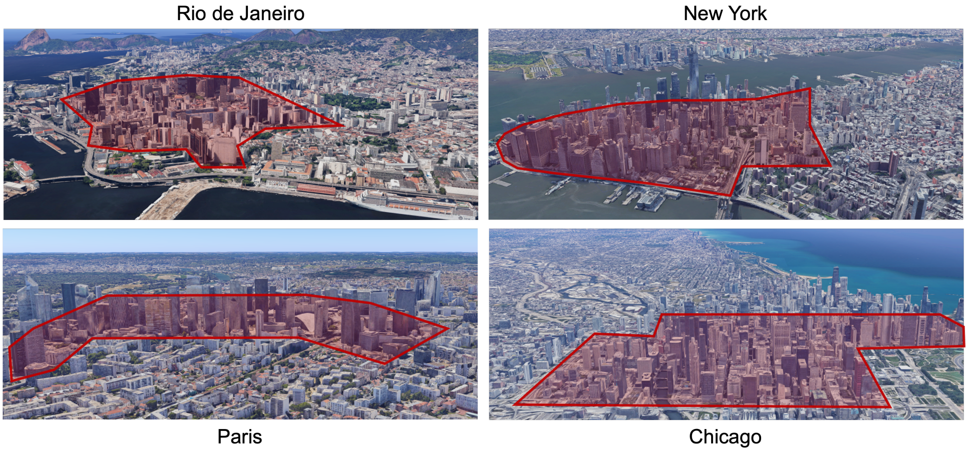

Figure 1.2: Examples of large cities with highlighted high density areas.[1]

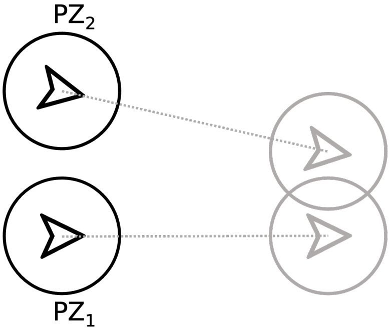

Figure 1.3: Example conflict between two aircraft, with a predicted protection zone (PZ) breach.

ensure safety in such high density traffic situations.

One of the most investigated category of conflict detection methods is state-based [17], presented in Figure 1.4. With state-based methods, conflicts are predicted by linearly extrapolating the current state (i.e., position, heading, velocity) of the aircraft and determining whether the distance at the closest point of approach (CPA) is predicted to be smaller than the minimum separation requirement. Then, a resolution manoeuvre is chosen such that this distance is increased, thus mitigating the conflict.

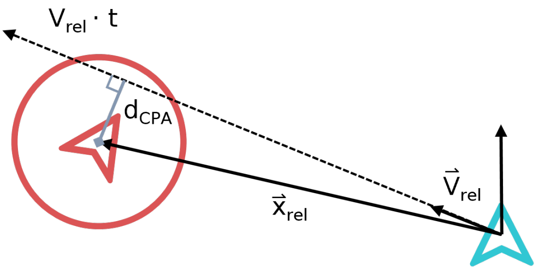

Figure 1.4: State-based conflict detection: the relative position (x_{rel}) and velocity (v_{rel}) between two aircraft is used to find the distance at the closest point of approach (d_{CPA}).

Strategic conflict detection and resolution

Strategic conflict detection and resolution methods aim to resolve conflicts within a larger time horizon than tactical methods, often through the use of global optimisation algorithms [13]. Such methods are generally centralised, with deconfliction being achieved through the use of 4D route planning.

It is generally accepted that strategic deconfliction is an important component of the U-space framework [11], with extensive research focusing on the development of such methods [18–20]. However, the adaptation and implementation of such methods within VLL urban airspace, both constrained and open, still needs to investigated, as the complexity of the environment hinders long-term prediction accuracy.

1.3. U-SPACE CD&R SYSTEM ARCHITECTURE

According to the latest U-space Concept of Operations as of the writing of this work [21], the conflict detection and resolution process is performed according to the following phases:

1. **Pre-departure strategic planning phase**
   Before the departure time of a mission, the operator must submit a flight plan to the local air traffic management authority. The flight plan contains

information such as the origin and intended destination, preferred route, and aircraft type. Then, in function of other in-flight traffic or waiting to depart, the flight plan can undergo modifications for optimisation and deconfliction purposes.

2. **Pre-tactical dynamic capacity management phase**
   During the cruise phase, the dynamic capacity management module can react to unexpected traffic developments, such as the appearance of bottlenecks or airspace closures. Aircraft can then be strategically rerouted to avoid the problematic areas and maintain airspace capacity efficiency.

3. **Tactical conflict detection and resolution phase**
   The tactical CD&R module detects potential conflicts within a short look-ahead time horizon and issues manoeuvres to aircraft such that the minimum separation threshold is not breached.

One of the ongoing areas of research is determining the best the degree of centralisation of the aforementioned modules. In classical aviation, both the strategic and tactical phases are handled by a central authority (air traffic control), with only limited decentralisation such as the traffic collision avoidance system (TCAS), which supersedes the instructions of air traffic controllers.

As U-space operations are distinct in many ways from classical aviation, with considerably higher expected traffic density, a decentralisation of the CD&R services has been considered. Research preceding this work has investigated the decentralisation of tactical conflict detection and resolution in both conventional aviation and U-space operations [12, 22–25], as well as the required degree of centralisation and integration with strategic planning. This question is one of the main focuses of the dissertation project at hand.

1.4. CHALLENGES OF CD&R FOR URBAN AIR OPERATIONS

The complexity and restrictiveness of constrained VLL urban airspace poses major challenges for air traffic management systems. First, as the trajectories that the aircraft can take are restricted to airspace above the existing street network, the capacity and traffic flow are reduced and more difficult to manage, leading to a lower level of safety. Moreover, as aircraft need to perform a multitude of manoeuvres to navigate such airspace, the short and long-term predictability of flight plans is affected.

Another major consideration that needs to be accounted for is the higher impact of weather on urban airspace operations. Urban wind patterns are less predictable due to the presence of structures with a high variability in physical characteristics and dimensions. Thus, the emergence of difficult to predict hyper-local wind effects can disrupt flight plans and disrupt the flight plans of aircraft.

It is thus expected that existing CD&R methods might not perform well within constrained urban airspace. The paths that aircraft need to take are unpredictable and require frequent changes in state (i.e., heading, velocity) to navigate, thus affecting the performance of state-based CD&R algorithms. Furthermore, environmental factors such as wind (e.g., crosswind, tailwind, and headwind) can dramatically alter travel times, thus also potentially affecting strategic planning methods by inducing deviations in the flight plans. Thus, the algorithms and methods used to perform tactical and strategic deconfliction might need to be adapted to the unique characteristics and challenges that VLL constrained airspace poses.

1.5. RESEARCH OBJECTIVES

The research presented in this dissertation seeks to investigate the requirements for the conflict detection and resolution component of an urban airspace air traffic management operational framework. The main question of this research is the following:

Main Research Question

What strategic and tactical conflict resolution algorithms and rules enable the safe operation of small aircraft in very-low-level urban airspace?

The dissertation is structured such that each chapter contributes to answering the main research question. The remainder of this section presents the objective of each.

Chapter 2 investigates the limitations of current conflict detection and resolution methods when simulated within a constrained urban airspace environment. While it is relatively clear that state-based methods are probably not suitable for such airspace, testing them in this manner helps with understanding the reasons for it. Thus, the following research sub-question can be formulated:

Research question: Chapter 2

What are the limitations of current ATM methods when applied in VLL urban airspace?

Chapter 3 explores different methods through which tactical CD&R can be improved in constrained VLL urban airspace. It explores the use of intent, the impact of navigation rules on airspace safety, and the use of less restrictive algorithms where possible. It builds upon the knowledge of the previous chapter, but also the methodology and results of the Metropolis 2 project [26], which sought to determine the best degree of centralisation of an air traffic management system required to ensure the safety and efficiency of U-space operations in

VLL constrained airspace. The guiding research question of this chapter is the following:

Research question: Chapter 3

How can current conflict resolution algorithms be improved to increase the safety of operations in VLL urban airspace?

Strategic conflict detection and resolution is an important part of future U-space operations, as it enables better global planning against traffic bottlenecks and conflicting situations. It is often implemented as a central authority that processes and approves flight plans globally [27].

On the other hand, tactical CD&R occurs on a local level, when a conflict is predicted to occur within a short look-ahead time horizon. Such manoeuvres can thus induce a deviation from the strategically deconflicted flight plan, potentially leading to a snowball effect as more tactical manoeuvres are required in the future. Thus, the question of what the best balance between these systems arises. Chapter 4 investigates the degree of centralisation required for a hybrid CD&R system by quantifying the magnitude of the contribution of strategic and tactical conflict resolution to airspace safety. The research question for this part of the project is the following:

Research question: Chapter 4

How does the degree of centralisation of air traffic control in VLL urban airspace affect operational safety and efficiency?

Chapter 5 builds upon the work presented in Chapter 3 by further diving into the use of short-term intent information for tactical CD&R. Research for classical aviation has found the use of intent to be unnecessary. However, constrained VLL airspace is a different environment, in which the navigational restrictiveness compared to open airspace plays a major role in the predictability and usefulness of intent information. Thus, the following research question is investigated:

Research question: Chapter 5

What are the benefits of using short-term intent information on the safety and efficiency of VLL urban airspace operations?

The research in the previous chapters showcases the importance of accounting for the effect of uncertainties in strategic and tactical conflict detection and resolution systems. Chapter 6 thus presents the work performed to augment CD&R systems to better deal with operational and environmental uncertainties by increasing the robustness of the flight plans to disturbances induced by tactical resolution manoeuvres and the presence of wind. This investigation is guided by the following research question:

Research question: Chapter 6

How can strategic and tactical conflict resolution methods be adapted for resilience and robustness against environmental and operational uncertainties?

1.6. GENERAL METHODOLOGY

As of the time of writing, U-space operations have not yet been launched or implemented within VLL urban constrained airspace. Thus, the research presented in this work relies on fast-time simulations for designing and testing air traffic management rules and concepts for U-space operations in VLL airspace. For this purpose, the BlueSky Open-source Air Traffic Simulator [28] was augmented with the capability to simulate aircraft in constrained urban environments.

In general, each part of the research project follows these steps:

1. A new method is developed to tackle operational issues within the CD&R process of U-space operations.
2. The method is implemented as a plugin for the simulation software.
3. A constrained urban airspace area is selected for study.
4. Air traffic scenarios based on future demand predictions are generated.
5. The safety and efficiency performance of the novel method is tested using the generated traffic scenarios.
6. The results of the simulations are used to further improve CD&R for U-space operations.

1.7. GUIDE TO THE READER

Each chapter of this dissertation is based on published work, and can be read as a stand-alone piece. However, they are arranged such that they provide context for the continuity of the work performed during the span of the doctoral project. Thus, the reader is encouraged to initially read the abstracts of all chapters for a more in-depth understanding of the progression of this work. Figure 1.5 presents the outline of this thesis.

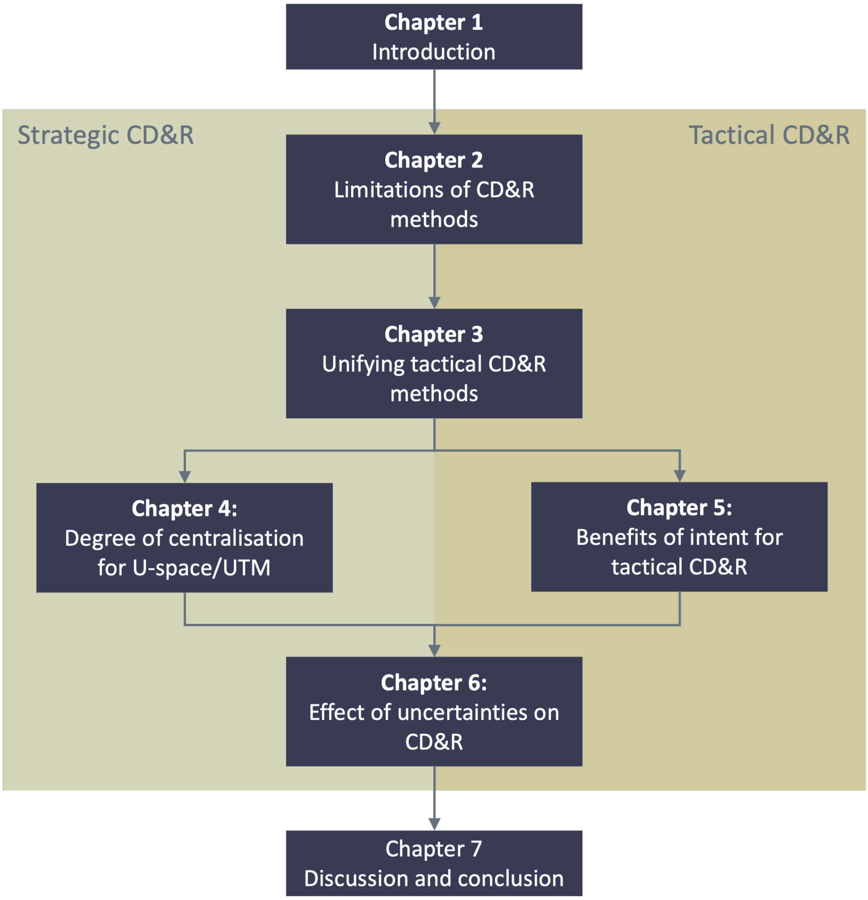

Figure 1.5: Outline of this thesis, with chapters divided into two categories: focused on tactical CD&R methods, or focused on a hybrid CD&R ATM framework.

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2

LIMITATIONS OF CURRENT CD&R METHODS IN VLL URBAN AIRSPACE

Urban Air Mobility (UAM) operations have the potential to decrease congestion in densely populated urban areas. The prevailing assumption within literature is that these will predominantly occur above the tallest structure. However, increasingly many cities around the world have areas with very high buildings, where this strategy might prove inefficient. In such areas, aircraft would be constrained to flying above the existing street network.

The work presented in this chapter investigates the limitations of current tactical conflict detection and resolution (CD&R) methods when applied in constrained urban airspace. It serves as motivation for the rest of the work presented in this dissertation. Thus, cover to cover readers are encouraged to go through this chapter in its entirety.

This chapter is based on the following publications:

- C. Badea, A. Morfin Veytia, M. Ribeiro, M. Doole, J. Ellerbroek and J. Hoekstra. 'Limitations of Conflict Prevention and Resolution in Constrained Very Low-Level Urban Airspace'. In: *11th SESAR Innovation Days*. 2021
- A. Morfin Veytia, C. A. Badea, J. Ellerbroek, J. Hoekstra, N. Patrinopoulou, I. Daramouskas, V. Lappas, V. Kostopoulos, P. Menendez, P. Alonso, J. Rodrigo, V. Terrazas, D. Bereziat, A. Vidosavljevic and L. Sedov. 'Metropolis II: Benefits of Centralised Separation Management in High-Density Urban Airspace'. In: *12th SESAR Innovation Days*. 2022

ABSTRACT

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

2.1. INTRODUCTION

Urban air mobility is attracting the interest of commercial operators and investors as a potential decongesting solution for high-density cities. One industry that has the potential to greatly benefit from the introduction of unmanned aerial systems (UAS) is the parcel delivery domain. A recent study predicted the demand for urban drone-enabled parcel delivery for Germany and the United Kingdom to be in the order of several billion missions per year [3]. Therefore, the further development of concepts of operations for very low level urban airspace is needed.

Several proposed urban airspace concepts of operations suggest that drones should fly above buildings as much as possible [4–6]. However, this might not always be desirable (noise and privacy issues in formerly undisturbed areas) or even feasible in most cities (e.g., in cities with large high-rise areas such as New York). In such cases, aircraft would be constrained to flying above the existing street network. This introduces several challenges for conflict prevention and resolution not present in open airspace. Among these are the restrictions of heading manoeuvres, non-linear trajectories, and traffic flow intersections.

There have been studies that focused on constrained airspace [7–9]. However, these largely studied orthogonal street networks. In comparison, organically developed street networks entail traffic patterns and situations that result in a high degree of uncertainty and variation in the required navigation manoeuvres, such as intersections with an odd number of entry and exit points, which create merging and diverging traffic flows. This area of urban air navigation requires more research.

In this chapter, an organic street network is investigated to get a broader picture of the limitations imposed by a constrained environment, with emphasis on the issues with current airspace structure design and conflict resolution techniques. Using an open-source Air Traffic Control Simulator[10], fast-time simulations of a highly constrained urban environment are performed to analyse the behaviour of aircraft and determine the influence of operating in constrained airspace on flight efficiency and safety. Recommendations for future research in the urban airspace structure and conflict resolution domains are made based on the results.

2.2. MOTIVATION

We identify four main challenges that are unique to constrained airspace in comparison with other airspace types: (i) the challenge of coping with traffic at intersections, (ii) the imposed directions of travel by the street network, (iii) the limitations of state-based conflict detection, and (iv) the turn dynamics. The following paragraphs will go more into detail about each challenge. Previous works [8, 9] in constrained airspace have dealt with some of these challenges. However, they assumed a maximum number of traffic flows entering/exiting each intersection, and a fixed turning speed/radius respecting the distance between buildings at all intersections. The work at hand does not make these assumptions.

While there are cities around the globe that do have parts with a grid-like structure (e.g., New York, Barcelona), many others have a more organic infrastructure sprawl, especially in Europe (e.g., Amsterdam, Rome, Vienna). This produces a larger variation in the topological properties of intersections. Fig. 2.1 shows examples of these intersections in Vienna. The investigation of these kinds of intersections helps in analysing the limitations of currently proposed conflict prevention and resolution methods in constrained airspace.

The Metropolis project [6] proposed a layered airspace design for lowering

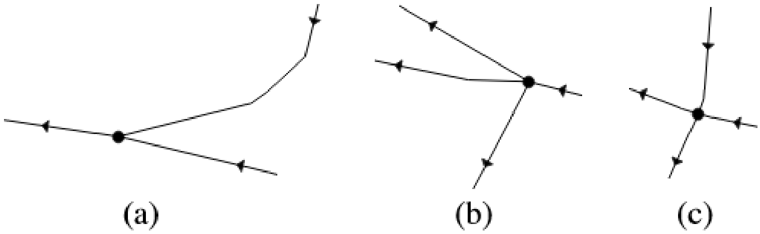


Figure 2.1: Examples of intersections in the city of Vienna: (a) merging intersection, (b) diverging intersection, and (c) classical four-way intersection.

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

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

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

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

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

2.3. METHODS

2.3.1. Iterative speed-based conflict resolution

As previously described, due to the assumption that aircraft will only use streets to navigate dense urban airspace, aircraft are restricted in heading-based movement. Thus, most conventional conflict resolution methods are not appropriate in this situation, as most make use of heading manoeuvres to solve conflicts [11].

In this chapter, an iterative speed-based conflict resolution algorithm is used, based on principles used in [12–14]. The latter makes use of trimmed velocity obstacles, as shown in Fig. 2.2, as they extend the available solution space for conflict resolution. Thus, solutions with a time to the closest point of approach that is past the conflict look-ahead time are discarded. The resulting minimum relative velocity change solution **u** is then projected on the velocity vectors of each aircraft, resulting in a speed-only velocity vector change. As the velocity change is only a projection of **u**, it is not a guaranteed solution. However, a viable solution is found through further iterations, moving the relative velocity outside the velocity obstacle.

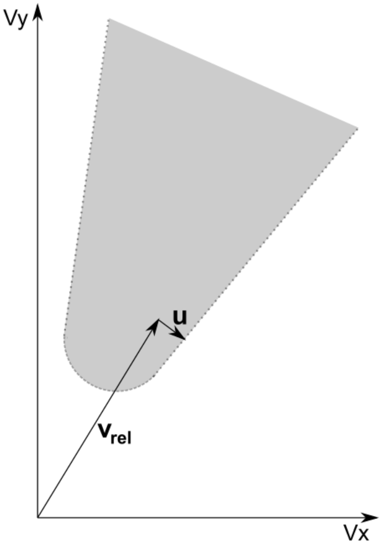


Figure 2.2: Trimmed velocity obstacle in relative velocity ($\mathbf{v}_{\mathrm{rel}}$) space, with minimum velocity change solution (**u**).

2.3.2. Conflict prevention by airspace structure design

The Metropolis project [6] showed that an effective airspace structure can have beneficial effects on safety and capacity, by reducing conflict probability [15]. With the Layers concept, the available airspace is divided into several cruising layers (segmentation), in which the allowable heading range is limited for each layer (alignment). These two policies were then formalised as geovectoring [16]. Two recent studies applied this strategy to a constrained airspace [8, 9], but only for largely orthogonal street networks with low bearing entropy values of 2.65 and 1.63 (a value of 1 means that the street network is perfectly orthogonal), placing them in the top 30% percentile of organisation from the cities ranked in [17]. The street network used in this work is not orthogonal and has a bearing entropy of 3.10, ranking in the lower 40% percentile.

Two airspace structuring concepts were tested within the chosen street network. The first is a simple structure where all drones are restricted to an altitude 25 ft above the minimum flight level. The second structure, presented in Fig. 2.3, is similar to those from [8] and [9]. The difference is that it is difficult to ensure vertical segregation of North/South and East/West streets. Fig.2.1 (a) shows how a street with an initial South bearing progressively bears West. Therefore, individual streets are first assigned to a group of continuous streets and then allocated a cruising height based on the overall bearing of the group. For this reason, North and South bearing streets generally contain the cruising layer at 25 ft, while East and West bearing streets have it at 75 ft. Both of them share a turn layer at 50 ft.

The speed limit at cruising layers for both concepts is 30 kts. In the event of a turn larger than 20°, aircraft must decelerate to 10 kts in both concepts, the same method used in [8] and [9]. All heading turns are performed in the turn layer, which is expected to be (mostly) depleted of traffic. Aircraft then move to a cruising layer once the turn is finished.

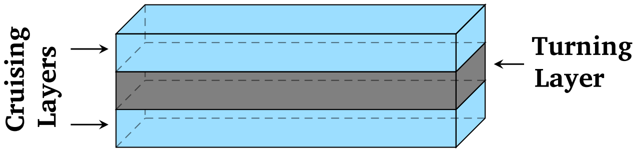


Figure 2.3: View of the airspace structure with vertical segmentation: two cruising layers with a turning layer in between. Airspace structure without vertical segmentation contains only one cruising layer.

2.4. EXPERIMENTAL DESIGN AND PROCEDURE

2.4.1. Simulation software

Experimental results were obtained through fast-time simulations using BlueSky, an open air traffic simulator[10]. This tool has an Airborne Separation Assurance System (ASAS) to which different conflict detection and resolution (CD&R) implementations can be added; therefore, allowing for all CD&R to be tested under the same scenarios and conditions.

2.4.2. Aircraft models

Only certain types of aircraft will likely be able to operate in constrained airspace. Aircraft with hovering capabilities are more suitable for navigating constrained urban environments. Thus, a DJI Matrice 600 Pro hexacopter drone model was used for the simulations. Specifications are shown in Table 2.1.

2.4.3. Independent variables

The experiment uses three independent variables:

1. **Traffic density**: Low, medium, and high traffic densities are employed. The traffic levels were selected based on [8], and are shown in Table 2.2.

Table 2.1: DJI Matrice 600 model specifications.

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

Table 2.2: Number of aircraft concurrently in-flight for each traffic density.

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

2. **Conflict resolution**: The iterative speed-based conflict resolution (CR) method is compared with a baseline situation with no CR.

3. **Conflict prevention by airspace structure**: A layered airspace is compared with a baseline situation where all aircraft travel at the same altitude.

Thus, the experiment is performed on 12 flight conditions, as presented in Table 2.3. Each condition was simulated using 10 mission scenarios, each approximately one hour in length, resulting in a total of 120 simulations.

Table 2.3: Experiment conditions. **None** corresponds to a situation without conflict resolution where aircraft all travel at the same altitude.

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

2.4.4. Conflict prevention: urban airspace structure

A 4.4 km^2 area in the city of Vienna was selected for the experiment, due to the presence of a combination of grid-like and organic street patterns. In the simulation, the city layout is represented as a multi-directed graph, with streets and intersections represented by edges and nodes, respectively. Street data was obtained from OpenStreetMap (OSM) using OSMnx [18]. Simplifications were made to the street graph for ease-of-use. These are (i) removing slip roads, (ii) removing dead-ends, (iii) merging parallel roads in proximity, (iv) removing other redundant connections between nodes. Moreover, all roads were forced to be one-way, as that has been shown to reduce the conflict probability [8].

In one-way, grid-like street networks, deciding the directionality and vertical segmentation of the streets is trivial [8]. However, this is not the case for organic street networks, as intersection topology may vary, as shown in Fig. 2.1. Although the street network in Fig. 2.4 contains some grid-like attributes vertically, the strategy for vertical segmentation and directionality is not immediately discernible. This is handled with the following steps:

Step 1: Extract the natural continuity using the Continuity in Street Networks (COINS) algorithm [19]. COINS groups all streets into different strokes to ensure continuity over intersections. For example, in Fig 2.1 (a) the street in the top right merges with the one in the bottom right. However, it is not immediately clear which street continues left after the intersection. Here, COINS calculates all interior angles at the intersection and group the two streets with the angle closest to $180°$. Note that groups with $90°$ turns were split manually.

Step 2: Calculate the bearing of each group from start to end node, dividing them into two separate groups: North/South and East/West bound. This enables the use of the vertical segmentation method portrayed in Fig. 2.3 to the street layout in Fig. 2.4.

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

The genetic algorithm is initialised with a random distribution of stroke directions and searches for a directionality combination that yields the lowest cost. The latter is the distance it takes to get from all intersections to all other intersections. If a path cannot be found, a 100 km penalty is added to the cost. The selected directionality of strokes is illustrated with the arrows in Fig. 2.4. It was applied to both the structures with and without vertical segmentation.

2.4.5. State-based conflict detection

State-based conflict detection was employed to identify potential minimum separation violations. Detection is achieved by linearly extrapolating the current position of the drone along its velocity vector, within a look-ahead time. The

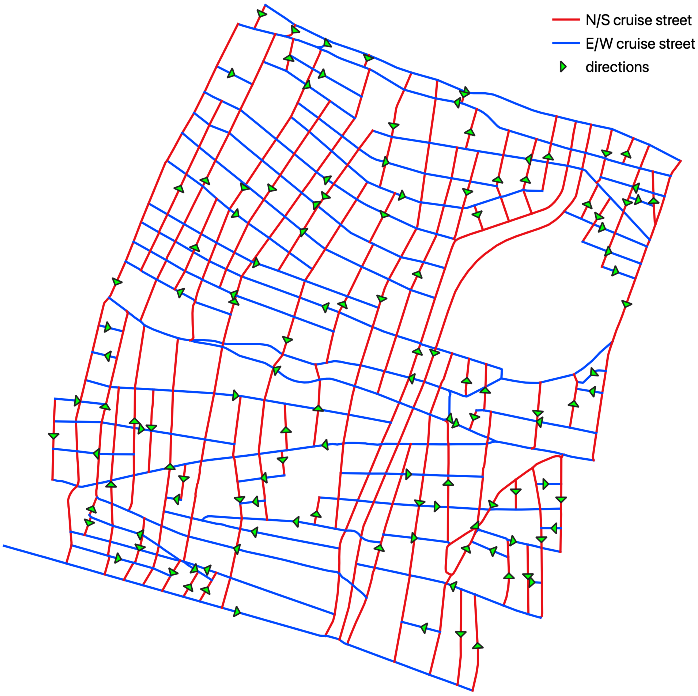


Figure 2.4: Street layout of the experimental area with traffic flow directions.

vertical and horizontal separation margins are set to 25 ft and 105 ft, respectively. The values are obtained from the signal-in-space performance requirements from Table 3.7.2.4-1 of [20]. To limit the number of false-positive detection events (detected conflicts that cannot result in an intrusion due to airspace topology), a look-ahead time of $10s$ was chosen, as it means that drones only need to look-ahead about $150m$ when cruising.

2.4.6. Missions

Building data from the government of Vienna [21] was processed to create a database of geofences. Routes are pre-planned with the shortest path algorithm from [18] to follow the street-network and avoid collision with geofences.

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

2.4.7. Simulation time

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

2.4.8. Dependent measures

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

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

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

2.5. EXPERIMENTAL RESULTS

The following chapter presents the experimental results. Figs. 2.5, 2.7, 2.8, 2.9 and 2.10 show box-plot representations. Each of these contains three subplots, one for each traffic density. The conflict prevention and resolution method is shown on the horizontal axis (**N**, **A**, **CR**, **CRA**, see Table 2.2), and the dependent variable of interest is presented on the vertical axis.

Fig. 2.6 shows the conflict pair heat-map of each conflict prevention and resolution method ((**N**, **A**, **CR**, **CRA**). Note that aggregated values for the three traffic densities are shown.

2.5.1. Safety

Fig. 2.5 shows that the number of pairwise conflicts increase for all conditions as the traffic density increases. This was expected because higher density leads to a higher chance that a conflict will be encountered. Additionally, it was seen that vertical segmentation reduces the number of conflicts (**A**, **CRA**) compared to the case without segmentation (**N**, **CR**). This was also expected, as the same traffic is split over different layers, and thus the traffic density per layer is decreased. Furthermore, due to the iterative nature of the conflict resolution algorithm, the number of detected conflicts is substantially higher in the **CR** condition. If, as a result of following the street below, one of the involved aircraft needs to adjust their heading, the conflict solution might become invalid. As a result, the same conflict pair can be counted more than once for the conflict metric.

This is also the case for back-to-back conflicts. The solution found by the CR method (see Fig. 2.2) guarantees that no conflict will occur within the lookahead time, but not necessarily that the conflict is resolved permanently. The conflict may just have been postponed to after the lookahead time. Due to this, back-to-back conflicts require iteration to reach the conflict solving solution (velocity matching), and thus may be counted more than once. However, a notable observation is that the number of conflicts in the **A** and **CRA** cases are similar, which points towards the fact that many of the conflicts detected in the **CRA** condition were prevented through the use of layered airspace.

