Autonomous UAV Operations in U-space: Information Provision, Safe Separation with Uncooperative Drone, and 4-D Trajectory Planning

PhD dissertation

Ivan Panov

Aarhus BSS
Aarhus University
Department of Business Development and Technology
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Executive summary

Launching uncrewed air traffic in Europe has a high potential to create a new industry that unlocks previously unseen services, like last-mile goods delivery with drones, human transportation with no pilot onboard, low-cost aerial emergency operations, robotic inspections and monitoring. However, to make it cost-efficient, many experts and scientists underline the essentiality of the high autonomy of the U-space operations. This thesis focuses on the advancing research in the field of uncrewed autonomous operation within U-space. In particular, the following research questions (RQs) provided a foundation for the study:

• RQ1a. What are the essential constraints for the UAV autonomous operations in the U-space?

• RQ1b. What is the important information provision required on the last (forth) stage of U-space deployment?

• RQ1c. What are the gaps between the EUROCONTROL's Concept of Operations [1] and the information needed to allow UAV autonomous traffic in the U-space?

• RQ2a. How to identify a safety separation with uncooperative drone of unknown model but known type?

• RQ2b. How can UAV autonomous guidance system plan horizontal manoeuvre to avoid a loss of separation with uncooperative drone?

• RQ3. How to plan 4-D trajectories for the uncrewed air traffic to minimise flight time for each consecutive UAV?

Uncooperative drones are UAVs that neither communicate with nor collaborate with U-space services or other drones. Cooperative drones, on the other hand, do communicate and collaborate to coordinate their intentions.

In section II, a systematic literature review was performed to address RQ1a, RQ1b, and RQ1c. The foundation of the section is a paper published in the MDPI Aerospace journal through a peer-reviewed process.

Section III addresses RQ2a and RQ2b. The main instrument here is mathematical modelling relying on flight dynamics fundamentals and a global UAV database analysis. The section replicates and extends a paper published through a peer-reviewed process in the proceedings of the IMAV2024 scientific conference, held in Bristol. In the same conference proceedings, another paper was published addressing RQ3; its text is replicated with significant modifications in section IV.

Section V provides a discussion on the scientific novelty and importance of the findings, reflections on addressing the research questions, a critical view of the research, and general perspectives. Furthermore, section V includes an analysis of the relevance of the study for industry and society, suggestions for future research, personal meaning associated with conducting the research, discussion on techno-optimism and cautions, including concluding remarks.

The paper concludes with an appendix and co-author statements.

The core contribution of the thesis is a valuable advance in understanding what the essential information needs are to allow U-space autonomous guidance, what are the gaps between the Concept of Operation of U-space and the information needs, and what should be done to close the gaps. Furthermore, the thesis offers a novel method for determining the safe separation to an unknown-model uncooperative UAV in U-space. Finally, the thesis includes the Gen4jectory 2.0 algorithm which allows 4-D trajectory planning with minimised flight time for multiple rotary-wing UAVs. All these findings address the safety-critical issues which must be resolved to ensure the safe autonomous uncrewed operations of drones over Europe.

Danish Summary

Lanceringen af ubemandet lufttrafik i Europa har et stort potentiale for at skabe en ny industri, der muliggør hidtil usete services som f.eks. last-mile-levering af varer med droner, persontransport uden en pilot ombord, billigere udførelse af redningsaktioner fra luften samt robotinspektion og -overvågning. For at gøre dette omkostningseffektivt er U-space-operationernes store autonomi ifølge mange eksperter og forskere et vigtigt aspekt. Denne afhandling fokuserer på den stadigt fremadskridende forskning inden for autonome ubemandede operationer i U-space. Følgende forskningsspørgsmål (RQ'er) dannede grundlag for studiet:

• RQ1a. Hvad er de væsentlige begrænsninger for autonome UAV-operationer (drone-operationer) i U-space?

• RQ1b. Hvad udgør den vigtige information, som kræves i den sidste (fjerde) fase af U-space-ibrugtagningen?

• RQ1c. Er der mangler med hensyn til EUROCONTROLs 'Concept of Operations' [1] og de informationer, der er nødvendige for at tillade autonom UAV-trafik i U-space?

• RQ2a. Hvordan fastlægger man en sikkerhedsafstand til anonyme droner af ukendt model men kendt type?

• RQ2b. Hvordan kan et autonomt UAV-styresystem planlægge horisontale manøvrer for at bibeholde sikkerhedsafstanden til anonyme droner?

• RQ3. Hvordan fastlægges en kurs i 4-D for ubemandet lufttrafik for at minimere flyvetiden for hver efterfølgende UAV?

Anonyme droner er UAV'er, der hverken kommunikerer eller samarbejder med U-space-services eller andre droner. I modsætning til disse kommunikerer og samarbejder ikke-anonyme droner med henblik på at koordinere deres aktioner og adfærd.

Som det fremgår af afsnit II blev der udført en systematisk litteraturgennemgang for at besvare RQ1a, RQ1b og RQ1c. Grundlaget for dette afsnit er en fagfællebedømt artikel offentliggjort i tidsskriftet MDPI Aerospace.

I afsnit III behandles RQ2a og RQ2b. Det primære værktøj her er matematisk modellering baseret på flyvedynamikkens grundbegreber samt en analyse af en global UAV-database. I afsnittet gengives et publiceret og fagfællebedømt konferencebidrag i forbindelse med IMAV2024-konferencen, som blev afholdt i Bristol. I det samme konferenceskrift blev en anden artikel publiceret, der behandler RQ3; denne tekst er gengivet og udvidet i afsnit IV.

Afsnit V indeholder en diskussion af værdien af den nye, videnskabelige viden og væsentligheden af resultaterne, refleksioner over besvarelsen af forskningsspørgsmålene, en kritisk vurdering af forskningen samt yderligere, generelle perspektiver. Derudover indeholder afsnit V også en analyse af studiets relevans for industrien og samfundet, forslag til fremtidig forskning, personlige refleksioner over forskningen, en diskussion om tekno-optimisme og eventuelle forbehold samt afsluttende bemærkninger.

Afhandlingen afsluttes med et appendiks og medforfattererklæringer.

Afhandlingens kernebidrag udgør et værdifuldt fremskridt i forståelsen af, hvad de væsentlige informationsbehov er for at tillade autonom flyvning i U-space, hvilke mangler der er med hensyn til

’Concept of Operation’ i U-space og den information, der absolut bør foreligge, og hvad der bør gøres for afhjælpe manglerne. Desuden præsenterer afhandlingen en ny metode til at bestemme sikkerhedsafstande til en anonym UAV af ukendt model i U-space. Endelig indeholder afhandlingen Gen4jectory 2.0-algoritmen, som muliggør planlægning af ruter i 4-D med minimeret flyvetid for flere UAV'er med roterende vinger. Alle disse resultater adresserer de sikkerhedskritiske spørgsmål, der skal løses for at sikre, at autonome, ubemandede drone-operationer over Europa finder sted på en sikker måde.

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List of Abbreviations

2D (also 2-D) – two-dimensional

2.5-D – two dimensions and constant altitude

3D (also 3-D) – three-dimensional

4D (also 4-D) – three dimensions and time

5G – 5th generation mobile network

AGL – above ground level

AI – artificial intelligence

ATC – air traffic control

ATM – air traffic management

BADA – Base of Aircraft Data

BTECH – Department of Business Development and Technology

BVLOS – beyond visual line of sight

CD – conventional drone

CFD – computational fluid dynamics

CFIT – controlled flight into terrain

ConOps – Concept of Operations

DAA – detect-and-avoid

DREAMS – DRone European Aeronautical information Management Study

EASA - the European Union Aviation Safety Agency

EVLOS – extended visual line of sight

FAA – the Federal Aviation Administration

FIMS – flight information management system

GNSS – global navigation satellite system

GPS – global positioning system

IMAV – International Micro Air Vehicle Conference and Competition

IMPETUS – Information Management Portal to Enable The integration of Unmanned Systems

LIDAR – light detection and ranging

Li-Fi – light fidelity

LoS – loss of separation

ML – machine learning

MOTOR5G – Mobility and Training for Beyond 5G Ecosystems

NAA – National Aviation Authority

NASA – the National Aeronautics and Space Administration

NEU – North East Up

NOTAM – notice to airmen or notice to air missions

OBB - oriented bounding box

PhD – Doctor of Philosophy

QoS – quality of service

RPIC – remote pilot in command

RQ – research question

SAR – search and rescue

SAT – Separating Axis Theorem

SDNs – software defined networks

SDU – the University of Southern Denmark

SESAR – the Single European Sky Air Traffic Management Research

TRL – technology readiness levels

U1 – U-space foundation services

U2 – U-space initial services

U3 – U-space advanced services

U4 – U-space full services

UAM – urban air mobility

UAS – unmanned aircraft system

UAV – unmanned aerial vehicle

UD – uncooperative drone

UDKM – uncooperative drone of a known-model

UDUM – uncooperative drone of an unknown model

US – the United States of America

USD – United States dollar

USSP – U-space service provider

UTM – Unmanned aircraft systems Traffic Management

VLL – very low level

VLOS – visual line of sight

I. Introduction

I.1. Motivation

According to the Grand View Research study [2], the European commercial drone market will rise from 5.90 billion United States dollars (USD) in 2023 to 13.56 billion USD in 2030. This implies ≈ 130% of revenue growth in 7 years. The report encompasses a comprehensive set of civil unmanned aerial vehicle (UAV) operations. For example, drones can be used for fast consumer goods delivery, minimising ground infrastructure usage. For a country like Denmark, which has hundreds of islands, quick medicine aerial deliveries can minimise costs and save lives. Another promising use case is the monitoring of hardly accessible infrastructure like wind turbines, which can be specifically relevant for Scandinavia. Human transportation with uncrewed flying taxis promises a new level of aerial mobility with a new level of freedom for the customers. There are many other potential areas where drones can add value: photography, mapping, surveillance, etc.

The Single European Sky Air Traffic Management Research (SESAR) predicts that about 400 000 drones will do commercial and government missions over Europe in 2050 (Figure I-1) [3]. The agricultural segment will have the largest economic impact, amounting to 4 200 million Euros, which is about 29% of the total contribution. The segment includes mainly monitoring, spraying, and pellet applications. Mobility and transport operations include passenger transportation and railway inspection. It is the second-largest impact, associated with a quarter of the total, which is 3 600 million Euros. The segment of delivery includes e-commerce, deliveries of parcels, medical supplies, and cargo carried by air freight fleets. Its impact is about 20%, which is equal to 2 900 million Euros. The energy segment consists of the inspection and monitoring of infrastructure sites, pipelines and power lines, and tethered wind energy production. Its share is about 11% which is 1 600 million Euros. Public safety and security along with the others have about 8% each with 1 200 million and 1 100 million Euros correspondingly. The numbers look promising, however, to make them real, extensive research efforts are required.

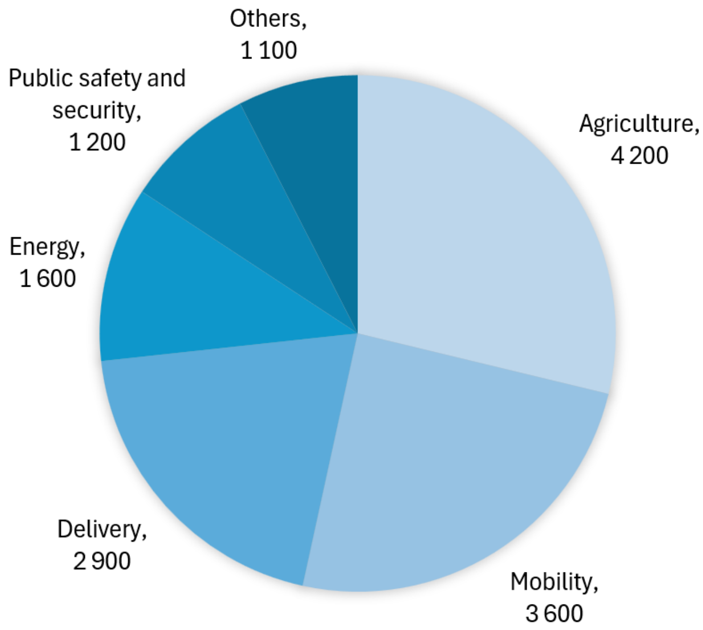

Figure I-1. Forecasted economic impact in Europe by 2050 (in million Euros) [3].

To allow drones to operate together and share airspace with manned aviation, there is a need for Unmanned aircraft systems Traffic Management (UTM) which is called U-space in the European Union [4]. U-space is an innovative set of services and procedures to allow the safe, secure, and efficient operation of drones at the Very Low Level. Supported by the European Commission, U-space is advancing from a theoretical concept to test zones and daily-life services in many European industries. Analytical forecast papers by EUROCONTROL on the European UAV market and by Vascik et al. on the United States note that drone usage is associated with a high economic impact and promising business opportunities. [3], [5]. SESAR and EUROCONTROL made a significant contribution to the development of U-space, and alongside NASA they anticipate a high degree of UAV autonomy within UTM [1], [6]. On the regulatory front, the European Union Aviation Safety Agency (EASA), Europe's equivalent of the FAA, plays a central role in overseeing the integration of drones into U-space.

Compared to crewed aviation, drones can be smaller and lighter since they do not need to carry the weight of a pilot. This fact implies better cost efficiency and simplification of UAV deployment in the area of operation. However, alongside the advantages come also disadvantages. For example, Beyond Visual Line of Sight (BVLOS) flight implies a high complexity in terms of situational awareness for a remote pilot in control (drone operator) [7]. Being a drone operator also requires, e.g., education, certification, salary, and rest time, and it implies unpredicted sick leaves. To overcome these disadvantages, market requests for UAV autonomy research and development appear.

SESAR and the European Organisation for the Safety of Air Navigation (EUROCONTROL) have planned four stages of U-space deployment – from the initial services to a full set of services, where system autonomy will be widely integrated into U-space [8]. Potentially, autonomous UAVs will be able to execute various operations, starting from simple and repeating ones; for example, clinic-to-hospital medical sample delivery. With technological advancement, autonomous drones will be able to perform more and more complex tasks. For instance, new object inspection or human transportation to any available landing location. However, extensive research is required to replace people in smart autonomous systems.

Drone autonomy, which refers to the ability of UAVs to execute tasks and make decisions without human intervention, is associated with various challenges. Firstly, there is a complexity of sharing the same airspace for uncrewed and manned air traffic. Coordination with traditional aviation requires a set of rules and solutions to allow sustainable, secure, and safe operations in the same airspace. Autonomously flying UAVs must act according to the dynamically changing situation. Some factors can have a significant impact on the initial flight plan; for example, strong winds, turbulence, various system failures, or high-priority services requiring freeing a certain volume of airspace, etc. To address this complexity and safely manage hundreds of autonomous uncrewed aircraft in the same airspace, advanced algorithms are required.

Secondly, communication and connectivity requirements imply the need for available communication networks and reliable data links. It is essential to plan and manage uncrewed air traffic based on reliable communication. Insufficient connectivity quality can lead to situations where autonomous drones do not receive information about each other in a timely manner. In this case, their further manoeuvres are at risk of losing separation implying a potential midair collision. Communication systems and technology advancement [9] implies higher availability and reliability of the links between vehicle-to-infrastructure, vehicle-to-vehicle, and vehicle-to-everything. Stable communication aids flight safety, timely coordination of air traffic, and proper responses to contingencies. One of the essential organisational challenges associated with communication and connectivity is limited infrastructure deployment of the cell networks. Additionally, drones require a higher priority in case of network overload because unstable communication can have a high impact on flight safety. Solving these issues implies investment, which is becoming complicated, as autonomous operations are significantly limited under the current regulations [10]. This fact significantly constrains autonomous operations which prevents investments in the needed communication infrastructure.

Thirdly, regulation is another fundamental problem of autonomous operations. The issues of privacy, responsibility, and investigation procedures in case of accidents and incidents remain challenging. Another problematic area can be associated with cross-border operations where different requirements, regulations, and even standards could prevail. Making regulation on a global scale is a complicated and time-consuming process that includes many stakeholders.

Furthermore, drones' autonomy requires complex decision-making, including 4-D trajectory planning and replanning, obstacle avoidance, control of loss of separation, adequate behaviour in case of uncooperative (rogue) UAV appearance, proper decision-making in case of operations with limited information about wildlife and new on-surface obstacles appearance, etc. The autonomous guidance system must be reliable, sustainable, safe, secure, and accurate enough to guide the uncrewed air traffic. To make this happen, the author of this PhD thesis expects the development and incorporation of highly advanced algorithms and machine learning techniques.