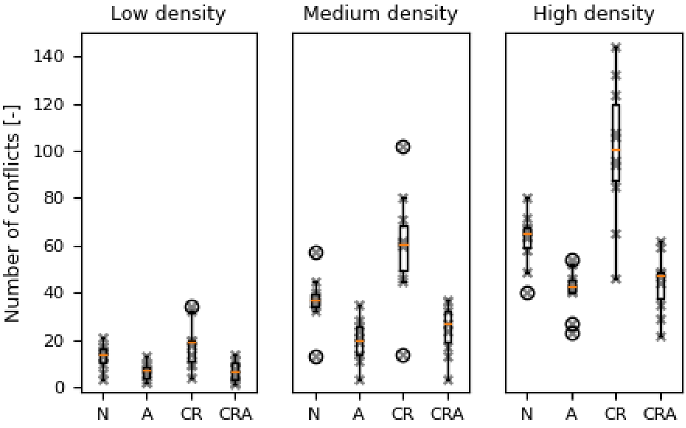
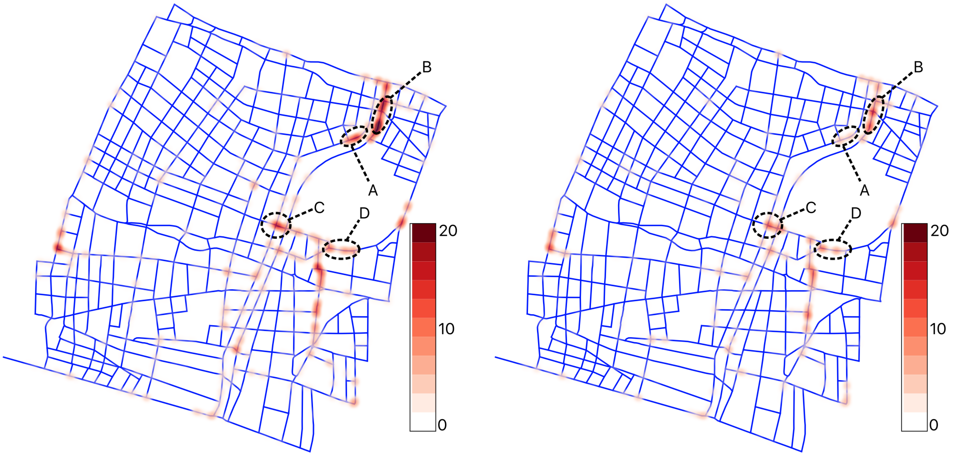


Figure 2.5: Number of conflicts for each traffic density, conflict prevention, and resolution method. × = measurement point, ∘ = outlier.

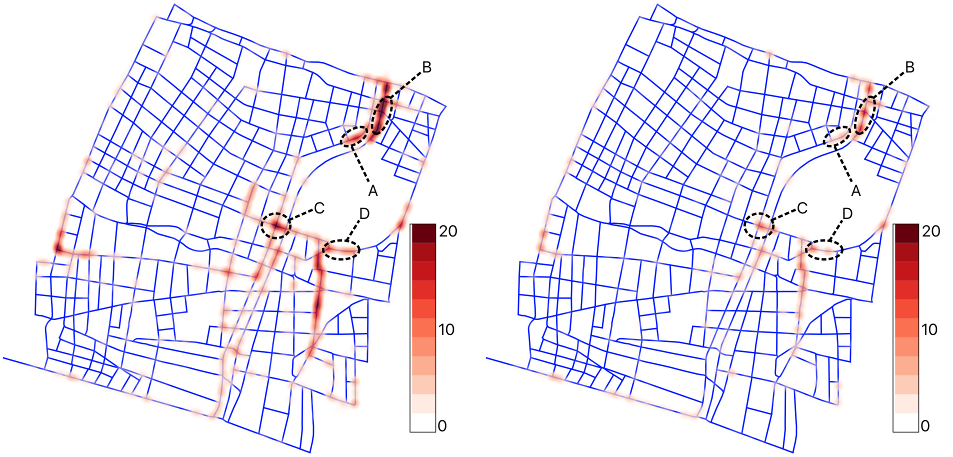
More observations can be made when analysing the locations of the conflict pairs within the street network. Fig. 2.6 shows the heat map of conflict pair locations in the street network, with clusters of interests marked out. The trends observed in Fig. 2.5 are visible on the map. Clusters A and B are in false-positive conflicts with each other because the state-based conflict detection method linearly extrapolates the location of all drones with a 10 second look-ahead time. Thus, aircraft on these two parallel streets appear to be in conflict, even though they will not intersect if they follow their planned paths. When comparing the intensity of clusters A and B when no vertical layering is applied in the airspace

(Figs. 2.6a and 2.6c) with the opposite case (Figs. 2.6b and 2.6d), it can be observed that the vertical airspace structure helped mitigate the false-positive conflicts. This is because aircraft in the area of cluster B had a higher chance of being in a different cruise or turn layer than aircraft in the area of cluster A. While this solution is specific to this topology, it indicates that such situations can occur in highly organic street networks and can be mitigated through airspace design.



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

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



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

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

Figure 2.6: Heat map of number of conflict pairs.

Cluster C shows conflicts at an intersection. Again, comparing situations with vertical airspace structure (Figs. 2.6a and 2.6c) to cases without it (Figs. 2.6b and 2.6d), shows that vertical segmentation reduces the number of conflict pairs at this intersection. However, it does not avoid all conflicts; when a North/South aircraft and an East/West aircraft turn at this intersection, they will both ascend or descend to the same layer, leading to a conflict.

Cluster D shows aircraft in conflict at a diverging intersection. The heat maps do not show a great difference in the number of conflicts at that location between experimental conditions. This is because, as shown in Fig. 2.4, both streets that meet at this intersection are in the E/W layer category, thus at the same height. Due to the turning rules, drones coming from the right must move to a turning layer to continue in any of the streets at that intersection. Therefore, false conflicts are still detected ahead of the turning manoeuvre even if aircraft continue along different streets after passing the intersection.

However, looking at conflicts does not give a complete picture of the situation. Although **CR** and **CRA** create more conflicts than their counterparts in **N** and **A**, they prevent more losses of separation overall (Fig. 2.7). This gap becomes more evident as the traffic density decreases. When looking at **CR** and **CRA**, it is seen that vertical segmentation had minimal effect on the number of losses of separation at high and low densities. This implies that most conflicts that were not solved by the conflict resolution algorithm occurred when aircraft were turning. If airspace is not layered, aircraft that slow down to turn will produce back-to-back conflicts with aircraft coming from behind. When aircraft are in the same layer, losses of separation are more likely to occur. As the conflict resolution algorithm did not account for turn manoeuvring and back-to-back conflicts, these situations were not solved.

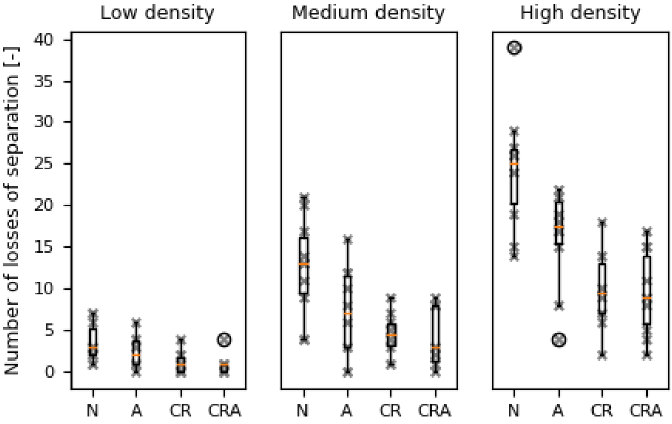


Figure 2.7: Number of losses of separation for each traffic density, conflict prevention, and resolution method. × = measurement point, ∘ = outlier.

The number of geofence breaches is another measure of safety, but it is also a measure of the compatibility of the used conflict resolution methods with the task of following a pre-determined path through constrained airspace. Due to the lack of obstacle avoidance measures, breaches can occur when two aircraft select resolution velocities such that the conflict between them is solved, but do not account for the reduction in velocity needed in case a sharp turn follows. Since drones are travelling in constrained airspace, the maximum turn angle that does not result in a geofence breach varies according to the layout of the streets. In Fig. 2.8, it is seen that performing no conflict resolution (**N**, **A**) led to fewer geofence breaches compared to conditions with conflict resolution enabled (**CR**, **CRA**). There is no difference when comparing between **N** and **A** because the horizontal speed in both is similar, thus the number of geofence breaches is equal.

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

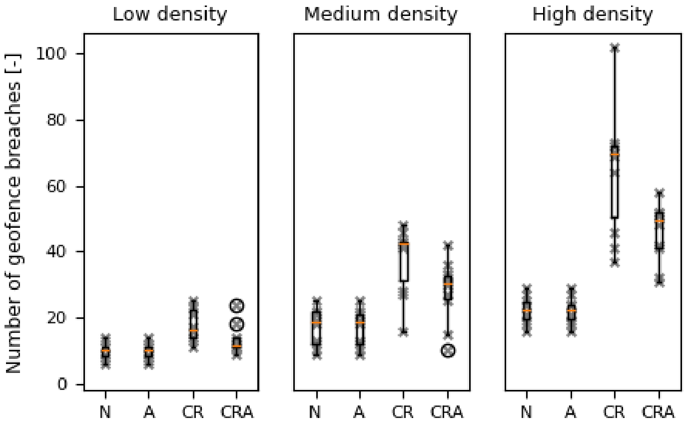


Figure 2.8: Number of geofence breaches for each traffic density, conflict prevention, and resolution method.

2.5.2. Efficiency

The average travelled distance (Fig. 2.9) is a measure of efficiency. At all traffic densities, it is clear that the conditions with vertical segmentation (**A**, **CRA**) travel more distance than those without vertical segmentation (**N**, **CR**). This was expected due to the vertical travel component in this airspace structure. Although a speed-only resolution method is applied, conflict resolution also produces an increase in flight distance. When correlated to the recorded number of geofence breaches (Fig. 2.8), the explanation for this is that aircraft in conflict were forced to maintain their conflict resolving speeds until the conflict was resolved, or delayed past the look-ahead time, thus often overshooting turns where a turn speed of 10 kts would have normally been enforced.

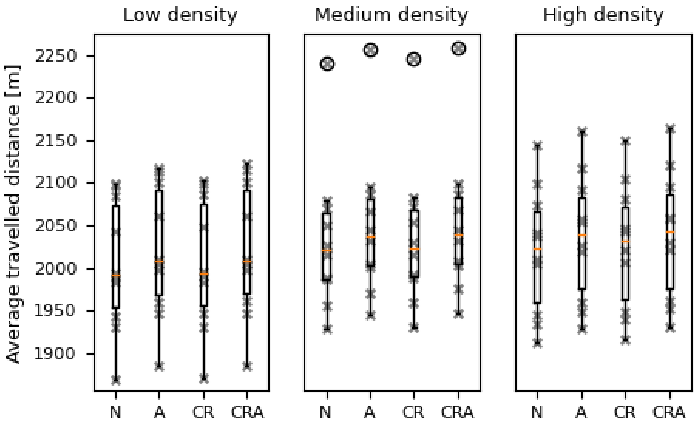


Figure 2.9: Average flight distance per aircraft travelled for each traffic density, conflict prevention, and resolution method.

The second considered efficiency metric is the average flight time, presented in Fig. 2.10 for each concept, and each traffic density condition. It can be seen that in the conditions without conflict resolution (**N**, **A**), the travel time is not affected by the vertical airspace structure. This is because the horizontal speed of the drones (turn and cruise speed) is the same in both cases, and is not influenced by the presence of vertical manoeuvring. Employing the use of conflict resolution increased flight time, as aircraft slow down to solve conflicts. This difference increases as the traffic density increases: more aircraft result in more conflicts. However, adding a layered airspace structure reduces the number of conflicts.

2.6. DISCUSSION

The results illustrate several areas where the current knowledge in constrained airspace is lacking and requires further development. Firstly, state-based conflict detection that linearly extrapolates the state of the aircraft for a certain look-ahead time is unsuitable in constrained airspace without adaptations, as it results in false-positive conflicts. For example, when looking at clusters A and B in Fig. 2.6, the streets do not intersect. Thus, a conflict should not occur between aircraft following them. Previous research [8, 9] with orthogonal street networks

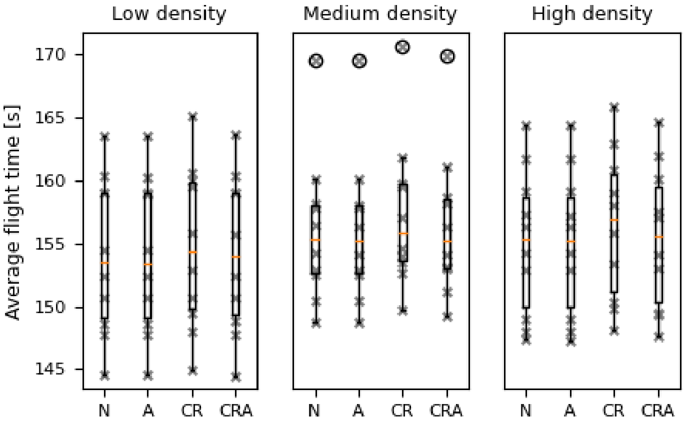


Figure 2.10: Average mission flight time per aircraft for each traffic density and conflict prevention and resolution method.

also has similar issues when linearly extrapolating. Even though it aligns with the street orientation during cruising, it does not work when performing a turn or when changing altitudes. This illustrates the need for an improved way to implement conflict detection (e.g., by using intent information or predictive airborne separation assurance systems [12]) and conflict recovery (i.e., recovery should not produce more immediate conflicts). Velocity obstacles can also be used to avoid turning into a conflict, thus preventing otherwise missed conflicts due to the lack of exchanging intent information [22].

Another knowledge gap is highlighted by horizontal traffic merging and diverging situations. This is seen in cluster D of Figs. 2.6b and 2.6d. In previous research [8, 9], the design of the vertical airspace layer structure was straightforward. In orthogonal networks the N/S and E/W (or similar divisions), layers are vertically segmented and cruising aircraft will not intersect. However, due to the organic nature of the street network in cluster D, this is impossible to avoid. As seen in Fig. 2.4, there are several intersections where streets of the same layer heights would conflict when using a cardinal division of street heights. It is not efficient to add unique layer heights for these streets, as that would quickly saturate the airspace.

From the results, it was not evident that the use of vertical segmentation led to fewer losses of separation when also having conflict resolution (Fig. 2.7). However, this may be dependent on the airspace structure used in this study, and thus requires more investigation involving a diverse set of urban street layouts. Furthermore, other vertical segmentation combinations with a different number of vertical layers should be explored to find the ideal configuration. Moreover, vertical layers can also be used for vertical conflict resolution.

Finally, although routes are pre-planned such that they do not intersect buildings, breaches occurred due to turn dynamics and conflict resolution manoeuvres. Previous research in constrained airspace [8, 9] assumed that all turns may be handled using a fixed turning speed/radius. However, in non-orthogonal street networks, intersections have greater topological variation, and thus a dynamic turn method is required. Furthermore, from Fig. 2.8, it is clear that conflict resolution manoeuvres lead to more geofence breaches. Aircraft must take static obstacles into account when resolving conflicts, as well as the required manoeuvring speed in case of a turn.

2.7. CONCLUSION

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

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

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

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3

IMPROVING TACTICAL CD&R METHODS IN TOPOLOGICALLY ORGANIC URBAN AIRSPACE

The previous chapter highlighted many of the challenges that very low level (VLL) constrained airspace poses for air traffic operations. As one of the operational concepts for this environment, utilising the existing street network for navigation requires the development of adapted conflict detection and resolution (CD&R) methods to ensure safety and efficiency both within constrained airspace and at its boundaries with unrestricted, open airspace.

The following chapter investigates several concepts aimed at enhancing the performance of tactical CD&R in the context of a greater U-space operational framework. These include the use of intent information for reducing false-positive detections, investigating the effect of vertical manoeuvring on airspace safety, and allowing heading-based manoeuvres in open airspace.

This chapter is based on the following publications:

- C. A. Badea, A. Morfin Veytia, N. Patrinopoulou, I. Daramouskas, J. Ellerbroek, V. Lappas, V. Kostopoulos and J. Hoekstra. ‘Unifying Tactical Conflict Prevention, Detection, and Resolution Methods in Non-Orthogonal Constrained Urban Airspace’. en. In: *Aerospace* 10.5 (2023), p. 423. DOI: 10.3390/aerospace10050423

ABSTRACT

The use of small aircraft for a wide range of missions in urban airspace is expected to increase in the future. In Europe, effort has been invested into developing a unified system, called U-space, to manage aircraft in dense very low-level urban airspace. The Metropolis II project aimed to research what degree of centralisation an air traffic management system should use in such airspace. This chapter investigates improvements that can be brought to the tactical conflict prevention, detection, and resolution module of such a system to harmonise these components with an organic high-density U-space environment. The proposed improvements are: prioritisation of vertical conflict prevention in intersections, the use of intent in detecting and resolving conflicts, and the use of heading-based manoeuvres in open airspace. Results indicate that the use of intent information in the conflict detection process, as well as the implementation of suitable tactical prevention procedures, can greatly increase airspace safety. Furthermore, experiments reveal that the effectiveness of conflict resolution algorithms is highly dependent on the airspace rules and structure. This reiterates the potential for increasing the safety and efficiency of operations within constrained airspace if the tactical separation modules are unified with the other components of air traffic management systems for U-space.

3.1. INTRODUCTION

The popularity of the use of small drones in recent years has grown greatly, especially for entertainment and leisure purposes. This sparked an increase in research on the possibility to use these aircraft for a wide range of missions, from package delivery services [2] to urban air mobility [3] and infrastructure surveillance [4]. However, if small aircraft are to become a core transportation method in cities, new air traffic management systems need to be developed to handle the issues and obstacles that this environment creates.

Compared to conventional airspace, urban airspace has a higher degree of complexity [5]. Because operations take place at a lower altitude, factors such as obstacles, local weather, and privacy considerations have a greater influence in this type of airspace. There is currently no established procedure for how aircraft should safely and efficiently navigate this kind of airspace [6]. While several initial concepts of operations have been created [7–9], the rules for new types of airspace still need to be investigated and set.

One of the airspace volumes for which research and development is still ongoing for the creation of a common set of rules is the ”Zu” volume, defined as urban airspace controlled by a U-space system [10]. The lower part of this volume, defined as very low-level (VLL) airspace (i.e., airspace between ground level and an altitude of 500ft (152.4 m) [11]), might host a very high volume of small aircraft traffic in the future.

The Metropolis II project sought to investigate the impact of the degree of centralisation in terms of separation management on the efficacy of a U-space air traffic control system. Both ends of the centralisation spectrum imply advantages and disadvantages: an air traffic control architecture focused around a central authority (as used in conventional air traffic control) has the potential to better optimise airspace use [12], while a decentralised approach (comparable to how car traffic is organised) has the benefit of being more responsive to unexpected events (i.e., weather, congestion) and more easily handle large volumes of aircraft [13]. The Metropolis II project results indicate that a combination of decentralised and centralised elements (i.e., a hybrid concept) provides a system architecture that includes the benefits of both ends of the centralisation spectrum [14].

The chapter at hand focuses on improving the tactical conflict prevention, detection, and resolution (CPD&R) component of urban small aircraft operations, with the aim of providing the insight and tools necessary for a better integration within a future hybrid U-space air traffic control architecture. Such an architecture will need to include both a centralised, strategic component, and a decentralised, tactical one. The paper is structured as follows: Section 3.2 presents a summary of the decentralised air traffic management concept of operations developed within the Metropolis II project, as well as the proposed improvements for the tactical CPD&R module of the concept; Section 3.3 explains the experimental environment and conditions used to simulate traffic scenarios; Sections 3.4 and 3.5 contain the results and discussion on the observed effects of the modifications on airspace safety and efficiency. Lastly, Section 3.6 presents the conclusions and recommendations for future research.

3.2. METHODS

The following section presents a brief description of the decentralised concept of operations we developed within the Metropolis II project [15], with an emphasis on the tactical conflict detection and resolution (CD&R) algorithm, together with the proposed improvements to this system. More details about the concepts designed within Metropolis II can be found in the project publication database [16].

3.2.1. Decentralised air traffic management principles

A decentralised air traffic management system is hypothesised to offer several benefits in the high air traffic density situations of VLL airspace, including scalability and a high level of fairness [17]. By distributing the separation responsibility among operators, operational bottlenecks associated with a highly centralised system are potentially mitigated. The decentralised concept of operations described in the chapter at hand is designed according to the following principles, derived from [13]:

1. Due to privacy and communication bottleneck considerations, minimal information is exchanged between operators;
2. All operators should have equal access to the airspace, and departure delays should be minimal;

3. All operators plan their paths individually, with minimal knowledge about the missions of other aircraft;
4. All deconfliction is performed tactically following predefined rules.

3.2.2. Urban environment

Within the Metropolis II project, we chose to use the city of Vienna, Austria as a subject for the development of air traffic management concepts of operation. The city authorities offer a wide range of open-access information on infrastructure and demographics, such as wealth distribution and population density [18]. Thus, realistic operational scenarios could be designed and considered by designing missions focused on parcel deliveries and emergency flights.

The U-space airspace around the Vienna was taken as a circle with a radius of $8km$ from the centre of the city, as shown in Figure 3.1. This area was further divided into two airspace types: open airspace, representing the area on the outskirts of the city, and constrained airspace in the city centre. In open airspace, aircraft can fly direct routes, assuming that the lowest flight level is above the highest obstacle. Restricted areas, such as parks, important landmarks or cemeteries, need to be avoided. In constrained airspace, aircraft must follow the existing street network due to factors such as privacy and obstacle avoidance. It should be noted that this design choice was made to study the interactions between aircraft that occur at the border between open and constrained airspace, and does not constitute a proposal for urban airspace design.

3.2.3. Missions

A wide range of potential missions were included and modelled within the research presented in this chapter. These were reduced to the following three fundamental types of missions, depending on their flight planning characteristics:

1. **Hub and spoke missions**, which are characterised by aircraft departing from a major vertiport (i.e., parcel distribution centres);
2. **Point-to-point missions**, in which aircraft depart and arrive from any point to any other point in the city;
3. **Emergency missions**, which take the highest priority above all other missions, but are relatively rare (0.05% of traffic).

The first two types of missions were also assigned a priority level between 1 (lowest) and 3 (highest), which would depend on the degree of importance of the mission. These were allocated such that an equal proportion of each priority level would be present in the airspace.

3.2.4. Airspace structure

In the research at hand, we chose to design the structure such that the individual decisions of the agents are facilitated, while also setting global rules to increase

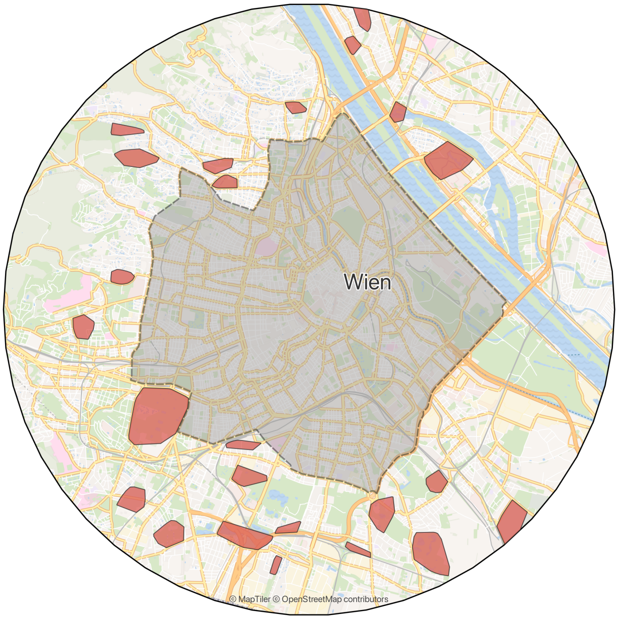


Figure 3.1: The urban environment used to develop the air traffic management concepts of operation within the Metropolis II project. The central area is constrained airspace, the outer area is open airspace with restricted air volumes.

traffic alignment and increase safety. This was done by using the method of air traffic layers and one-directional travel along streets. The first segments traffic and distributes it across set flight levels. The latter increases traffic alignment and prevents head-on conflicts.

Layering

The first Metropolis project showed that, by segmenting the airspace in layers and aligning aircraft in function of their relative speed, the number, and severity of conflicts and intrusion events is reduced [19]. Thus, within the concept of operations at hand, we chose to use such a structure for both constrained and open airspace, which imposes constraints on the heading range an aircraft can select.

Within open airspace, an airspace structure similar to the one used within the first Metropolis project was designed, presented in Figure 3.2. The aircraft are separated in function of the bearing of their track, thus achieving a high degree of velocity alignment. Each layer had a heading range of 45^o, starting at 0^o at the lowest altitude level. There are two sets of layers (i.e., layer set presented in Figure 3.2 represents one set, there are two sets stacked vertically), such that aircraft have access to more cruising altitude options.

For constrained airspace, a different approach was taken. As aircraft are

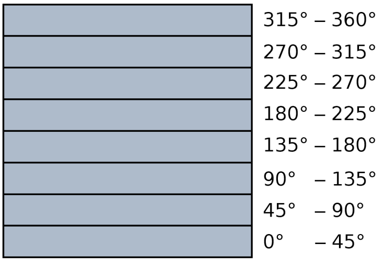


Figure 3.2: Layer configuration in open airspace.

limited to flying along the existing street network, their possible heading ranges are locally limited. Due to this, if the heading range method would be used, aircraft would be unevenly distributed on a local level. Another challenge within constrained airspace is handling intersections, as turning aircraft must slow down in order to not under- or overshoot, hindering other aircraft from cruising normally, and creating conflicts.

Therefore, a modified version of the urban airspace structure developed in [20] was used. The authors introduce turning layers within the airspace such that aircraft that slow down to perform a turn first descend in such a layer while not affecting other aircraft. The airspace structure also staggers cruise layers at intersections to avoid conflicts and interactions between cruising aircraft coming from different streets. The structure was modified to include more cruise layers and fewer turning layers, as the Metropolis II project aimed to test very high traffic densities.

The resulting airspace structure is presented in Figures 3.3 and 3.4. The categorisation of the streets in two groups (East/West and North/South) is explained further on in this chapter. In Figure 3.3, an isometric view of an intersection and one layer set is presented. The two cruising layers do not intersect, thus allowing aircraft that do not turn to continue cruising unhindered. The turn layer is at the same altitude on both streets, meaning that turning aircraft do not turn directly into a cruise layer, but must find a way to merge safely.

Figure 3.4 shows a representation of the full layer structure in function of street category. To ensure that cruising aircraft have minimal interaction at intersection, certain altitudes are reserved for cruising within either street type. This results in the existence of unused layers within the structure.

Street directionality

Previous research has shown that one-way streets are safer than two-way streets in an urban airspace environment [21], as this eliminates the possibility of head-on encounters. This principle was incorporated in the design of the constrained airspace structure for the concept of operations presented in this chapter.

Figure 3.3: Isometric view of layers at intersections, configured such that cruising aircraft do not interfere with each other, and turn layers always at the same altitude.

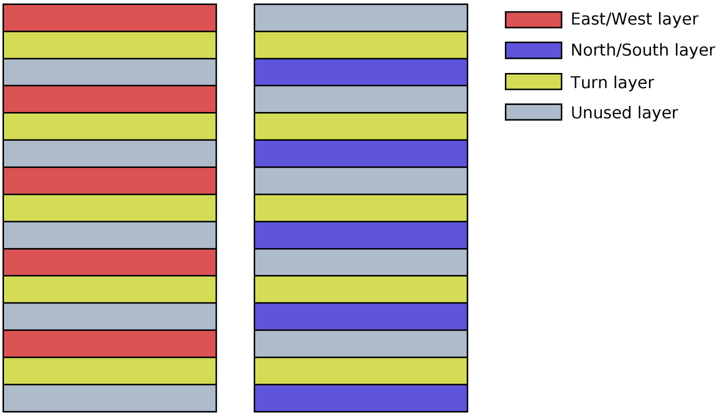


Figure 3.4: Layer configuration in function of street categorisation. Certain altitudes are reserved for cruising either in the East/West or North/South directions. Each layer is 30ft in height.

Thus, the streets contained within the defined constrained airspace area in Vienna were categorised into two cruising groups. This was done by extracting the street network graph of the city using OSMnx [22]. The individual edges of the street network graph were grouped into larger street strokes using the COINS algorithm, which groups the edges of the graph in function of their continuity [23]. These street strokes were then allocated within one of the two cruising groups through the use of a genetic algorithm optimisation method. The cost function was defined in function of intersections where cruising layers of the same type intersect, with the scope of globally minimising such intersections. More information about the method can be found in [24]. The method yielded the directional graph presented in Figure 3.5.

In this network, one group tends to be aligned with the North/South direction

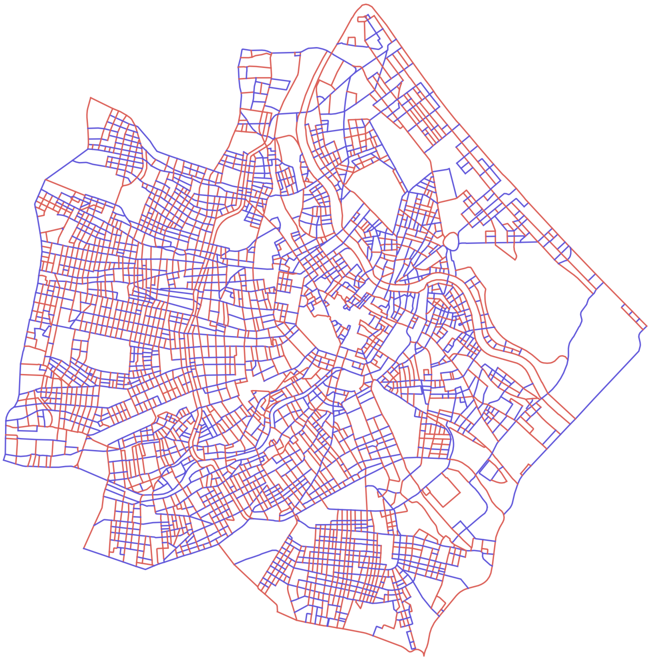


Figure 3.5: The resulting categorisation of streets within constrained airspace into mostly North/South (blue) and mostly East/West (red) directions by the genetic algorithm optimisation method.

(blue), and the other with the East/West direction (red). These groups were further categorised using another genetic algorithm to designate the direction in which aircraft are allowed to move along them. To ensure that all destination nodes can be reached from any origin node, the graph had to be modified by eliminating some edges and nodes.

3.2.5. Mission planning and capacity balancing

Within a decentralised concept, the responsibility for flight planning and management lies with the individual agents and operators. Thus, each agent is required to plan their flight path from the origin to the destination without knowledge of the flight paths of other agents in the system. However, comparable to how car traffic management tackles capacity balancing through the use of centralised systems (i.e., navigation mobile applications with congestion information, or lane management on motorways), the proposed air traffic management system includes a central entity responsible with supervising and managing traffic flow.

Thus, a path planning component for each individual aircraft is implemented. When the mission route is planned, live congestion information provided by the central entity is used to balance travel distance with predicted travel time. Aircraft can also replan their route while the mission is ongoing if the congestion information experiences changes.

The proposed path planning approach is a unified methodology for both open and constrained airspace. The entirety of the airspace is described as a directional graph such that, using the D* Lite algorithm [25, 26], the shortest path connecting the origin and destination waypoints can be calculated. After D* Lite computes the optimal path, the path segments contained in open airspace are post-processed by a smoothing algorithm to minimise unnecessary turns. The path planning algorithm is completely decentralised, every aircraft generates its flight plan with no knowledge of current or future flight plans and thus includes no strategic deconfliction.

The centralised capacity balancing component is inspired by the work done in [27]. It gathers the current positions of all aircraft in the air at a constant frequency. The positions of the aircraft are used to compute the current local traffic densities, which are globally provided as congestion information. The capacity balancing component is not responsible for the replanning process, nor for modifying a flight plan. When aircraft receive the updated traffic data they update their graph costs based on the traffic density and use the D* Lite algorithm to replan when appropriate.

3.2.6. Conflict detection method

An important component of the decentralised concept of operations presented in this chapter is the tactical conflict detection and resolution algorithm. It is a major contributor to safety, and is the main subject of the research at hand. Within the following section, detection and resolution algorithms developed as part of the Metropolis II project are presented. Later in this chapter, the possible improvements to these algorithms are described.

The first action that the CD&R system performs is conflict detection (CD). For this research, a state-based conflict detection algorithm was used, due to its robustness and flexibility [28]. Such algorithms linearly extrapolate the current state of aircraft within a certain look-ahead time, and determine the distance at the closest point of approach (CPA), as shown in Figure 3.6. A conflict is detected when this distance is lower than the minimum allowed safe separation, and a conflict resolution (CR) algorithm has the role of increasing this distance beyond the minimum allowance within the look-ahead time. For the simulated traffic scenarios within this chapter, a look-ahead time of 10 seconds was used, in combination with a minimum separation distance of 32 metres horizontally and 25 feet (7.62 m) vertically. These values are estimated from the signal-in-space performance requirements in Table 3.7.2.4-1 of [29].

3.2.7. Conflict resolution algorithm

The automation of conflict resolution manoeuvres has been proposed within the air traffic management domain for an extended period of time [30]. However,

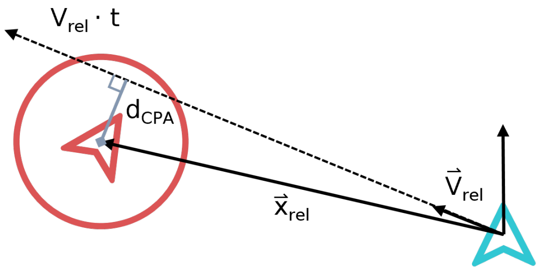


Figure 3.6: Functioning principle of state-based conflict detection. The relative speed (V_{rel}) and relative position (x_{rel}) are used to determine the distance at closest point of approach (d_{CPA}), and check if this distance is smaller than the minimum allowance within the look-ahead time (t).

it has never gained full traction for conventional aviation. As predictions estimate a large number of unmanned aircraft will operate in VLL airspace [31], automated conflict resolution becomes a promising solution for handling high traffic densities.

Due to the topology of constrained urban airspace, the solution space for conflict resolution manoeuvres is limited in the horizontal dimension. As the aircraft must follow the street network, the only possible manoeuvres that do not risk collision with obstacles are altitude-based or velocity-based. Thus, due to the similarity of the conflict resolution problem, inspiration was drawn from the way conflicts are tackled for car traffic on motorways.

Similarly to how car traffic must cruise in the right-most lane if possible, aircraft within the decentralised concept must cruise within the lowest cruise layer, if possible. If a faster aircraft approaches from behind, a conflict will occur. In this case, regardless of the mission priority assigned to the slower aircraft, the manoeuvring responsibility would always lie with the aircraft behind, as this is predicted to result in a more stable situation than requiring lower priority aircraft to move out of the way. Thus, the faster aircraft can initiate an overtake manoeuvre by ascending to a superior cruise level if possible, or otherwise adjust their velocity such that the conflict is solved.

For lateral conflicts, a non-cooperative velocity obstacle method [32] is used, as presented in Figure 3.7. In such situations, the aircraft with the lower priority is responsible for performing the resolution manoeuvre. The required change in velocity (Δv) is achieved by only changing the absolute value of the velocity vector. Thus, the heading of the aircraft does not change, as it is restricted by the direction of the path it is following. Multi-aircraft conflicts are also resolved using this method by stacking multiple velocity obstacles. A summary of the resulting algorithm used for conflict resolution within the decentralised concept of the Metropolis II project is presented in Algorithm 3.1.

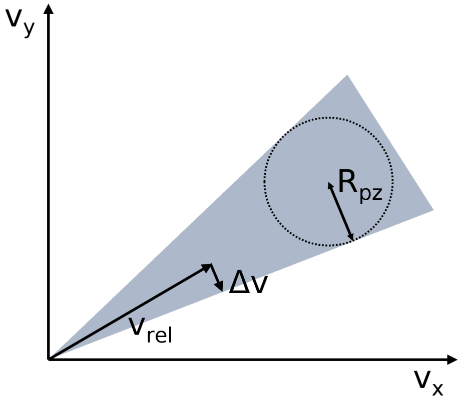


Figure 3.7: Velocity obstacle methods calculate the required change (Δv) in relative speed between two aircraft (v_{rel}) in order for the minimum separation distance (defined by the radius of the protection zone R_{pz}) to not be breached.

Algorithm 3.1: Conflict resolution algorithm of the decentralised concept of operations

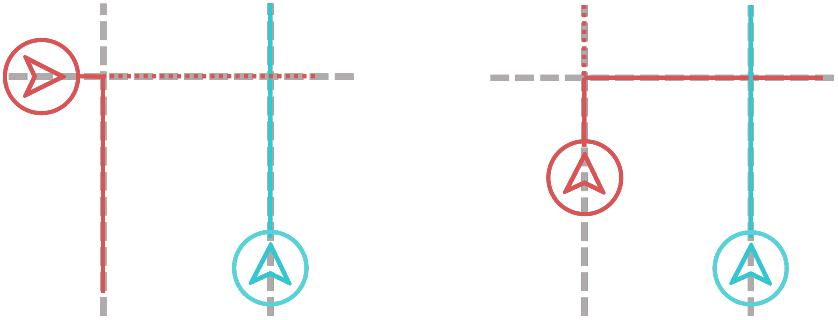
```
for each intruder of this ownship do
    if intruder is behind then:                              ▷ ownship does not perform an action
        return Continue cruising
    else if intruder is in front then:
        if ownship can ascend then:                          ▷ ownship can ascend to next cruise layer
            return Ascent command                            ▷ ownship overtakes
        else                                                 ▷ ownship cannot overtake
            return Speed-based CR command
    else if intruder is directly above or below then:
        set ownship and intruder vertical speed to 0         ▷ stop vertical manoeuvring
        if ownship has priority then:                        ▷ ownship continues cruising
            return Maintain altitude, continue cruising
        else                                                 ▷ intruder has priority
            return Slow down to let intruder merge
    else                                                     ▷ intruder is coming from the side
        if ownship has priority then:                        ▷ ownship does not perform an action
            return Continue cruising
        else                                                 ▷ intruder has priority
            return Speed-based CR command
```

3.2.8. Proposed improvements for conflict prevention, detection, and resolution

The following section presents the potential improvements that were investigated as part of the research at hand, with the purpose of improving the tactical conflict resolution component of an urban airspace air traffic management system.

Use of intent in conflict detection

The first proposed investigation concerns the conflict detection method. A major issue with the use of a state-based conflict detection algorithm in a constrained urban environment (as used in the baseline concept of operations) is the risk of incorrectly assessing the conflict situation [14]. As presented in Figure 3.8, scenarios can arise in which conflicts are detected that will in reality not occur based on the flight paths of aircraft (false-positive detection events, shown in Figure 3.8a). There is also a risk of not detecting conflicts in a timely manner (false-negative detection events), as shown in Figure 3.8b.



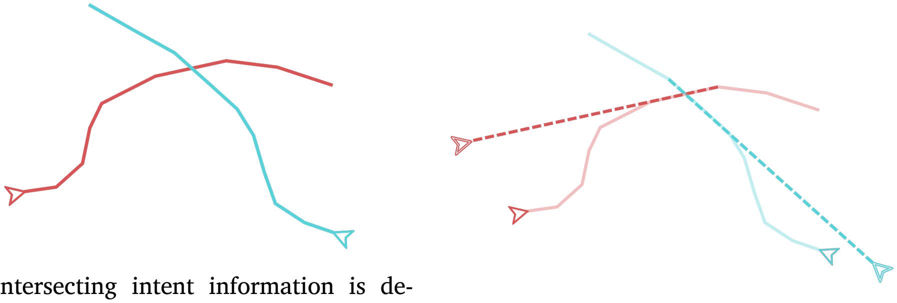
(**a**) False-positive conflict, blue aircraft detects a conflict based on a linear extrapolation of the current state of the red aircraft.

(**b**) False-negative conflict, the blue aircraft has no knowledge of the future turn of the red aircraft, and cannot anticipate the conflict.

Figure 3.8: Situations in which a state-based conflict detection method is considered unsuitable.

The proposed solution for this issue is the use of intent information. Agents would be responsible to communicate their intent within the look-ahead time, and consider this information when deciding whether a conflict is occurring or not. Previous studies have explored the use of intent within conflict detection and resolution systems [33–35] for open airspace or conventional aviation. However, the use of this information could produce a destabilising effect on the airspace, as any resolution manoeuvre also changes the intent of aircraft. In constrained airspace, the intent information remains constant, as aircraft cannot change their intended path or heading due to a conflict. Thus, this kind of conflict detection has the potential to be suitable for urban traffic situations.

Thus, a detection algorithm that includes intent information while retaining the robustness of state-based methods was developed. In the initial stage of the algorithm, a fast geometry-based search is conducted on the paths and intent information of aircraft. Aircraft pairs with intersecting intent paths are further investigated to determine whether a conflict event is occurring or not. As presented in Figure 3.9, the states of the aircraft are projected linearly from the intersection point in function of route distance. A state-based conflict detection method is then applied, determining whether the aircraft will breach the minimum separation distance at the intersection point.



(**a**) Intersecting intent information is detected between two aircraft in constrained airspace.

(**b**) Aircraft states are projected such that a state-based conflict detection method can be applied.

Figure 3.9: Projection-based conflict detection method: if intersecting paths are detected, the intruder is projected linearly from the intersection point, and a linear detection algorithm is applied.

While the prediction is inaccurate when turns are present, it is expected that the iterative nature of the algorithm will account for these inaccuracies, incrementally adjusting the resolution manoeuvre until a solution is reached. However, the filtering of false-positive events should not be affected, as they are mostly characterised by a lack of intersecting paths.

Algorithm 3.2: Projection-based conflict detection algorithm

```
for each aircraft close to this ownship do:
    check intersections of own path with intent information
    for each intersection do:
        determine projected state of intruder
        determine projected state of ownship
        apply state-based conflict detection method
        if conflict is detected then:
            return Projected conflict geometry
        else
            return Not a conflict
```

For open airspace, due to the lack of a predetermined network that needs to be followed, the use of intent information would produce the destabilising effects described in literature. Thus, a state-based detection method continues to be applied in situations where both aircraft are in open airspace. Furthermore, the projection-based algorithm does not consider vertical intent. For such conflicts, a state-based method is also used for both open and constrained airspace.

Enabling heading manoeuvres in open airspace

For the baseline decentralised concept of operations, we decided to limit conflict resolution manoeuvres in open airspace to velocity-only as well, similar to constrained airspace. This was done to avoid situations in which aircraft choose trajectories that would result in breaches of restricted airspace, as well as the emergence of a high frequency of altitude changes due to the heading ranges presented in Figure 3.2. However, this has the potential of unnecessarily restricting the solution space, especially when faster aircraft need to overtake slower aircraft.

Thus, the final proposed improvement investigated within the chapter at hand is the enabling of heading manoeuvres for conflict resolution in open airspace to investigate the benefits on overall airspace safety. A simple method, based on the one described in Figure 3.7, was implemented. The priority rules described in constrained airspace still apply (i.e., aircraft in front has priority, mission priority levels). While this method may result in an increase in the number of restricted area breaches, the investigation at hand does not consider these events for the performance analysis, as the aim is to isolate the benefit of enabling heading-based overtake manoeuvres.

Vertical conflict prevention during turn manoeuvres

The final investigation concerns the conflict prevention component of a decentralised system. In the baseline system, aircraft are obligated to use a turn layer when decelerating to perform a manoeuvre at an intersection. The aircraft first checks if it can use the turn layer below, then it checks if it can use the one above. If none are available, it attempts to still use the turn layer below and perform a merge manoeuvre within this layer. This is done to prevent horizontal conflicts that would result from the aircraft slowing down with the aircraft behind it in a turn layer.

The potential to improve this system stems from the observation that merge manoeuvres are the main source of intrusions in constrained urban airspace [21]. Thus, the proposed change to the baseline concept of operations is to eliminate the obligation to merge and use the turn layer to decelerate, thus giving priority to preventing vertical conflicts over horizontal ones. Aircraft are required to check if either the turn layer above or below is free to use. Otherwise, they will just use the cruise layer to decelerate. While this has the potential to affect cruising aircraft behind the turning aircraft, it is expected that horizontal conflicts are easier to solve than vertical merging conflicts.

It is important to note that this method implies that aircraft will most probably end up in an unused layer when turning from a cruise layer onto another street, as evidenced by Figure 3.4. Thus, the obligation to merge back into a cruise layer after the turn manoeuvre is maintained.

3.3. EXPERIMENTS

The following section presents the experiments performed to determine the effect of the proposed improvements to conflict prevention, detection, and resolution on safety and efficiency metrics when compared to the original methods.

3.3.1. Traffic scenarios

The traffic scenarios were generated by considering the population density and local gross productivity values for the city of Vienna, assuming that these would correlate with the demand for urban air traffic services. Thus, origin and destination nodes were placed throughout the districts of the city, with their density depending on the aforementioned factors.

The service demand was then estimated as a function of current parcel delivery demand in 20% increments from 20% to 100%. The scenarios were then generated for one hour of operations. The resulting number of aircraft that need to operate within an hour is presented in Table 3.1. For each density, 9 different repetitions were created.

Table 3.1: Number of aircraft per one hour scenario for each traffic density.

Density	Number of missions per scenario	Peak aircraft density per sq. km
Very Low	1660	1.74
Low	3340	3.48
Medium	4990	5.47
High	6650	7.46
Very High	8290	9.95

Several simplifying assumptions were made to better control the variables of the experiment and focus on the cruising phase of the operations. Thus, the aircraft were simulated using a point-mass model, and elements such as parcel weight and energy consumption were not taken into account. Furthermore, the landing phase of missions was eliminated, as it would create a disproportional number of vertical conflicts and intrusions during this process, affecting cruising results.The take-off phase was kept, as it plays an essential role in the way aircraft spawn within the simulation (when the traffic density around the take-off point is low enough).

3.3.2. Simulation environment

The traffic scenarios were simulated using the BlueSky Open Air Traffic Simulator [36]. The previously described algorithms were implemented as plugins. Two types of aircraft were used, based on the model of the DJI Matrice 600 included in BlueSky, differing only in their cruise speed, as shown in Table 3.2.

Table 3.2: Simulated aircraft specifications.

Internal aircraft name	**MP20**	**MP30**
Max horizontal speed [m/s]	13	18
Average cruise speed [m/s]	10	15
Max vertical speed [m/s]	5	5
Min vertical speed [m/s]	0	0
Max take-off mass [kg]	15	15
Max acceleration/deceleration [m/s^2]	3.5	3.5

3.3.3. Independent variables and experiment conditions

Three separate experiments were conducted to determine the effect of each proposed modification on safety and efficiency metrics when compared to the baseline case. These were run in very similar conditions. All shared the same traffic scenarios, mission procedures, urban environment, and safety parameters (i.e., minimum separation, look-ahead time, etc.). The only difference between conditions are the proposed modifications to the tactical conflict prevention, detection, and resolution modules. Thus, each experiment had different independent variables.

Experiment 1: Conflict detection

The independent variable of the first experiment is the detection method used within constrained airspace. Four conflict detection algorithms were tested, presented below:

1. **State-based**, representing the baseline condition also used within the Metropolis II project;
2. **Projection-based**, representing the direct implementation of the projection-based method, as described in Section 3.2.8;
3. **Projection-based filter**, where an initial state-based detection iteration is performed, and the false-positive conflicts are filtered using the projection-based algorithm by only considering the conflicts that are detected by both methods;
4. **Projection-based and state-based**, where both methods are run in parallel, and all detected conflicts are pooled and send to the conflict resolution module.

Experiment 2: Conflict resolution

The conflict resolution experiment had two experimental conditions: the baseline condition, where heading-based conflict resolution manoeuvres are not allowed in open airspace, and the "heading" condition, where such manoeuvres are enabled.

Experiment 3: Conflict prevention

The final experiment was conducted to determine the effect of the modified turn logic on airspace safety and efficiency. Thus, the two experimental conditions consist in the baseline turn logic, used within the original Metropolis II concept, and the modified turn logic presented in this chapter.

3.3.4. Dependent measures

The metrics that were used to analyse whether the methods improved upon the baseline case are:

- **Number of conflicts**, both in total and in constrained airspace;
- **Number of intrusions**, both in total and in constrained airspace;
- **Earliest detection time of conflicts that resulted in an intrusion**, i.e., the maximum time duration, limited at 60 seconds, between the detection of a conflict and the intrusion event between the two conflicting aircraft;
- **Distance travelled efficiency**, computed as a percentage of the ideal route distance for each mission;
- **Mission duration efficiency**, computed as a percentage of the ideal duration for each mission.

3.3.5. Hypotheses

Experiment 1: Conflict detection

The projection-based conflict detection method is hypothesised to increase airspace safety when compared to the baseline case, as conflicts that were not detected by only using a state-based method should be detected by including intent information. Furthermore, out of the three variations of the projection-based method, the one augmented with state-based detection will perform the best, as more conflicts will be detected and accounted for.

Experiment 2: Conflict resolution

Allowing aircraft to laterally overtake in open airspace is hypothesised to produce a small benefit on overall airspace safety, as faster aircraft will not be forced to slow down and wait behind slower aircraft, creating repeat conflicts and potential intrusion events.

Experiment 3: Conflict prevention

The initial strategy for turning was developed under the assumption that the use of turn layers would reduce conflicts and improve intersection throughput. However, issues with this strategy were observed at high densities, when several aircraft would attempt to use turn layers at the same time. Thus, it is hypothesised that the modified turn logic will improve airspace stability and reduce the number of intrusions, as aircraft will not attempt to merge into a turn layer if there are other aircraft within it. At the same time, the duration of missions is expected to increase, as cruising aircraft will have to slow down for turning aircraft more often.

3.4. RESULTS

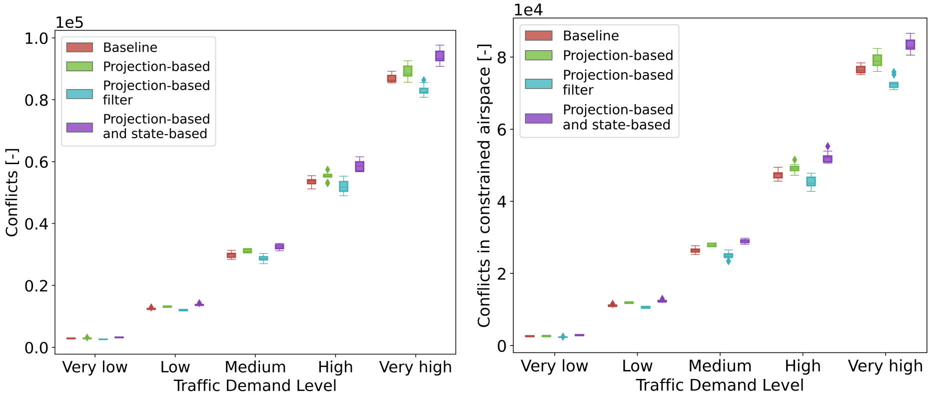
The following section presents the results of the experiments performed to determine the effect of the proposed modifications to the tactical conflict prevention, detection, and resolution module of the decentralised concept of operations developed as part of the Metropolis II project. The results are divided into three subsections, one for each experiment.

3.4.1. Experiment 1: Effect of intent information on conflict resolution performance

The first experiment to be discussed concerned the inclusion of intent information within the conflict detection process. The safety metrics of this experiment are presented in Figure 3.10. Using intent information increased the number of conflicts that were detected, with the greatest increase observed in the case where both projection-based and state-based methods were used. As expected, filtering presumably false-positive conflicts also resulted in a lower number of detected conflicts.

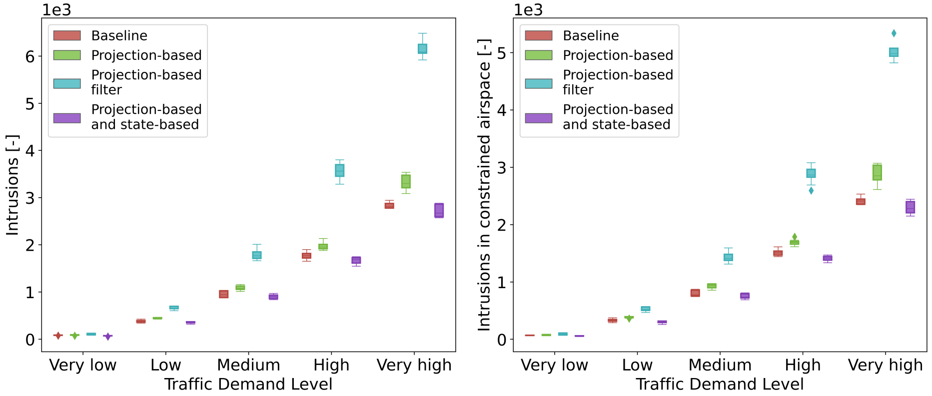
In terms of the number of intrusions, the results were relatively unexpected. The projection-based method experienced more intrusions than the baseline method, especially at high densities. On the other hand, the best performing method was the combined one, with a slightly better intrusion performance when compared to the baseline. Finally, the worst performing method was the projection-based filter, which experience a significantly higher number of intrusions than all other methods.

One of the reasons for the increased number of intrusions can be seen by analysing the first detection time for these events. In Figure 3.11, the frequency distribution of the first warning time for a conflict within a maximum of one minute ahead of the intrusion is plotted as compared to the baseline case. In the projection-based case, there is a noticeable increase in detections that occur within 5 seconds of the intrusion event, meaning that aircraft had less time to act and solve the conflict than in the baseline case. This means that many conflicts that resulted in an intrusion were initially discarded, but then considered only when an intrusion was inevitable (within 3 seconds).



(**a**) Total number of conflicts per scenario in function of traffic density.

(**b**) Number of conflicts per scenario that occurred within constrained airspace in function of traffic density.



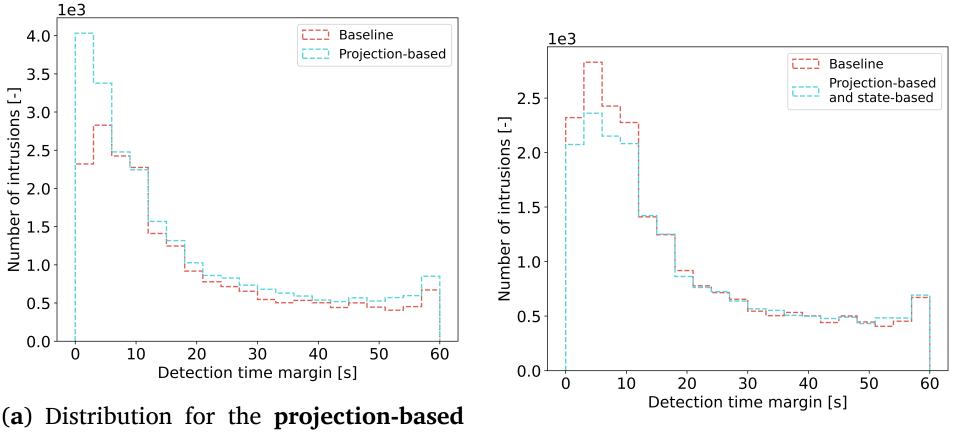
(**c**) Total number of intrusions per scenario in function of traffic density.

(**d**) Number of intrusions per scenario that occurred within constrained airspace in function of traffic density.

Figure 3.10: Safety metrics of the projected conflict detection method when compared to the baseline state-based method.

However, adding intent information to the state-based method resulted in a distribution comparable to the baseline case, showing that more conflicts were detected in a timely manner. Thus, the peak of the projection-based method at the low detection times was mitigated.

Another interesting result of the experiment can be seen when analysing the intrusion prevention rate for each conflict detection method, presented in Figure 3.12. The most notable difference comes in case of the projection-based filter method, which achieved the lowest conflict prevention rate. This can



(**a**) Distribution for the **projection-based** case.

(**b**) Distribution for the **projection-based and state-based** case.

Figure 3.11: Distributions of the earliest detection time of conflicts that resulted in an intrusion for the three detection method cases compared to the baseline case for a high density scenario.

be explained by the fact that intrusion events will always be detected by the state-based detection method, but they only pass the filter when there is little time to act, thus decreasing the prevention rate. The other methods have a similar prevention rate, with the combined projection and state-based method being slightly better. This shows that not only did the method detect more conflicts, but the conflict resolution module was also able to use the extra information to better solve the conflicts.

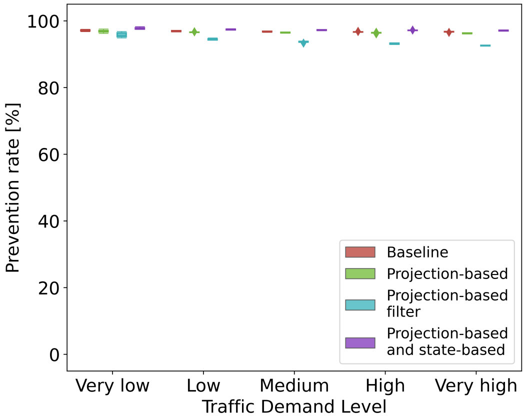
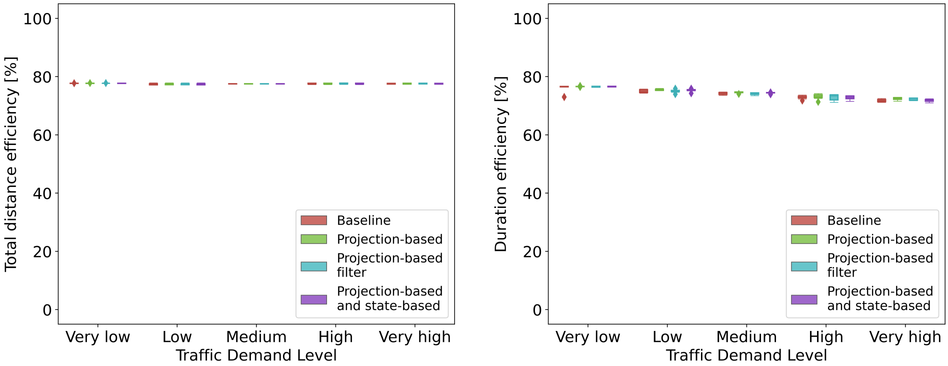


Figure 3.12: Intrusion prevention rate for the conflict detection methods.

Lastly, in terms of efficiency performance, presented in Figure 3.13, the conflict detection method did not have significant effect on the distance or duration of missions. The small differences can be attributed to the fact that solving more conflicts is associated with an overall slower cruising velocity, as the main solving strategy is speed reduction.



(**a**) Average flight route length efficiency per scenario in function of traffic density.

(**b**) Average flight route duration efficiency per scenario in function of traffic density.

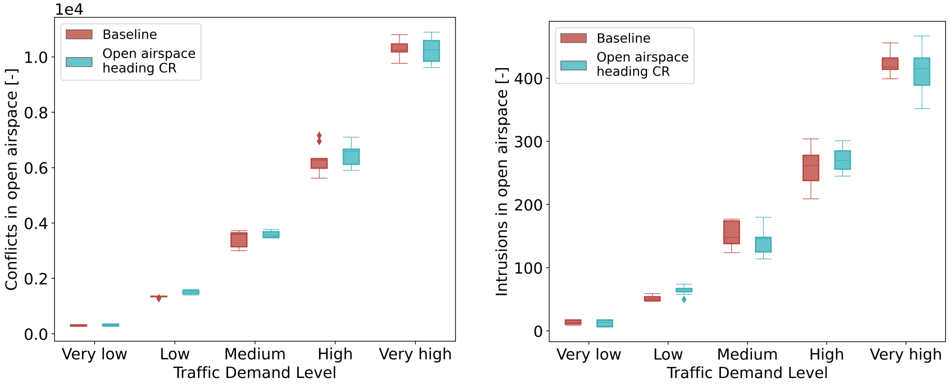
Figure 3.13: Efficiency metrics of the projected conflict detection method when compared to the baseline state-based method.

3.4.2. Experiment 2: The use of heading-based conflict resolution in open airspace

The following section presents the results of the experiment in which the effect of introducing heading-based conflict resolution algorithms in open airspace is compared to the baseline case, which uses a speed-based algorithm. All results in this case show little to no improvement over the baseline case. This is most probably due to the already established airspace structure in open airspace, where aircraft are allocated a certain cruise altitude based on their heading. Due to this, encounters between aircraft usually happen with a small heading deviation and relative velocity, where a speed-based solution already performs well. Thus, in terms of the safety metrics, presented in Figure 3.14, the performance of the two methods are similar.

3.4.3. Experiment 3: Improving turning logic for conflict prevention

The third experiment aimed to determine the effect of the modified turn logic on airspace safety. The results of the safety metrics, presented in Figure 3.15, show an unexpected improvement brought by the proposed modification, with a reduction of up to approximately 30% in conflicts and 40% in intrusions that occurred in constrained airspace. This shows that merging within an already



(**a**) Average number of conflicts in open airspace per scenario in function of traffic density.

(**b**) Average number of intrusions in open airspace per scenario in function of traffic density.

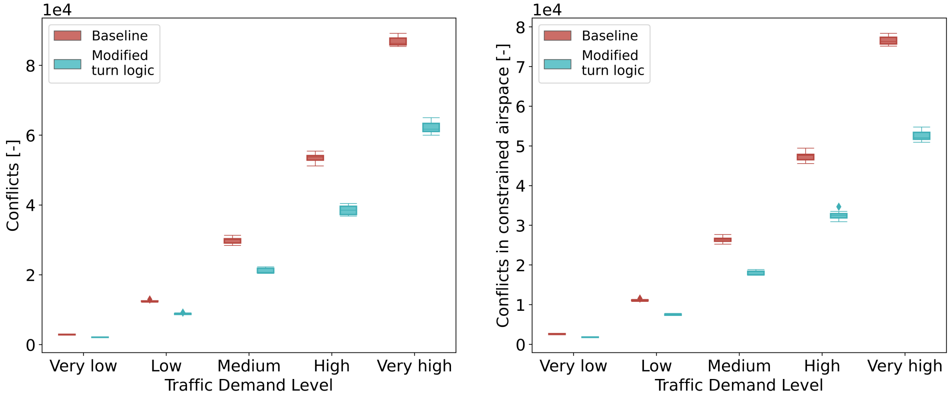
Figure 3.14: Safety metrics of the heading-based conflict resolution algorithm when compared to the baseline method for open airspace.

populated turn layer was one of the major contributors to conflicts in the original Metropolis II decentralised concept, especially at high traffic densities.