Cybersecurity will play a significant role in the reliability of autonomous vehicles [11]. U-space must be secured from hacking attempts and malicious interference. It is reasonable to expect a multi-layer defensive system against hacking attempts, jamming of communication systems, etc. The cybersecurity system must be properly encrypted, data ownership must be clearly defined and access must be limited to ensure seamless system functionality. The system must be able to identify operators and devices, managing access according to the role-based access. The cybersecurity system must be able to mitigate interference with GPS, 5G, Wi-Fi, and other communication technologies, ensuring redundancy in communication pathways. Artificial intelligence (AI) and specifically machine learning solutions can be useful in unusual patterns or anomaly recognition which helps in identifying hacking and malicious actions.

Social acceptance is perhaps one of the most essential factors. If a democratic society does not accept a certain technology, its integration becomes less possible. For example, regarding Urban Air Mobility, the European society is mainly concerned with noise, safety, privacy, benefits, and visual annoyance [12]. According to [1], public acceptance of UAV services is approximately 92–97%. It means that uncrewed air traffic has a positive foundation for further advancement. However, it remains crucial to maintain the highest level of flight safety, because accidents may significantly delay technology deployment.

Historically, Air Traffic Management relies on radar systems, human decision-making, and voice communication. This approach was sufficient for piloted air traffic; however, it is very limited for managing air traffic of drones where proper decisions must be taken very quickly due to the small separation between UAVs and operations at very low altitudes. For very low-level operations, the situation changes very quickly, requiring artificial intelligence capabilities.

There is a significant role of technological advancement that supports the industrial and governmental belief that autonomous uncrewed air traffic will become a reality in U-space. For example, recent achievements in sensing and perception systems provide a solid foundation for situational awareness of drones [13]. Modern light detection and ranging (LIDAR) solutions, infrared cameras, radars, and high-resolution video cameras allow the collection of surrounding information with off-board and on-board systems. This fact enhances drones' capability to detect-and-avoid (DAA) dynamic obstacles, which is essential for ensuring flight safety. The sensors supply autonomously guided drones with essential information on the free and non-free space, including flying and on-surface object data. Based on this data, the surrounding objects can be classified, and their behavioural limitations can be predicted. For example, if a recognition system identifies a known model car, its displacement limitations can be well predicted. This knowledge is essential for the drone's 4-D trajectory planning to avoid a loss of separation event.

The rapid development of artificial intelligence and machine learning creates a promising foundation that collected data about the surrounding world will be properly analysed and used for 4-D trajectory planning based on various predictions that include object/subject behaviour patterns (see, for example, [14], [15]). Fast computation capabilities will support timely trajectory replanning and smart decision-making using on-board and off-board hardware and software. The author of this PhD dissertation also acknowledges the essential role of technological advancement in the following areas: Global Navigation Satellite Systems, edge computing, cloud connectivity, digital twin and simulations, cybersecurity, aircraft motors and engines, and batteries of high capacity.

The author's main motivation for writing the dissertation was the promising alignment of his industrial expertise and education in the areas of flight physics, flight safety, telecommunications and computer science with rapid advancements in UAV technologies and high expectations in the emerging market. Autonomous operations can be associated with better cost efficiency, human factor mitigation, and significantly faster reactions in the dynamically changing situation. Having in mind the high expectations of the economic impact and unresolved problems in the field of uncrewed air traffic autonomy, the author of this PhD dissertation decided to conduct research to address some of these issues of high importance.

I.2. Structure of the dissertation

The deployment of autonomous uncrewed air traffic is influenced by various factors (economic, technical, regulatory, etc.), as outlined in the Motivation section. However, this PhD dissertation focuses on enabling the autonomous operation of drones in U-space, prioritising flight safety and, additionally, operational efficiency. Specifically, the contribution of the dissertation is narrowed down to the following interconnected papers (Table I-1):

1. Section II (the first paper): It is essential to ensure the proper provision of information to enable safe and efficient autonomous operations of UAVs in U-space. To achieve this, the constraints of autonomous guidance must first be identified. Additionally, the study proposes a comparison between the latest version of the U-space Concept of Operations [1] and the identified essential information requirements.
   The selected criteria for parameter selection are flight safety and operational efficiency. These categories are among the most important for U-space. "Safety first" is a fundamental principle in aviation, while operational efficiency is a key driver of cost-effectiveness. Ultimately, both factors directly influence the feasibility of U-space and its potential for business success.
2. Section III (the second paper): This paper discusses the issue of uncooperative drone interference in conventional uncrewed air traffic. This problem directly impacts flight safety by posing a risk of mid-air collisions. The authors propose a global UAV database analysis and a mathematical model that addresses the challenge of determining the minimum safe and recommended separation distances from a rogue drone of unknown model.
3. Section IV (the third paper): This paper addresses the challenge of 4D trajectory planning, ensuring that autonomous UAVs are guided according to both spatial and temporal constraints. The algorithm proposed in the paper takes into account flight safety and operational efficiency by minimising flight time for each consecutive UAV.

Together, these three papers advance research in the field of UAV autonomous guidance, contributing valuable knowledge that addresses safety-critical issues and limitations in operational efficiency.

The dissertation comprises primary and supplementary sections. The primary section Introduction (I) outlines the research motivation, the structure of the dissertation, identified research gaps, research questions, and the chosen methodology. The primary sections II-IV replicate three published articles with additions and improvements.

Table I-1. Published papers that are incorporated in the dissertation.

Section	Paper's title	Publisher	Reference
II	A Critical Review of Information Provision for U-space Traffic Autonomous Guidance	MDPI Aerospace journal	[16]
III	A method for determining the safe separation to an unknown-model uncooperative UAV in U-space	15th ANNUAL INTERNATIONAL MICRO AIR VEHICLE CONFERENCE AND COMPETITION (IMAV2024)	[14]
IV	Gen4jectory algorithm – 4-D trajectory planning with minimised flight time for multiple rotary-wing UAVs	15th ANNUAL INTERNATIONAL MICRO AIR VEHICLE CONFERENCE AND COMPETITION (IMAV2024)	[17]

In section V, Discussion and Perspectives, the dissertation describes the scientific novelty and significance of the study, the relevance for industry and society, suggestions for potential future research, personal reflections, and the problem of techno-optimism and cautions.

Additionally, the dissertation includes the supplementary sections Acknowledgements, Executive summaries in English and Danish, Table of Contents, Lists of Figures, Tables, and Abbreviations. Also included are Appendix and Co-authorship statements.

I.3. Identified research gaps and research questions

The rapid advancement of UAV technologies has stimulated stakeholders' high expectations and extensive research on many aspects of U-space. However, many organisational, technical, regulatory, and scientific issues remain unresolved. In both Europe and the United States, regulatory frameworks and operational concepts have yet to address the challenge of integrating autonomous UAVs into airspace [1], [6]. Among other issues, the information provision needs are especially important because any safety-critical decision relies on a proper information flow. In this section, the dissertation explains the selection of thesis research gaps and questions for the PhD thesis, along with their scientific foundation and significance.

Some researchers argue that there is a strong need for a high level of automation in UAV operations due to safety reasons and cost-efficiency [18], [19], [20]. Campusano et al. note that the full commercial potential requires drones' autonomy [21]. Furthermore, the SESAR 3 Joint Undertaking states that enabling "high-density operations of multiple automated drones" is a key-principle of the U-space [22]. However, to integrate autonomous UAVs in U-space, corresponding information flows are required.

In the USA, the Concept of Operations of the FAA discusses many essential aspects of UTM; however, it does not provide an analysis of the constraints and information provision requirements for the autonomous operations of uncrewed air traffic [6]. Also in Europe, the Concept of Operations of U-space does not consider the information provision analysis for the last U4 stage of U-space deployment where the drones' autonomy will be common [1]. The lack of the information provision analysis (research gap) was identified by the project DREAMS (DRone European Aeronautical information Management Study) [18], which alongside a project of SESAR, Information Management Portal to Enable the integration of Unmanned Systems (IMPETUS) [19], made a significant contribution to identifying the information required to support U-space operations. However, the document stated that it contributes with information needs identification only for the U1-U3 stages (foundation, initial, and advanced services), and partly for the final stage U4 (full services) of U-space. The information provision needs are emerging as a response to existing constraints on UAV autonomous operations. To address the issue, the following study was performed in [16], and this paper is replicated in section II.

The dissertation incorporates high-level and more specific research questions. In the first article [16], we conducted high-level research by addressing the following questions.

- RQ1a. What are the essential constraints for the UAV autonomous operations in the U-space?
- RQ1b. What is the important information provision required on the last (forth) stage of U-space deployment?
- RQ1c. What are the gaps in between the EUROCONTROL's Concept of Operations [1] and the information needed to allow UAV autonomous traffic in the U-space?

The UAV autonomous guidance constraints analysis is essential for the information provision study. This is the case because certain information is required to address the existing constraints. The information is a crucial resource of the autonomous system that supports proper decision-making. For example, if there is no information about other airspace participants, a flight will entail with a risk of loss of separation (LoS) and even a collision. Similarly, the risk of controlled flight into terrain (CFIT) increases if the autonomous guidance system does not possess information on a UAV's position, orientation, and terrain map. In this light, the existing constraints must be analysed together with information provision requirements for the fourth stage of U-space with highly advanced autonomy.

However, just listing the essential constraints and information needs is not enough to suggest further research and development of U-space. The valuable research contribution is the highlighting of the existing gaps between the existing Concept of Operations [1] and the information needs. That is why RQ1a, RQ1b, and RQ1c are grouped within the same section in the dissertation.

One of the gaps identified in the paper [16] was safety-critical information about the position and classification of airspace intruders. An uncooperative or a rogue drone is an example of this. For instance, Souli et al. argue that rogue drones' threats make it necessary to address public safety, security, and privacy issues [23]. This dissertation is aligned with this statement; however, it is not enough, and finding a safe separation from uncooperative drones is one of the most important concerns for flight safety.

The rogue drone problem poses a significant threat of midair collision with manned and unmanned aircraft. For example, in December 2018, hundreds of flights at Gatwick Airport in London were cancelled due to a drone incident [24]. The rogue drone classification is essential to separate it safely - with reasonable reserve - to avoid a potential collision. Since midair collisions can lead to loss of life and property, the following research questions were raised in the second paper [14]:

- RQ2a. How to identify a safety separation with uncooperative drone of unknown model but known type?
- RQ2b. How UAV autonomous guidance system can plan horizontal manoeuvre to avoid a loss of separation with uncooperative drone?

Discussing UTM issues, Baum directly highlights the research problem: "noncooperative traffic not participating in the system remains a separation challenge" [4]. RQ2a requires an assumption that information on UAV type is possible to collect. Such an assumption looks reasonable based on the advancement of drone classification algorithms and techniques [15], [25]. UAV model identification ability is not enough since the uncooperative drone of an unseen model can be assembled by a layman with any widely available set of spare parts and technologies. This fact implies an uncertainty regarding the aircraft performance data which again implies an inability to predict uncooperative drones' limitation in mobility. Bearing in mind that the intentions of the rogue drone are also unknown, answering RQ2a constitutes a complex multi-dimensional task.

Answering RQ2b is essential to demonstrate how a safe separation distance can be used for ordinary UAV to plan its level flight in the vicinity of the rogue drone. For most operations, UAVs typically cover long distances (kilometres and dozens of kilometres) at a relatively small altitude (up to 150m above ground level). This implies that the study of level flight has high priority since in most cases the trajectory of the ordinary UAV will likely be horizontal.

Aircraft performance based 4-D trajectory planning is a common approach in the field of commercial aviation [26]. U-space airspace participants operate at a very low level, which implies new constraints and new challenges for 4-D trajectory planning.

Aggarwal et al. highlight the essentiality of the following challenges for optimal path planning: path length, cost-efficiency, time-efficiency, energy-efficiency, optimality, robustness, and collision avoidance [27]. Trajectory planning includes path planning considering the time aspect. We expected that flight time minimisation could be one of the most essential requests for UAV operations. For example, pizza or medicine delivery could require completing drone operations as fast as possible. Additionally, time complexity is essential for quick 4-D trajectory calculation. This is the case since an expected separation for uncrewed air traffic is measured in metres; however, drones can fly dozens of metres in seconds, which implies that, if required, the trajectory recalculation must be performed very quickly.

EUROCONTROL directly states that full U-space services will be associated with uncrewed aircraft's autonomous capability to detect and avoid collision with any surrounding aircraft [1]. This implies that a 4-D trajectory planner should plan UAV trajectory in a way that excludes a loss of separation case. If two aircraft do not lose their separation they, can never collide.

All these aspects motivated us to raise the following research question:

- RQ3. How to plan 4-D trajectories for the uncrewed air traffic to minimise flight time for each consecutive UAV?

This research question is discussed in the Section IV.

UAV 4-D trajectory planning is a multifactor complex task where computation complexity, atmosphere, limited knowledge about the environment, and sensor constraints have a significant impact [28]. The problem complexity increases once dozens of autonomous drones have an intention to operate in the same area. Tang et al. wrote: "It should be noted that when obstacle buildings are densely arranged, it is necessary to envelop UAVs according to their shape and performance and set them at a safe distance from each other" [29]. In comparison with ground robots, UAVs dynamics are associated with higher complexity [30]. The greater complexity of calculations implies higher time complexity for the trajectory computation, and the more drones that participate in the same volume of airspace, the more time-complex 4-D trajectory planning becomes. [28]. These ideas were the motivation for raising RQ3.

Trajectory planning in robotics implies that the desired state of the vehicle is known, and its control system should be able to execute the mission via minimising deviations between current and desired states. To overcome the issue of deviation, higher separation values can be used. Additionally, 4-D trajectory planning can find the trajectories based on the idea that all drones have a smaller value of the available thrust according to the level of the identified deviations. The smaller thrust in the planning stage gives a reserve for the UAV controller to match the desired UAV position with the current state via the reserve usage. The dissertation states that such an approach has the potential to find a very fast way of 4-D trajectory computation for solving practical problems for uncrewed air traffic autonomous guidance.

I.4. Methodology and Research Design

I.4.1. Reflections on scientific paradigm selection

There are several classical approaches to conducting research, each with its strengths and limitations. This section begins with a brief overview of these approaches, outlining the methodological choices available for this study. Considering this foundation, the dissertation provides a rationale for selecting Design Science Research as the most suitable framework.

The inductive method requires extensive observation, including analysis and conclusions that are as impartial as possible [31]. Inductivism relies on experience as a foundation for knowledge. Based on the observations, it is possible to synthesise new knowledge through generalisation and propose a new law. This approach fits very well for building knowledge from experience; however, it is constrained by its ability to create entirely new systems. Additionally, the paradigm can be criticised for its limitations in addressing the outliers' case and dealing with the problem of overgeneralisation. In the context of modern technological progress, the paradigm gives a philosophical foundation for machine learning techniques. For example, artificial neural networks are trained on the generalised experience (a dataset) often demonstrating high effectiveness. However, often such solutions are inefficient in case of outlier events [32]. Finally, the inductive method is associated with significant limitations in addressing novel artifact creation, which is a major part of the dissertation.

The deductive method implies that research starts with theories and laws, trying to explain, predict, or analyse the phenomena [31]. A deductivist uses hypotheses and checks them through known knowledge to predict the behaviour of an object. A typical example here is the displacement of a rigid body under known conditions. The body moves under the impact of the acting forces experiencing resistance of air and other mechanical frictions. The laws of physics can perfectly describe the phenomena and predict their behaviour through mathematical calculations. However, the paradigm completely depends on the accuracy of the theory and availability to collect essential data on the study object and its environment. For instance, in the study discussed in this PhD thesis, the algorithms directly depend on the input of aircraft performance data, sensors' bias, and simplifications of physical modelling. Another example is the first landing on the Moon. Since no prior experience existed, the inductive method was lightly applicable. However, through theory usage, this engineering task of safe landing can be well calculated in advance.

The supporters of the hypothetical-deductive method admit disadvantages associated with the inductive and deductive methods [31]. The hypothetical-deductive method extends the deductive paradigm by testing theory-based ideas in practice. This approach tries to combine the strong sides of both, using hypothesis, theory, and experiments together. However, the method relies on the idea that hypotheses must be structured in a way that they can be tested and potentially proven false. In practice, it is not always easy to frame hypotheses in this way, especially in theoretical physics and even social science, where abstract aspects and/or a significant number of interconnected factors can often be present.

The research design of the PhD thesis relies on Design Science Research, as traditional approaches in natural science are limited "when the goal is to study the design, construction, or creation of a new artifact, i.e., something that still does not exist, or to conduct research focused on problem solving" [31]. The focus of the PhD thesis is creating new knowledge based on an extensive literature review, developing two new algorithms to address the issues of finding safe separation with uncooperative drone of unknown model, and planning 4-D trajectories for the multiple rotary-wing uncrewed aircraft in urban environments. Both algorithms are validated through mathematical calculations and computational modelling. Additionally, the Gen4jectory 2.0 algorithm was tested in several hundred simulations across various scenarios (see Section IV).

Historically, Design Science Research has its roots in the field of engineering [33]. This alignment is unsurprising as engineering science focuses mainly on developing solutions rather than studying natural phenomena. The Design Science Research paradigm typically relies on iterative cycles of developing, improving and testing artefacts, aiming to find a practical solution to a task. Therefore, Design Science is a suitable choice for the thesis, and it aligns well with the innovative problem-solving focus of the study. Further, it helps build and validate new methods; also, it enables practical contributions to U-space development, including regulation and guidance for further research, highlighting essential gaps that must be addressed to allow U-space traffic autonomous guidance.

The Design Science Research paradigm is well aligned with the National Aeronautics and Space Administration's (NASA) Technology Readiness Levels (TRL) concept [34]. Both paradigms are oriented towards practical problem solving, the creation of artifacts, and iterative development through the maturity levels. Evaluation and validation play a significant role in proving the artefact's effectiveness in real-world engineering issues. Additionally, both concepts rely on the fusion of theory and practical applications. However, the research questions underpinning this PhD thesis require resource-intensive research to reach the later TRL stages, which is practically unattainable within the limitations of a PhD. In this light, the dissertation includes an extensive literature review, identifying essential constraints, and comparing them with information provision needs and the state of the art of the Concept of Operation of U-space; two algorithms were developed where the Gen4jectory 2.0 was tested in simulations. Each paper of the PhD thesis gives further guidance for the scientific community to continue research on the achieved findings. This approach reflects very well the ideas of NASA TRL and Design Science Research.

I.4.2. Design Science Research Cycles

Hevner [31] suggests Design Science Research Cycles as an effective implementation and evaluation of Design Science Research. He argues that Relevance Cycle, Rigor Cycle, and Design Cycle usage offers a well-structured framework that bridges theory and practice, delivers a rigorous research foundation, and ensures consecutive development through iterations. Figure I-2 was inspired by and partially adapted by Hevner's approach. The Design Science Research Cycles approach relies on three pillars: Environment, Design Science Research, and Knowledge Base. Also, there are three cycles: Relevance Cycle, Design Cycle, and Rigor Cycle. The Environment and Knowledge Base provide an essential background to the research. A combination of the researcher's experience and expertise, findings collected from the U-space test zones, social expectations, U-space stakeholders' needs, and technological advancements created a vision of a scientific problem to address. Additionally, the initial literature review gave reliable evidence that information provision for the autonomous guidance for U-space requires an extensive study, and this is an essential research gap [18]. This helped to formulate the initial ideas for the research issue, select relevant scientific literature and industrial reports, and develop RQ1a, RQ1b, and RQ1c accordingly. Based on the research questions, it was decided to conduct the literature review by analysing the constraints, information needs, and recent version of the Concept of Operations of U-space [1].

The formulated research questions provided a foundation to see them from a broader perspective, specifically how essential the findings could be to allow autonomous guidance in U-space. This new vision reflects the Relevance Cycle and is well-aligned with U-space stakeholders' needs, social expectations on drones in Europe, and technological advancements; all of which are discussed in section II.

An extensive literature review was performed to address RQ1a, RQ1b, and RQ1c. This revealed the existing constraints, essential information needs, and existing U-space services that cover associated information. This allowed highlighting of the existing research gaps and proposing a high-level methodology on how to address the gaps. In the conclusion section, recommendations to test the findings in practice are given. The study can be associated with TRL 2 because it systematically formulates the conceptual framework of information provision for the U4 stage, highlighting paths for future research and development without experimental validation or testing a prototype [34]. This finalises the first stage of the research (section II).

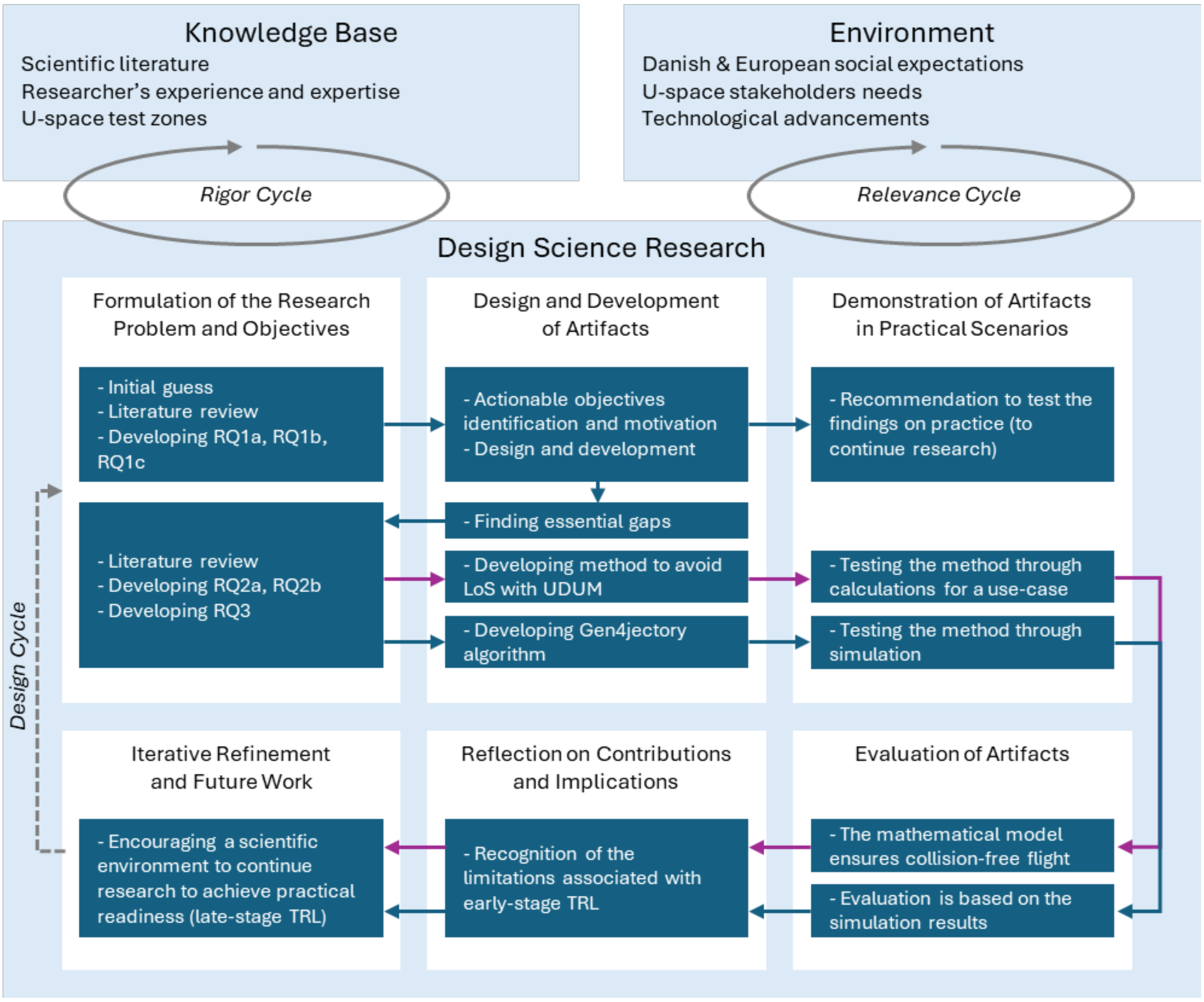

Figure I-2. Design Science Research Cycles. Inspired by and partially adapted from [35].

The revealed research gaps gave a foundation for research continuation. Specifically, it was decided to select safety-critical issues regarding finding a safe separation with uncooperative drones and 4-D trajectory planning of multiple rotary-wing drones with minimised flight time. The gaps gave a start to investigating new literature and formulating RQ2a, RQ2b, and RQ3. This concludes the formulation of the research problem and objectives within our research frame.

From this moment, the research was split in two parallel directions. The first direction (violet arrows) was focused on addressing RQ2a and RQ2b, while the second direction (dark blue arrows) had the purpose of resolving RQ3. Precisely, at the design and development of artifacts stage, the mathematical (physical) model of uncooperative drone and its limitations was developed. Simultaneously, the Gen4jectory 2.0 algorithm was programmed based on the mass-point mathematical (physical) model of rotary-wing UAV motion combined with the theta-star algorithm.

Ideally, the demonstration of artifacts in practical scenarios would require real-world flight tests. However, in aviation science, the aerospace systems go through a relatively similar approach: concept, mathematical (physical) modelling, tests in simulations, laboratory or stand tests, and real-world flight tests. Our case is not an exception; therefore, the research was started by advancing through these stages. However, due to the limitations associated with the time allocated for the PhD research, the method addressing RQ2a and RQ2b was tested only through a use case and associated mathematical calculations. The Gen4jectory 2.0 algorithm (dealing with RQ3) was tested in simulations (see IV.5. Simulation results).

The theoretical approach in the evaluation of the artifacts slightly differs in two studies (sections III and IV). The method for finding a safe separation was demonstrated to be reliable through the mathematical logic proposed in the study (section III). The Gen4jectory 2.0 algorithm also relies on the mathematical logic; however, additionally, it was tested in simulations. Both studies reflect the limitations associated with a low level of TRL, which is aligned with the reflections on contributions and implications. The study conducted in section III reflects a TRL 3 level because the key technology (method) was demonstrated analytically through mathematical modelling [34]. The Gen4jectory 2.0 algorithm (section IV) was developed to TRL 4 as it was tested in simulations using a set of random scenarios.

At the iterative refinement and future work stage, the scientific community was encouraged to continue research by testing findings, methods, and algorithms proposed in order to improve them and advance through the TRL scale. This concludes the first design cycle and opens new opportunities for further research and development. This fact also implies that through the Rigor Cycle, the knowledge base was updated and new research will start from more advanced positions.

The study created new valuable knowledge, which is confirmed by three peer-reviewed papers published. Additionally, through the Relevance Cycle, the author of the PhD thesis received an important confirmation of the scientific relevance through industrial acknowledgement of the findings expressed by the FAA in the US and Odense Robotics in Denmark.

I.4.3. Mathematical modelling and simulations

Mathematical modelling is a classical approach in engineering science [35]. Specifically, in the aerospace domain, it provides a reliable capability for predicting aircraft displacement under known conditions. As part of analytical studies, mathematical modelling can be associated with TRL 3 and later stages in NASA's TRL classification [34]. Mathematical modelling and simulations are essential parts of the dissertation for Sections III and IV. The calculations provided in these sections represent scientific evidence constrained by the assumptions made.

Mathematical modelling, alongside coding, plays a central role in algorithm creation. The research questions on safe separation and 4-D trajectory planning required modelling drone motion, which is a core part of the algorithms developed in the research. Properly calculated UAV motion allows one to state that, in theory, a UAV can cover a certain distance in a given time. However, research practice in the aerospace field shows that complex systems require practical tests and experiments to ensure that a solution is reliable; this is because flight experiments often reveal hidden issues associated with sensor bias, hardware limitations, specific use cases, etc. In light of this, the algorithms should be tested in simulations, flight experiments, and real-world flights. The theoretical basis for the use of simulations arises from the necessity of testing a technology while minimising expensive real-world flight tests under various conditions and exploring a wide diversity of use-case scenarios. The PhD study is very limited in terms of timeframe and resources; therefore, the dissertation provides only mathematical modelling in Section III and mathematical modelling with simulation of flights in Section IV. While simulations cannot fully replace real-world conditions, they provide significant cost savings and efficiency in early TRL stages by enabling extensive testing and development under controlled virtual conditions with predefined inputs.

The PhD dissertation incorporates mathematical modelling to address RQs2 and RQ3. Specifically, RQ2a is the primary research question explored in Section III. Addressing this question provides valuable new insights into how to calculate the minimum separation distance and safety radius from an uncooperative drone of unknown model but known type.

In mathematical terms, the answer is presented in the final equation for minimum separation distance equation (9.1), provided in Section III.5. Discussion. The safety radius can be calculated using equation (13); see Subsection III.4, Mathematical Model.

RQ2b is a supplementary research question. Its role in the study is to provide an example of how calculations of minimum separation distance and safety radius can be used in planning horizontal manoeuvres to avoid a loss of separation with an uncooperative drone. The paper presents a solution for head-on approach use cases (rho-two problem); see Subsection III.4, Mathematical Model, equation (21).

The level of flight safety in Europe is very high; for example, EASA reports: "In the EU, over 7.3 million commercial air transport flights took to the skies in 2023 – which were accomplished without any fatal accidents involving an EASA member state operator" [36]. To align more closely with the highest achievements of the EU commercial aviation industry, it would be beneficial to simulate several million flights to test the proposed algorithms. However, due to the limitations previously discussed, the research on the Gen4jectory 2.0 algorithm was limited to testing a specific set of scenarios (see Section IV.5. Simulation results). This highlights the necessity for further research.

RQ3 does not have a direct answer in the form of a single equation. However, it is addressed through the maths- and logic-based Gen4jectory 2.0 algorithm (Section IV). The mathematical model of rotary-wing UAV motion is represented in the equations in Section IV (1–39). The core idea here is to consider the main aerodynamic forces, as their contribution to aircraft motion plays a primary role.

Rotary-wing UAVs vary in their mass, thrust, drag coefficient, cross-sectional area, and maximum angle of tilt. To minimise flight time, it is essential to fly at the maximum possible tilt angle, as in this case the thrust vector has its greatest component in straight and level motion. However, if a rotary-wing UAV has a low thrust-to-weight ratio (see Modes IA, IB, IIB in Table IV-1), it cannot maintain level flight at the maximum tilt angle. In such a case, the aircraft would descend. Therefore, to stay level and reach maximum velocity, it is essential to determine the maximum possible tilt angle at maximum thrust. Equation (24) in Section IV gives a direct answer to this.

For rotary-wing UAVs with a high thrust-to-weight ratio (see modes IIA, IIIA, IIIB in Table IV-1), it is necessary to fly at their tilt angle limit. However, thrust must be adjusted accordingly; otherwise, the UAV will ascend. Equation (30) in Section IV directly addresses this, as θ is at its maximum.

Inertia is also essential; it is modelled in the equations in Section IV (40–50).

Priority in trajectory planning is based on the fundamental principle of U-space, which states that there should be equal access to airspace (excluding emergency services, which have higher priority). In practical terms, equal access implies that each subsequent UAV is given the best possible option to plan its 4D trajectory in accordance with existing plans.

Translation of assumptions into mathematical equations

It is important to note how the assumptions were translated into equations in the study. Sections III and IV are based on a mass-point approach for UAV motion modelling, assuming standard atmospheric conditions and no wind. However, air density is treated as a variable (see equations (2) in Section III and (10) in Section IV), which implies that the proposed algorithms can perform accurate calculations for any realistic air density. The main aerodynamic forces are considered, while moments are ignored. For example, see equations (1–9) in Section III and equations (10-24) in Section IV.

Section III assumes that it is essential to extend the global UAV database with data on maximum thrust force, drag coefficient, cross-sectional area, and UAV mass. While maximum level speed analysis is important, it cannot stand alone, as two different UAVs may have the same maximum speed but significantly different weight, thrust, and drag coefficients. Such differences can lead to substantially different climbing and diving performance. The authors encourage the scientific community to continue research to address this issue. The study proposes mathematical calculations based on the assumption that an extended global UAV database exists and is available for use.

Another essential assumption in Section III simplifies the manoeuvrability of the UDUM. Since the characteristics of the UDUM are unknown, it is safer to assume that it can change its direction of flight immediately. While this does not reflect real aircraft behaviour, this approach ensures flight safety by covering all existing cases, including the most manoeuvrable UDUMs. This simplification allows for the definition of a safety area around a UDUM (see Equation (13)).