Thus, it is apparent that the conflicts generated by aircraft not using turn layers destabilise the airspace less than the ones generated by aircraft attempting to merge within a turn layer. This information can be seen in Figure 3.16, which shows the distribution of intrusion events in function of the layers in which the two aircraft were found in. In the baseline case, most intrusions occurred when both aircraft were inside a turn later (T-T), or were attempting to merge into a turn layer from a cruise layer (C-T).

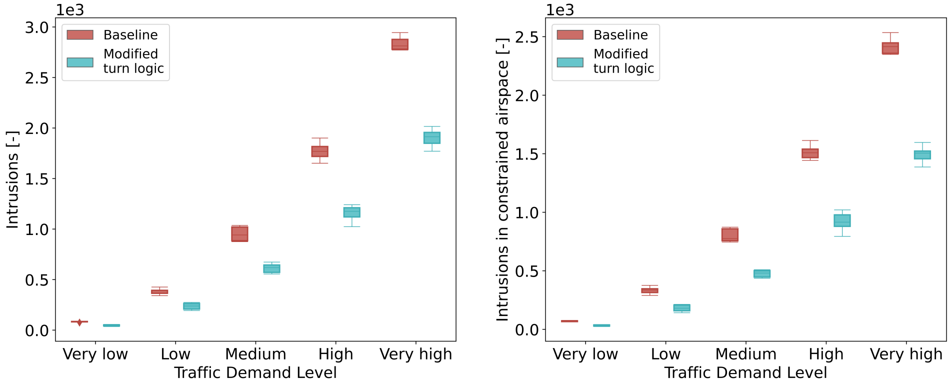
By changing the turn logic, many of the turn layer related intrusions were eliminated, while the number of intrusions between aircraft in cruise and unused layers (C-U) experienced a slight increase. This can be explained by the fact that, if an aircraft turns from within a cruise layer onto a street that has a different layer configuration, it will find itself within an unused layer (as seen from Figure 3.4), and only then attempt to merge back into a cruise layer. Such merges appear to be more successful, as traffic within cruise layers is more predictable than in turn layers, and aircraft are less prone to initiate vertical manoeuvres.

Finally, a difference can be observed in the efficiency metrics, presented in Figure 3.17. The modified turn logic shortens the duration of flights, an effect that can be attributed to the presence of a lower number of conflicts, and thus less time spent at lower, conflict resolution velocities.



(**a**) Total number of conflicts per scenario in function of traffic density.

(**b**) Number of conflicts per scenario that occurred within constrained airspace in function of traffic density.



(**c**) Total number of intrusions per scenario in function of traffic density.

(**d**) Number of intrusions per scenario that occurred within constrained airspace in function of traffic density.

Figure 3.15: Safety metrics of the modified turning method when compared to the baseline turning method.

3.5. DISCUSSION

The experiments and results presented in the chapter at hand show that improvements can still be made for the decentralised tactical component of a future hybrid concept of operations for U-space.

The inclusion of intent information within conflict detection proved to be beneficial to overall airspace safety and stability when the information is used in parallel with state-based linear extrapolation methods. The results indicate that the inclusion of more information about the aircraft in proximity

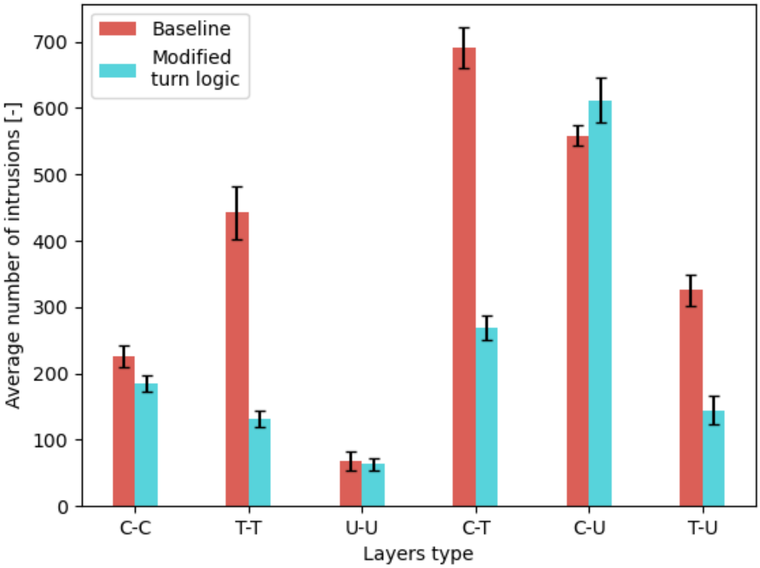
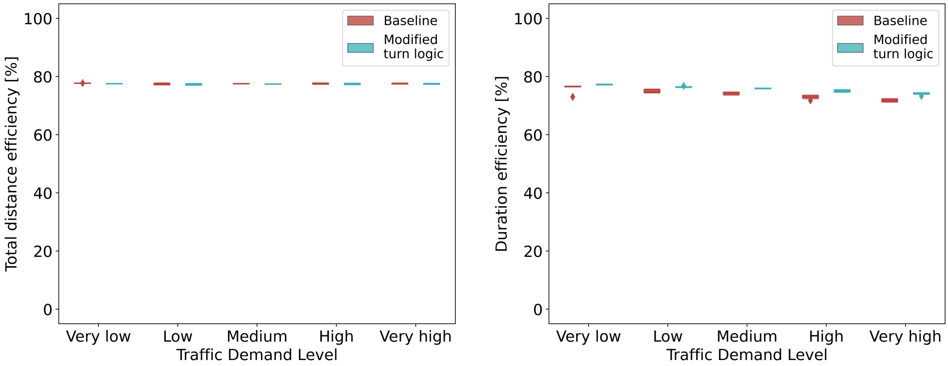


Figure 3.16: Classification of intrusions in function of the layers in which the aircraft were when the loss of separation event occurred, averaged over high-density scenarios.



(**a**) Average flight route length efficiency per scenario in function of traffic density.

(**b**) Average flight route duration efficiency per scenario in function of traffic density.

Figure 3.17: Efficiency metrics of the modified turning method when compared to the baseline turning method.

is more beneficial than filtering out conflicts and thus excluding information. However, it should be noted that this implementation would require increased communication between agents, which would be compatible with a hybrid air traffic management system.

An interesting implication of the findings presented in this chapter is that false-positive conflicts appear to have a stabilising effect on the airspace. Aircraft that solve these conflicts typically adopt a slower velocity in situations where the traffic density is high and other aircraft are present in the area. This then helps to prevent and solve real conflicts. This effect can be compared to the concept of “defensive driving”, as car drivers are encouraged to slow down even if the certainty of a conflict occurring is not high. This can have an effect on efficiency, as mission duration will increase. However, the results presented in this chapter show that the difference is small.

It should be mentioned that the projection-based method developed for this research does not account for inaccuracies resulting from aircraft slowing down for turns. Instead, the algorithm relied on subsequent iterations to adjust for these situations. However, a downside of this was that a binary decision (conflict or not a conflict) was taken based on the intent information, which led to some conflicts only being detected very late, when the accuracy of the intent information was higher. Thus, the algorithm can be improved by accounting for these inaccuracies and uncertainties, possibly by implementing greater safety margins, or using probabilistic-based predictions and decision-making.

The method could also potentially be improved by considering vertical intent, especially as altitude changes are another important source of unpredictability. Aircraft could consider the intention of other traffic when a vertical manoeuvre is desired.

The hypothesis regarding the effect of including intent information in the conflict detection process is partly rejected, as the projection-based method did not outperform the state-based method. However, in line with expectations, using both methods in parallel did increase airspace safety.

The results of the second experiment show that using a speed-based conflict resolution method in layered open airspace achieves similar results to a heading-based method. This can be explained by the fact that traffic had a high degree of alignment due to similar routing patterns and the narrow heading-ranges of layers. However, this result is highly specific to the chosen layer structure and routing method. In the research at hand, while traffic was heterogeneous, it still had a high degree of homogeneity. Heading-based conflict resolution might still be the preferred option if vehicles with more considerable differences are flying within the same airspace layers, and the faster aircraft will have to overtake the slower ones.

Thus, the hypothesis stated previously on the effect of using heading-based manoeuvres in open airspace is rejected. It was expected that the ability to overtake slower aircraft would reduce the number of conflicts and intrusions. However, in the traffic scenarios created and simulated as part of the research, the traffic speed heterogeneity and density were not great enough to observe this effect.

The last experiment produced results with unexpected magnitudes in the observed differences between cases. Both the number of conflicts and intrusions were greatly reduced by using the modified turning strategy, showing that slowing down traffic in cruise layers is a more stable turning strategy than forcing the use of a turn layer in high density cases. This can be explained by the fact that vertical conflicts are more complex than horizontal conflicts, and the speed-based conflict resolution algorithm was more suitable for the latter. Furthermore, traffic in cruise layers is more predictable, as vertical manoeuvres are less likely to be initiated, whereas aircraft in turn layers are forced to perform two vertical manoeuvres during a turn when using the baseline turning strategy.

The analysis of the distribution of intrusions in function of the layer types they occurred in reveals that a major source of conflicts are transitions that involve turn layers. With the modified turning strategy, many of these intrusion events do not occur, with only a few of them being transferred to the cruise-unused layer category. Thus, even though the obligation to merge into a cruise layer after turning is maintained, this manoeuvre is better handled by the conflict detection and resolution module than the merge within a turn layer. This could be explained by the fact that, if two aircraft decide to merge within the same turn layer, a conflict in which both aircraft have a vertical velocity emerges, which is more difficult to solve than a situation in which only one aircraft is performing such a manoeuvre.

Furthermore, the conflict resolution algorithm presented in Algorithm 3.1 commands aircraft to stop ascending or descending while the manoeuvre is being performed. When merging within a turn layer, such a command might stop the aircraft at an altitude at which it conflicts with both cruising aircraft and aircraft in the turn layer, thus increasing the conflict and intrusion probability in an already unstable part of the airspace (areas before intersections). Thus, the increased predictability of simply slowing down within the cruise layer and not performing vertical manoeuvres is beneficial to stability and safety.

Therefore, the hypothesis regarding the proposed modification to the conflict prevention module is partly accepted, as it did increase the safety of the airspace. A surprising result, that goes against the hypothesis, is that the average mission duration efficiency was positively impacted. The magnitude of the difference in the number of conflicts and intrusions means that aircraft were solving fewer conflicts overall, spending more time at cruise speed than at slower, resolution speeds.

Overall, the improvements brought to the decentralised concept of operations developed within the Metropolis II research project show both that the original concept was relatively robust, but also that more research is needed to improve the tactical components of future hybrid air traffic control systems for U-space. Partial decentralisation of operations can offer a great benefit in terms of safety and efficiency for urban operations, and the complex emerging behaviours that are produced as a result of high traffic densities need to be further studied and understood.

3.6. CONCLUSION

This chapter aimed to investigate improvements to the tactical conflict prevention, detection, and resolution module of the decentralised concept of operations for

U-space developed as part of the Metropolis II research project. For this, urban air traffic scenarios, amounting to over one million missions, were simulated within constrained airspace designed for the city centre of Vienna. The proposed improvements were the following: improved conflict detection in constrained airspace through the use of intent, and an alternative conflict prevention strategy in turning manoeuvre situations.

Several conclusions can be drawn from the results of the different experiments performed for this work. Firstly, while the use of intent does improve conflict detection and resolution performance in constrained airspace, it only does so when used in combination with established state-based detection methods. This effect shows that false-positive detection events might have a stabilising effect on the airspace, equivalent to the concept of preventive car driving.

The second set of results indicate that major improvements can still be achieved in the field of tactical conflict prevention. The proposed modification greatly increased safety within constrained airspace, as aircraft were only allowed to use turn layers if the chance of another aircraft intending to do the same was small. Thus, most aircraft performed turns directly within cruise layers, creating simpler conflict situations at intersections, and increasing airspace stability. Performing less vertical manoeuvres would also have the benefit of improved energy efficiency, as such manoeuvres have a high-energy consumption.

The results of the Metropolis II project show that, in terms of degree of centralisation, a combination of decentralised and centralised components is a good way to manage air traffic in urban airspace. The proposed improvements presented in this chapter contribute to a more in-depth understanding of the traffic behaviour and dynamics produced by the tactical component of air traffic management systems, which serves towards the development of a future hybrid concept of operations that will safely and efficiently route aircraft in constrained urban airspace.

Further research should therefore focus on developing tactical CD&R strategies to be better suited for handling high traffic densities in constrained urban environments. Tactical conflict prevention algorithms are shown to have the potential of greatly increasing airspace safety, and better strategies to achieve this should be investigated (e.g., using machine learning methods). CD methods should be further researched and developed to better make use of the extra information that constrained airspace provides over open airspace. CR algorithms also need to be adapted and integrated with the other components of a hybrid air traffic management concept of operations (i.e., central strategic planning authority, airspace structure and rules, etc.) to achieve system harmonisation and cooperation. Furthermore, if intent information will be an integral part of tactical conflict resolution, communication methods and security considerations need to be a part of the investigation.

Lastly, more work is required for studying the feasibility of urban airspace operations. Factors such as energy consumption and on-board processing power are key hardware-related elements that need to be considered. Furthermore, the take-off and landing phases of missions are critical operations during which many conflicts can occur, and thus require procedures to be developed to ensure operational safety.

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4

REQUIRED DEGREE OF CENTRALISATION FOR THE U-SPACE CD&R SERVICE

The results of the previous chapters emphasise the importance of developing tactical and strategic conflict detection and resolution (CD&R) methods in tandem for operating in constrained urban airspace at very low altitudes. When integrating these two components into a single system, it is important to account for how they might influence each other. The integration should be carried out in a way that ensures neither component compromises the effectiveness of the other.

The following chapter investigates the interactions between tactical and strategic CD&R methods when used within a unified, hybrid system. The performance of several complexity levels of strategic pre-departure planning is tested when disrupted by tactical manoeuvring and uncertainties such as wind and departure delay. The simulation results reveal valuable insights on how the strengths and weaknesses of both strategic and tactical methods can be leveraged to improve their unified effectiveness, but also the significant deterioration of the performance of these methods in the presence of uncertainties such as wind and departure delay.

This chapter is based on the following publications:

- C. A. Badea, A. Vidosavljevic, J. Ellerbroek and J. Hoekstra. 'Evaluating the Synergy of Conflict Detection and Resolution Services for U-space/UTM Operations'. In: *IEEE Open Journal of Intelligent Transportation Systems* (2024). DOI: 10.1109/OJITS.2025.3530516

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 a matter of debate. One important component of such a system is that of conflict detection and resolution (CD&R). Both the strategic and tactical CD&R approaches have been investigated, with several methodologies proposed. However, 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 has yet to be determined. The following chapter presents an investigation of a hybrid (strategic and tactical) CD&R system 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.

4.1. 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 [2–4] and UTM [5, 6] proposals for the management of urban air traffic in the EU and US, respectively, set the foundation for the development of the services required for such operations.

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 [7], both pre-departure strategic flight plan optimisation and tactical CD&R are required within high-density constrained very-low-level (VLL) urban airspace. These services are extensively studied in literature: strategic methods typically gravitate towards global optimisation approaches [8–12], while tactical algorithms are often designed to reactively resolve conflicts locally [13, 14].

Both modules have also been investigated within the context of a hybrid CD&R system (i.e., combined use of strategic and tactical CD&R with both centralised and decentralised components). The Metropolis 2 project developed and investigated several concepts for the CD&R U-space service with varying levels of centralisation [15]. The USEPE project created an initial set of requirements for the tactical and strategic deconfliction modules [16]. Capitan et al. [17] developed and tested an architecture able to integrate both dynamic strategic planning and tactical conflict avoidance manoeuvres.

However, a more in-depth analysis on the potential compatibility issues between these two services is still missing: tactical manoeuvres induce a deviation from the flight plan established before departure, which could produce a snowball effect and increase the number of conflicts. Moreover, high degrees of operational and environmental uncertainties (i.e., the presence of wind and departure delay) lead to a higher amount of tactical manoeuvring, potentially affecting the ability of aircraft to remain compliant with their flight plan.

The aim of the chapter at hand is to determine the necessary steps for the development of an effective and unitary CD&R for VLL constrained urban airspace. It serves as a follow-up of the Metropolis 2 project [15], which points to the necessity of the use of both centralised and decentralised deconfliction services for safe and efficient U-space operations. The analysis at hand seeks to provide a more in-depth insight into the strengths and shortcomings of strategic and tactical CD&R methods, when used individually and together, and quantify the magnitude of the contributions of each to the level of safety and efficiency. Traffic demand scenarios are created based on predictions of future urban air traffic. Several combinations and levels of tactical and strategic CD&R are tested by simulating these scenarios using the BlueSky Open Air Traffic Simulator [18] under multiple operational conditions, including high-uncertainty situations (e.g., wind and departure delay).

4.2. CONSTRAINED URBAN AIRSPACE OPERATIONS

To evaluate a hybrid CD&R system and identify areas for improvement, the following considerations about operations in urban airspace environments were taken into account based on literature and previous research. Firstly, due to privacy considerations and the presence of urban obstacles such as buildings, aircraft are assumed to be constrained to flying above the existing street network. This strategy, used in previous work [9, 19], ensures that the risk of collisions of aircraft with immobile obstacles is minimised. Furthermore, it improves the efficiency of operations, as aircraft can fly at lower altitudes.

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 [20]. Furthermore, as vertical manoeuvres are generally undesirable due to their effect on manoeuvring predictability [21], 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 [22]. 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 [23], and must thus be treated separately.

4.3. PRE-DEPARTURE STRATEGIC PLANNING

The following section presents the strategic deconfliction method used in this work. It is 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 [8]. 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.

4.3.1. Assumptions

The problem is formulated based on the following assumptions:

1. Aircraft take off and land vertically above their designated origin and destination vertiport.
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).

4.3.2. 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 [8].

4.3.3. 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

4.3.4. 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

4.3.5. Constraints

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

$$\sum_{k \in K_f} x_k = 1, \forall f \in F \tag{4.1}$$

Due to the definition of the decision variables y_f and $d_f, \forall f \in F$ as discrete, Equation 4.1 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.

$$(t_p^1 + d_{f_p^1}) - (t_p^2 + d_{f_p^2}) + s_p^{12} \leq 0, \forall p \in P \tag{4.2}$$

OR

$$(t_p^2 + d_{f_p^2}) - (t_p^1 + d_{f_p^1}) + s_p^{21} \leq 0, \forall p \in P \tag{4.3}$$

The constraint 4.2 ensures separation compliance when flight f_p^1 passes before flight f_p^2 at the intersection point of conflict p, and 4.3 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.

4.3.6. Objective function and optimisation process

The objective is to minimise the total travel time, shown in Equation 4.4.

$$\text{Minimise} \sum_{f \in F} \left(\delta_f(y_f) + d_f\right) + \sum_{k \in K} b_k x_k \tag{4.4}$$

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 [24].

4.3.7. Levels of strategic planning

In this work, four levels of strategic planning are defined:

- **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.

4.4. 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 [14]. 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. Previous research shows that these methods are effective in both conventional aviation [25] and urban airspace environments [16].

Moreover, such methods have proven to be robust in the face of operational uncertainties such as wind and delay [21]. Thus, a state-based CD&R method developed for urban airspace operations was selected to serve as the tactical deconfliction module within this work.

4.4.1. Tactical conflict detection

The tactical CD&R algorithm detects conflicts using velocity obstacle (VO) theory, previously used in [19]. The relative position ($\mathbf{x}_{\mathrm{rel}}$) 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 Equation 4.5.

$$\mathrm{CC} = \left\{ \mathbf{v} : \|\mathbf{v} - \frac{\mathbf{x}_{\mathrm{rel}}}{\tau}\| \leq \frac{\mathrm{R}_{\mathrm{pz}}}{\tau}, \forall \tau \in (0, \infty) \right\} \tag{4.5}$$

Thus, the collision cone represents the set of all relative velocities ($\mathbf{v}_{\mathrm{rel}}$) 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:

$$\mathbf{v}_{\mathrm{rel}} \in \mathrm{CC} \implies \text{Conflict} \tag{4.6}$$

A visual representation of the relative collision cone is presented in Figure 4.1.

4.4.2. 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 [21]. Thus,

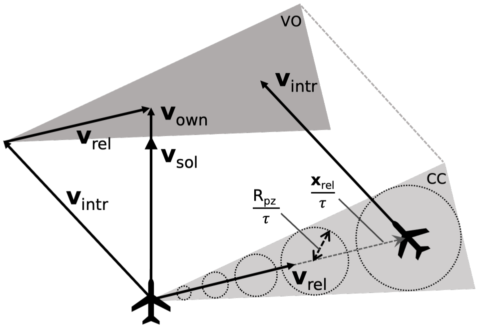

Figure 4.1: State-based conflict detection and resolution using velocity obstacles.

the conflict resolution method presented in [19] is used, as it uses velocity obstacle theory to calculate a speed-based avoidance manoeuvre.

The collision cone (CC) in Figure 4.1 is translated using the velocity of the intruder ($\mathbf{v}_{\text{intr}}$) to obtain the velocity obstacle (VO) in function of the velocity vector of the ownship ($\mathbf{v}_{\text{own}}$). As previous research has shown that lower relative velocities increase the safety level [26], the resolution velocity ($\mathbf{v}_{\text{sol}}$) is chosen along the direction of the ownship velocity vector ($\mathbf{v}_{\text{own}}$) 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 4.1.

4.5. EXPERIMENT

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

4.5.1. Hypotheses

The experiment seeks to test the following hypotheses, based on the conclusions of previous studies [15]:

Algorithm 4.1: State-based speed-only CR algorithm, from [19].

```
conflict_pairs = **all** (ownship, intruder) | conflict pair
**for** 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
    **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
    ▷ Aircraft are issued cruise speed commands if they have priority over all intruders.
**for** aircraft **do**
    **if** aircraft *has priority in all involved conflicts* **then**
        **return** Cruise speed command
```

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 [15], 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 [19] 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.

4.5.2. Simulation software

The BlueSky Open Air Traffic simulator [18] was used for the experiment at hand. This software has been previously used within U-space/UTM research [16, 27], and allows for the implementation of custom plugins for the CD&R methods, the wind model, and the departure delay model. The simulations can also reliably be rerun by using BlueSky scenario files.

4.5.3. Constrained urban airspace environment

The simulation environment used for this work is based on the street network within the central districts of Vienna, Austria, presented in Figure 4.2. This area was selected due to its diverse topological characteristics: parts of the network are orthogonal in aspect, while others are highly organic.

The street network was extracted from the OpenStreetMap database [28] using the OSMnx Python library [29]. The obtained graph was then processed

Figure 4.2: Constrained airspace structure extracted from the street network of the city centre of Vienna.

further by assigning singular directions to the edges. First, the edges were grouped into strokes (i.e., groups of consecutive edges that present a smooth street-like geometry) using the COINS algorithm [30]. 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 [31]. Lastly, the airspace is divided into 10 cruise altitude layers, each with a thickness of 50 ft (15.24 m), in accordance with [20].

4.5.4. 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 [32], 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/m). While these are higher than the expected demand in the near future [32], 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 [33]. 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 [21], and is an assumption encountered in literature [9].

4.5.5. 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 4.1.

Table 4.1: DJI Matrice 600 model parameters in BlueSky, based on manufacturer specifications [34].

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°

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 4.7 and 4.8.

$$\omega = \frac{g \tan \phi}{V} \tag{4.7}$$

$$R = \frac{V^2}{g \tan \phi} \tag{4.8}$$

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 4.8 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 Figure 4.3. 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.

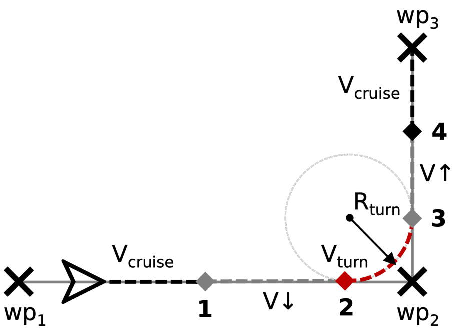

Figure 4.3: Turning manoeuvre as simulated within BlueSky.

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.

4.5.6. 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 [35]. This work 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 4.5.3) within the street network according to Equation 4.9.

$$\mathrm{mag}_{street} = \mathrm{mag}_{roof} \cos\left(\Delta_{bearing}\right) \tag{4.9}$$

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 4.11.

$$\text{dir}_{street} = \begin{cases} 1, & \text{if } \Delta_{bearing} < 90° \\ -1, & \text{otherwise} \end{cases} \tag{4.10}$$

$$\Delta_{gs} = \text{mag}_{street} \times \text{dir}_{street} \tag{4.11}$$

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.

4.5.7. 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 [36]. 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.

4.5.8. Independent variables

To test the hypotheses presented in section 4.5.1, 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.

4.5.9. 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 [15, 19].
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.

4.5.10. Controlled parameters

The parameters presented in Table 4.2 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).

4.6. 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.

Table 4.2: 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

4.6.1. Nominal scenarios

The overall safely level within the airspace can be observed from the number of intrusion events that occurred throughout a scenario. Figure 4.4 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.

The contribution of the tactical CD&R module can be seen in Figure 4.5 in terms of intrusion severity. Figure 4.4 already shows that the use of state-based CR lowers the number of intrusions in all cases, Figure 4.5 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 Figure 4.6. 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.

Another interesting observation from Figures 4.5 and 4.6 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 in other cases solved using strategic planning.

The operational efficiency performance of the different CD&R strategies can be observed in the average flight time values, presented in Figure 4.7. 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

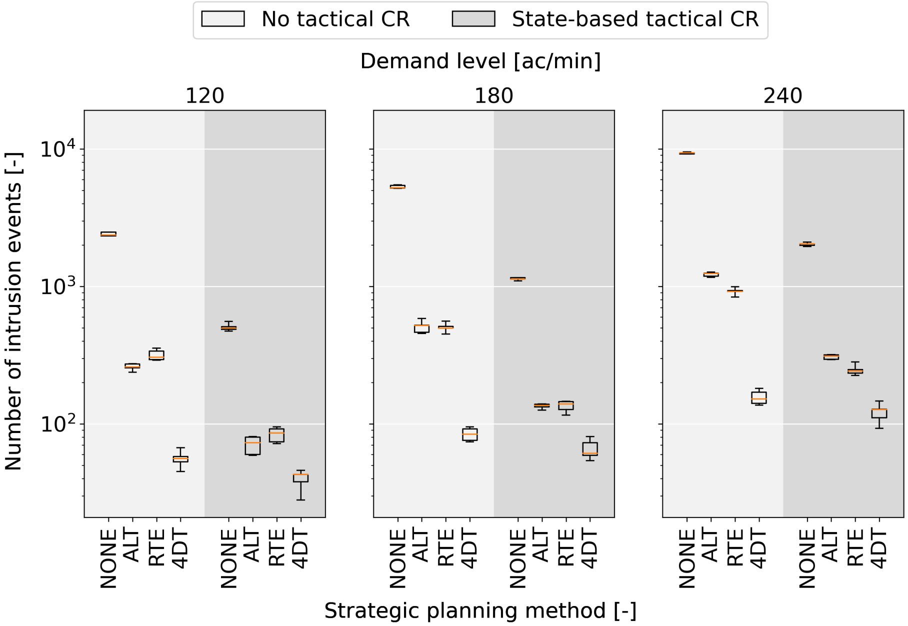

Figure 4.4: The number of intrusion events in function of demand level and CD&R configuration.

4DT case experiences a slight increase in flight duration compared to the RTE strategy. This suggests that the optimisation model underestimates aircraft travel times. Lastly, the presence of state-based CD&R does not significantly affect the average mission travel time.

4.6.2. 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 Figure 4.8, 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.

However, 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

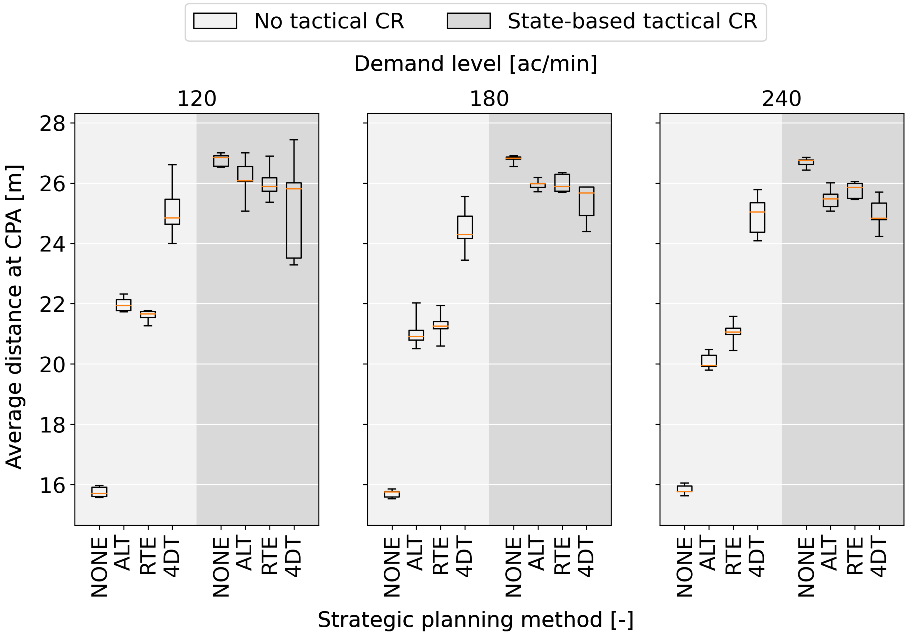

Figure 4.5: Average distance at CPA in function of demand level and CD&R configuration.

required compensation past the velocity performance limits of the aircraft. In these cases, the tactical CD&R module maintains a constant level of performance throughout all conditions.

The effectiveness of the tactical CD&R module against the presence of wind can be seen in Figure 4.9. 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.

Lastly, no significant differences were observed in the average mission duration results.

4.6.3. 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 [37].

As the occurrence of a departure delay alters the flight plan significantly, the increase in the number of intrusion events seen in Figure 4.10 is according to

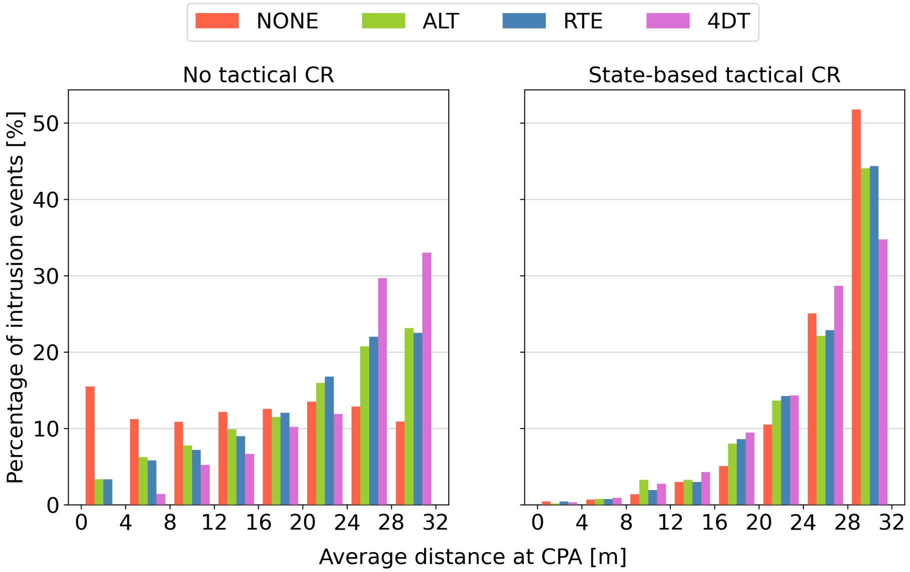

Figure 4.6: Histogram of the average distance at CPA in function of tactical and strategic CD&R configuration, with a 4m bin size.