Section IV assumes that the aircraft performance data of each UAV is known, and that the uncrewed aircraft traffic management system operates in a centralised manner. The centralised approach implies that one entity has real-time data on all UAV positions in the airspace, and that trajectory planning calculations are made for the entire uncrewed air traffic in the area of operations, considering the intentions of every drone. Finally, the Gen4jectory 2.0 mass-point model assumes that UAVs conduct flights with limited manoeuvring, executing mainly direct routes, which is essential for delivery missions, for example. Conversely, Gen4jectory 2.0 is not recommended for drone races, where flights involve aggressive and frequent manoeuvring.

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II. A Critical Review of Information Provision for U-space Traffic Autonomous Guidance

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Abstract: This paper identifies and classifies the essential constraints that must be addressed to allow U-space traffic autonomous guidance. Based on an extensive analysis of the state of the art in robotic guidance, physics of flight, flight safety, communication and navigation, uncrewed aircraft missions, artificial intelligence (AI), social expectations in Europe on drones, etc., we analyzed the existing constraints and the information needs that are of essential importance to address the identified constraints. We compared the identified information needs with the last edition of the U-space Concept of Operations and identified critical gaps between the needs and proposed services. A high-level methodology to identify, measure, and close the gaps is proposed.

Keywords: U-space; U-space information; UAV autonomous guidance; unmanned aircraft system traffic management

II.1. Introduction

The Single European Sky Air Traffic Management Research Joint Undertaking (SESAR JU) defines U-space as “a set of new services and specific procedures designed to support safe, efficient, and secure access to airspace for large numbers of drones” [1]. SESAR JU expects that U-space services will be supported by advanced automation functions and digitalization in multiple autonomous unmanned aerial vehicles (UAVs) [1].

Unmanned aircraft system traffic management (UTM), named “U-space” in Europe, is a new paradigm of Air Traffic Management (ATM), characterized by a cooperative approach, which provides safe and efficient services for UAVs to allow their operations at the Very Low Level (VLL) [2]. While ATM is a system with a key human role, UTM is based on computing infrastructure with high automation for managing UAVs’ operations. “Ultimately, U-space will enable complex drone operations with a high degree of automation to take place in all types of operational environments, including urban areas” [1].

D.M.K. Zoldi et al. argue that humans can be superseded in any respect of drone operations by machines with further unmanned aircraft system (UAS) autonomy development [3]. A flight without human control requires that a U-space traffic autonomous guidance system is in place. The system can be centralized, decentralized, or hybrid [4,5]. The fundamental difference between these three types is that a centralized system provides a single entity with the functions of management and control over uncrewed air traffic. The decentralized system relies on multiple entities. The hybrid system combines both, depending on the area of operation. For instance, the highly dense uncrewed air traffic may benefit from local centralization, but for remote areas, a decentralized approach can be preferable. The centralized traffic management system needs significant infrastructure, but it allows for the optimization of traffic as a holistic system. A decentralized system has much less demand for infrastructure, but its optimization potential is limited. The authors of the European project "Metropolis 2" suggested the hybrid approach since it is more effective in preventing conflicts from happening rather than trying to resolve them after they occur [5]. From our viewpoint, the hybrid system is highly possible to expect in the future due to its flexibility to address various constraints. Our analysis in this article is accompanied by comments when it is important to note that this information is necessary only for a specific type of system (centralized, hybrid, or decentralized). All other information needs described in the article are universal for all system types. In all cases, it should manage unmanned aircraft 4D (three dimensions and time) trajectories in real time and without human intervention. The decision-making process [6] is a significant part of it, which requires relevant information provision and a combination of AI-based algorithms with, e.g., machine learning (ML).

Eurocontrol predicts significant AI integration in autonomous aviation [7]. We also find that AI implementation will play a crucial role in autonomous guidance. For example, situation awareness is hardly possible without image recognition [8] for many types of missions (surveillance, inspection, etc.). Path planning algorithms, which are a part of AI science, are essential to guide UAVs autonomously in dynamically changing airspace [9]. However, the complexity of some missions and the currently limited progress of AI [10] will imply a step-by-step substitution of human functions with machines [11].

Autonomy in various systems and functions within U-space will first emerge in services where it is easiest to deploy. For example, equal access to airspace relies on a priorities policy that normally does not require complicated decision-making, and thus AI can plan uncrewed traffic according to a priority algorithm without human intervention. Another example is the daily delivery of medical samples by UAVs from one hospital to another. The flight route remains mostly constant, and such an operation is not unique. These missions can be automated more easily than a unique operation like inspecting a new bridge with a drone or pizza deliveries to various addresses in highly congested uncrewed air traffic. The strong side of AI is its reliability in constant and repeatable operations. However, new tasks, new environments, and new conditions can be challenging for modern autonomous systems. Nevertheless, the borders of autonomy implementation in the U-space will change over time until humans' roles are reduced to the consumption of UAV services.

U-space traffic autonomous guidance will likely rely on robotic navigation, which is a well-developed discipline. The usage of robotic navigation in airspace is just a case of operating in a 3D (three-dimensional) environment [12] with the constraints described in this paper (see Tables II-(1–6)). To tackle the constraints, it is essential to collect the corresponding information. This issue has been partly solved or already included in the deployment phases of U-space services. For example, the Drone Aeronautical Information Management Service provides terrain maps with altitudes to aid with addressing the issue of static obstacles. However, there are still multiple gaps that the current paper highlights with an analysis.

Table II-1. Physics of flight constraints.

Physics of Flight Constraints	Needed Information	U-Space Service	Note
UAV performance	UAV performance	✓Common Information Service	U3
	Angles during flight	-	Gap
Battery charge/fuel available	Available energy on board	-	Gap
Weather and turbulence	Visibility Ordinary and hyper-local wind velocity, direction, gusts Ordinary and hyper-local precipitation Temperature Humidity Atmospheric pressure	✓Weather Information ✓Monitoring	U2
	Natural turbulence map	-	Gap
	Area and time of operation for heavy aircraft generating wake vortices at VLL	-	Gap
	UAV wake vortex category	-	Gap
	Lightning strike threat areas	-	Gap

Table II-2. Trajectory computation constraints.

Trajectory Computation Constraints	Needed Information	U-Space Service	Note
Time complexity	Selection among algorithms to plan a trajectory with a suitable time complexity for real-time operations	-	Gap
4D trajectory optimality	Drone user's preferences in 4D trajectory planning	-	Gap
Scalability, adaptability, learning capability, robustness	Selection among software solutions to allow suitable scalability, adaptability, learning capability, and robustness	-	Gap

Table II-3. Collision avoidance constraints.

Collision Avoidance Constraints	Needed Information	U-Space Service	Note
Static obstacles	Static obstacles' location and height	✓Geographical Information Service	U2
	Terrain map with altitudes	✓Drone Aeronautical Information Management	U1

Dynamic obstacles	Coordination with ATM for flight in controlled airspace	✓Procedural Interface with ATC	U2
	U-space traffic with 4D trajectories or temporarily occupied airspace	✓Traffic Information ✓Strategic Conflict Prediction ✓Strategic Conflict Resolution ✓Monitoring	U2
		✓Dynamic Capacity Management ✓Tactical Conflict Resolution ✓Tactical Conflict Prediction	U3
	ATM traffic with 4D trajectories	✓Collaborative Interface with ATC	U3
	Position and classification of on-surface dynamic obstacles	-	Gap
	Position and classification of airspace intruders and wildlife	-	Gap
Separation	Demands to separation	✓U-space Separation Management Service	Potential U-space service (proposed by the BUBBLES project)
Obstacle uncertainty	3D map of known and unknown environment	-	Gap
Vertiport availability	Vertiport capacity	✓Vertiport Resource Allocation Management ✓Vertiport Dynamic Information Service	U3
	UAV flight characteristics	-	Gap
	UAV size	-	Gap
	Requirements for charging and fueling	-	Gap
	Ground handling needs	-	Gap
	UAV noise category	-	Gap

The European consortiums DREAMS (DRone European Aeronautical information Management Study) and IMPETUS (Information Management Portal to Enable the integration of Unmanned Systems) have contributed significantly to investigating the information requirements for U-space [13,14]. The required information includes aeronautical, meteorological, terrain and obstacles, surveillance, communication, and other information [15]. Both studies were highly influenced by the ATM heritage, where manned aviation has a prime role. However, the information needs of U-space traffic autonomous guidance were not addressed completely.

Table II-4. Communication navigation surveillance constraints.

Communication Navigation Surveillance Constraints	Needed Information	U-Space Service	Note
Communication network availability, coverage, and load	Map of communication network availability at VLL Status of communication network availability at VLL	✓Communication Coverage Information ✓Communication Infrastructure Monitoring	U2
Electromagnetic interference	Electromagnetic interference	✓Electromagnetic Interference Information	U2
Navigation network availability	Map of GNSS coverage and navigation network availability Status of link with navigation networks	✓Navigation Coverage Information ✓Navigation Infrastructure Monitoring	U2
Aircraft position	Real-time UAV position	✓Tracking	U2
		✓Vertical Alert Service	U3
		✓Vertical Conversion Service	U3
Surveillance for guidance	Surveillance data	✓Surveillance Data Exchange	U2

Table II-5. Institutional constraints.

Institutional Constraints	Needed Information	U-Space Service	Note
Registration and identification	UAV registration and identification	✓Registration ✓Network Identification	U1
Airworthiness	Status of airworthiness	-	Gap
Emergency	Emergency status of UAV (including status of onboard systems)	✓Network Identification	U1
		✓Emergency Management	U2
Risk assessment	Flight risk evaluation	✓Operation Plan Preparation/Optimisation Service ✓Risk Analysis Assistance ✓Flight Authorisation Service	U2
	Population density map	✓Population Density Information	U2
	Location of suitable landing areas in case of emergency	-	Gap
	Runway and Vertiport surface conditions	-	Gap
	Incident and accident data, legal recording	✓Legal Recording ✓Incident/Accident Reporting ✓Digital Logbook	U2

Geofencing	Restricted areas' coordinates and duration, controlled airspace map, NOTAM	✓Geo-awareness (Geo-fence Provision) ✓Geo-awareness	U2 U1
The spatial limits	The spatial limits of the U-space airspace	✓Common Information Service	U3
Security	UTM security breakthrough (status and level of threat)	-	Gap
Noise reduction	Map of noise-sensitive areas	-	Gap
Regulation demands	Rule awareness in terms of robotic algorithms	-	Gap

There are four phases of U-space development: U1, U2, U3, and U4 (see Figure II-1) [16]. It is expected that at each stage, the level of connectivity and automation will be increased. The first three phases U1–U3 are well defined already [17]. U1 is a set of foundational services, which include Registration, Network Identification, Drone Aeronautical Information Management, and Geo-awareness. The U2 phase unites initial services such as Tracking, Weather Information, Operation Plan Preparation/Optimization Service, etc. The U3 phase should deliver suitable services assisting with more complicated operations specifically in dense zones where capacity management and detect and avoid (DAA) will play a significant role. U4 is expected to include full services; it is the final phase with the highest level of automation and digitalization. The set of U4 services has not been defined yet. However, this paper contributes to establishing a significant basis for U4 understanding and formalization by identifying essential information provision gaps that will be unavoidable in defining and developing U4.

Table II-6. Mission type constraints.

Institutional Constraints	Needed Information	U-Space Service	Note
Delivery Transportation Inspection Surveillance Photography Search and rescue Watering, sowing, and spraying Filming Mapping Communication network deployment UAV shows Leisure flights with passengers	Take-off and landing locations	✓Operation Plan Preparation and Optimization Service	
	Classification/identification and coordinates of object/subject/area of interest Applicable in case of dynamic missions	-	Gap
	Mission's purpose and specialty inputs, matching with available algorithms Applicable in case of dynamic missions	-	Gap

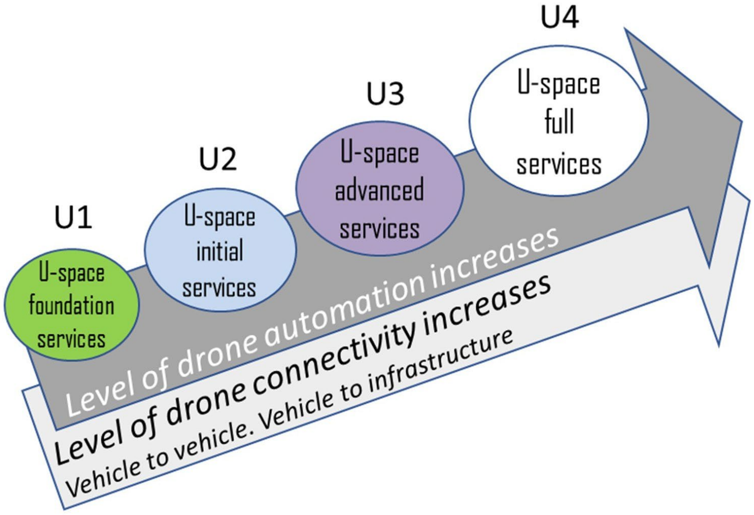

Figure II-1. Four phases of U-space development. Redrawn based on [16].

For a more informative analysis, it would be better to compare how U-space [17] and Federal Aviation Administration (FAA) UTM [18] address the information needs. However, such a detailed study is beyond the scope of this article. Generally speaking, both approaches are founded on the services, procedures, legal framework, and infrastructure to ensure flight safety and efficiency for UAV operations in uncontrolled and controlled airspace for Visual Line of Sight (VLOS), Beyond the Visual Line of Sight (BVLOS), and Extended Visual Line of Sight (EVLOS) operations [17–19].

U-space Concept of Operations (ConOps) defines three categories for U-space services: mandated, recommended, and optional. Similarly, FAA UTM proposes the following categories for the services: required to be used, may be used, and add assistance to a drone operator. U-space and FAA UTM rely on a Remote Pilot in Command (RPIC) to operate the UASs with established responsibilities. Manned aviation has a higher priority than uncrewed air traffic. Both concepts identify the three layers of separation: strategical, tactical, and collision avoidance, where DAA equipment plays a significant role. A continuously accessible information network assists in airspace coordination for U-space and FAA UTM.

From a general perspective, it is possible to state that both approaches propose comparable services. For instance, U-space includes a collaborative interface with Air Traffic Control (ATC), while FAA UTM addresses a similar function with the Flight Information Management System (FIMS). Other examples of commonality of the services are weather, registration, e-identification, surveillance, monitoring, geo-fencing, terrain data, aeronautical information, data regarding mission intent, etc. Both systems will be interconnected with the Urban Air Mobility (UAM) airspace system [20,21]. In case of emergency, the drone operator must announce the issue immediately to the National Aviation Authority (NAA) and other relevant airspace users.

U-space will be deployed in four phases: U-space foundation services (U1), U-space initial services (U2), U-space advanced services (U3), and U-space offering full services (U4). Similarly, FAA UTM uses a spiral concept where the services will be deployed according to the complexity of the operations—the less complex first.

The last major similarity is that both approaches plan UAV operations on a VLL. FAA UTM defines the height Above Ground Level (AGL) as 400 ft. For U-space, the height is defined differently: 120 m above the Take-Off point.

Considering the operational risk level, U-space defines three categories for operations: open, specific, and certified. Instead, FAA UTM relies on performance authorization provided by UTM participants. This authorization guarantees that a particular operation complies with safety and regulatory requirements.

This article is organized in the following way. In the first section, we start with an introduction. The second section proposes an analysis of the existing constraints, corresponding information needs, which must be addressed to tackle the constraints, and the information needs' matching the U-space services. The analysis identifies the existing gaps, which must be filled to allow the U-space traffic autonomous guidance.

In the third section, we propose a prioritization of the identified gaps that reflect the different levels of necessity for further research and development.

The fourth section contains high-level methodology to identify, measure, and close the gaps. The fifth section outlines promising approaches and technologies that have the potential to assist in filling the extant information gaps. Finally, we offer some conclusions and avenues for further research.

The main contributions of the paper are the identification of important constraints, the classification of essential information required, and the identification of information provision gaps, achieved by comparing the information requirements with Eurocontrol's Concept of Operations [17] to enable UAV autonomous guidance within U-space.

II.2. Constraints, information needs, U-space services

This section is divided into six groups of constraints: flight physics, trajectory computation, collision avoidance with static and dynamic obstacles, communication navigation surveillance, institutional ones, and mission type. While the division is conditional, it reflects the impact of the problem statements obtained from different areas of knowledge and sciences. For instance, flight physics imposes unique constraints on the aircraft, while trajectory computation relies on optimization techniques from pathfinding and computer science.

II.2.1. Flight physics

II.2.1.1. Aircraft Performance and Maneuverability

A UAV is a robot that operates in a 3D environment bearing constraints of the physics of flight that any aircraft has. For example, fixed-wing aircraft are limited in their performance (required take-off/landing distance, velocity, fuel efficiency, ceiling, range, climb rate, and controllability speeds). Aircraft also have limitations regarding gross weight, maximum horizontal velocity, minimum velocity for fixed-wing (due to stall threat), and maximum descent velocity due to flatter hazard [22]. In practice, it means that geometrically the shortest path cannot be feasible at all for most fixed-wing aircraft if the trajectory planner proposes too high pitch angles, for example. Additionally, aircraft normally have limitations regarding turning radius, flutter susceptibility, load factor, and payload [23,24]. A rotorcraft has similar limitations, but it does not have a minimum speed, since it can hover. Also, a rotorcraft needs a suitable take-off/landing area instead of a runway. Typically, the UAVs have an onboard energy storage, such as batteries or fuel tanks [25]. This fact implies a limitation on the flight time with various regimes of flight, including climb, flight with maximum speed on constant altitude, maximum endurance, gliding or hovering (for rotorcraft), descent, etc. The Common Information Service will address this issue in phase U3 [17].

To plan a feasible 4D trajectory in U-space, there is a need for uncrewed aircraft performance databases for all models of UAVs that are presented in U-space traffic [9]. In Europe, a similar issue has already been solved for commercial aviation for Air Traffic Control purposes via Base of Aircraft Data (BADA) and Trajectory Computation Infrastructure software [26,27]. U-space deals with a more complicated environment since UAVs do flights at VLL with a huge diversity of potential static and dynamic obstacles. Therefore, to manage more complicated environments, it is necessary to collect various VLL-related data, which we analyze hereunder.

For flight safety matters, it is essential to control the aircraft's angles (pitch, roll, yaw) and flight status information (altitude, speed, direction) during the flight to avoid stalling [13]. A 4D trajectory planning system must consider UAVs' limitations with pitch and roll angles. Additional complexity comes with the fact that all models of aircraft differ concerning the aforementioned characteristics and limitations due to diversity in aircraft design, weight, and propulsion systems [28].

The shortest path does not always satisfy fuel and time efficiency. For example, the best climb rate for a fixed-wing aircraft means maximizing aerodynamic efficiency (maximum value of lift and drag coefficient ratio) [29]. In other words, a climb with maximized aerodynamic efficiency gives the best time for reaching the needed altitude.

II.2.1.2. Weather Conditions

S. Cambel et al. significantly contributed to the analysis of weather information needed for UAS operations [30]. Weather, for example, the wind's vector and wind gusts, temperature, humidity, air pressure, and precipitation can heavily influence the physics of flight. T. Bonin et al. proposed weather conditions expected to affect UAM, among them: icing, temperature, reduced visibility and low ceiling, turbulence, wind gusts, urban canyons, wind shifts, updrafts and downdrafts, wind shear, precipitation, convection, and storms [31]. Generally, our literature review analysis conceptually confirmed their findings; however, we propose a slightly different terminology, and we also find it essential to recognize the lighting threat.

Temperature and air pressure directly influence the key aerodynamic forces – aircraft drag and lift [24]. The presence of humidity influences air density as well; the higher the humidity, the lower the air density [24].

With high atmospheric temperatures, the aircraft's rate of climb capability will be significantly decreased, which must be taken into consideration to process the 4D trajectory. U-space must collect weather data in order to transmit it to an autonomous guidance system, regardless of whether this system is part of U-space or not.

In the worst scenario, weather affecting the flying conditions can temporarily close the airspace for flights. The traditional global meteorological models for manned aviation do not provide hyper-local weather information [13]. In the case of U-space ordinary and hyper-local weather information, it is essential to plan and execute flights safely; however, hyper-local ones still do not exist as a widely available service [15]. In any case, the weather susceptibility category of UAVs is essential to plan missions safely under various weather conditions. Hyper-local velocity, direction, and the gust of wind generate an additional vector of force that can influence the aircraft [24]. Strong wind can make the flight too risky, inefficient, or even impossible. For example, crosswinds can provide a significant impact on the landing for large UAVs on runways [30]. To collect hyper-local weather information, the current methods include weather microstations, mobile and portable sensors attached to transport and infrastructure, traditional weather stations, satellite data, predictive weather models, and ML and AI algorithms to predict weather changes. However, the current coverage of the hyper-local weather information collection is still at a very early stage [32].

Aircraft icing hazard threatens flight safety in case of operations near and below freezing temperatures [33]. The icing of wings and stabilizers, sensors, propellers, aircraft mechanization, aircraft control, and other moving parts is extremely dangerous and can lead to catastrophic results [34].

Visibility can be essential for robotic navigation if video cameras [35] are used for situational awareness [36]. In the case of surveillance, search and rescue (SAR) missions, inspection, etc., the level of visibility can affect the UAV 4D trajectory.

Precipitation affects landing surfaces and aircraft flight aerodynamics. For instance, heavy rain distorts the upper wing surface's shape which can reduce total lift force by up to 30% [24].

Lightning strike threat becomes important when an aircraft is flying near the area of charge in thunderstorms or volcanic ash clouds, so UAVs can initiate a discharge [37] and be damaged. Metal protection is commonly used in the aircraft industry to protect safety-critical parts from critical damage [38]. However, light UAVs are very limited in available energy on board; thus, any additional weight is unwanted. If future U-space regulation allows the usage of UAVs without lightning protection, then information on areas with lightning strike threats would be critical for flight safety.

The overall impact of weather varies between different types of aircraft and from one UAV model to another. We expect that the issue will be addressed through a weather susceptibility classification for UAV models.

II.2.1.3. Turbulence

Turbulence is a well-known threat to aviation, and each year, it brings injuries, structural damage, and even deaths [39]. Significant wake vortices appear behind large airplanes, and the effect migrates in space (normally with slow descent), remaining for several minutes [24]. It can seriously affect the controllability of the aircraft, which enters a wake vortex area. To avoid the negative effects of wake vortices, it is essential to have information on the UAV wake vortex category and area of operation for all sufficiently heavy airplanes that do flights next to the operational area [13]. The heavy aircraft appear at VLL near runways. This circumstance would allow limiting the UAV operations in this area for a certain period.

Natural turbulence can appear even at VLL with high ground, mountains, high buildings, thermal effects, and convective activity [39]. Buildings and terrain generate turbulence with wind field flow. It is a subject of UTM interest since the effect's influence on the UAV can be significant [40]. However, there is no need to install sensors on each corner of the buildings because, in conjunction with real-time observations, the computational fluid dynamics approaches [40] can help with turbulence map generation. It is essential to get access to urban buildings and surface 3D maps for the estimation of wind vectors via computational fluid dynamics techniques.

In the second phase of the U-space, the Weather Information service will be deployed to inform stakeholders about the weather conditions. The service should provide weather forecasts and corresponding warnings with hyperlocal weather information, when and where available or required [17].

Monitoring is another U-space service that will share various alerts, including the ones of high importance that come from the Weather Information service [17].

II.2.1.4. Identified Gaps

Nevertheless, neither service tackles the problems of turbulence, the UAV wake vortex category, or lightning strike hazards. The analysis given in Table II-1 allows us to conclude that important information on angles during flight is missing. The available onboard energy is normally available to the RPIC; this could be a reason why a corresponding U-space service has not been proposed yet. In the case of centralized or hybrid systems, such data must be shared with traffic guidance autonomous systems to manage UAV trajectories safely.

In this article, we use the term “needed information” which means the essential information for tackling the specific constraints in the UAV autonomous guidance deployment.

II.2.2. Trajectory computation

The robotic Sense-Think-Act cycle is a classical approach to aligning the actual state of the world to robotic perception. The concept was borrowed from research on human cognition [12]. Various interconnected on-board and on-ground sensors collect data on the environment, then the software interprets it and builds a map for actions and/or navigation. Among these sensors are lidars, radars, infrared and video cameras, Global Positioning System (GPS) receivers, etc. Meanwhile, map representation is not an obvious task since various constraints, advantages, and disadvantages must be taken into consideration.

II.2.2.1. Time Complexity

Using hundreds of uncrewed aircraft, especially in congested airspace, puts high demands on the processing of 4D trajectories, because the safety-critical guidance decisions must be made quickly due to a separation that measures in meters [13]. This fact seriously limits borrowing practices from highly automated commercial aviation and ATM where large separation (usually 3 or 5 miles) between the aircraft gives greater freedom in time and space for making a safe decision [13].

A two-dimensional (2D) map uses XY coordinates, and such an approach aids faster computation and is well suited for guidance on the surface but is disadvantageous for UAVs because they operate in a 3D space. Different altitudes of obstacles and navigation points bring challenges for 2D mapping.

To keep the advantages of 2D map representation and not neglect the variability of altitudes, it is possible to employ a 2.5-D approach [41]. The idea is to use two-dimensional maps as layers, where each layer means a fixed altitude. Supporters of the 2.5-D approach argue that conventional air transport operates mainly on fixed altitudes and that it is reasonable to expect that this approach can be inherited (at least for the top layers of VLL) by UTM as a successor of ATM [42].

While 2-D and 2.5-D approaches exhibit better time complexity than 3D, as airspace involves three dimensions, 3D maps enable more flexible modeling with fewer assumptions. Nevertheless, the 3D approach comes with increased computation costs. To solve the pathfinding issue, there are plenty of approaches representing the UAV’s map and trajectory planning [25]. A comprehensive taxonomy for the most known techniques was proposed by S. Aggarwal et al. [43] and L. Yang et al. [44], among them Sampling-based algorithms, Node-based algorithms, Mathematic-model-based algorithms, Bioinspired algorithms, and Multifusion algorithms.

Flight time planning is vital for avoiding collisions and aiding operational efficiency. However, not all UAV trajectory planning algorithms consider time which leads to another significant issue. For example, a group of UAVs cannot move safely on the same route without being separated timely. If the time factor is ignored, then each next trajectory must be planned without intersection with all existing ones to avoid a potential collision. Neglecting the time in trajectory planning leads to inefficiency of airspace usage.

Various algorithms exhibit different advantages and limitations in the context of different missions and approaches for 4D trajectory planning. We propose the development of a set of algorithms to address the issue. Selecting among these algorithms would enhance time complexity and trajectory optimality.

It is hard to propose more quantitative demands to time complexity as it depends on the concrete mission type, system type (centralized, decentralized, hybrid), U-space traffic density, regulatory demands to separation, etc. We acknowledge the importance of further research in this direction.

II.2.2.2. Four-Dimensional Trajectory Optimality

Since “safety first” is a core principle of U-space [16], the shortest trajectory has a lower priority against flight safety. In the case of guidance within the U-space, the optimal trajectory for some missions means the shortest flight path after taking into consideration flight safety, security, and related obligatory regulatory demands in the U-space.

One of the most recent proposals regarding UTM notes that with services’ maturity, the Flight Planning and Authorisation service will include 4D trajectories relying on aircraft performance [9]. For example, A. Gardi et al. [9] proposed a 4D Trajectory planner/optimizer for a UAV Mission Management System using cost functions with the following parameters: maximum endurance, minimum flight time, cost, emissions, and noise. However, the minimum flight time and the maximum endurance are needed for different missions. For example, the quickest delivery puts a higher demand on flight time minimization. But surveillance often needs greater endurance—i.e., flight time maximization for flying over selected waypoints as long as possible. The various UAV users’ preferences for different missions bring additional complexity. In some cases, minimum flight time has a higher priority, or maximum endurance, or maximum distance of flight, or minimization of emissions and noise. Also, a combination of these parameters can reflect the specific demands for missions’ diversity. Potentially, a holistic U-space traffic optimality can influence the UAV’s trajectory planning. With that, we find the “optimal trajectory” planning to be a subject that must be addressed according to each specific type of mission and drone user preferences while taking into consideration a comprehensive set of the existing constraints.

II.2.2.3. Scalability, Adaptability, Learning Capability, Robustness

For centralized or hybrid systems, the trajectory computation scalability can have a significant impact in the event of episodic or permanent traffic (or obstacles) volume growth [45]. It is essential to address this constraint to mitigate the risk of system overload. In the context of a decentralized system, a question arises: How should multiple decentralized subsystems collaborate in the same area to provide safe 4D trajectory planning from the perspective of scalability, adaptability, learning capability, and robustness? To answer this question, additional research is suggested.

Adaptability constrains an autonomous guidance system in the event of significant changes in the environment [46], U-space traffic, regulations, and other factors. For instance, rare weather conditions can sometimes significantly alter the visual landscape, posing a challenge for autonomous surveillance systems that rely on video cameras and typical patterns for that region’s visual landscape database. Another example can be changes in regulation. Hence, the trajectory computation should be flexible for adaptations.

Robustness is essential for UAV trajectory generation [47] since it allows for accomplishing the mission despite the environmental changes. For instance, wind can change its direction and speed. To address these issues, potential changes should be properly considered at the algorithmic level. In this light, the learning capability may play a significant role in environmental change prediction, operation planning, situational awareness [48], traffic optimization, etc.

In summary, we conclude that a proper selection among software solutions is essential to achieve the optimum trajectory computation, as the expected system complexity will likely be based on a set of interconnected algorithms and ML techniques that are integrated through the software solutions.

II.2.2.4. Identified Gaps

Table II-2 summarizes trajectory computation constraints. None of them are addressed at U-space yet [17]. This fact states an existing information provision gap concerning U-space traffic autonomous guidance. Selection among algorithms and software solutions is essential for autonomous guidance; however, an additional investigation is recommended to decide whether to include a specific service in U-space architecture or not. Alternatively, the issue can be addressed with regulation or standardization requirements.

II.2.3. Collision avoidance

The International Civil Aviation Organization proposes three layers of conflict management: "strategic conflict management through airspace organization and management, demand and capacity balancing, and traffic synchronization; separation provision; and collision avoidance" [49]. Strategic conflict management and demand and capacity balancing alongside traffic synchronization can be perfectly achieved via a centralized system or hybrid system. However, a decentralized system significantly limits the potential benefits.

For example, achieving holistic traffic optimization with 4D trajectories is not feasible within a decentralized system. On the other hand, separation provision and collision avoidance can be effectively addressed in any type of system.

U-space ConOps defines strategic deconfliction as a process that allows for the reduction in the probability of a conflict to an appropriate level [17]. However, tactical conflict deconfliction and resolution services are becoming essential if the plan is not followed accurately enough.

Collision avoidance is a fundamental principle of flight. Trajectory planning relies on pathfinding techniques, where free space and non-free space are always distinguished [50,51]. There is a plethora of path-finding algorithms that can build a collision-free trajectory while minimizing traveling distance with varying degrees of computational complexity [44] (the rate of deviation in minimization depends on the concrete algorithm). While there are plenty of technologies to tackle the problem, typically, to avoid collision, there is a need to know the UAV and potential obstacles' positions in a 4D environment [52]. In the case of tactical deconfliction, there is a need for information regarding motion vectors, for example, between the UAV and another aircraft [53]. To make it happen, sensing methods collect data via ground-based and air-based technologies with cooperative and non-cooperative sensing [54].

Static obstacles are buildings, bridges, cranes, trees, power lines, and other ground and on-surface infrastructure. In 3D airspace, the terrain is a basic static obstacle; to prevent controlled flight into the terrain, there is a need for the terrain map to list altitudes above sea level [55]. To address the problem of static obstacles, U-space will be supported with Geographical Information Service in phase U2 and Drone Aeronautical Information Management in phase U1 [17].

The dynamic aerial obstacles at VLL include U-space traffic, ATM traffic, airspace intruders, and wildlife [56]. Since airspace intruders and wildlife do not report their position and intentions, their presence in the area of operations is a potential hazard. To mitigate the risk of collision, it is important to detect and classify the hazard. Classification can help with 4D trajectory planning in a safe way according to the level of threat. The level of threat differs according to different types of aircraft or wildlife; the hazard directly depends on flight characteristics and the behavior in the case of animals. For example, an air balloon will follow the wind flow with a potentially slow descent or climb, meanwhile, some eagles can hunt small-size UAVs [57], reaching hundreds of kilometers per hour when diving. In practice, it means that safe separation from air balloons and hunting eagles must be very different. To allow for suitable separation, there is a need for information on the classification of airspace intruders and wildlife.