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. 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 Figure 4.11. 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.

4.7. 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 due to the use of an improved version of the strategic optimisation model compared to previous implementations in [8, 15].

A surprising result can be observed when comparing the ALT and RTE strategic planning strategies, which performed similarly across all simulated scenarios.

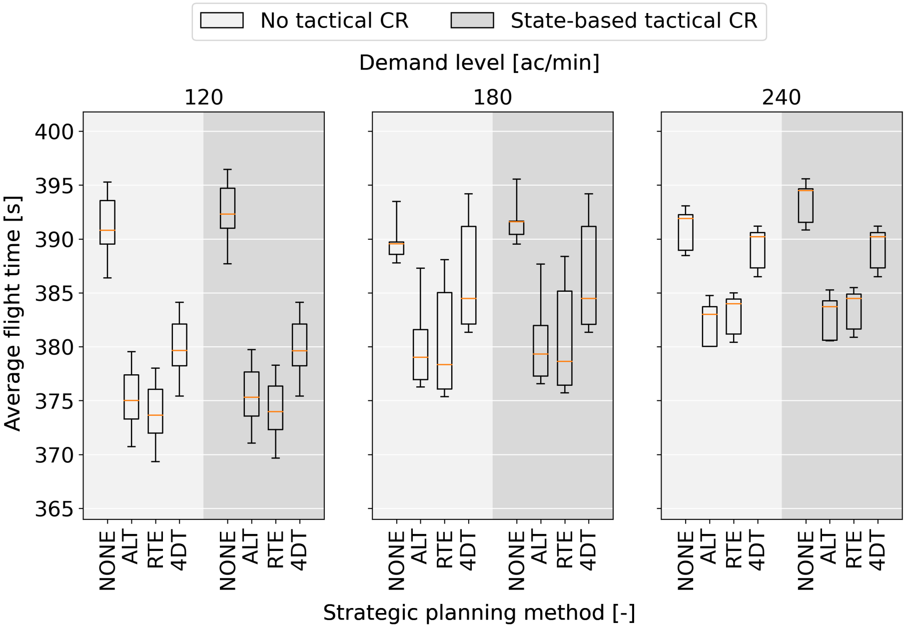

Figure 4.7: Average mission duration in function of demand level and CD&R configuration.

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 the fact 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

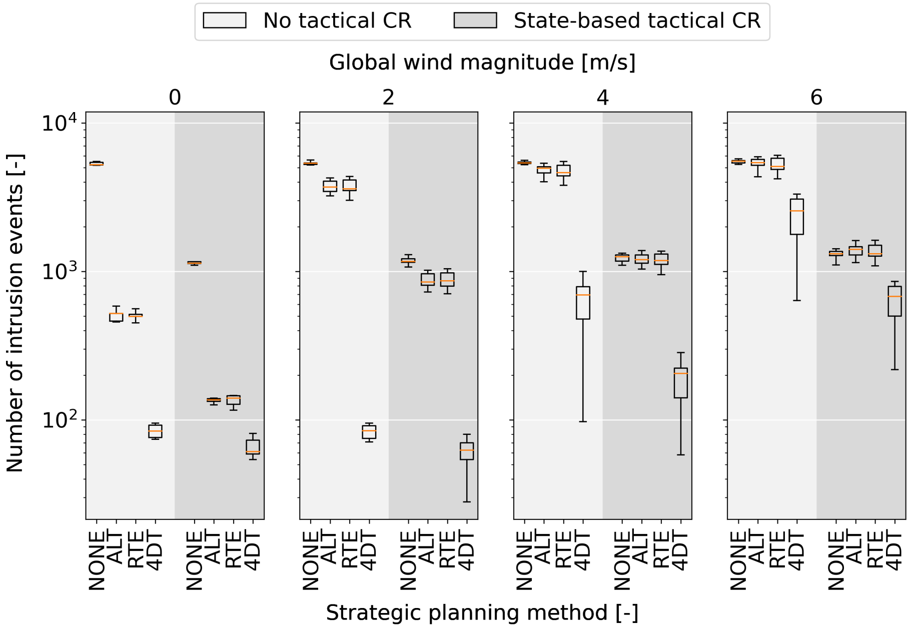

Figure 4.8: The number of intrusion events for wind scenarios in function of wind magnitude and CD&R configuration, averaged over all wind directions.

compensate for the delay by using higher cruise velocities. This implies that future U-space/UTM research should focus on the prediction and incorporation of uncertainties within the tactical and strategic CD&R modules, as the latter is especially susceptible to such factors.

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.

However, the incompatibility between the state-based tactical CD&R method and the strategic planning is apparent when uncertainties such as wind and delay are involved. Their combined performance degrades, despite the robustness of the state-based algorithm against such factors [19]. Thus, a better integration of tactical and strategic CD&R methods is required for improved resilience against low and high levels of wind and delay.

Overall, results prove that current tactical and strategic CD&R algorithms proposed for use within U-space/UTM operations contribute towards increasing the safety level in VLL constrained urban airspace. Furthermore, they highlight the potential of the tactical module to be improved such that the required level of planning detail of the strategic module is reduced, leading to better operational

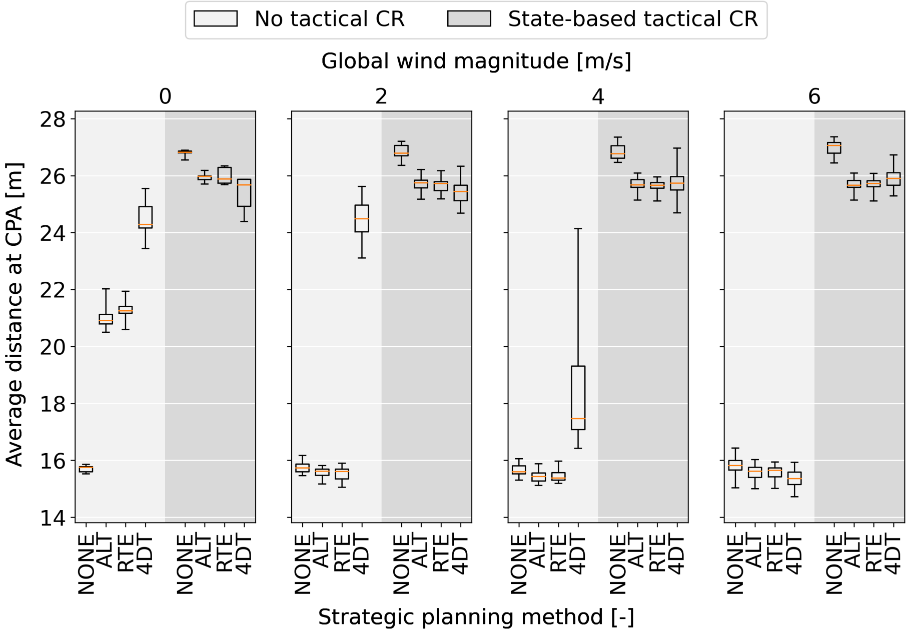

Figure 4.9: Average distance at CPA for wind scenarios in function of wind magnitude and CD&R configuration, averaged over all wind directions.

efficiency and reduced system complexity. However, future developments should aim to increase the compatibility of these modules to better account for uncertainties such as wind and delays.

4.8. CONCLUSION

4.8.1. Main findings

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 prevalent departure delay. In such situations, tactical CD&R provides the required short-term reactivity required to

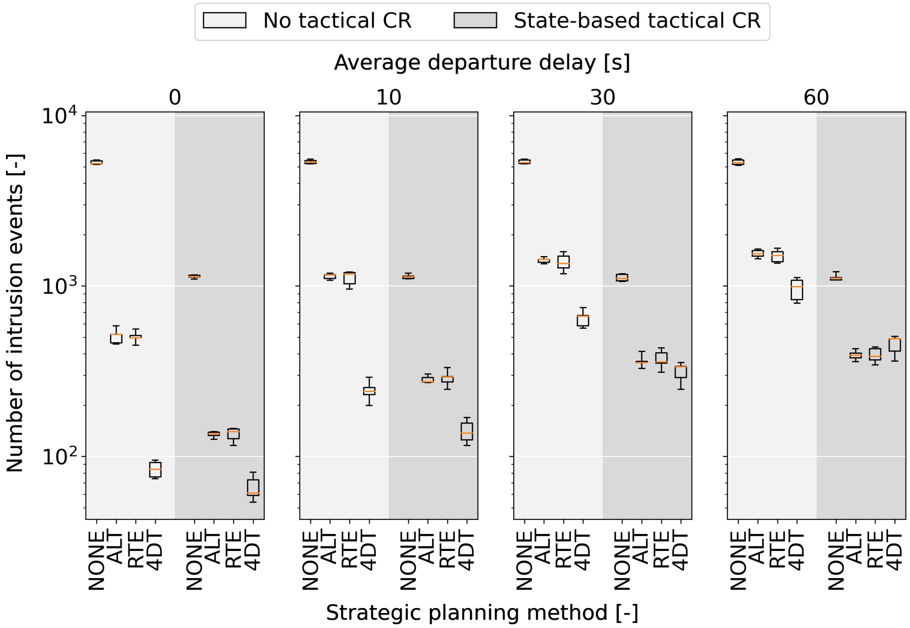

Figure 4.10: The number of intrusion events for departure delay scenarios 10% delay probability.

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.

4.8.2. Recommendations for future research

An important focus for future research is 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 [22], which is undesirable. Thus, future research should investigate whether more efficient methods can be used to better account for such operational uncertainties.

The present study uses two commonly used strategic and tactical methods. Previous studies in literature mostly focus on only one of the aforementioned modules, with simplified implementations of the other [8, 9, 19]. While this work reveals some issues of VLL urban airspace CD&R systems that still need to be resolved, future research may still be required to investigate a wider range of methods and combinations.

Lastly, the study in this chapter implements simplified vehicle, wind, and delay models to better isolate the performance of the CD&R methods and

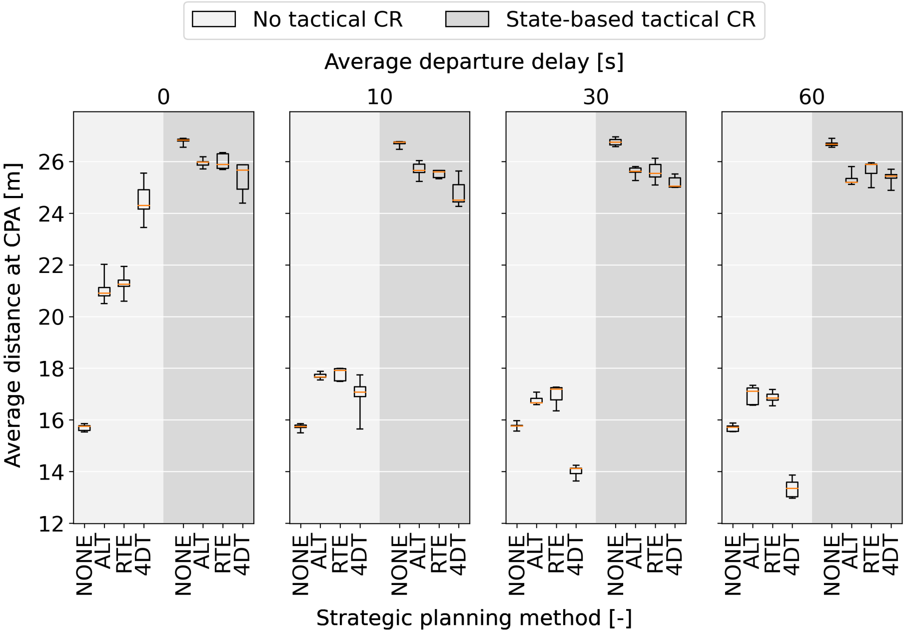

Figure 4.11: Average distance at CPA for departure delay scenarios; 10% delay probability.

reduce confounding factors. 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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5

INTENT INFORMATION IN TACTICAL CD&R FOR VLL U-SPACE

One of the shortcomings of state-based tactical conflict detection and resolution (CD&R) methods when used within a topologically organic network airspace is the high prevalence of false-positive and false-negative detections. These can result in unnecessary disruptions in the traffic flow, or conflicting situations with a very short time for resolution manoeuvring.

In this chapter, a set of novel tactical CD&R algorithms are developed and tested for use in very low level (VLL) constrained urban airspace. These make use of the network topology and intent information from other agents respectively to improve the resolution process and reduce the false-positive and false-negative detection rates. The results of the simulations indicate that such methods can significantly improve the airspace level of safety, while also showing that intent information is not necessarily required as long as aircraft are confined to flying above the existing street network.

This chapter is based on the following publications:

- C. A. Badea, J. Ellerbroek and J. Hoekstra. 'The Benefits of Using Intent Information in Tactical Conflict Resolution for U-space/UTM Operations'. In: *IEEE Transactions on Intelligent Transportation Systems* (2024). DOI: 10.1109/TITS.2024.3505981

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 work in the chapter 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.

5.1. 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 [2] to urban air mobility [3] and infrastructure surveillance [4]. 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 [5]. High-level concepts of operations have been developed to set general functioning principles and a framework for both U-space [6–8] and UTM [9, 10] 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 [7]. Literature shows that this method is highly effective at improving urban airspace safety [11–13]. 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 [14].

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 [15–17]. 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 [18]. 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 [19]. 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)[20]. 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 [21]. A study of a comparable algorithm in [22] 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 should be implemented [23]. Prototype implementations of U-space services, such as [14], 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 [24].

5.2. 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.

5.2.1. 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 5.1. Using state information only (Figure 5.1a) 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 5.1b). Lastly, if intent information is also exchanged between agents, it can better facilitate the CD&R process (Figure 5.1c). A conflict detection and resolution algorithm is developed for each of these levels of information, presented further in this work.

5.2.2. Tactical conflict detection methods

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 [21][15]. 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 [17]. A predicted intrusion is then considered a conflict.

A visual representation of the conflict detection method used in this work is presented in Figure 5.2. 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 ($\mathbf{x}_{\mathrm{rel}}$) and the protection zone radius (R_{pz}) in function of time (τ) as follows:

$$\mathrm{CC} = \left\{ \mathbf{v} : \|\mathbf{v} - \frac{\mathbf{x}_{\mathrm{rel}}}{\tau}\| \leq \frac{\mathrm{R}_{\mathrm{pz}}}{\tau}, \forall \tau \in (0, \infty) \right\} \tag{5.1}$$

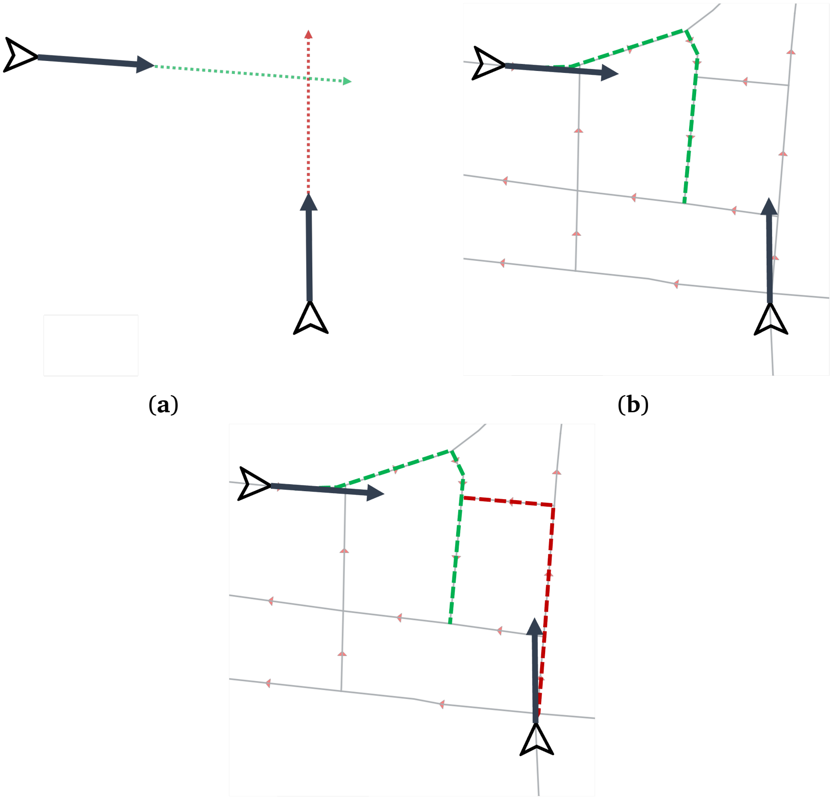
If the relative velocity between two aircraft ($\mathbf{v}_{\mathrm{rel}}$) is within the bounds of the shaded area, an intrusion event is predicted to occur:

$$\mathbf{v}_{\mathrm{rel}} \in \mathrm{CC} \implies \text{Conflict} \tag{5.2}$$

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.

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 (instead of 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 consider all possible actions of others and make decisions


(a)

(b)

(c)

Figure 5.1: Information sources for CD&R in constrained airspace: (a) state only; (b) state + street topology; (c) state + street topology + intent.

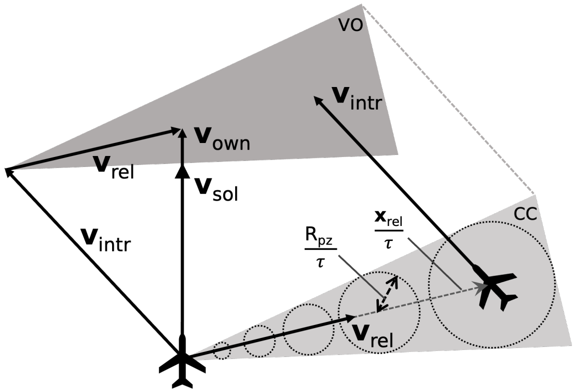


Figure 5.2: State-based conflict detection and resolution using velocity obstacles.

accordingly to prevent dangerous situations from occurring.

A visualisation of the functioning principle of the worst-case CD method is presented in Figure 5.3. The ownship (AC1) is aware of its 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 5.1. For each of the possible conflict nodes, the along-path distance and number of turns are computed and communicated to the conflict resolution module.

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 [25]. The use of intent for CD&R in constrained urban airspace is hypothesised to have the benefit of reducing routing uncertainty and lower the number of false-positive conflict detections [26]. 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 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

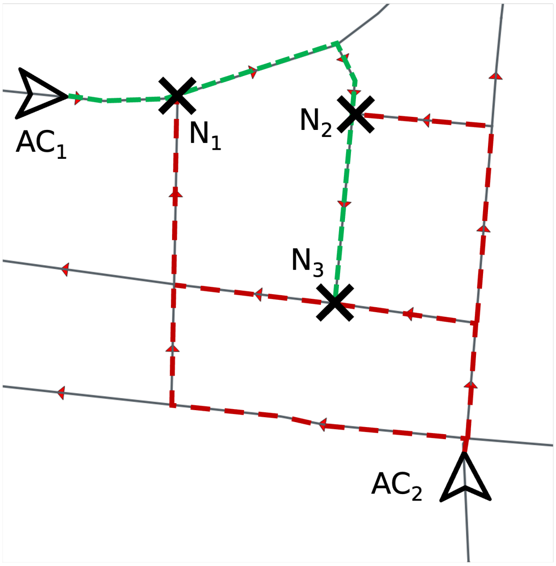


Figure 5.3: Functioning principle of the worst-case conflict detection method. The ownship (AC1) accounts for all possible paths that the intruder (AC2) could take, and determines all possible conflict nodes (marked with “x”).

Algorithm 5.1: Worst-case CD algorithm from the ownship perspective.

```
pairs = all (ownship, intruder) | distance < max_dist
for 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
    for intersection nodes do
        Calculate the distance to node
        Determine the number of turns until node
        Store calculated values to node_data_array
Append conflict pairs that were only detected by state-based detection to conflict_pairs
return conflict_pairs, intersection_nodes, node_data_array
```

conflict node. A visualisation of the method is described in Figure 5.4, where two aircraft locate a conflicting node within a directional street network using exchanged intent information.

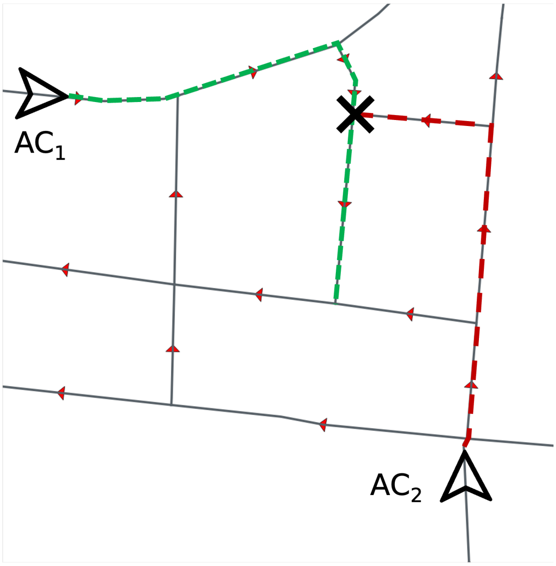


Figure 5.4: Functioning principle of the intent-based conflict detection method. The ownship (AC1) is aware of the intended route of the intruder (AC2), and locates the conflict node (marked with “x”).

A pseudocode representation for the intent-based conflict detection algorithm is presented in Algorithm 5.2. 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.

5.2.3. Tactical conflict resolution methods

State-based conflict resolution

The state-based conflict detection method is used in combination with a velocity-obstacle resolution algorithm [27], as the lack of access to street topology information limits the effectiveness of halting manoeuvres (used within the other CR methods presented in this work). Furthermore, this combination has been studied in previous work ([20, 26, 28, 29]), 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 5.2. The collision cone (CC) obtained during the detection process is transposed using the velocity of the intruder ($\mathbf{v}_{\text{intr}}$) to the frame of reference of the ownship to obtain the velocity obstacle (VO). A solution ($\mathbf{v}_{\text{sol}}$)

Algorithm 5.2: Intent CD algorithm from the ownship point of view

```
pairs = all (ownship, intruder) | distance < max_dist
for 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
    for intersection nodes do
        Calculate the distance to node
        Determine the number of turns until node
        Store calculated values to node_data_array
Append conflict pairs that were only detected by state-based detection to conflict_pairs
return conflict_pairs, intersection_nodes, node_data_array
```

can be chosen along the direction of the ownship velocity ($\mathbf{v}_{\text{own}}$) 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 [30]. Due to the nature of the allocated airspace, aircraft cannot solve conflicts cooperatively as in previously proposed CD&R algorithms (e.g., [31, 32]), as aircraft must unilaterally slow down for turns to reduce overshoot. Thus, to determine which aircraft must perform a manoeuvre, the resolution algorithm is augmented with priority logic, as shown in Algorithm 5.3. 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.

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;

Algorithm 5.3: State-based CR algorithm used in this work.

```
conflict_pairs = all (ownship, intruder) | state-based conflict
for 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
    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
        ▷ Aircraft are issued cruise speed commands if they have priority over all intruders.
for aircraft do
    if aircraft has priority in all involved conflicts then
        return Cruise speed command
```

2. Otherwise, the aircraft with the shortest estimated time of arrival at the intersection node has priority.

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 5.5, involves determining the position at which the aircraft of lower priority must stop 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.

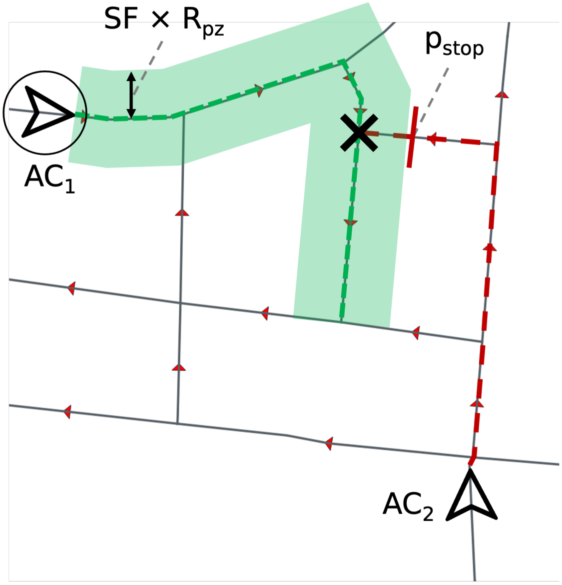


Figure 5.5: Functioning principle of the conflict resolution method used with the worst-case and intent CD methods. The protection radius of the ownship (AC1) is shown as a circle. The route of the higher priority aircraft is buffered by the protection radius scaled with a safety factor ($SF \times R_{pz}$) to determine the location of the stopping point p_{stop}.

The pseudocode representation of this conflict resolution method is presented in Algorithm 5.4. The logic accounts for the existence of multiple intersection nodes, each with its 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.

Algorithm 5.4: CR algorithm used in combination with Intent-based or Worst-case CD from the ownship point of view

```
for ownship, intruder in conflict_pairs do
    if state-based only conflict then
        Apply state-based Algorithm 5.3
    else if intruder is behind andon same route then
                                        ▷ ownship has priority, continue cruise
        return None
    else if intruder is in front andon same route then
                                        ▷ intruder has priority
        return Match intruder speed
    else
                                        ▷ Create empty list of potential solutions
        solutions = []
        for 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
        Select the most conservative solution (slowest) as the main solution.
```

If this set of rules and algorithm would be applied to the situation described in Figure 5.3 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).

Given these solutions and following the logic presented in Algorithm 5.4, the resolution action for both aircraft at this 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 5.5 occurs, where the intruder (AC2) must stop ahead of the conflict node to resolve the conflict.

5.3. EXPERIMENT

5.3.1. 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.

5.3.2. Simulation environment

A simulation environment is used to test the hypotheses presented in Section 5.3.1, based on the layout of the city centre of Vienna, shown in Figure 5.6, extracted and converted into graph format using OpenStreetMap [33] data and the OSMnx Python package [34]. 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 [35]. 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 [36].

Figure 5.6: Constrained airspace structure extracted from the street network of the city centre of Vienna.

The BlueSky Open Air Traffic simulator [24] 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 [37].

5.3.3. 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:

1. All streets have a singular direction of travel (one-way). This reduces the probability of head-on conflicts occurring and increases safety [38].
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 [26, 28].
3. Aircraft must follow the centre axis of streets to avoid interference with urban obstacles (e.g., buildings).

5.3.4. 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 [39]. 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 [40]. Furthermore, as previously mentioned, vertical manoeuvres are not during the cruise phase, as these have a major negative effect on airspace safety [26]. 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 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.

5.3.5. 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 5.1.

Table 5.1: Characteristics of the DJI Matrice 600 drone model included in BlueSky, based on manufacturer specifications [41].

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

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 [42].

5.3.6. 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 [35]). 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:

$$\mathrm{mag}_{street} = \mathrm{mag}_{roof} \cos\left(\Delta_{bearing}\right) \tag{5.3}$$

$$\mathrm{dir}_{street} = \begin{cases} 1, & \text{if } \Delta_{bearing} < 90 \\ -1, & \text{otherwise} \end{cases} \tag{5.4}$$

Thus, the effect on the cruising ground speed (Δ_{gs}) of an aircraft flying along a street is computed using Equation 5.5.

$$\Delta_{gs} = \text{mag}_{street} \times \text{dir}_{street} \tag{5.5}$$

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 [43]. Thus, as aircraft must traverse several streets 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.

5.3.7. 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 [15, 39].
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.

5.3.8. 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 5.3, 5.2, and 5.1.
3. Total number of intrusion events
   - Within the present study, the minimum separation limit between two aircraft was set as 32 metres, used in previous studies on U-space operations [15, 26].
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.

5.3.9. Control variables

Table 5.2 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.

Table 5.2: 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

5.4. RESULTS

5.4.1. Safety

The following section presents the results of the safety metrics obtained from simulating the no-wind traffic scenarios. Figure 5.7 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.

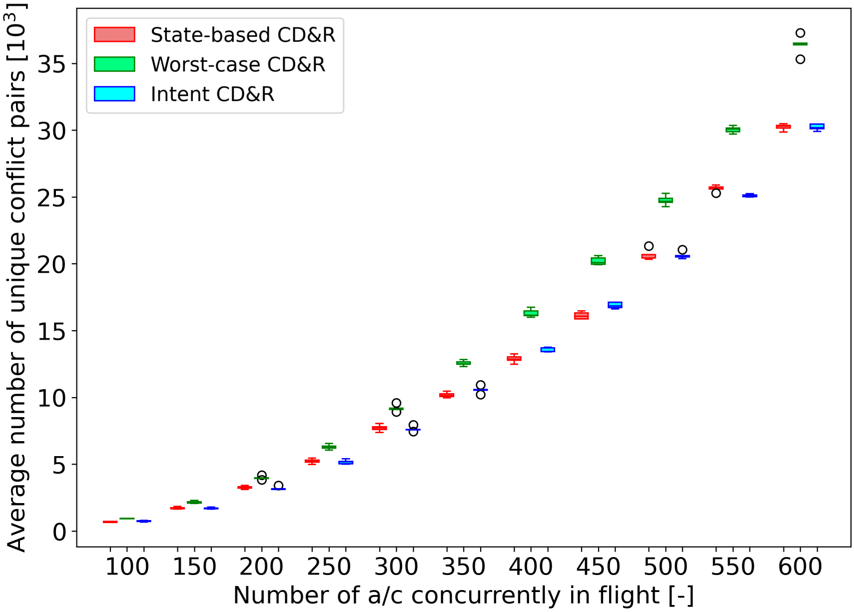


Figure 5.7: Average number of unique conflict pairs detected by each method in function of traffic demand level for no-wind scenarios with conflict resolution enabled.

The average number of intrusion events for each scenario is presented in Figure 5.8. 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 indicate that the intent and worst-case CD&R methods consistently performed similarly in mitigating conflicts.

Figure 5.9 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.

The last safety metric considered in this work is the average distance at the

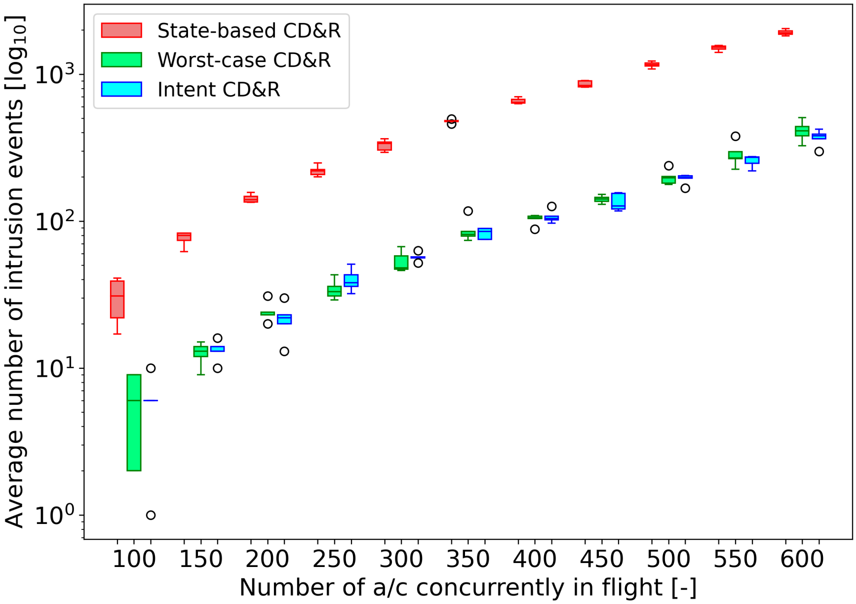


Figure 5.8: Average number of intrusions detected by each method in function of traffic demand level for no-wind scenarios with conflict resolution enabled.

closest point of approach, presented in Figure 5.10. 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 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.

5.4.2. 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 5.11. 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.

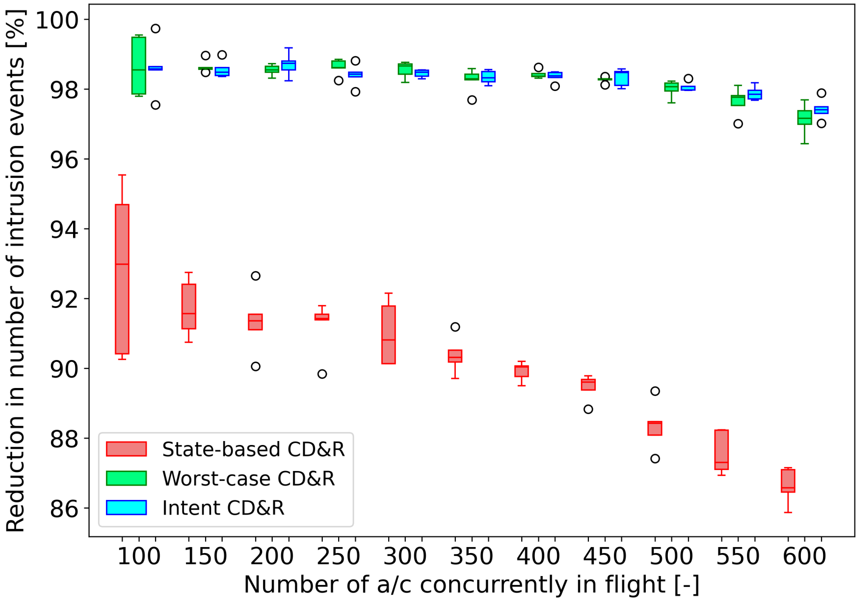


Figure 5.9: Percentage reduction in the number of intrusion events from the use of CD&R compared to traffic scenarios with no CD&R enabled.

5.4.3. Wind traffic scenarios

The following section presents the safety and efficiency results of the wind-inclusive simulations. Figure 5.12 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 slowdown 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 5.13. 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 [15].

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 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

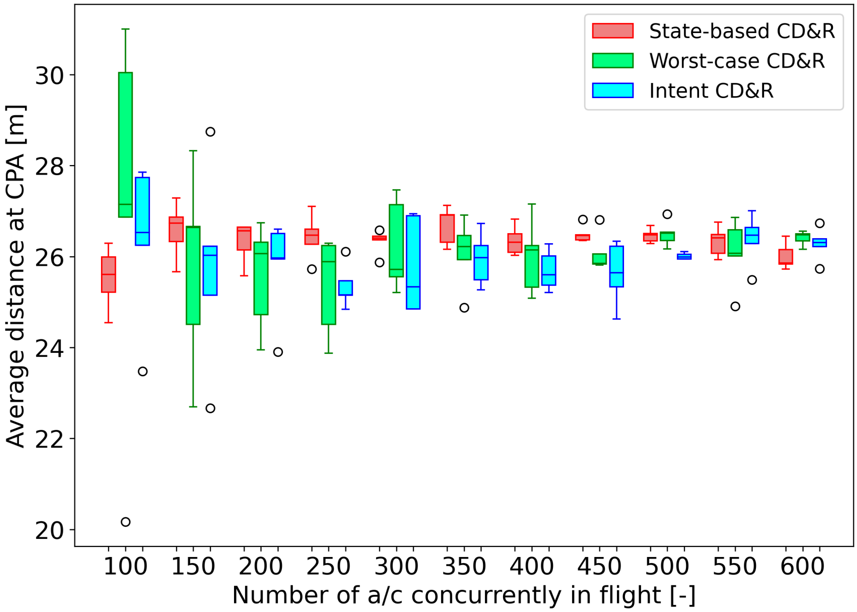


Figure 5.10: Average distance at CPA during intrusion events in function of traffic demand level for no-wind scenarios with conflict resolution enabled.

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 5.14. This indicates that the inclusion of street geometry information within the detection process increases the safety level in high-uncertainty conditions.

5.5. 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 indicate 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

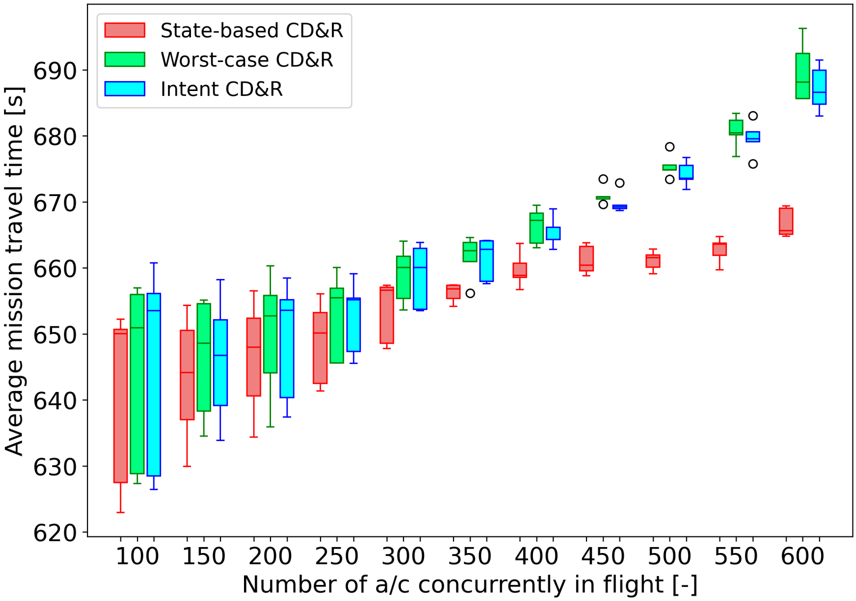


Figure 5.11: Average mission travel time for each method in function of traffic demand level for no-wind scenarios with conflict resolution enabled.

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

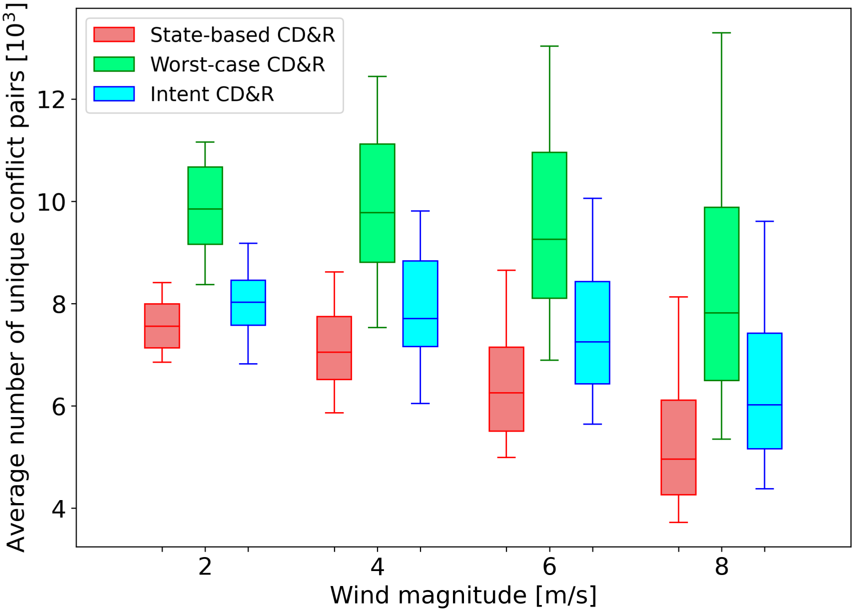


Figure 5.12: Number of conflicts for varying wind magnitudes with 300 aircraft concurrently in flight, averaged over all tested wind directions (0°, 90°, 180°, 270°).

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 have been proposed and studied [43, 44], as well as urban wind models produced through computational fluid dynamics simulations [45, 46]. The further development and scaling of these methods for use across large urban areas is important for future U-space operations.

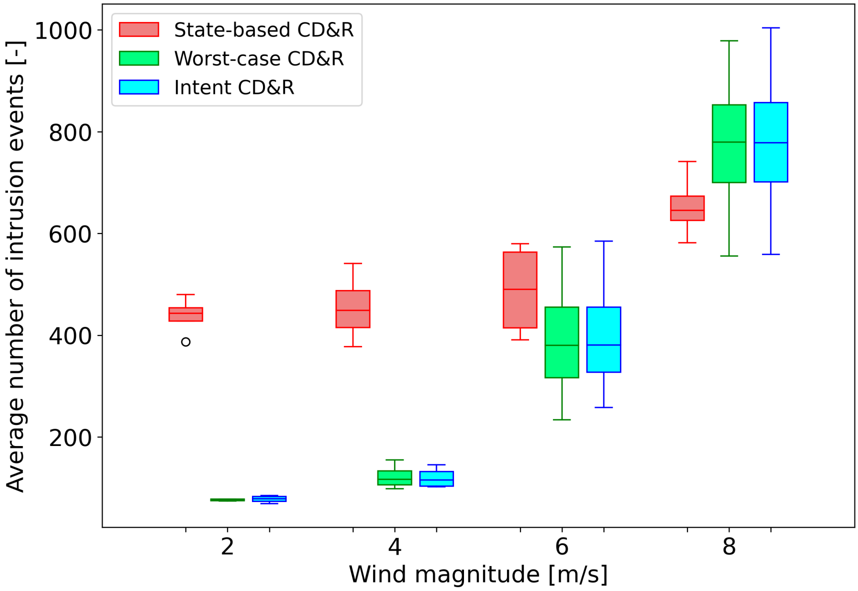


Figure 5.13: Number of intrusion events for varying wind magnitudes with 300 aircraft concurrently in flight, averaged over all tested wind directions (0°, 90°, 180°, 270°).

Overall, the results strongly suggest 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.

5.6. CONCLUSION

5.6.1. Main findings

The study in the chapter 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

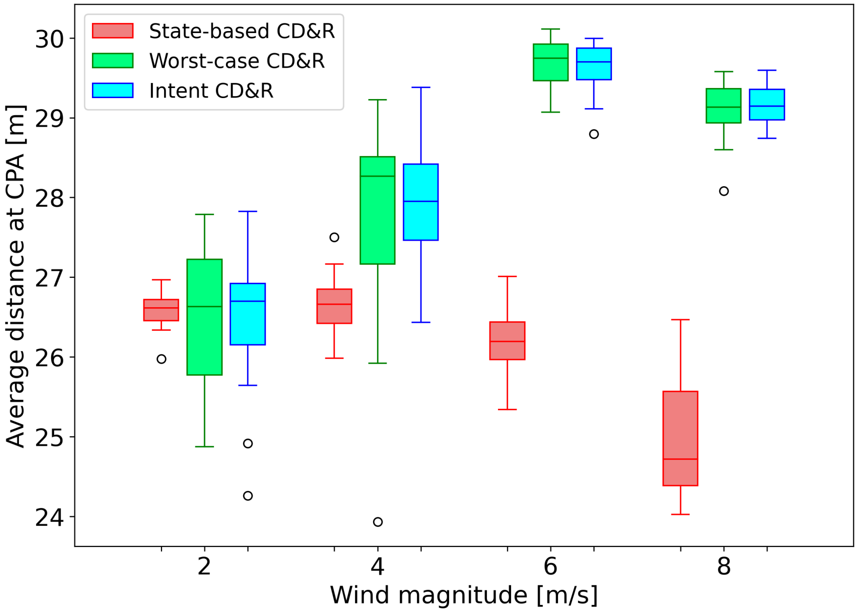


Figure 5.14: Average minimum distance during intrusion events for varying wind magnitudes with 300 aircraft concurrently in flight, averaged over all tested wind directions (0°, 90°, 180°, 270°).

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 in safety and efficiency 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 chapter 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.

5.6.2. 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 [39]. 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 can 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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6

ADAPTING CD&R METHODS FOR UNCERTAINTIES

Part of the investigations presented in the previous two chapters focused on observing the effect of uncertainties such as wind and departure delay on the performance of both strategic and tactical deconfliction approaches. The benefits of using pre-departure flight plan optimisation are shown to rapidly degrade with increasing level of uncertainty, and the use of tactical conflict detection and resolution (CD&R) is often unable to compensate for this. This can mostly be attributed to flight plan over-optimisation, leading to reduced safety margings for the purpose of increasing efficiency.

The following chapter presents a more robust approach towards a hybrid CD&R system seeking to improve the resilience of flight plans against uncertainties. The conservative tactical CD&R method presented in the previous chapter is combined with a strategic pre-departure flight planning approach that aims to better distribute traffic within the airspace network. This lead to a significant improvement in the robustness against uncertainties while minimally impacting the safety and efficiency levels when compared to the methods investigated within the previous chapters.

This chapter is based on the following publications:

- C. A. Badea, A. Vidosavljevic, J. Ellerbroek and J. Hoekstra. 'Robust Conflict Detection and Resolution for High-Uncertainty Very-Low-Level Constrained Urban Airspace Operations'. In: *Transportation Research Interdisciplinary Perspectives* (2024). Submitted. DOI: 10.4121/d3855a88-7ab8-40ae-93ae-09c0c5ab1fca

ABSTRACT

The concept of urban air mobility is rapidly advancing, with much research being dedicated towards the development of the air traffic management services required for such operations. An important component of unmanned air traffic management (U-space/UTM) is conflict detection and resolution (CD&R), tasked with ensuring the operational safety of such systems. Strategic flight plan optimisation and tactical CD&R methods have generally been studied independently, leading to suboptimal performance when deployed simultaneously in simulated high-density very-low-level constrained urban airspace environments. Furthermore, the limited flexibility of pre-departure 4D trajectory planning methods towards dynamic and uncertain environmental and operational conditions (i.e., wind and delay) produces a degradation in safety that is difficult to mitigate using tactical manoeuvring. In this work, we design a traffic-flow capacity strategic optimisation method that aims to be robust against flight plan deviations and to better complement tactical CD&R methods. The performance of the proposed strategic and tactical deconfliction module is tested within constrained urban airspace traffic scenarios simulated using the BlueSky Open Air Traffic Simulator. The results are compared with other methods, such as 4D trajectory planning and state-based CD&R.

6.1. INTRODUCTION

The substantial global interest in urban air operations has led aviation authorities worldwide to initiate concepts of operations for the management of this new type of air traffic. They promise to provide a safe and sustainable alternative to current ground-based transportation methods, and relieve the increasing congestion of cities [2]. For example, the U-space [3–5] and UTM (unmanned air traffic management) [6, 7] proposals, designed for managing urban air traffic in the European Union and United States respectively, establish the groundwork for developing the services for such operations.

An important component of U-space/UTM systems is the conflict detection and resolution (CD&R) module, tasked with ensuring that urban air operations are performed safely. This module is generally composed of two subcomponents: strategic, and tactical CD&R [8]. The role of the first is to proactively prevent unsafe operational situations well in advance of their occurrence, while the latter is used to resolve conflicts reactively within a short look-ahead time [9]. These components are an area of active research within the U-space/UTM domain, as their compatibility with other urban airspace systems and their robustness within dynamic and uncertain environments still needs to be improved [10].

One approach to creating a unified CD&R system is the use of dynamic re-routing in combination with tactical deconfliction [11, 12]. This method aims to resolve conflicts by modifying the flight plan of departed aircraft. However, such methods are highly susceptible to inducing airspace instability and negatively affect the predictability of the actions of agents within the system, and need to be intensely studied to predict and capture undesirable emerging behaviour within high-density multi-agent systems such as U-space/UTM.

Another proposal for the architecture of the CD&R module is the sole use of pre-departure strategic deconfliction in combination with tactical conflict resolution [13, 14]. The first is typically approached as a global optimisation problem [15], where all flight plans of requested missions are jointly deconflicted before departure. When relying on this manner of pre-departure deconfliction, compliance with the allocated trajectory is critical to maintain the safety level of operations, resulting in strict constraints in the execution of the flight plan [16].

A drawback of this highly constrained approach is that it can impair the effectiveness of the tactical CD&R module, especially if the requirements and functioning parameters of the latter are not accounted for [13]. The presence of environmental and operational uncertainties can also lead to degradation in the effectiveness of following the flight plan, as the frequent use of tactical manoeuvring can lead to performance degradation (i.e., conflict hotspots and traffic bottlenecks). Thus, the key question is whether to mainly rely on strategic deconfliction with the tactical module handling the remaining, unforeseen situations, or a combination in which the deconfliction responsibility is shared.

The aim of the work at hand is to investigate and develop a low-complexity and robust approach to pre-departure strategic flight planning and tactical CD&R for use in very-low-level (VLL) constrained urban airspace operations. In our previous work [13, 17], we identified several issues that still need to be addressed to improve the synergy and resilience of U-space/UTM operations in the presence of uncertainties (i.e., wind and departure delay). One of the most important factors we identified is the over-optimisation of flight plans (i.e., reducing safety margins for increased efficiency leading to decreased robustness), which greatly affects operational safety in the presence of uncertainties [18]. We thus propose a CD&R framework that combines traffic flow capacity management and a tactical resolution method tailored for use in urban airspace based on organic street networks to address this issue.

6.2. PRE-DEPARTURE STRATEGIC CONFLICT DETECTION AND RESOLUTION

The following section presents a pre-departure strategic flight planning concept aimed at improving the synergy when combined with tactical CD&R methods for constrained urban airspace and robustness against uncertainties such as wind and delay. The main functioning principle is to replace time or distance-based strategic separation with flow capacity management. Thus, the strategic deconfliction process focuses on mitigating traffic density hotspots, allowing the tactical deconfliction module to function more effectively and solve conflicts locally.

6.2.1. Design considerations

Our previous research on pre-departure strategic planning for VLL constrained urban airspace [13] shows that while 4D trajectory planning can be effective in preventing conflicts in nominal conditions, it is highly susceptible to environmental and operational uncertainties, which hinder the ability of aircraft to comply with their flight-plan and thus the effectiveness of the deconfliction method. As a consequence, conflict hotspots can arise, which in turn lead to further tactical manoeuvring, exacerbating flight-plan non-compliance.

One of the sources of instability and degraded performance against uncertainties is over-optimisation of flight plans in the pre-departure phase [18], which results in a low tolerance for deviations. In nominal conditions, conflicts are prevented, as aircraft are able to comply with the allocated flight plan, with tactical intervention rarely required. However, with increasing level of uncertainty (i.e., wind and delay), the majority of conflicts are resolved through the use of tactical manoeuvring, thus reducing the effectiveness of the strategic planning module [13]. Because higher local aircraft densities and multi-aircraft conflict hotspots result from these tactical interactions, the performance of tactical CD&R algorithms is also reduced.

Traditional methods like stochastic and robust optimisation could be used to address uncertainty in this optimisation problem. However, stochastic optimisation requires knowledge of the probability distribution of unknown variables, which may not be available [19]. On the other hand, robust optimisation, while guaranteeing feasibility against worst-case scenarios, can lead to overly conservative solutions that sacrifice system efficiency and capacity [18].

To mitigate these issues, we propose the use of flow-based capacity management as a replacement method for strategically planning the routes of aircraft in VLL constrained urban airspace in combination with a conservative tactical deconfliction algorithm. By limiting the number of aircraft that can traverse an intersection within a specific time window, traffic can be better distributed throughout the network, leading to lower local traffic densities. The focus of the strategic planning module is thus shifted, from resolving individual predicted conflict situations, to reducing their complexity (i.e., reducing the occurrence of multi-aircraft conflicts). Then, the tactical deconfliction module can function more effectively and resolve the remaining conflicts.

6.2.2. Trajectory planning in constrained urban airspace

The problem of trajectory planning in urban airspace with flow constraints has been previously investigated in [16]. This study formulates trajectory planning as an Integer Linear Programming (ILP) problem, and uses that to optimise a relatively high number of flights within the standard Sioux Falls network (24 nodes, 76 links) while enforcing a maximum link flow capacity. The issue with such an approach is that the number of variables of the problem increases greatly with increasing number of nodes and links, especially if drones are expected to fly above inner-city streets. The modelling of these areas requires a larger number of network features, increasing the required solving time beyond reasonable limits.

To tackle this, we propose to limit the trajectory choice to a set of pre-generated paths to reduce the number of variables in the problem. This method has been successfully applied in previous work [13, 20]. Thus, the set of possible paths for a single flight request is created using the method illustrated in Fig. 6.1. First, the shortest path between the origin and destination is computed. Then, alternatives are generated by making sections of the shortest route undesirable for travel (i.e., increasing the weight of using the network links). Alternatives 1,2 and 3 are generated by dividing the shortest route into three equal sections and routing around each at a time. The last alternative is routed such that the shortest route is avoided completely. A route generation example within the street network of Wien, Austria is presented in Fig. 6.2.

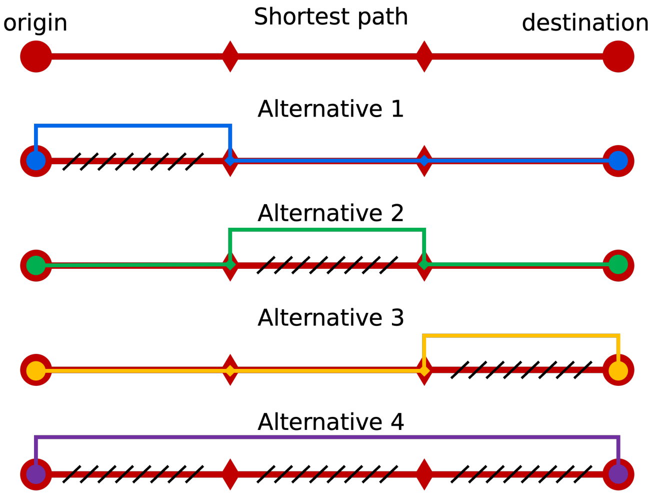


Figure 6.1: Alternative route generation functioning principle: routes are generated such that either a part or the whole shortest route is avoided.

It should be noted that the methodology used to generate alternative routes is not the main focus of this work, and is only applied to obtain a diverse set of routing possibilities while still maintaining the total travel distance within reasonable margins. Compared to the route generation method used by Berzeiat et al. [20] (i.e., selecting a random intermediate node), the strategy used in this work does not result in self-intersecting or infeasible trajectories. Future iterations of this method should be improved through the use of historial traffic data to generate alternative routes that avoid conflict and traffic hotspots.

6.2.3. Network flow capacity management

The functioning principle of the strategic CD&R method introduced in this work is the planning of aircraft trajectories such that the number of aircraft that can

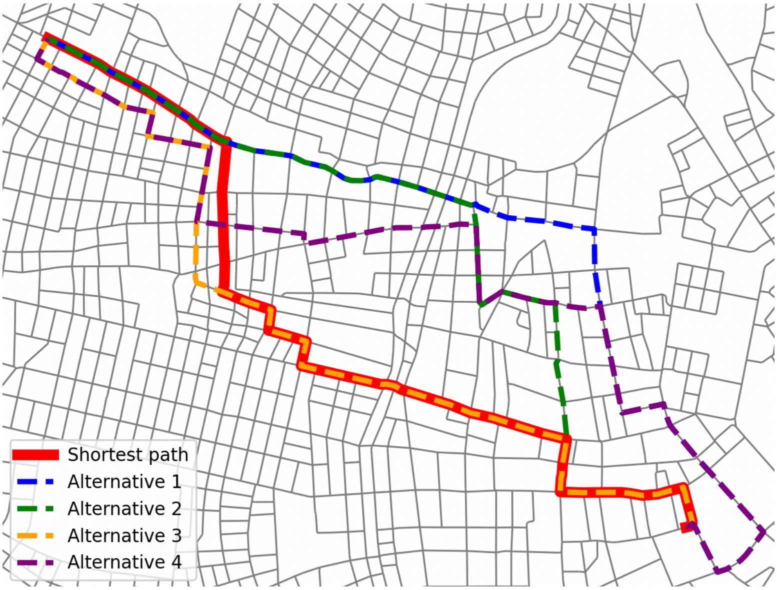


Figure 6.2: Route generation example within a street network graph, with the origin in the right bottom corner.

traverse an intersection (i.e., network node) within a given time window (T_w) is limited. An overlapping time window structure is used, as shown in Fig. 6.3, to avoid high traffic densities at the boundaries of the time windows. For example, if an aircraft is predicted to be at a node at time $1.8T_w$ and only one aircraft is allowed within one time window, then no other aircraft cross the node between $1T_w$ and $2.5T_w$.

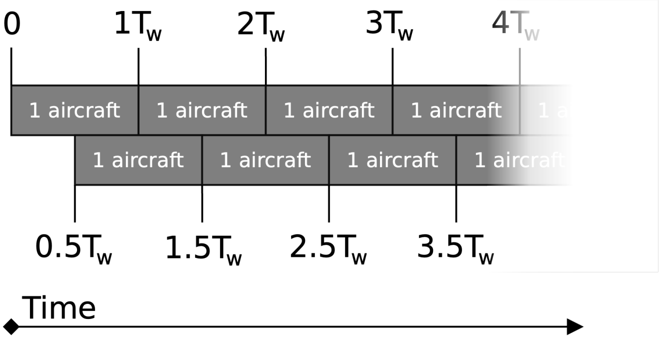


Figure 6.3: Structure of overlapping time windows at each intersection within the urban airspace network.

To enforce a flow limit, the time of arrival at each intersection (network node) is estimated for all pre-generated paths. Thus, a parameter can be created that quantifies within which time windows are aircraft predicted to traverse a node in function of the selected path. The optimisation consists in allocating paths such that the flow capacity at all nodes is respected, and the total estimated travel time is minimised. In this work, we investigate three time window values: 5, 10, and 20 seconds (equivalent to 0.5x, 1x, and 2x of the tactical CD&R look-ahead time).

6.2.4. Problem formulation

The flow-based flight planning method can be formulated as an ILP optimisation problem. The following section presents the assumptions, parameters, decision variables, constraints, and objective function.

Assumptions

- Aircraft do not change flight altitude during cruise.
- The target cruise airspeed is constant throughout the flight. The actual airspeed adapts in function of flight conditions.
- Take-off and landing manoeuvres do not count towards the flow capacity.
- Aircraft perform turning manoeuvres with a turn radius of 5 metres if the turn angle is greater than 25^o.
- Intended departure time cannot be changed.

Parameters

- F: set of all flight plans
- P_f: set of paths that can be allocated to flight f, $\forall f \in F$
- N: set of all nodes in the street network graph
- Y: set of all available flight levels
- T: set of all time windows
- b_p: estimated cruise flight time if path p is allocated to flight f, $\forall f \in F, \forall p \in P_f$
- $x_{p,n,\theta} \in \{0, 1\}$: 1 if flight f using path p enters node n within time step θ, else 0, $\forall f \in F$, $\forall p \in P_f$, $\forall n \in N$, $\forall \theta \in T$
- C_n: maximum flow for node n, $\forall n \in N$
- $\delta_{f,y}$: estimated time for flight f to ascend to and descend from flight level y, $\forall f \in F, \forall y \in Y$

Decision variables

The optimisation problem is governed by the following decision variable, which represents the allocated flight level and route for each mission:

- $z_{p,y} \in \{0, 1\}$: 1 if path p and flight level y are allocated to flight f, else 0, $\forall f \in F$, $\forall p \in P_f, \forall y \in Y$

Constraints

The first set of constraints ensure that all aircraft are allocated only one path and one flight level.

$$\sum_{p \in P_f} \sum_{y \in Y} z_{p,y} = 1, \quad \forall f \in F \tag{6.1}$$

The next set of constraints enforces the flow capacity limit C_n for each node and time window.

$$\sum_{f \in F} \sum_{p \in P_f} x_{p,n,\theta} z_{p,y} \leq C_n, \quad \forall n \in N, \forall \theta \in T, \forall y \in Y \tag{6.2}$$

Objective function

The objective of the optimisation is to minimise the sum of all mission durations, represented as the summation between the estimated vertical and horizontal travel times for each flight, presented in Eq. 6.3.

$$\text{Minimise} : \sum_{y \in Y} \sum_{f \in F} \sum_{p \in P_f} z_{p,y}(\delta_{f,y} + b_p) \tag{6.3}$$

Flow constraint relaxation

During the testing phase, we encountered situations in which, because of the traffic pattern, airspace configuration, and flow capacity limits, some missions could not be accommodated such that flow constraints are satisfied. As the goal of the proposed flow capacity management model is to reduce local traffic density as to increase the efficiency of tactical CD&R methods, we consider the relaxation of the flow constraint (Eq. 6.2). As a consequence, the enforcement of flow capacity limits is not guaranteed, but is part of the objective function minimisation process. Thus, a second decision variable, that is proportional to the flow capacity violation, is introduced for every node, flight level, and time window:

- $v_{n,\theta,y}$: constraint violation at node n within time window θ at flight level y, $\forall n \in N$, $\forall \theta \in T$, $\forall y \in Y$

Then, the constraint presented in Eq. 6.2 can be reformulated to allow violations, as shown in Eq. 6.4.

$$\sum_{f\in F}\sum_{p\in P_f} x_{p,n,\theta} z_{p,y} - C_n \leq v_{n,\theta,y}, \quad \forall n\in N, \forall\theta\in T, \forall y\in Y \tag{6.4}$$

The violation variable needs to be positive to ensure that capacity is not gained through the use of negative values.

$$v_{n,\theta,y} \geq 0, \quad \forall n\in N, \forall\theta\in T, \forall y\in Y \tag{6.5}$$

Lastly, the objective function presented in Eq. 6.3 is reformulated to include the penalisation of the total violation of the flow constraints, as shown in Eq. 6.6.

$$\text{Minimise}: \sum_{y\in Y}\left(\sum_{f\in F}\sum_{p\in P_f} z_{p,y}(\delta_{f,y} + b_p) + \sum_{n\in N}\sum_{\theta\in T} v_{n,\theta,y}\right) \tag{6.6}$$

Planning time horizon heuristic

To reduce the size of the problem as well as create a solution-oriented approach, the model can be used in combination with a moving planning time horizon, thus allowing the progressive optimisation of flight plans as they are requested. In this work, we use a planning time horizon of 30 minutes. After an initial batch of flight plans is optimised, the decision variable $z_{p,y}$ is fixed for the aircraft that are predicted to still be airborne during the next 30-minute interval. This is achieved by adding the set of constraints described by Eq. 6.7, where the parameter $z^{prev}_{p,y}$ represents the values taken by the decision variable z for the previous batch of flight plans F^{prev}.

$$z_{p,y} = z^{prev}_{p,y} \quad \forall p\in P_f, \forall y\in Y, \forall f\in\{F\cap F^{prev}\} \tag{6.7}$$

6.2.5. Baseline method

To evaluate the performance of the proposed planning algorithm, we compare it to a baseline method. For this we select a 4D trajectory (4DT) strategic deconfliction method that was previously presented in [13]. This type of flight plan management has been previously investigated in both civil and urban airspace operations [13, 21, 22], with promising results in delivering improved operational safety.