There are three services to control and advise U-space traffic in the U2 phase: Traffic Information, Strategic Conflict Resolution, and Monitoring. The U2 Strategic Conflict Prediction service relies on the probability of occupying 4D cells by the UAV, and if the probability is high, then the potential conflict is predicted [17]. In the later U3 phase, other U-space services are planned to manage 4D trajectories and temporary occupied airspace, namely Dynamic Capacity Management, Tactical Conflict Prediction, and Tactical Conflict Resolution [17].

There is a need for coordination with ATM for collision-free flight in the controlled airspace. To address the problem, the Procedural Interface with ATC was proposed in the second phase (U2) [17]. For the U3 stage, a higher level of cooperation has been planned via the Collaborative Interface with ATC. With that, the information on ATM traffic with 4D trajectories at VLL in the controlled airspace will be available for U-space stakeholders.

Operations near the ground can generate a risk of collision with dynamic on-surface obstacles, among them people, cranes, on-surface transport, machines, and animals. For example, if a transportation or parcel delivery mission includes landing outside specially allocated and protected areas (vertiports), then the classification of surrounding objects is needed to make a proper decision on the corresponding risk. For example, if dogs or children are playing nearby, then landing next to them corresponds to a higher risk. It means that the classical approach to robotic navigation space segregation between free and non-free is not enough. The objects' classification is needed to deal with hazards during landing. In this case, the autonomous guidance system should act like a human [5] - i.e., collect data on the environment, classify surrounding objects and the related level of threat, and then make decisions on the landing options.

The traffic's lateral, vertical, and longitudinal separation is vital for flight safety [9]. Geometrically, it means that the UAV flight path should be presented as a tube (possibly a cubic one), which is marked as temporary non-free airspace on a 3D map. Also, separation is needed to keep a safe distance from on-surface obstacles [9]. One of the recent European projects, BUBBLES [58], proposed using AI models and techniques in the U-space Separation Management Service to address the problem of separation. The service delivers computation of separation minima in an automatic regime according to the selected target level of safety.

The vertiport availability will limit flight planning since UAVs must be compatible with the vertiport. To handle this issue, there is a need for information regarding UAV size, flight characteristics, refueling/charging options, and noise [17]. Information on vertiport capacity performance is essential for organizing the vertiport traffic efficiently and safely [13,15]. The traffic planning system must therefore be informed in real time: at which vertiport, how many UAVs are landed, and how many unoccupied stands of aircraft are left at the vertiports. The Operation Plan Preparation and

Optimization U-space service collects information on the vertiport capacity; however, it is not enough to address the vertiport availability. Though U-space ConOps proposes a Vertiport Dynamic Information Service, its description is at a high level: “Responsible for managing status, resources (open/closed/availability, capacity) information about the vertiport in real time” [21]. Similarly, the Vertiport Resource Allocation Management service function is explained very vaguely: “The ability to allocate resources of vertiports to accommodate UAS requests” [59]. With that, we conclude that a more detailed description of the services is essential. Without a detailed description, we recognize a gap for UAV flight characteristics, UAV size, requirements for charging and fueling, ground handling needs, and UAV noise category.

Identified Gaps

Obstacles’ uncertainty makes 4D trajectory planning more complicated than if the position of the obstacles is already known. In such cases, Simultaneous Localization and Mapping techniques are commonly used to assist autonomous guidance via building an environmental 3D map in real time with the simultaneous interpretation of the robot’s position [60]. A set of on-board and on-surface sensors can collect data regarding the airspace participants, and alongside the airspace traffic information, they make a 3D map in real time where free and non-free spaces are distinguished. However, if the sensors cannot cover the whole area of operation, obstacle uncertainty will be experienced. In other words, the estimated time to the closest point of approach [61] can be too short. In this case, additional efforts are needed to plan the 4D trajectory safely. For example, to avoid a potential collision, it is reasonable to expect a regulatory limitation of the flight speed when the UAV approaches an unknown environment according to the level of a potential threat. Among possible solutions for making the airspace known, we can list lidars, photo/video cameras, infrared cameras, radars, and even radio [62–64]. A 3D map of known and unknown environments is needed to tackle the problem; however, it is not addressed among the U-space services yet [17].

With the summary of analyses in Table II-3, we may conclude that information about on-surface dynamic obstacles’ position and their classification, along with the position of airspace intruders and wildlife and their classification, is missing.

II.2.4. Communication Navigation Surveillance

A reliable wireless communication link between the UAV and the traffic management system is essential for effective real-time U-space traffic management. The literature indicates that robust mobile network coverage should extend to over 98% of the operational area [65]. A reliable wireless communication link allows for exchanging various indispensable data including the UAV position, status of onboard systems, sensors’ data, situational awareness, commands for the correction of the 4D trajectory, mission-specific directives such as cargo drop or initiating photo/video recordings, and many more. The Quality of Service (QoS) in communication links refers to the ability to ensure a certain level of performance in terms of reliability, low latency, and high throughputs. The reliability is more associated with uninterrupted connectivity among drones and with control stations with high data rates and minimum possible packet loss. Similarly, the minimum possible time taken in a complete communication cycle refers to latency. The QoS in drone communications can be achieved with several techniques; for example, dynamic spectrum allocation, quality-aware routing, and adaptive modulation and coding schemes, which is not possible without Software Defined Networks (SDNs) [66]. The QoS is a promising approach to ensure the safety and security of drones and avoid unforeseen situations such as collision, trajectory derailing, etc., in U-space where prompt response and continuous connectivity are required. Similarly, availability, accuracy, continuity, and integrity characterize Navigation and Surveillance needs [67].

For the centralized and hybrid systems, an emergent status of the UAV, e.g., Loss-of-Control or Loss-of-Engine/Energy [14], is important information that must be transmitted to the 4D trajectory management system immediately to mitigate the risk of potential collision during uncontrolled flight or unplanned descent. To stay in an area of stable connection, there is a need for a map and the status of the communication network availability at VLL—see Table II-4. In the second phase of U-space, the Communication Coverage Information service should tackle the issue with the coverage map, and the Navigation and Communication Infrastructure Monitoring service will provide control of the status information concerning communication infrastructure [17].

For the decentralized system, a stable connection is also important, for example, for real-time updates regarding restricted areas. A geographic node speed drone-based routing is proposed in [68] to minimize the communication overhead at the cohort level in order to ensure reliable communication, whereas, conventionally, an internet-protocolbased (IP-based) approach has been used so far. The trends of the presented graph in [68] show significant improvements in terms of connection loss rate, latency, data rate, and getting updates of location information. Similarly, in a decentralized system where the drone-to-everything concept is utilized in a multiple-layer cooperative architecture in combination with hybrid bioinspired grey wolf optimization, waypoint traceability has been proposed [69], resulting in significant improvements in latency and reliability.

To mitigate the risk of electromagnetic interference, there is a need for information on radio frequency availability [16,70]. To address the problem, the electromagnetic interference information service of U-space has been planned for phase U2 [17]. Other common attacks on drone communication links are denial of service, de-authentication attacks, man-in-the-middle attacks, trojans, etc., discussed in detail in [71]. The possible solution to mitigate these attacks, or at least to tackle them, could be the use of a machine learning approach for the identification of legitimate drones and, in addition, a common database [72], deep learning algorithms for the routing protocols [73], and blockchain technology for the encryption and decryption of secure information [74].

GPS and the Global Navigation Satellite System (GNSS) play a significant role in outdoor guidance and navigation by providing information on the UAV's position [75]. The ground-based navigation network can also be used to aid navigation and guidance purposes, for example, a ground-based augmented system—a classical approach for commercial aviation [76]. Also, the beacon-based ground systems have the potential to be used for UAV navigation and guidance purposes [77]. To plan the 4D trajectories safely, it is essential to have access to maps of the GNSS coverage and the availability of supplementary navigation networks. Phase U2's Navigation Coverage Information U-space service is responsible for that [17]. However, it is also important to control the status of the link to the navigation networks. The Navigation Infrastructure Monitoring service in phase U2 will deliver this function [17].

The real-time position of UAVs is crucial information for U-space traffic planning. There is a specific service planned in phase U2 to tackle this issue - Tracking [17]. To address the issue of the geometric height of flight, the Vertical Conversion Service was proposed in the U3 stage 17. It is also planned that the Vertical Alert Service would provide the height warnings.

Presently, the surveillance brings critical information about the situation awareness for the RPIC during BVLOS flights. During the mission, a human analyzes and interprets the video, classifying surrounding objects and subjects, their position, intentions, potential level of threat, and so on. With technological progress, such video data have the potential to be used for the same purposes by the autonomous guidance system. It is expected that the Surveillance Data Exchange service will be deployed in phase U2 to manage surveillance data [17].

II.2.5. Institutional constraints

For all aircraft, including UAVs, their operation consists of Phases of Flight: planning, take-off, climb, cruise, descent, approach, and sometimes taxi [78]. In the planning phase, registration and identification are needed to execute the U-space control fundamental function. This happens via verification of the UAV's owner, the UAV's serial number and model, the UAV's size, the persons responsible for continuing airworthiness, the status of airworthiness (the certification status, UAV's system status, maintenance checklist, etc.), the legal affairs with the UAV's owner, the legal responsibility for the UAV operation (legal recording), and incident and accident reporting [16]. Also, it is necessary to manage the capacity of the airspace [15]. Initial U-space services deliver registration and identification functions (Registration and Network Identification) [17]. In the second phase of U-space, Legal Recording, Incident/Accident Reporting, and Digital Logbook services will be responsible for incident and accident data and legal recording [17].

Presently, UAS operators must comply with airworthiness and operational directives issued by the European Union Aviation Safety Agency [79]. However, in the future, it is possible to expect an emergence of AI-based services for controlling the airworthiness status of UAVs. In any case, the information on the UAV's airworthiness status is critical for flight safety, which is needed for an autonomous traffic planner. Without such information, it can be too risky to permit take-off.

According to [80], the Network Identification service should collect information on the emergency status of the UAS. In the second phase, U2, the Emergency Management service will assist RPIC in case of emergency. However, we expect that at some level of automation integration into the U-space, AI will be analyzing the problem by delivering aircraft guidance to tackle the appearing risk efficiently.

To mitigate the risks, it is essential to make a risk evaluation before the flight [81]. Joint Authorities for Rulemaking on Unmanned Systems proposed a Specific Operations Risk Assessment that can be used for the estimation of the level of risk for specific missions [82]. P. Hullah et al. proposed U-space Airspace Risk Assessment that addresses four core sources of risk in U-space operations: safety risks, security risks, privacy risks, and environmental risks [83]. The U-space ConOps mentioned three U2-phase U-space services to address flight risk: Operation Plan Preparation/Optimization, Risk Analysis Assistance, and Flight Authorisation service [17].

To mitigate the risk of collision with people and on-surface objects, it is essential to take into consideration the potential emergency landing options [17,84] in UAV trajectory planning. For example, the autonomous trajectory planner should be informed in advance of what places will be potentially safe for landing (uninhabited roofs, wastelands, etc.) and what must be avoided (highways, railways, crowd-gathering areas, etc.). To decrease the risk of collision with pedestrians during an emergency landing or loss of control, it is essential to have a population density map [16,85]. For example, E. Arcel et al. describe a casualty estimation model that relies on population density data to estimate the nonparticipant casualty risk [86]. The Population Density Information service was proposed for the second phase of U-space deployment for this purpose [17].

Runway and Vertiport Surface Contamination can be critical for taxing, take-off, and landing safety, especially with a combination of water, ice, and snow [87]. Surface contamination is a hazard not only for fixed-wing UAVs, but can also be dangerous for small rotorcraft in cases of heavy contamination of water due to a sink risk. Runway and Vertiport Surface Condition includes contamination and other issues [88]. Though the authors of [59] discuss Surface Condition Awareness as a part of U-space capabilities, it is not clearly stated what U-space service should be responsible for that.

Restricted areas [17] can be deployed to mitigate the safety and security risks. For instance, there can be a permanent restricted area over a nuclear plant, or a temporary one during an airshow. To plan the UAV 4D trajectory, there is a clear need for real-time updates on the position of restricted areas and their duration. For autonomous trajectory planners, those areas mean non-free airspace. Automated reading of Notice to Airmen or Notice to Air Missions (NOTAM) messages could interpret and remove irrelevant information [89]. To make it readable for the autonomous guidance system, there is a need for an interpretation of these data into free/non-free airspace coordinates within a time frame. In phase U2, it has been planned that the Geo-awareness service will start providing geofencing information with 4D coordinates [17].

Fair and equal access to airspace is one of the U-space principles [1]. However, ordinarily, the police and emergency services have a privilege of priority; thus, UAV 4D trajectory planning should be able to work within the metrics of priorities [90]. Hence, it is possible to say that for planning 4D trajectories, a regulation priority policy is needed. The European Union regulation 2021/664 article 10, paragraph 8 describes two levels of priorities for flights: normal and prioritized [80]. Meanwhile, Airbus UTM researchers argue that complex implementations of fairness (related to airspace access) need further study [90]. We expect a significant development of priority regulation as U-space is further developed. One of the potential improvements can be related to holistic traffic optimization versus a single flight.

The spatial limits of the U-space airspace are essential for conducting operations in the allowed area. The U3 phase, Common Information Service, will be responsible for that [1].

UTM secure operations reflect U-space fundamental principles [1]. It is essential to secure the communication channels, provide reliable identity, organize proper access management, and respond timely to incidents and breaches. To mitigate the risk of security breaches, it is vital to be informed about the security system status and level of threat [91,92].

Noise is another major public concern [93] regarding the mass integration of UAVs into airspace, so it is reasonable to expect the development of regulations related to this issue. Restricted areas may be marked to protect some areas from acoustic disturbance. Noise reduction is a complicated multifactor task, and it is reasonable to predict that flights over noise-sensitive areas [94] will be forbidden for some types of UAVs. Exceptions can be established for flights in the gliding regime or noiseless air balloons. To protect the population from unacceptable noise, there is a need for a map with areas of limited operation time windows and unacceptable levels of noise. We expect a performance-based approach for deploying such limitations.

Rule awareness regarding priority, privacy, noise reduction, etc., is essential for executing regulation demands. Presently, the regulation is written by humans for humans. We find it possible that in the later stages of U-space development, the regulation demands will be written by humans (regulators) for machines (the autonomous traffic management systems) in terms of algorithms (computer code) that will be readable for the U-space AI. Such an approach has the potential to address and implement regulation updates immediately to the autonomous traffic management systems on a large or even global scale.

Identified Gaps

The analysis provided in Table II-5 identifies the next essential information, which is not addressed within U-space services yet: status of airworthiness, runway and vertiport surface conditions, location of suitable landing areas in case of emergency, UTM security breakthrough status and level of threat, map of noise-sensitive areas, and rule awareness in terms of robotic algorithms. To solve the problem of information provision for the U-space traffic autonomous guidance, we expect that new U-space services will be appearing respectively.

II.2.6. Mission type

Missions' diversity brings additional demands to UAV trajectory planning - see Table II-6. For example, the delivery mission can be carried out in various ways. Some approaches propose dropping cargo on a parachute [95]. For heavy cargo delivery via fixed-wing UAVs, it is also possible to expect a strict demand for landing on a runway only. Another approach has been tested by the American company Wing for parcel delivery by hovering where the parcel is roped down with a winch [96].

Human transportation entails a risk for human lives [97]; thus, UAV 4D trajectory planning with passengers on board can have additional safety demands; for example, a demand for a greater value of separation. Maneuvering with passengers onboard must be done in a slow and non-aggressive way. To aid passengers' comfort and safety, it is reasonable to expect stricter (compared to the other types of missions) limitations on the descent speed, load factor, aircraft angles, or planning trajectory in favor of a better view.

Missions for data collection and dissemination include surveillance [98], photography [99], inspection [100], mapping [101], and communication network deployment [102,103]. Such missions can have a wide range of degrees of trajectory planning complexity. For instance, surveillance or communication network deployment missions with dozens of meters of altitude can put less demand on the UAV trajectory planner than an inspection of a bridge involving taking high-resolution photos of the specifically selected areas while operating in a congested urban environment.

SAR missions such as assisting humans in danger via UAV [104] can be very complicated due to a high diversity of circumstances. Sometimes SAR must relate to very specific conditions of operation; for instance, fires or natural disasters. Fire itself is an imminent danger for a drone because the combustion is accompanied by a high temperature, vortices [105], and the degradation of visibility. This means that the autonomous guidance system would need a model to estimate the area and level of hazard to operate safely.