In the baseline 4D planning method we use in our comparison, strategic conflict detection and resolution is performed by ensuring that the minimum separation threshold (32 metres in this work) between aircraft is respected at intersections. Thus, aircraft are allocated a route, cruise altitude, and departure time, and are issued a required time of arrival (RTA) for each waypoint within their route. Drone operators are then required to comply with the flight plan through the use of speed adjustments. Tactical conflict detection and resolution is then performed if the need arises during the cruise phase. For more details, refer to [13].

6.3. TACTICAL CONFLICT DETECTION AND RESOLUTION

To investigate the performance of the proposed strategic flight planning strategy within a U-space/UTM system, we implemented and developed three tactical CD&R algorithms previously used within VLL constrained urban airspace research. The first algorithm, used as a baseline method for comparison with previous work, is based on velocity obstacle (VO) theory [23]. The second method is developed specifically for use within airspace defined as a (street) network, and uses knowledge of the airspace topology to predict worst-case situations and resolve conflicts using halt manoeuvres. Lastly, the third algorithm is a combination between the first two: conflicts are detected using velocity obstacles, and resolved using halt manoeuvres.

6.3.1. State-based CD&R using velocity obstacles

Conflict detection and resolution using velocity obstacle theory has been researched and used in previous work pertaining to both classical aviation and U-space/UTM operations [24, 25], and is used as a baseline method within the investigation at hand. The relative position ($\mathbf{x}_{\text{rel}}$) and the protection zone radius (R_{pz}) between aircraft in a conflict pair are linearly extrapolated in time (τ) to obtain the collision cone (CC) according to Eq. 6.8. The obtained set contains all relative velocities ($\mathbf{v}_{\text{rel}}$) that would result in the occurrence of an intrusion event within the look-ahead time (i.e., the minimum separation threshold between two aircraft would be breached).

$$\text{CC} = \left\{ \mathbf{v}_{\text{rel}} : \|\mathbf{v}_{\text{rel}} - \frac{\mathbf{x}_{\text{rel}}}{\tau}\| \leq \frac{R_{\text{pz}}}{\tau}, \forall \tau \in (0, \infty) \right\} \tag{6.8}$$

The velocity obstacle can then be obtained by translating the collision cone using the intruder velocity ($\mathbf{v}_{\text{intr}}$), as shown in Fig. 6.4. Thus, the resolution velocity ($\mathbf{v}_{\text{sol}}$) is obtained by reducing the ownship velocity ($\mathbf{v}_{\text{own}}$) until it lies outside the VO area. The implementation of the velocity obstacle state-based CD&R algorithm is presented in Alg. 6.1.

6.3.2. Worst-case CD&R using halt manoeuvres

The worst-case CD&R method uses a conservative approach to deconfliction that takes advantage of knowledge of the street network characteristics to improve the conflict detection accuracy (more extensively explained in [17]). It is shown to perform better in nominal conditions compared to the state-based VO method through the use of halt manoeuvres performed closer to the predicted conflict location. Thus, many false-positive conflicts are resolved before any action is required, which improves airspace stability and lowers the

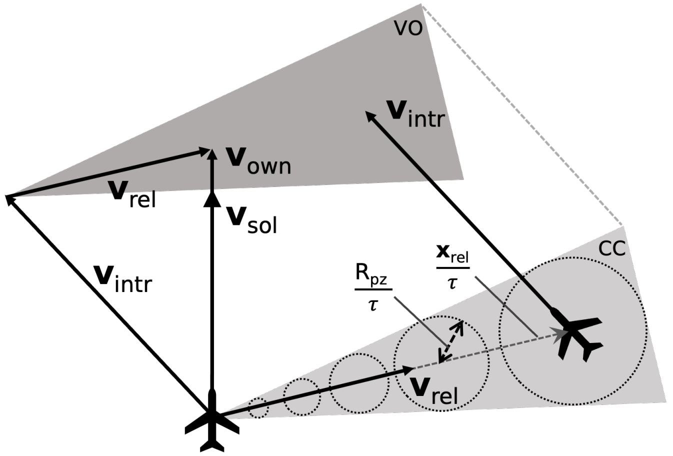


Figure 6.4: State-based conflict detection and resolution using velocity obstacles.

Algorithm 6.1: State-based CR using velocity obstacles.

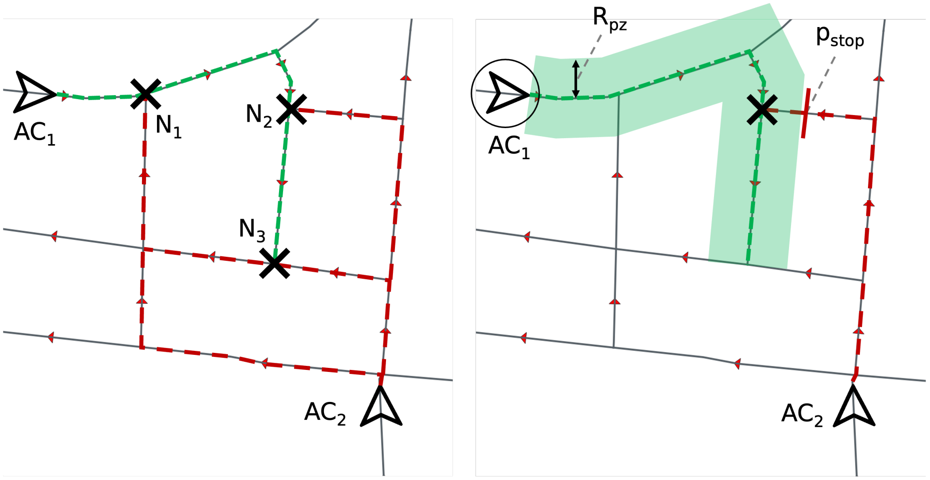
```
conflict_pairs = all (ownship, intruder) | state-based conflict
for ownship, intruder in conflict_pairs do
    if loss of separation then
        if intruder is in front or closer to path intersection then
            return Halt
    else if intruder is in front then
        return Match intruder speed
    else if intruder closer to intersection then
        return Lower speed VO command
for aircraft do
    if aircraft has priority in all involved conflicts then
        return Nominal cruise speed command
```

flight-plan non-compliance rate. However, its performance degrades significantly in situations where wind is present due to the resulting increased local densities and decreased position prediction accuracy.

Conflicts are detected by considering all the possible paths that a potential intruder can follow within the constrained airspace network, portrayed in Fig. 6.5a. In this example, three potential conflict nodes are identified by the ownship (AC_1). For each node, the priority ranking is determined in function of the distance to the node: the closest aircraft has priority.

The conflict resolution strategy makes use of halting manoeuvres ahead of intersections to allow aircraft with priority to pass. For the situation presented in Fig. 6.5a, the most imminent potential point of conflict is node N_2, for which the ownship (AC_1) has priority. Thus, the resolution manoeuvre presented in Fig.

6.5b is implemented, where the intruder AC_2 halts at point p_{stop} such that the minimum separation distance between the aircraft is respected. The algorithmic implementation of the worst-case algorithm used in this work is presented in Alg. 6.2.



(a) (b)

Figure 6.5: Functioning principle of the worst-case CD&R method. The ownship (AC_1) accounts for all possible paths that the intruder (AC_2) could take, and determines all possible conflict nodes (N_1, N_2, and N_3). The intruder resolves the conflict by stopping at p_{stop} ahead of the most immediate conflict node, ensuring the minimum separation distance R_{pz}.

6.3.3. State-based CD&R using halt manoeuvres

The third and last tactical CD&R algorithm used in this work attempts to combine the advantages of the state-based VO and worst-case methods. The first excels in high-uncertainty environments due to its simplicity and adaptability [26], while the latter performs better within constrained urban airspace by using the (street) network topology to only react when deemed necessary [17]. Thus, the aim of the development of this method is to investigate whether the use of halting manoeuvres can improve the false-positive manoeuvring rate of the state-based CD&R method while retaining its robustness against uncertainties such as wind.

For this method, the detection process remains the same as described in Fig. 6.4. However, instead of selecting a resolution velocity using VO methods, a halt command is issued ahead of the estimated point of intersection between the two aircraft, as shown in Fig. 6.6. The algorithm is implemented similarly to Alg. 6.1, with the only difference consisting in the issuing of a “Halt command” instead of a “Lower speed VO command”.

Algorithm 6.2: CR algorithm used in combination with Worst-case CD from the ownship point of view

```
for ownship, intruder in conflict_pairs do
    if intruder is behind andon same route then
        return None
    else if intruder is in front andon same route then
                                                    ▷ intruder has priority
        return Match intruder speed
    else
        solutions = []
        for 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
                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
        Select the most conservative (slowest) solution.
```

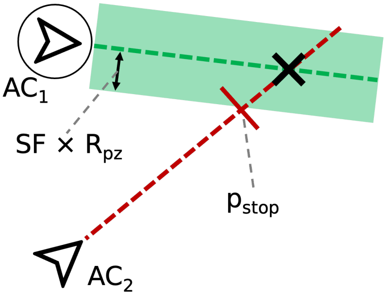


Figure 6.6: Resolution using halt manoeuvres for state-based conflict detection methods: the intruder (AC_2) must halt at point p_{stop} ahead of the predicted intersection.

6.4. EXPERIMENT

The following section presents the experiment design used to investigate the proposed conflict detection and resolution methods. The setup is identical to that used in our previous work [13] to enable the comparison of results of a 4D trajectory strategic deconfliction method with the novel network-flow method in this work.

6.4.1. Hypotheses

The 4D trajectory planning method is expected to achieve a higher level of safety and efficiency in nominal conditions (i.e., no wind or delay) compared to the flow-based strategic planning method, especially when RTA commands are enforced. Such methods allow a higher proportion of aircraft to use shorter routes, thus lowering the flight time. Furthermore, the use of RTA commands ensures that aircraft comply with the optimised flight plans, reducing the occurrence of conflicting situations. Thus, hypothesis **H1** is formulated as follows:

H1 The use of the 4D trajectory planning method will result in a higher safety level in nominal conditions compared to the flow-based strategic planning method.

On the other hand, the flight plans produced by the flow-based strategic planning method are expected to be more resilient when uncertainties are present. Due to the more even distribution of aircraft within the airspace network, the severity of resulting bottlenecks and conflict hotspots should be lower than when using the 4DT pre-departure deconfliction strategy. However, this is also expected to increase the average mission travel time. Therefore, the following hypotheses are formulated:

H2 The safety level of operations will experience a lower degradation rate when using the flow-based strategic planning method compared to the 4D trajectory deconfliction methods, at the expense of efficiency.

The last hypotheses considered in this experiment concern the selection of tactical CD&R strategy. The worst-case CD&R method is expected to deliver the highest level of safety due to the conservativeness of resolution manoeuvres. For the same reason, the use of halting commands is also predicted to improve the performance of the state-based tactical CD&R method. However, in both cases, this might come at the cost of increased travel time, leading to the following hypotheses:

H3 The worst-case tactical CD&R method will deliver the best safety performance level across all conditions due to its conservative conflict handling algorithm.

H4 The performance of the state-based tactical CD&R method will increase across all conditions when using halt commands due to the reduction in false-positive conflict resolution manoeuvres.

H5 The use of halt commands will increase the average mission travel time compared to VO-based manoeuvres.

6.4.2. Simulation software

The BlueSky Open Air Traffic Simulator [27] is used to simulate traffic scenarios and study the proposed CD&R methods. This software has been utilized previously in U-space/UTM research [28, 29], and facilitates the implementation of custom plugins for CD&R methods, the wind model, and the departure delay model. Simulations can also be reliably reproduced using BlueSky scenario files.

6.4.3. Navigation in constrained very-low-level urban airspace

The simulation environment for this research is based on the street network of the central districts of Wien, Austria (Fig. 6.7), chosen for its varied topology: some sections are grid-like, others have an organic topology. The network is extracted from OpenStreetMap [30] using OSMnx [31], then processed to give each edge a single direction. Edges are grouped into smooth “strokes” using the COINS algorithm [32], then a genetic algorithm (detailed in [33]) assigned stroke directions to minimize total travel distance between any two nodes while ensuring unidirectionality. Lastly, the airspace is divided into 50 ft (15.24 m) flight layers, to a maximum height of 500 ft (152.4 m) above the lowest allowable flight altitude.

6.4.4. Traffic scenario generation and optimisation

Air traffic demand scenarios are generated within the considered urban airspace environment by planning point-to-point missions between the nodes of the network. Flight requests are generated for a demand level of 120 aircraft per minute (ac/min), based on the high end of estimated future traffic levels [34, 35].

Figure 6.7: The constrained VLL urban airspace network used in this work, based on the street network of the city centre of Vienna, Austria.

To further process the flight requests, an implementation of the proposed flow capacity management method is created using the Python package of the Gurobi optimiser [36] (available online: [37]). The No Relaxation Heuristic method is used to rapidly obtain feasible solutions, and then allowed to further run up to a cut-off time of 30 minutes to improve the route selection and average travel time. The optimisation is performed on a machine running Ubuntu 22.04.3 LTS on an AMD Ryzen 5950X CPU and 128 GB of RAM using the following parameters:

- CPU Threads : 16
- Time Limit : 1800 seconds
- Presolve method : 2
- Optimality threshold (MIPGap) : 1%

The processed flight plans are then converted to BlueSky scenarios and simulated.

6.4.5. Aircraft model and characteristics

In this experiment, we focused on a single aircraft type, the DJI Matrice 600 drone, to reduce the effect of confounding factors on the results and to focus on the fundamental differences between the CD&R methods. The BlueSky simulator includes a simplified model of this drone, with characteristics detailed in Table 6.1. The turn velocity is used when the drone must perform a change in heading of more than 25° to avoid overshoot and remain within the limits of the streets.

Table 6.1: Characteristics of the DJI Matrice 600 drone model included in BlueSky, based on manufacturer specifications [38].

Maximum horizontal speed	18 m/s
Horizontal acceleration	3.5 m/s^2
Maximum bank angle	25°
Maximum wind resistance	8 m/s
Turn velocity	4.78 m/s
Turn radius	5 m

6.4.6. Uncertainty models

Wind model

A simplified wind model is used to induce variations in the cruise velocity of cruising aircraft, described by Eq. 6.9, 6.10, and 6.11. A global wind magnitude (mag_{roof}) is selected and projected onto streets in function of the bearing difference between the street and wind direction ($\Delta_{bearing}$).

$$\text{mag}_{street} = \text{mag}_{roof} \cos\left(\Delta_{bearing}\right) \tag{6.9}$$

$$\text{dir}_{street} = \begin{cases} 1, & \text{if } \Delta_{bearing} < 90 \\ -1, & \text{otherwise} \end{cases} \tag{6.10}$$

Then, the effect on the ground speed of aircraft (Δ_{gs}) is given by the street wind magnitude (mag_{street}) and the wind direction (dir_{street}), producing either an increase or decrease in velocity. Furthermore, the maximum attainable velocity of aircraft is also lowered by the same amount.

$$\Delta_{gs} = \text{mag}_{street} \times \text{dir}_{street} \tag{6.11}$$

Departure delay model

The departure delay is modelled as an exponential distribution in accordance to literature [39]. Similarly with past experiments [13], the probability that a flight is delayed is set to 30%. Then, a random delay value, limited to a maximum of 5 minutes, is sampled from an exponential distribution (λ = average delay magnitude^{-1}) and added to the nominal departure time.

6.4.7. Independent variables

The experiment conditions are given by the following independent variables:

1. Pre-departure strategic CD&R method (4 conditions)
    - 4D trajectory deconfliction method (4DT) with waypoint required time of arrival enforcement, and flow management method with $T_w = 5s$, 10s, and 20s
2. Tactical CD&R method (3 conditions)
    - State-based VO, state-based halt, and worst-case halt
3. Rooftop wind magnitude (3 conditions)
    - 0 (no wind), 2, and 4 m/s
4. Rooftop wind direction (4 conditions)
    - 0°, 90°, 180°, 270°
5. Average delay magnitude (3 conditions)
    - 0 (no delay), 10, and 30 seconds

The experiment consists of three distinct parts: nominal conditions, wind variations, and delay scenarios. Each experimental condition is replicated five times using different sets of randomly generated traffic requests, resulting in a total of 660 simulated traffic scenarios and over 7 million missions.

6.4.8. Dependent measures

The following performance metrics are considered during the experiment, used to quantify the operational safety and efficiency performance of the proposed CD&R models.

1. Total number of detected conflict aircraft pairs
    - A conflict is defined as a situation that requires intervention to prevent an intrusion event from happening.
2. Total number of intrusion events
    - Within the present study, the minimum separation limit between two aircraft is set as 32 metres, as used in previous work [13].
3. Intrusion distance at closest point of approach
    - Used to quantify intrusion severity
4. 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.

6.4.9. Control variables

Table 6.2 summarises the control variables of the experiment. Most of these conditions are identical to previous experiments in [13] to allow the comparison of results.

Table 6.2: Control variables used for all experiment conditions.

Name	**Value**
Traffic demand level	120 ac/min
Node flow capacity C_n	1 ac/min
CD look-ahead time	10 s
CD&R module update interval	0.5 s
Maximum flight altitude	500 ft (152.4 m)
Minimum flight altitude	50 ft (15.24 m)
Number of flight layers	10
Target cruise velocity (true air speed)	15 m/s
Minimum separation threshold	32 m

6.5. RESULTS

The following section is divided into two parts: the first presents the results of the flight plan optimisation process; the second part contains the results of the air traffic scenario simulations.

6.5.1. Flight plan strategic optimisation

The flight plan optimisation process was able to successfully allocate routes to aircraft without flow violations (described in Eq. 6.2) in most cases. Furthermore, the objective function value was within approximately 5% of the lowest bound in most cases, including when the process was interrupted due to the time constraint. However, in one instance ($T_w = 20$s, repetition 3), a single flow violation was not resolved within the allocated time, leading to an optimality gap of 15%.

The optimiser was able to allocate the shortest path between the origin and destination to most aircraft, as shown in 6.8. Out of the alternative routes, the most used was alternative 2, which avoids the middle section of routes. This was expected, as this section will on average be closer to the city centre, and thus more congested. The fourth alternative, which completely avoids the shortest route path, was used the least in all cases (less than 0.4% of flights). Thus, a high percentage of traffic (80% or more) used the most efficient routing, with much of the rest being diverted around one portion of the ideal path. Lastly, increasing the time window value (i.e., the average time separation between two aircraft as shown in Fig. 6.3) resulted in greater use of alternative routes, as this resulted in a lower flow allowance for every node.

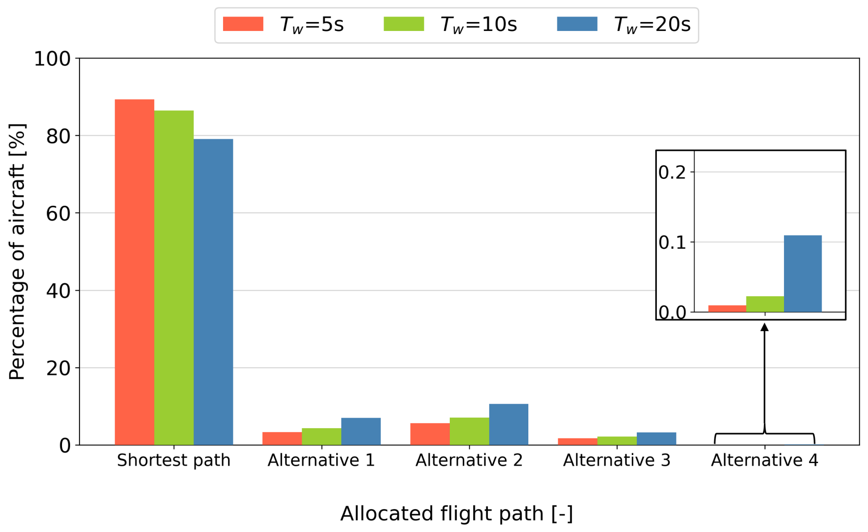


Figure 6.8: Histogram of allocated flight paths in function of flow time window value. The alternative routes are labelled in accordance with Fig. 6.1.

The altitude allocation results also show a similar trend. In all cases, the majority of aircraft were assigned to the lowest flight level, and an increase in the time window value led to higher altitude flight levels being increasingly used, as shown in Fig. 6.9. The altitude distribution of the $T_W = 10$s case is most similar to the 4D trajectory planning method. However, it should be noted that, in the case of the 4DT method, the optimiser (described in [13]) was able to allocate all aircraft to their respective shortest routes.

Table 6.3 presents the performance metrics of the flight plan optimisation tool. The optimisation was performed using the No Relaxation Heuristic method of Gurobi [36]. The gap parameter represents the percentage difference between the final value of the objective function and the lowest possible bound value at the end of the optimisation process. In one case ($T_W = 20$s, repetition 3, planning time window 1800s-3900s), one violation remained when the time limit of 1800s was reached, resulting in a high gap value.

6.5.2. Simulated performance metrics

Fig. 6.10 shows the number of unique conflict pairs considered by the tactical CD&R methods. The results between the two state-based methods (VO resolution or halt manoeuvres) are similar, with the use of halt manoeuvres leading to a relatively small increase in the number of conflicts. Furthermore, the worst-case method detected significantly more conflicts, in line with expectations.

However, an important result can be seen when comparing the results in Fig. 6.10 between strategic planning methods. Regardless of the choice of tactical

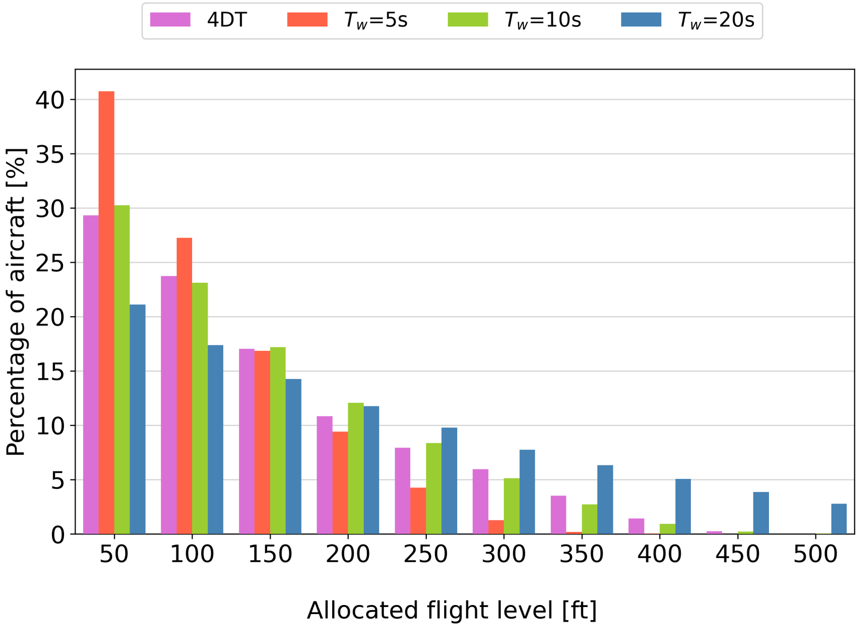


Figure 6.9: Histogram of allocated altitude levels in function of strategic planning method.

Table 6.3: Flight plan optimisation performance for every air traffic scenario.

T_W [s]	Rep.	Planning time window [s]								
		0-2100			1800-3900			3600-5700		
		Time to no violations [s]	Total time [s]	Gap [%]	Time to no violations [s]	Total time [s]	Gap [%]	Time to no violations [s]	Total time [s]	Gap [%]
5	1	23	679	0.97	31	140	0.92	38	100	0.68
	2	25	619	0.99	33	169	0.92	51	113	0.78
	3	20	875	0.99	30	152	1.00	40	99	0.76
	4	20	524	0.99	36	97	0.97	38	86	0.71
	5	25	696	1.00	31	102	0.99	61	113	0.74
10	1	46	1800	1.86	48	1800	1.14	64	331	0.95
	2	49	1800	2.24	54	1800	1.16	60	390	1.00
	3	44	1800	1.93	45	1800	1.06	54	288	0.97
	4	31	1800	1.90	48	1800	1.13	57	301	0.94
	5	31	1800	1.94	51	1800	1.11	63	237	0.99
20	1	567	1800	4.81	919	1800	2.31	1566	1800	1.71
	2	850	1800	4.91	1560	1800	2.60	1249	1800	1.71
	3	896	1800	5.06	-	1800	15.78	-	1800	1.37
	4	350	1800	4.46	968	1800	2.27	941	1800	1.43
	5	442	1800	4.85	1539	1800	2.73	1395	1800	1.70

CD&R method, the use of a flow time window value of 20 seconds led to the detection of considerably fewer conflicts. This resulted in the occurrence of fewer intrusion events, as shown in Fig. 6.11. The number of intrusions in nominal conditions also reveal that the use of the worst-case tactical CD&R method in combination with the flow capacity management with T_W = 20 yielded the

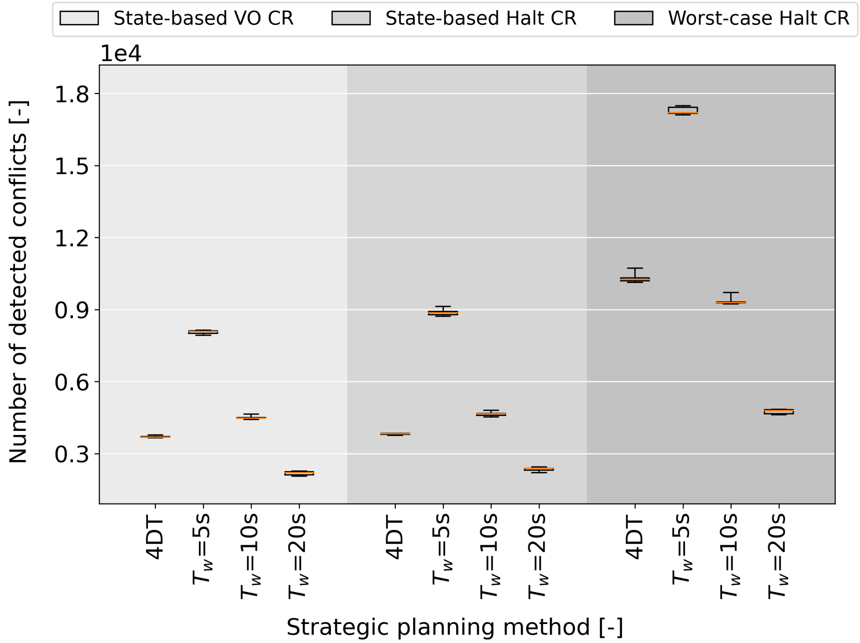


Figure 6.10: Average number of unique conflict pairs detected by each tactical CD&R method in nominal conditions (no wind and delay).

highest level of safety. While the use of halting manoeuvres improved the performance of the state-based method, enhancing conflict predictions using knowledge of the airspace network topology helped greatly reduce the number of intrusions.

The simulations in which wind was present reveal that the use of halting manoeuvres results in a lower degradation in performance when compared to nominal conditions, as shown in Fig. 6.12. Furthermore, results indicate that the worst-case CD&R method performed best when flight plans were optimised using the $T_w = 20$s method, with minimal degradation in the safety level. The traffic scenarios in which 4D trajectory planning was used were also robust against wind, as the use of RTA commands for each waypoint enabled aircraft to adapt their velocity and remain compliant with their flight plan.

On the other hand, the scenarios optimised using the 4DT method experienced a high degree of degradation when departure delay uncertainty was present, presented in Fig. 6.12. Whereas in nominal conditions, the safety level is comparable to the $T_w = 20$s method, the increase in delay led to the occurrence of more intrusion events when compared to the flow-based capacity management methods, which remained relatively consistent in performance with increasing uncertainty level. This results from the need for aircraft to cruise at higher velocities to comply with the RTA commands for each waypoint, attempting to

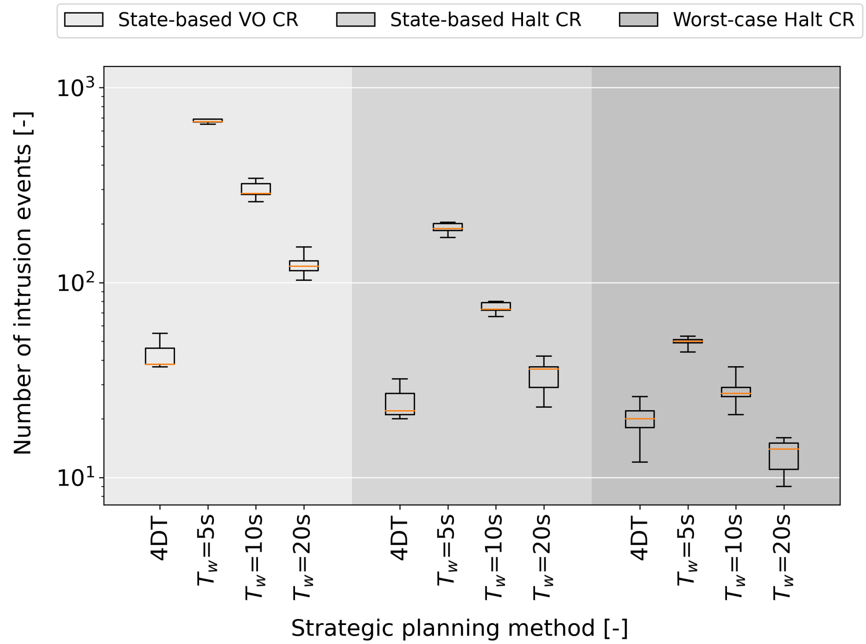


Figure 6.11: Average number of intrusion events in function of strategic and tactical CD&R method in nominal conditions (no wind and delay).

enter a state of flight plan compliance.

A noteworthy result is that, for the high average departure delay case (30s), the 4DT method performed similarly to the flow-based method with $T_w = 5$s when combined with the worst-case tactical CD&R algorithm. This shows the susceptibility of 4D trajectory optimisation methods to over-optimise flight plans, leading to reduced resilience against uncertainties, also reported in other work [18].

The higher robustness of the flow capacity management methods can also be observed in Fig. 6.14, which presents a histogram of the distance at the closest point of approach during intrusion events. In all situations, the use of the flow-based capacity management method resulted in a higher proportion of low-severity intrusions (i.e., smaller intrusion distance). This can be a result of the higher use of shortest routing when using the 4DT method (i.e, over-optimisation), leading to higher local traffic densities and thus higher conflict complexity (multi-aircraft conflicts). The use of alternative routes contributed towards the mitigations of such situations. Furthermore, while the results also indicate that the use of the worst-case CD&R method also leads to an increase in the intrusion severity level, it should be noted that the total number of such events was considerably lower when this tactical algorithm was used, leading to higher safety overall.

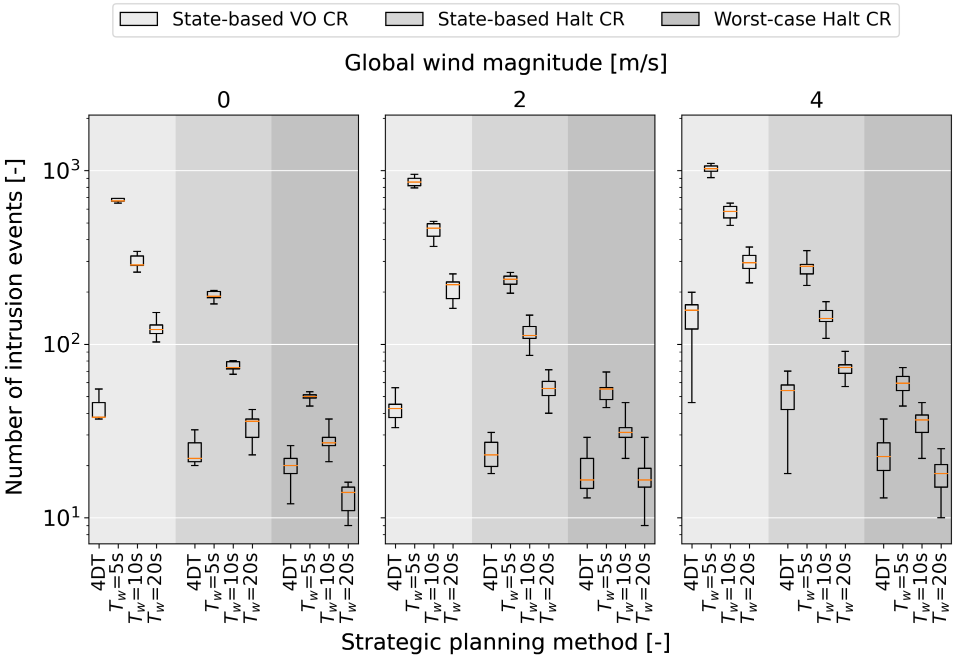


Figure 6.12: Average number of intrusion events in function of strategic and tactical CD&R method in function of global wind magnitude.

Lastly, the results portrayed in Fig. 6.15 show that the increase in safety level achieved by the flow-based capacity management method is achieved by modestly sacrificing operational efficiency. With increasing flow time window value, the average mission time increased by approximately 20 seconds (approximately 5%) compared to the 4DT case, which allocated the shortest route for all missions. The tactical CD&R method used did not have a significant influence on the average mission travel time, thus resulting in a higher level of safety with no impact on operational efficiency.

6.6. DISCUSSION

The results presented in this work highlight the benefits of designing tactical and strategic conflict detection and resolution methods that can effectively cooperate towards higher airspace safety when facing high traffic densities or uncertainty levels. While the 4D trajectory planning method performed better in combination with the state-based velocity obstacle tactical CD&R method, the reduction in the number of conflicting situations while using flow capacity management allowed the worst-case CD&R method to function more effectively in ensuring separation, as a result of distributing aircraft more evenly within the airspace. The use of RTA commands to ensure flight plan compliance was unable to compensate

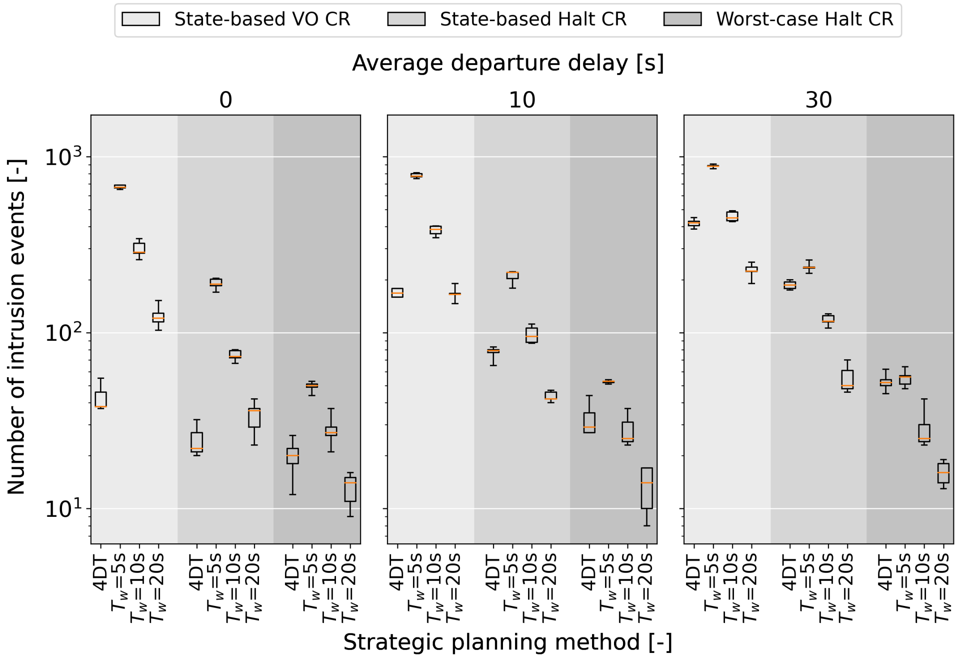


Figure 6.13: Average number of intrusion events in function of strategic and tactical CD&R method in function of average departure delay.

for the deviations induced by the presence of wind and departure delay. Thus, hypothesis **H1**, which states that the use of the 4DT method would result in a higher safety level compared to the flow-based method, is rejected.

The other hypotheses concerning the performance of the strategic CD&R methods (**H2**) can be accepted. The network flow capacity management method produced flight plans that are more robust against time deviations. By enforcing flow constraints instead of using the time-based separation strategy of the 4D trajectory planning method, traffic was better distributed throughout the airspace network, achieving lower traffic densities regardless of the uncertainty level.

The robustness of the flow-based flight planning method was further enhanced by using overlapping time windows, which reduced the effect of the inaccuracies in the time of arrival estimations for each waypoint within a trajectory. This induced a more conservative approach, and the increased use of alternative routes for more strict flow constraint levels. However, this produced a modest increase in the average travel time due to the more prevalent use of non-optimal routing.

Hypotheses **H3** and **H4** regarding the tactical conflict detection and resolution methods can also be accepted. The results strongly suggest that the use of halting manoeuvres improves the safety level of constrained urban airspace, as reactions to false-positive conflicts can be delayed until the need to stop arises,

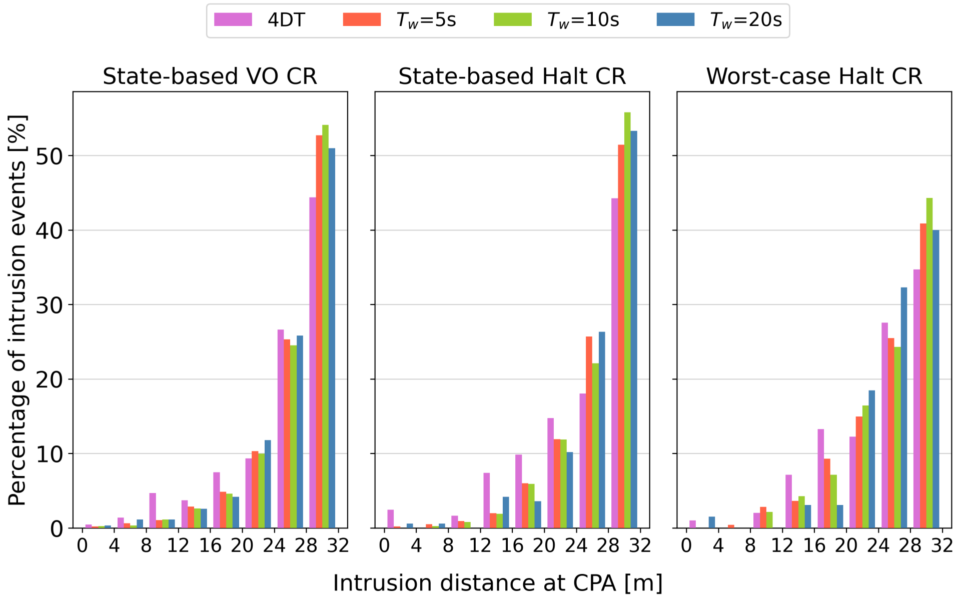


Figure 6.14: Histogram of the distance at the closest point of approach (CPA) during intrusion events in function of tactical and strategic CD&R method in nominal conditions (no wind or delay).

rather than applying a resolution velocity upon first detection. This effect is further strengthened when airspace structure information is used to further reduce unnecessary manoeuvring and lower operational disruptions resulting from tactical intervention. Furthermore, the reduction in the number of tactical interventions also compensates for the operational inefficiency of halt manoeuvres, as the average mission travel time was not significantly affected by the choice of tactical CD&R method. Thus, hypothesis **H5** can be rejected.

Overall, the study at hand shows that improved compatibility between tactical and pre-departure strategic CD&R methods for VLL urban airspace operations is beneficial for airspace safety while producing a relatively low effect on the efficiency level. Flight plan over-constraining through the use of strict 4D trajectory planning is thus not necessary, as it can lead to over-optimisation and decreased flexibility in the face of uncertainties such as wind and departure delay. The delegation of the responsibility for local deconfliction towards the tactical deconfliction module can be beneficial, and can thus result in a reduction in the required complexity of the CD&R module of a U-space/UTM system, while increasing both the levels of efficiency and safety.

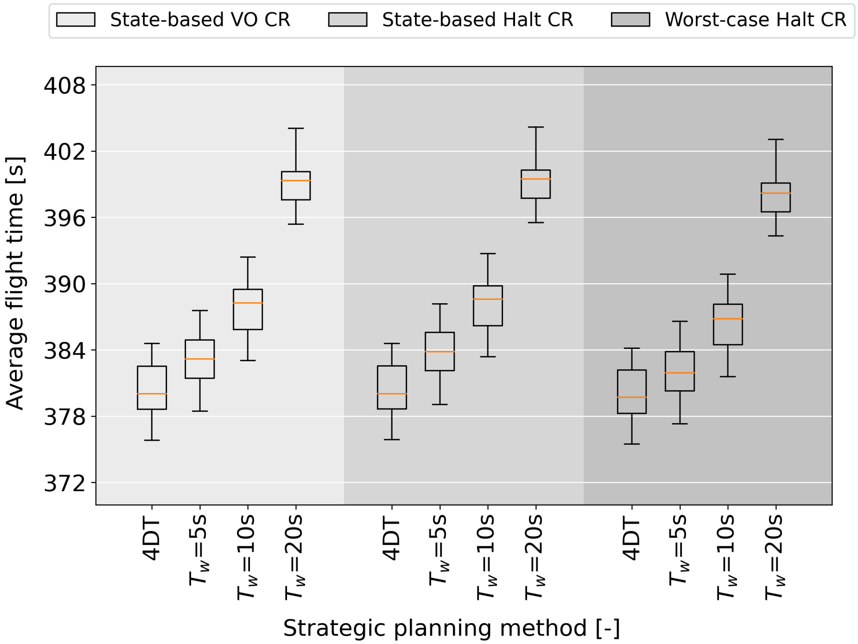


Figure 6.15: Average flight time per simulation scenario in function of tactical and strategic CD&R method.

6.7. CONCLUSION

6.7.1. Main findings

The study at hand sought to develop and test combinations of pre-departure strategic, and tactical conflict detection and resolution methods that are resilient in dynamic and uncertain operational environments. We developed and tested a traffic-flow capacity management planner with the aim of delegating a higher proportion of the deconfliction responsibility to the tactical CD&R module, while improving the distribution of traffic within the airspace network. Several combinations of strategic and tactical methods were tested using high-density urban air traffic scenarios, and compared with 4D trajectory optimisation pre-departure methods.

Simulation results indicate that the use of flow-based strategic planning achieves a higher safety level at the strictest flow capacity allowance when compared to the baseline 4D trajectory method, regardless of the choice of tactical CD&R strategy. Furthermore, the use of the Worst-case CD&R method is the most resilient against the effects of wind and departure delay, as this tactical method benefits from the reduction in local traffic density and conflict complexity. However, the use of flow-based strategic planning results in a (modest) decrease in operational efficiency due to the more prevalent use of alternative routes.

Overall, we demonstrate the importance of designing conflict detection and resolution methods for interoperability and system-wide compatibility with other services. Furthermore, our findings indicate that delegating a higher proportion of the deconfliction task to the tactical resolution module benefits the safety of operations. By eliminating the need for strict flight plan temporal compliance, the complexity of air traffic management for U-space/UTM systems can be reduced.

6.7.2. Recommendations for future research

The methods presented within this study are subject to several limitations that require future research and development ahead of a potential deployment. First, the alternative routes generated by the method described in Fig. 6.1 are highly dependent on the geometry of the shortest path between the origin and destination, and the topology of the surrounding network. This process can be further enhanced by considering historical traffic density and conflict information, similar to the method presented in [11], to provide more effective routing that better avoids known traffic bottlenecks.

Another limitation of our work stems from the simulated traffic scenarios and conditions. While the traffic density is consistent with future urban air traffic demand predictions, the distribution of origin and destination vertiport is homogenous throughout the airspace network. In reality, certain areas within cities are subject to higher demand for departures and arrivals, creating traffic patterns that might influence the performance of the CD&R methods presented in this work. Lastly, the simulation of uncertainties is limited, as both the implementation of wind and delay makes use of simplified models that might capture a relatively narrow range of possible uncertainties in urban airspace environments. Thus, future research should focus on higher-fidelity simulations including heterogenous traffic, as well as live experiments and demonstrations, to further validate the performance of the proposed capacity management and deconfliction modules in realistic conditions.

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7

DISCUSSION AND RECOMMENDATIONS

This dissertation investigated and developed algorithms and rules for performing conflict detection and resolution (CD&R) in very low level (VLL) constrained urban airspace. The strategic and tactical methods presented within the previous chapter are the result of all the research and conclusions of this work. This chapter compares these methods with existing approaches in the literature and suggests areas for future investigation.

7.1. OVERVIEW

Urban air mobility holds the potential to deliver a sustainable alternative to traditional ground-based transportation and to alleviate mounting urban traffic congestion [1]. The U-space initiative [2, 3], designed to manage urban air traffic within the European Union, establishes the groundwork for developing the necessary services to support such operations. While a robust foundation has been established, further research and development are still needed to translate this conceptual framework into a fully implementable system.

A vital component of the U-space system is conflict detection and resolution (CD&R), responsible for guaranteeing the safe execution of urban air operations [4]. Research efforts have been focused on establishing how this service will be provided, with a particular emphasis on ensuring its effectiveness, reliability, and scalability to meet the demands of the anticipated increase in urban air traffic [5]. This includes investigating both centralised and decentralised CD&R architectures, as well as methods to ensure the resilience of operations against uncertainties (e.g., wind, delay).

The challenge with these components lies in their integration into a larger, unified U-space framework [5]. Each element must be compatible with the others to address both pre-flight and in-flight uncertainties, while also accommodating factors like weather or airspace restrictions. In this dissertation, we developed a CD&R concept for very low level (VLL) U-space operations that mainly relies on two components: a pre-departure flight plan management module, and a tactical deconfliction algorithm. Other elements, such as dynamic capacity planning and in-flight strategic deconfliction, are envisioned to provide a minor, albeit important contribution.

The pre-departure flight plan optimisation strategy, presented in Chapter 6, focuses on modifying mission flight paths such that traffic bottlenecks are avoided even in high-uncertainty situations. Thus, the probability of conflicts occurring is reduced. Furthermore, by shifting the focus of this module from deconfliction, which requires a high degree of accuracy and is highly sensitive to unexpected disruptions, to capacity and flow management. Then, the tactical CD&R module can more effectively resolve the remaining conflicts locally (i.e., when the level of uncertainty is low) while minimally disrupting traffic flow.

The tactical CD&R method proposed in this work is also tailored to maximise the use of available information while reducing the reliance on information from other aircraft such as intent. By taking a conservative approach and accounting for the airspace network structure, a high level of safety can be achieved. Furthermore, the use of halt manoeuvres increases the predictability of traffic, and the loss in efficiency is compensated for by the reduction in false-positive detections.

7.2. ANALYSIS AND DISCUSSION

The following section presents an analysis of the benefits and shortcomings of the CD&R methods developed and presented within this dissertation. A comparison with other work from existing literature is used to suggest directions for future research and development.

7.2.1. VLL urban airspace structure design

The method for urban airspace design presented in this work provides a straightforward and low-complexity framework for structuring a very-low-level urban airspace. It entails extracting the existing street network of a city from publicly available data sources (e.g., OpenStreetMap [6]) and using optimisation methods to assign directionality to individual streets. However, it is limited in leveraging the characteristics of the urban environment and requires a considerable manual post-processing effort, mainly serving as a functional starting point for further design iterations.

Similar variations of this method have been previously applied [7–9], as using the existing street network as a foundation inherently avoids buildings, thereby mitigating safety risks. It also aligns well with privacy considerations, as aircraft would primarily operate within publicly accessible spaces. However, flights could be performed more efficiently if aircraft were able to fly above buildings where possible. An approach that would enable this is the use of geofencing (i.e., restricting access to certain areas) [10, 11] to more precisely delimit restricted airspace in the altitude dimension, and thus expand the routing flexibility for U-space operations.

On the other hand, the results presented in this dissertation show that the use of a geospatial network graph for defining VLL constrained urban airspace can benefit safety by increasing action and emergent pattern predictability. As agents are generally expected to follow the geometry of air paths, the risk of the occurrence of a conflict can be better assessed and accounted for. This strategy can also be used if geofences are included within the definition of allowable airspace by adapting the network graph to include altitude-dependent edge weights that allow flying over buildings where permitted. Thus, we suggest that future iterations of VLL urban airspace designs should investigate combining the street network graph approach with that of geofencing to expand the capacity and efficiency of operations while enhancing predictability.

7.2.2. Pre-departure strategic planning

Existing research on strategic planning for U-space operations has concentrated on developing 4D trajectory planning methods as a pre-departure traffic management strategy. The U-space concept of operations [4] mentions the results of the BUBBLES project [12] as a promising approach, suggesting the use of protection zones whose areas adapt dynamically based on the assessed risk level and can thus accommodate the heterogeneous traffic and adapt to dynamic and uncertain conditions. Perez et al. [13] investigate how tactical manoeuvring can also be integrated within such a system that emphasises flight prioritisation.

However, this approach implies the existence of a central agent that manages the strategic and tactical routing of aircraft, which might lead to a high level of workload for air traffic controllers, or system supervisors if a high degree of automation is employed. One method to mitigate this would be decentralisation, as proposed by Ho et al. [14], where flight paths are deconflicted through iterative negotiation among the involved agents. Another issue with using 4D trajectory deconfliction methods, identified by Joulia et al. [15], is the decreased resilience against uncertainties due to the over-optimisation of flight plans.

Our approach to this problem, presented in Chapter 6, delegates a considerable part of the deconfliction task to the agents themselves. Then, the pre-departure strategic planning module is focused more on managing flow and capacity. This offers the benefit of reducing the complexity of the U-space air traffic management system by not requiring strict adherence to 4D trajectories. Furthermore, it offers increased resilience against uncertainties like wind and departure delays by mitigating traffic density and potential conflict zones. However, a limitation of this method is a reduction in operational efficiency: at higher traffic densities, many aircraft are assigned less-than-optimal routes, leading to increased average mission travel times (our experiments show an increase of 6%). Furthermore, this also poses issues on how such routes should be fairly allocated among flights. However, other methods used to account for uncertainties, such as robust flight plan optimisation or the use of safety margins, generally produce similar effects [16].

We suggest future research to continue to focus on finding a better balance between centralised and decentralised systems for the management of U-space operations. We obtained promising results by combining flow capacity management (centralised) with a local tactical deconfliction algorithm (decentralised), as the latter is better equipped to handle conflicts locally, where situational awareness is higher, and the prediction horizon is shorter. Other methods, such as the one proposed by Ho et al. [14], promise to further reduce the U-space traffic management system complexity and reduce the workload on air traffic controllers. Alternative routing could also be generated using historical traffic and conflict data, which could produce more efficient routing that only minimally deviates from the shortest route and thus be more fair towards the involved parties.

7.2.3. Tactical conflict detection and resolution

The U-space concept of operations [4] proposes a centralised approach to tactical deconfliction performed by air traffic controllers (or an equivalent system of higher automation). The BUBBLES project [16] presents a method through which tactical deconfliction is achieved by designating one of the aircraft of a conflict pair as the separator (i.e., lower priority, thus must give right of way). Jover et al. [17] build on this concept and developed a centralised algorithm that explicitly assigns priority to aircraft in conflicting situations.

However, as in the case of pre-departure strategic planning, a centralised approach to tactical deconfliction might limit the overall capacity of the airspace due to factors such as air traffic controller workload or system complexity. Thus, research has also been focused on investigating the feasibility of decentralising or automating the tactical CD&R service for VLL U-space operations. Von Roenn et al. [18] proposed an automated and decentralised deconfliction procedure for electric vertical take-off and landing (eVTOL) operations that maintains communication with a central traffic management authority. Ribeiro et al. [19] and Isufaj et al. [20] use reinforcement learning techniques to study the behaviour of aircraft when cooperative tactical CD&R manoeuvring is used.

In Chapter 5, we proposed a highly conservative tactical deconfliction method that enables aircraft to dynamically assess the local traffic situations and account for all possible conflicting situations. Compared to previous work, this ‘Worst-case’ CD&R algorithm is developed to be compatible with the flow management module used to plan mission routes strategically. The results of our simulations indicate that this combination can achieve a higher level of safety and robustness against uncertainties by delegating the local deconfliction task to the tactical module. However, this outcome is dependent on the structure of the airspace and how VLL constrained urban airspace operations will be conducted, and should thus be further investigated in a wider variety of configurations.

Firstly, the proposed worst-case method assumes that aircraft follow predictable trajectories given by a graph-based network. If another airspace structure is to be used (e.g., geofencing), then further adaptations are needed to achieve an equivalent safety level. Moreover, while the results of this work indicate that vertical manoeuvring should be discouraged, the tactical CD&R module should nonetheless be able to resolve such situations.

Another shortcoming of the worst-case CD&R method is that it relies on halt manoeuvres for resolving conflicts. While this approach is highly effective in increasing traffic predictability, it cannot be used by fixed-wing aircraft or others that do not have hover capabilities. If such aircraft will be allowed to operate within VLL constrained urban airspace, different methods need to be developed and integrated with the U-space air traffic management system.

Lastly, a wider range of uncertainties and operational conditions need to be studied. Factors such as hyper-local weather effects, aircraft prioritisation, and traffic heterogeneity could affect the performance of the tactical CD&R module and challenge our current understanding of these systems.

Based on the results presented in this dissertation, we suggest future research to focus on improving the synergy between the tactical deconfliction and strategic planning modules. This approach can lower the system complexity of the VLL constrained urban airspace air traffic management service by enabling the use of high-level automation and the distribution of the deconfliction task among all in-flight aircraft. Tactical CD&R methods should also be adapted to account for all aspects of VLL U-space operations, including vertical manoeuvres, take-off and landing, and a wider range of uncertainties. This might lower the workload of urban air traffic controllers or supervisors, and should thus increase safety [21].

7.2.4. Simulation of U-space operations

One of the strengths of our methodology for developing and testing the proposed CD&R methods is the use of simulations that aim to closely represent future implementations of VLL constrained urban airspace operations at high traffic densities, based on current traffic estimations [22]. The live demonstrations of U-space operations performed by the Metropolis 2 project [23] show that the BlueSky Open Air Traffic Simulator is capable of modelling drones with relatively high accuracy.

However, the simulations we performed were still limited in capturing a complete picture of urban airspace operations. Assumptions such as homogenous traffic, exclusion of take-off and landing phases from the tactical phase, and the use of simplified uncertainty models [24–26] might have a significant and unpredictable impact on the performance of a complete U-space system. This limitation (i.e., the exclusion of some U-space services) can be found in other work in this domain as well. For example, Joulia et al. [15] developed a simulation framework specifically for tactical CD&R services that only captures the services required for Phase U1 of U-space deployment.

A comprehensive approach towards better understanding the interactions between services in realistic settings is the use of live demonstrations. While the increasing prevalence of such research is a positive factor, they are still severely limited in scope and representativeness due to the restrictiveness of local laws and their limited scale [27, 28].

We thus recommend that, until the opportunity for larger-scale testing arises, a unified simulation platform is developed to simulate the implementations of all U-space services. As the use of the BlueSky is already prevalent in this domain [29–32] due to being open-source and continuously adapted to match the newest developments, it is a suitable candidate to serve as a foundation for higher-fidelity simulations. An example of such an implementation was created by Fremond et al. [33] by integrating the use of BlueSky into a larger simulation framework that includes other U-space services such as flight plan processing and risk assessment, and the interfaces between them.

7.3. FUTURE RESEARCH AND DEVELOPMENT

The past decade has seen great progress towards defining the framework for implementing very-low-level (VLL) U-space operations within urban environments. Research has been dedicated towards solving the associated challenges, including how to structure and navigate the airspace, as well as the creation of novel procedures for the management and deconfliction of traffic.

Within this dissertation, we presented and critically analysed the methods we developed and investigated for air traffic management within constrained VLL urban airspace. We primarily focused on the cruise phase of missions, and attempted to develop and improve concepts for urban airspace structure design, pre-departure strategic planning, and tactical conflict detection and resolution (CD&R). Then, acknowledging the limitations of our work and comparing it with other approaches found in literature, we converged on the following considerations and recommendations for future research within this domain:

1. Utilising the airspace above the existing street network is a viable option

for VLL U-space operations in urban areas. This approach should be factored into future planning, especially for areas with prevalent high-rise structures.

2. Over-reliance on 4D trajectory planning for conflict resolution can lead to the over-optimisation of flight plans, which negatively affects the resilience of U-space operations against uncertainties (e.g., wind, delay).
3. Decentralised or automated tactical CD&R manoeuvring should be considered in future developments, as it can lower the overall system complexity and interdependency, and reduce air traffic controller/supervisor workload.
4. More research should focus on understanding the effects of uncertainties such as weather and delay, and investigating ways in which these can be predicted and mitigated, as they greatly affect the effectiveness of pre-departure strategic planning.
5. A unified, open-source, and open-data simulation environment should be developed to better test and integrate all U-space services and ensure their compatibility.

7.4. RESEARCH IMPACT

The strong desire to improve the way we live combined with the rapid advancements in technology that our society is experiencing has lead to the development of novel ideas such as the U-space/UTM concept. The concept of significantly increasing the efficiency and sustainability of urban mobility and transportation by making use of the abundantly available vertical space above our cities has led to research and the creation of concepts that bring us closer to such a reality. This dissertation aimed to be part of this effort, studying and proposing approaches through which the U-space/UTM concept can be further refined and improved.

However, in our search for innovation, we should not let enthusiasm and novelty cloud our choices and judgement in deciding how urban areas should develop in the future. While the use of both small and large autonomous aerial vehicles for urban mobility promises a cost-effective and sustainable solution to the congestion problems of today, the implications of pursuing such a policy must be considered. The most immediate concerns are the potential for increased noise pollution in urban areas and the infringement on personal privacy. The constant buzz of delivery drones overhead could significantly alter the auditory landscape of our cities, potentially disrupting daily life and affecting the quality of life of residents. Moreover, the use of camera-equipped drones for navigation and delivery confirmation raises serious questions about privacy and surveillance, as these devices would have unprecedented access to observe private spaces.

Furthermore, the allocation of substantial resources and attention to developing and deploying U-space/UTM concepts may inadvertently divert focus from improving existing and potentially more effective solutions. Public transportation systems and cycling infrastructure, for instance, have proven highly effective in reducing urban congestion and promoting sustainable mobility. By prioritising these established methods, we can achieve immediate and tangible benefits for a broader segment of the population. Similarly, the expansion of package delivery through strategically placed pick-up locations and smart lockers offers a more inclusive and less disruptive alternative to drone deliveries, while still addressing the growing demand for efficient last-mile logistics.

We must also consider the potential for U-space/UTM technologies to exacerbate existing social inequalities. The introduction of air taxis and similar services, while technologically impressive, risks catering primarily to wealthier members of society. This could lead to a two-tiered transportation system where the wealthy enjoy rapid, congestion-free travel above the city, while those of lesser means remain bound to increasingly neglected ground-based infrastructure. Such a scenario would not only fail to address the core issues of urban mobility but could also contribute to the further marginalisation of vulnerable and disadvantaged groups.

In light of these considerations, we must approach the development and implementation of U-space/UTM concepts with a critical perspective. While the potential benefits of such technologies are apparent (e.g., medical emergency interventions through the use of drone-mounted automatic electrical defibrillators or medicine delivery), we must weigh them against the broader impacts on urban life, social equity, and environmental sustainability. As we move forward, we must ensure that our pursuit of innovative solutions does not come at the cost of exacerbating existing problems or creating new ones. Instead, we should strive for a balanced approach that integrates new technologies with improvements to existing systems, always keeping in mind the diverse needs of all urban residents and the overarching goal of creating more livable, equitable, and sustainable cities for everyone.

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LIST OF PUBLICATIONS

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Propositions

accompanying the dissertation

Conflict Detection and Resolution for Constrained Urban Airspace

by

Călin Andrei BADEA

1. Minimising the number of vertical manoeuvres performed by aircraft in high density urban airspace benefits predictability and safety. (This thesis)
2. The strategic and tactical modules for very-low-level constrained urban airspace operations need to be designed in a unified approach to ensure their compatibility. (This thesis)
3. Distributing the deconfliction task between the strategic and tactical modules of a conflict detection and resolution system improves robustness against uncertainties. (This thesis)
4. In constrained very-low-level urban airspace, tactical conflict detection and resolution can be safely performed without the exchange of intent information. (This thesis)
5. Science should be published in high-quality, open-access, university-sponsored journals that do not charge publication fees.
6. The best way to discover which leisure activities contribute most to your wellbeing is to plan your wedding.
7. A positive and supportive work environment contributes significantly more towards professional satisfaction and general well-being than the work itself.
8. We are **always** doing our best, and that is **always** enough.
9. The complexity of an idea does not correlate with its innovativeness.
10. Most bugs in code are found once work begins on the results section of a scientific article.

These propositions are regarded as opposable and defendable, and have been approved as such by the promotors Dr. ir. J. Ellerbroek and Prof. dr. ir. J.M. Hoekstra.