Watering, sowing, and spraying as well as inspecting are potential operations in agriculture [106,107]. For such missions, automation of the 4D trajectory planner has its own specialty. Since UAVs can fly at the lowest altitude, they can share airspace with manned agricultural aircraft which can potentially operate without ADS-B [108]. Finally, such operations can also happen in fields with lower human presence.

Entertainment missions provide filming, UAV shows, leisure flights, etc. [109]. Following and recording a cyclist in the mountains or filming a wedding day put specific demands on the UAV trajectory planner.

Surveillance and photography can be performed by recording an allocated area if needed. However, additional demands for such missions are also possible. For instance, it can be following a selected target during a surveillance mission or taking photos of specific objects (or subjects) [110].

Potentially, an even greater variety of missions lies ahead. It could be firefighting [111], construction, etc. [112]. With technological progress, more and more UAS missions will be delegated to robotic and autonomous guidance; it is just a matter of time [17]. Nevertheless, there is a commonality for all missions, namely information concerning take-off and landing locations. The AI of autonomous guidance systems needs to be informed of where the mission starts and where the UAS should finish it.

U-space ConOps notes that the drone operator will be responsible for the mission planning [21]. We expect an autonomous mission planner deployment in the later stages, initially for simpler missions and subsequently for more complex ones. The level of centralization in autonomous mission planning is an open issue, and we acknowledge a research gap here.

We distinguish between the terms “dynamic mission” and “pre-defined mission” to describe a UAS mission where the UAV does more than fly from one location to another with known waypoints before take-off [113]. For example, a routing mission, such as delivering medical samples from a remote hospital to a laboratory, is classified as a predefined mission. Conversely, surveillance or inspection of a new object may require decision-making during the flight; thus, we classify it as a dynamic mission.

The autonomous guidance system needs to be informed where the UAV’s service is needed. It means that the coordinates of the object/subject/area of interest are a common information demand for any dynamic mission execution.

Classification of the object/subject of interest can be necessary to execute some dynamic missions. For example, it can be surveillance operations involving following a car to aid the police, searching for an injured person in a SAR mission, plant classification for watering and spraying, etc.

The mission’s purpose and specialty information are needed to explain to the autonomous guidance system what the UAV should or should not do during the dynamic mission. For that, the UAS’s user inputs the specific demands to the autonomous guidance system, which explains to AI the type of service and where it is needed. For example, for filming, the user can expect a flight over the potential area/object/subject of interest with taking photos and videos during a selected period. The mission’s purpose, complexity, and special character should be compared with the capabilities of available specific algorithms. If the mission entails complex or unique decisions and there is no suitable algorithm, then human intervention is needed, and this statement is fair for all types of missions. The issue is one of a trade-off between the mission complexity and the algorithm’s ability to complete the operation effectively and safely.

The U-space deploys Operation Plan Preparation and Optimization service in the second phase U2 [21]. The service will collect information on take-off and landing locations and the area of operation. This approach can be sufficient for strategic deconfliction, but as was argued, it is not enough for dynamic missions.

Identified Gaps

With that, we may conclude that there are gaps related to information needs, namely the classification of object/subject/area of interest, mission’s purpose and specialty inputs, and matching with available algorithms. For pre-defined missions, such information may not be relevant. However, for some dynamic missions, it can be essential.

II.3. Identified gap prioritization

II.3.1. Gaps with a high priority

Not all the gaps constrain U-space traffic autonomous guidance equally. For example, the gaps related to flight physics are critical for flight safety [23]. Specifically, the monitoring and control of aircraft angles, available energy on board, natural turbulence map, area and time of operation for heavy aircraft generating wake vortices at VLL, UAV wake vortex category, and lightning strike threat areas are essential to guarantee flight safety.

Adaptability and robustness of the 4D trajectory computation can be safety-critical in case the airspace situation requires timely and proper trajectory re-computation. The autonomous guidance system must be able to respond correctly to each unique combination of the new circumstances that UAVs could encounter in the U-space airspace.

Time complexity can pose a threat to flight safety in scenarios like tactical deconfliction when the speed of calculations can have a significant impact on a new safe trajectory recomputation [43] or collision-avoidance maneuver. However, it should be less critical at the strategical deconfliction stage. Four-dimensional trajectory optimality can be essential for cost efficiency; however, safe flight remains possible even if the aircraft's trajectory is not optimal.

On-surface dynamic obstacles' position and classification, alongside information regarding UAV flight characteristics, and UAV size are safety-critical for avoiding collisions during taxi, take-off, landing, and flight at altitudes near on-surface objects. Additionally, information on UAV flight characteristics can be essential to avoid runway excursion.

The position and classification of airspace intruders and wildlife are safety-critical in any case, as a midair collision could result in aircraft damage, injuries, loss of life, or pose a threat to public safety and property [114].

Three-dimensional maps of known and unknown environments can have a significant influence on flight safety if UAVs enter unknown areas at a high speed. However, more research is needed to precisely define the level of threat. For example, a new wind turbine construction raises a new obstacle that must be considered by the autonomous uncrewed traffic planner to mitigate the risk of a potential collision.

The status of airworthiness, location of suitable landing areas, runway surface conditions, and UTM security breakthrough status can be critical for flight safety.

Rule awareness in terms of robotic algorithms is essential in order to follow official demands, where some rules can be critical for flight safety and security. For instance, changes in regulation on separation requirements must be reflected in the 4D trajectory planning algorithm. In general terms, U-space autonomous systems must always be updated according to the latest regulations.

Classification/identification and coordinates of the object/subject/area of interest alongside the mission's purpose and specialty inputs are essential only in the case of dynamic missions. It is highly possible that autonomous guidance at U-space will be started with the most simple missions like flying from one point to another. Nevertheless, for dynamic missions, the gap has a high priority.

II.3.2. Gaps with a moderate priority

In this subsection, we discuss the gaps for which the deployment priority can be classified as moderate.

Learning capability and 4D trajectory computation should be considered as essential fundamental principles for the development of the U-space autonomous guidance system. It must mitigate the risk of the system's inability to improve itself, based on the registered failures. Such demands may require significant technological advancement from the current state of the art of artificial intelligence [115]. We expect that the system learning function will be deployed under human supervision in the early stages and potentially self-learning characteristics can be incorporated in the later stages. We classify this as a long-term task with a moderate initial priority.

The scalability issue is essential to address for centralized or hybrid system deployment. However, if the system is at full capacity, it means no more orders for a certain period of time. It may have a significant negative economic impact, but it is not safety-critical. In this light, we consider the priority to be moderate.

Requirements for charging and fueling, ground handling needs, and UAV noise category are essential. We suggest collecting this information at the time of UAV certification or registration before flight. The lack of this information can result in significant inefficiency in vertiport usage. For example, in this case, a situation may arise when a hybrid-engine UAV is landing, but a vertiport does not have suitable fuel to fill the drones' tanks as only electrical charging is available. However, it is possible to state that this information is not safety-critical.

Maps of noise-sensitive areas relate to public comfort and have a negligible impact on flight safety.

II.4. A methodology to identify, measure, and close the gaps

This paper sheds light on the information needs and how they match with the U-space services. However, the word "match" does not mean that the services are ready to deliver their functions fully. As was shown in the previous sections, some of the U-space services do not exist yet. A real match will be achieved and tested with a step-by-step system development with significant contributions from daily practice and further research.

In a scientific approach, the fundamental component is the measurement of the topic of study. In this light, we propose a high-level methodology to identify, measure, and close the gaps (see Figure II-2). In the initial stage, conducting a literature review is essential for investigating the flow of safety-critical information required for autonomous guidance. This is precisely what our article delivers.

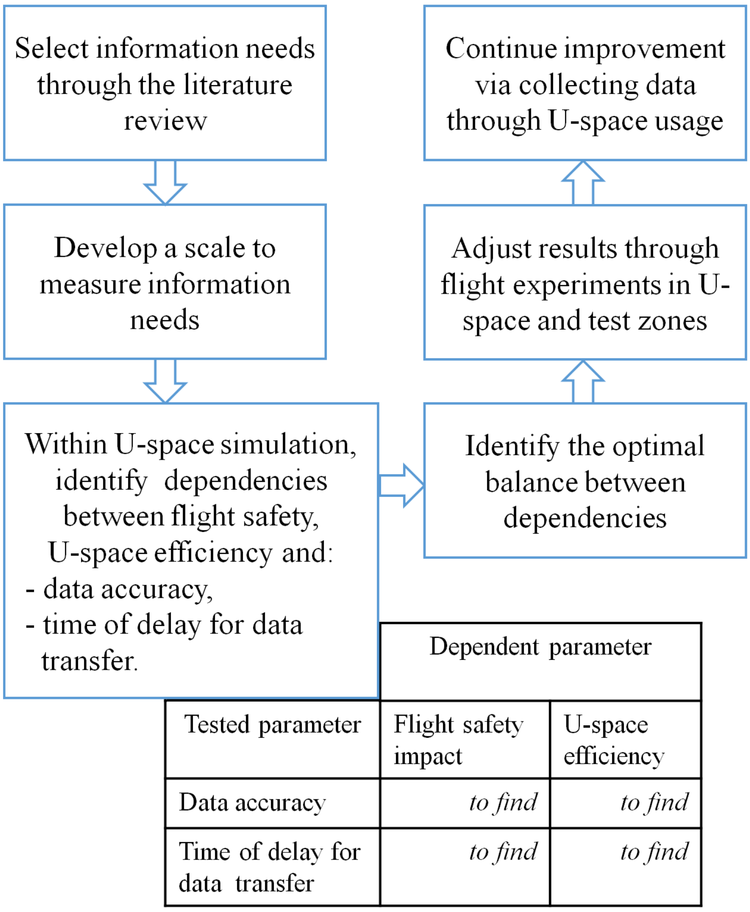

Figure II-2. A methodology to identify, measure, and close the gaps.

In the second stage, we suggest developing a scale to measure the information needs for each service specifically. Information required on angles during flight may significantly vary from one approach to 4-D trajectory planning to another. Some approaches could be based on simplified flight models, while others on more advanced leaving the responsibility for angles control to the onboard systems. The less precise flight models, the greater separation reserve will be needed.

For example, information regarding the angle of attack for a fixed-wing UAV is crucial for flight safety within 4D trajectory planning and replanning during flight. If this information is not of sufficient quality and comes to the remote autonomous guidance system with delays, it could lead to stalling and even spin of the aircraft posing a significant threat to flight safety. In case of approaching a high angle of attack, the autonomous aircraft should normally decrease its flight path angle to get acceleration from gravity and normalize the angle of attack. However, if a remote trajectory planner does not get angle information in time and of proper quality, it could lead to a situation where the autonomous trajectory planner provides a flight path that leads to an angle of attack greater than critical. It is a multi-factor issue that requires additional research on the quality and acceptable deviations of the information required.

Information on natural turbulence map, area, and time of operation for heavy aircraft generating wake vortices at VLL, UAV wake vortex category, and lightning strike threat areas can be estimated via modeling the areas and the identification of the acceptable level of the weather phenomena hazard and probability of the appearance.

To investigate a suitable level of information provision for trajectory computation, we suggest a mission-centric approach under a set of existing conditions. Each type of mission should be modeled and tested in simulations and experimental flights, and based on that, the acceptable level of the quality of the information can be found.

Position and classification of on-surface dynamic obstacles, airspace intruders, and wildlife are directly related to the separation required to guarantee the European level of flight safety. We recommend an additional study to investigate the existing aircraft performance range for the existing drone models and the wildlife behavior that is typical for European aerospace. Based on that data, the quality of information required can be identified.

A study on 3D maps of known and unknown environmental information should investigate what level of precision and online update is essential to guarantee a collision-free flight. Is it important to have a detailed 3D map of the area of operation; alternatively, simplified “generic” models can fulfill this role.

We suppose that UAV flight characteristics, UAV size, requirements for charging and fueling, ground handling needs, and UAV noise category must be collected during UAV certification processes, and the quality of this information should be similar to the general aviation requirements. However, it is also reasonable to expect a more generic approach and simplified models for the UAVs without people onboard. The status of airworthiness identification and corresponding procedures will likely vary for the different classes of UAVs. The expected range varies from a quick simple check for the smaller UAVs on the ground to a comprehensive pre-flight check for human transportation that is similar to the general aviation procedures.

The provided analysis identified that risk assessment should be extended with information on the location of suitable landing areas, in case of emergency, and runway and vertiport surface conditions. To identify the quality of the information, we suggest simulating flights with a need for an emergency landing. Analysis of such data could give evidence-based recommendations for measuring the quality of the information.

In a similar manner, UTM security breakthrough (status and level of threat) and noise reduction can be analyzed via modeling and simulations.

We suggest classifying rule awareness in terms of robotic algorithms on safety- and security-critical aspects and others. Safety- and security-critical updates should have higher priority for incorporation into the autonomous system.

Classification/identification and coordinates of the object, subject, or area of interest, along with information on the mission’s purpose and specialized inputs that match available algorithms, require extensive simulations and flight experiments. These are necessary to collect reliable evidence that the autonomous system can safely guide the UAV under certain conditions. As we expect that objects’ classification and identification will rely on machine learning techniques, comprehensive statistics are essential to estimate what level of deviation for information provision is acceptable.

In the third stage, it is essential to identify dependencies between flight safety, U-space efficiency with data accuracy, and time of delay for data transfer. It can be done via U-space simulation to get rough results without significant investments.

In the fourth stage, the optimal balance between dependencies should be investigated. This knowledge would allow us to recommend how to optimally close the gaps.

In the fifth stage, we suggest result correction by obtaining more data via flight experiments in U-space and test zones.

Finally, it is essential to continue improvement by collecting data through U-space usage.

II.5. Promising approaches and solutions

In the previous sections, we analyzed the provision of missing information that must be addressed to allow U-space autonomous traffic guidance. In the current section, we propose our view on the approaches and technologies that have the potential to fill the existing gaps.

UAV performance, maneuverability, and UAV wake vortex category data can be collected as part of an obligatory UAS certification process. We suggest classical approaches such as wind turbine tests, ordinary flight tests, or numerical computation methods. By collecting more data on UAV characteristics, it will be possible to use machine learning techniques for the quick prediction of the tested parameters.

Available onboard energy data can be collected by the U-space via cellular networks (4G/5G) [116], Wi-Fi, very high radio frequency, ultra-high frequency bands, or even microwave frequencies. Optical or laser communication has the potential to transfer data via laser beams with an advanced level of security, as it is hard to intercept the signal. Finally, a recent light fidelity (Li-Fi) technology [117] can be added to the list, as it promises high-speed communication.

The natural turbulence map can be built and updated with computational fluid dynamics, a set of sensors, and data on the weather [40]. For example, weather satellites are essential for the continuous observation of cloud movements, storms, etc. Such data provide a significant basis for working with natural turbulence phenomena. Lidars can collect data on the wind speed, its changes, and atmospheric structure. Radars are useful for detailed data collection on the atmosphere, specifically essential near weather fronts or storms. The weather stations can be placed on the ground, aircraft, weather balloons, sew buoy networks, sea vehicles, and ground vehicles.

Data on the area and time of operation for heavy aircraft generating wake vortices at VLL can be obtained directly from ATM services because heavy aircraft normally fly at VLL in controlled airspace.

Weather forecast analysis can help with the prediction of lightning strike threat areas. There is a set of technologies that can collect the data required. Weather Radar Systems tracks data on thunderstorms - their development, potential for lightning, and intensity. Satellites can monitor temperature, moisture, and cloud formations which is essential for predictions. Ground-based lightning detection networks, lightning detection and ranging systems [118], and atmospheric electric field meters can provide real-time electromagnetic pulses. Numerical weather prediction models can be beneficial as well.

Time complexity estimation can be achieved with mathematical modeling, graph theory [119] usage, and other trajectory planning approaches [43]. However, finding the appropriate level of time complexity is a non-trivial problem. For example, the following factors have a direct impact on it: regulatory safety demands, minimum separation requirements, type of mission, area of operation congestion, airspace availability, quality of communication, and aircraft performance.

Drone user preferences in 4D trajectory planning can be collected via the online software interface Drone User–U-space.

On-surface dynamic obstacles, airspace intruders, and wildlife data can be collected with various on-board and on-surface sensors and then classified with ML techniques [8]. Among the potential solutions are GPS and GNSS systems, lidar, radar, infrared and thermal cameras, and optical and video cameras. Finally, sonar can be used for special cases like the detection of an object in a forest.

Information about known and unknown environments can be collected and updated with on-board and on-surface sensors. However, a specific study on how to fuse multiple-source information in a constantly updated map will be needed.

The status of airworthiness and runway surface conditions should be the area of responsibility of the vertiports. The vertiports must inform the unmanned traffic management system of the corresponding issues via a software interface.

The location of suitable landing areas in case of emergency can be collected with a specific study and updated regularly. Potentially, ML [8] can aid this task by recording and analyzing the ground surface.

UTM security breakthrough status and level of threat can be analyzed with software solutions, where AI can play a significant role in identifying atypical activities that correspond with security breakthroughs.

A map of noise-sensitive areas and regulation demands can be shared by the regulators via a software interface.

In this section, we described the potential approaches that can aid in collecting essential information and filling the gaps. However, this is a high-level vision. There is a need for further detailed research and experiments to make a reliable U-space autonomous traffic guidance system.

This paper did not study how to determine what aspects must be incorporated into the U-space design regarding the U4 phase. To answer this question, we suggest a comprehensive study due to the essentiality of the issue. We admit that it is a multidimensional problem, where experience from manned aviation cannot be completely relied upon due to the different conditions associated with operations at VLL. Flight safety demands, technical limitations, business efficiency, stakeholders' expectations, and the principles of equality and open competition should be taken into consideration, and the optimal combination of U-space services and delegated functions could then be proposed.

II.6. Conclusions

This paper presented an identification and classification of the existing constraints, and essential information needs to allow for U-space traffic autonomous guidance. Further, it analyzed how information needs match U-space services, and gaps in information provision were identified. Also, we proposed a high-level methodology to identify, measure, and close the gaps. Finally, suggestions on promising approaches and solutions were proposed.

Based on the article's findings, the following conclusions can be summarized:

1. The present concept of U-space does not satisfy essential information needs for the U-space traffic autonomous guidance.
2. The identified gaps in information provision must be closed to allow U-space traffic autonomous guidance.
3. Filling existing gaps has different urgencies.

The identification of the information needs does not mean that the U-space traffic autonomous guidance is doable for all types of missions in a safe and efficient way with the modern progress of technologies. It is essential to continue the research to find what technologies can address the identified information needs. Therefore, a large-scale experiment, including dozens/hundreds of UASs, is recommended for testing promising technologies and systems via simulations, mathematical models, and flight experiments. We expect a significant impact of AI implementation for a varied set of tasks–from data capture and classification, including interpretation, pathfinding techniques, multi-factor optimization, and decision-making in heterogeneous scenarios.

We encourage the scientific community to continue researching the measurement and addressing of the identified gaps. The measurement will play an essential role in the U4 deployment by creating quantitative demands on the information and its quality. We suggest our high-level methodology as strategic guidance for future research in this area. The identified constraints and gaps significantly impact flight safety and/or the efficiency of U-space as a set of services. In this light, the paper's findings provide a solid foundation for information provision in the final stage of U-space design and deployment.

We also recognize that the literature review consolidates existing experiences with systems, theories, and solutions. However, we expect that the practical implementation of U-space U4 could pose new and non-trivial challenges. It is also reasonable to expect that potential AI advancements may radically impact many aspects of uncrewed traffic, including its operations and autonomous guidance.

To conclude, we acknowledge that autonomous guidance for uncrewed traffic at VLL is an immature concept that requires extensive research to measure and address the essential information provision gaps discussed in the paper.

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III. A method for determining the safe separation to an unknown-model uncooperative UAV in U-space

Research questions RQ2a and RQ2b were addressed in the paper, ‘A method for determining the safe separation to an unknown-model uncooperative UAV in U-space,’ available by the following link: I. Panov, J. Jepsen, M. Presser, and K. Jensen, “A method for determining the safe separation to an unknown-model uncooperative UAV in U-space,” presented at the 15th ANNUAL INTERNATIONAL MICRO AIR VEHICLE CONFERENCE AND COMPETITION, Bristol, United Kingdom: IMAV2024, Sep. 2024, pp. 208–217.

The link on the publication: https://www.imavs.org/papers/2024/25.pdf

Although some parts of the paper are reproduced here, this section also incorporates changes and additions beyond the original content.

Preamble

The paper addresses the issue of determining the minimum separation distance and the recommended separation (safety radius) for conventional uncrewed air traffic when encountering an uncooperative drone (UD) of an unknown model (UDUM). Ordinary U-space participants communicate with the traffic management system, making their intentions clear. In contrast, UDUMs may not communicate with other airspace users and can manoeuvre unpredictably. Therefore, traditional methods of trajectory planning and collision avoidance may be limited in their reliability.

To address this issue, the paper analyses a global UAV database, identifying the maximum speed limitations associated with each type of UAV. Based on these constraints, it proposes a mathematical model of potential UDUM movement over a given time period. If both time and maximum speed are known, it becomes possible to calculate the minimum separation distance from a UDUM. However, it may be inefficient to fly directly on the border of the minimum separation circle. In light of this, the paper proposes a trade-off between how close and how far a conventional UAV should plan its trajectory relative to the UDUM. Finally, the study addresses how the safety radius can be used to plan a conventional drone’s (CD) flight path if a UDUM moves directly towards the CD.

It is not always possible to identify the model of an uncooperative drone. In such cases, the authors assume that computer vision systems can at least identify the UDUM’s type. Since each UAV type has a distinguishable maximum level flight speed, it is possible to predict performance limitations for any UDUM of a known type.

As the global UAV database currently lacks detailed aircraft performance data, the paper makes assumptions regarding drag coefficient, cross-sectional area, and mass to model UDUM motion. All calculations are carried out for the worst-case scenario; for example, the UDUM is assumed to be the fastest of its type. This approach ensures that the UDUM’s motion remains within known constraints.

The paper also excludes highly advanced UAVs (e.g., jet-engine powered) from its analysis. This is a reasonable assumption, as U-space must primarily be protected against widely available technologies. The design and construction of the most advanced UAVs are very expensive, making their uncontrolled appearance in U-space highly unlikely during peacetime.

As is standard in aviation research, the model assumes standard atmospheric conditions. Finally, the algorithm does not consider the effects of wind or gusts.

Although a hypothesis is not explicitly stated in the paper, the authors address research questions RQ2a and RQ2b. Nevertheless, the hypothesis can be formulated as follows: "If a computer vision system can identify a UDUM's type, and a global UAV database contains relevant aircraft performance data, then it is possible to calculate the minimum separation distance and safety radius for the UDUM. These can subsequently be used in trajectory planning for CDs." The paper provides a positive answer to this hypothesis.

A global UAV database was analysed to identify the maximum level flight speed for all types of UAVs. This helped define performance limitations for each type. The paper also proposes the MATHryoshka method — a dynamic-physical model that allows the determination of the motion limits of a UDUM in any possible direction. This approach reflects the worst-case principle in UDUM motion prediction, which is essential for ensuring flight safety. Finally, the paper provides an example of how the safety radius can be used to plan a CD's trajectory in a theoretically optimal way under conditions of high uncertainty regarding a UDUM's intentions.

The core contribution of the paper is the proposal of a reliable and innovative method for determining a safe separation distance from UDUMs. The findings are both original and essential, as classical approaches to trajectory planning and collision avoidance do not adequately address this issue, posing a significant safety risk if a UDUM appears in the airspace.

Abstract

Unmanned aerial vehicles (UAVs), often referred to as drones, usher in a new era of aviation by delivering new services at very low-level airspace. Many technical and organisational issues must be addressed to ensure flight safety at the European level. This paper proposes a novel method for addressing the challenge of ensuring a safe minimum separation distance between a CD and UDUM. A CD follows regulations and maintains communication with other U-space traffic participants, while a UD conducts a non-conformance flight without permission from the U-space service provider (USSP), thereby posing a significant threat to flight safety.

The paper addresses the issue of determining the minimum separation distance and the recommended separation (safety radius) for conventional uncrewed air traffic when encountering a UDUM. Ordinary U-space participants communicate with the traffic management system, making their intentions clear. In contrast, UDUMs may not communicate with other airspace users and can manoeuvre unpredictably. Therefore, traditional methods of trajectory planning and collision avoidance may be limited in their reliability.

To address this issue, the paper analyses a global UAV database, identifying the maximum speed limitations associated with each type of UAV. Based on these constraints, it proposes a mathematical model of potential UDUM movement over a given time period. If both time and maximum speed are known, it becomes possible to calculate the minimum separation distance from a UDUM. However, it may be inefficient to fly directly on the border of the minimum separation circle. In light of this, the paper proposes a trade-off between how close and how far a conventional UAV should plan its trajectory relative to the UDUM. Finally, the study addresses how the safety radius can be used to plan a CD's flight path if a UDUM moves directly towards the CD.

Our safe separation method relies on a global UAV database analysis and assumes that a vision system or other passive sensing technology (a recognition system) can identify the type of UAV of an unknown model. Additionally, the method involves determining the minimum separation distance and safety radius of a UDUM using velocity vectors for both the CD and UDUM and performing geometric optimisation.

Our UDUM classification led to a significant improvement in measuring the minimum separation distance, resulting in an up to fivefold optimisation among different types of UAVs. We recommend the method for the future autonomous guidance system of CDs.

III.1. Introduction

U-space, the European implementation of an unmanned aircraft system traffic management (UTM) system, is expected to support UAV operations with very high levels of automation [1, 2, 3] including autonomous UAV guidance that relies on the planning of safe 4D trajectories encompassing three dimensions and time [4]. The autonomous system will rely on automated rule-based systems and, potentially, artificial intelligence to plan trajectories and continuously replan [4].

Collision avoidance is a fundamental principle of flight [5]. Through their literature review, J. K. Kuchar et al. made a significant contribution to the field by categorising the existing methods [6]. Some scientific articles have proposed various collision avoidance approaches for CDs [7], [8]. The performance and intentions of UDUM aircraft are unknown; therefore, classical methods such as probabilistic and deterministic approaches cannot be used, as they rely on this data. If U-space airspace is violated by a UDUM, it introduces an elevated risk of potential collision with surrounding aircraft. The fundamental question here is what “surrounding” means; in other words, what is the safe separation distance needed for each case.

In this paper, we discuss various UAV models and types. UAV models are characterized by a unique design or configuration, including specific features such as weight, size, and propulsion system. In contrast, UAV type refers to the physical configuration, operational characteristics, or usage of the UAV. We categorize UAVs into the following types: fixed-wing, rotary-wing, lighter-than-air, flapping-wing, and parafoil. For example, the DJI Phantom 4 is a model, and its type is rotary-wing.

M. Wisniewski et al. [9] proposed to use neural networks to identify a UAV model using its image. The safe separation distance of a known-model UD (UDKM) can be determined if the autonomous guidance system has information about the UDKM’s position, aircraft performance and, ideally, its vector of velocity. However, if the UD’s model is unknown, finding the minimum safe separation distance becomes significantly more complicated. To the best of our knowledge, there is no known effective solution for determining the minimum safe separation distance of UDUMs. If a UDUM is fast enough to collide with a CD before the flight terminates, and the autonomous guidance system of the CD does not adequately account for this situation, there is scope for flight safety improvements.

We argue that even if the recognition system is unable to identify the model of UD, at least it must be able to identify the UDUM’s type based on its image and/or its current speed. Knowing the type of UDUM is essential for calculating the minimum safe separation distance between a CD and a UD. The simple alternative solution of having a standard safe separation distance for all types of UDUMs leads to inefficient U-space airspace usage. This can be especially important for high-density unmanned air traffic.

To tackle the problem, we decided to approach the issue from a new angle. More specifically, we analysed the global database of UAVs [10], which contains information about the maximum speed in horizontal flight of almost 3,000 UAVs. One of our research objectives was to find the maximum speed of each type of UAV.

We start the paper by explaining the assumptions and the research method. After that, we discuss the results of the global database [10] analysis. Then we present a method for using drone-type classification to ensure safe minimum separation. Subsequently, we propose a geometric approach to determining an optimal margin for safe separation. To give an example of how it can be used, we solve a task involving a case scenario of a potential collision. We also discuss whether our method can be used for other cases. Finally, we present a conclusion in the last section.

III.2. Problem formulation and research method

We advance the hypothesis that if a UD's model is unknown, it is essential to know the maximum speed of its type, the minimum and maximum value of drag coefficient for the type, the aircraft dimensions to predict its cross-sectional area and the maximum and minimum mass range. Based on this information, we propose a method to suggest a safe separation distance between UDUMs and conventional U-space air traffic. The research question is how to find the minimum separation distance and safety radius of UDUMs to prevent collisions with CDs. Technically speaking, given an extensive global UAV database, no-wind conditions, and a known type of UDUM, what is the minimum separation distance and safety radius (in metres) required to prevent mid-air collisions between the CD and the UDUM? A safety bubble will likely have a nonspherical form (Figure III-8). However, in our simplified approach, the safety bubble is created by calculating the longest distance possible to fly in a predetermined value of time (Figure III-8). The points obtained from the calculations are symmetric along the vertical axis, which allows us to discuss minimum separation distance and safety radius on the horizon at a certain altitude (Figure III-9).

III.2.1. Assumptions

Based on the progress of machine learning techniques, we employ the assumption that an artificial intelligence system will be able to identify the type of any drone based on its image [9], [11].

We also make the decision to exclude the fastest highly advanced UAVs from the database, as it is highly unlikely that their model would be unknown. High-speed flight performance requires expensive technologies like jet or turbo engines [12]. Building a compound helicopter model involves very complicated [13] research and development processes, which sets a high bar for making this type of UAV. However, a simple quadcopter can be constructed in a garage or in a drone club by a layman [14]. In the latter case, the UAV's model can be unknown to the drone recognition system, and the CD's autonomous guidance system will not be able to predict a safe separation distance to the UDUM since its performance is unknown. One could argue that certain drones and rockets can fly at supersonic or even hypersonic speeds. However, once again, these technologies are not widely available, and safe separation from them should not be an operational issue for U-space airspace. Protection against such threats is related to defensive technologies and remains outside the scope of the current study.

We propose a solution for 4D (3D + time) space based on the global UAV database, where we categorise various types of UAVs and determine the maximum horizontal flight speed for each type. However, our database is limited in terms of aircraft model, type, and maximum speed, leading us to rely on assumptions concerning drag coefficient, cross-sectional area and mass of the UDUM. We acknowledge that further research is needed to find dependencies between the dimensions of a UAV and its maximum and minimum mass, cross-sectional area and drag coefficient. Based on the data on the UDUM's dimensions and type, the autonomous guidance system can calculate the safe separation distance using our method.

The limitations by type could help achieve collision-free flight in the vicinity of UDUMs operating at different altitudes. Aerodynamic drag, thrust, and mass significantly impact aircraft acceleration, deceleration, and maximum dive speed. While fixed-wing or rotary-wing UAVs may have lower drag coefficient values, some UAVs classified as airships have a large cross-sectional area, which leads to a higher value of the drag coefficient [15]. The greater the drag value, the more severe the limit of maximum diving speed due to the balance of aerodynamic forces [16].

Finally, we did not take into consideration the impact of weather conditions and other specific constraints [17] like restricted areas, sensor accuracy impact, etc. We also chose to disregard the air compression effect, as the increase in drag coefficient with rising speed does not have a detrimental impact on flight safety. Also, the drones we focus on rarely fly significantly faster than 100 m/s. The fastest UAV in our refined dataset has a maximum speed of 118 m/s, and at this velocity, the impact of the effect is relatively small. To fly significantly faster, the drones must dive with a large negative flight path angle γ , which they can only do within a short time interval.

III.2.2. Research method

In accordance with our assumptions, we refined the global UAV database by excluding the fastest highly advanced UAVs. Subsequently, we checked the maximum speed for each drone type. We developed a novel method, MATHryoshka, that uses data on maximum velocity, drag coefficient, cross-sectional area, mass, and current velocity of UDUM to calculate minimum separation distance and safety radius. To minimise the risk of collisions, we proposed an approach that involves measuring the safe separation distance.

III.3. Global UAV database analysis

III.3.1. Fixed-wing type

To shed light on the maximum speed of basic fixed-wing UAVs, we analysed 1,743 models of this type [10] (Figure III-1). We also included tilt-wing UAVs in this list. Some UAVs have a tilt rotor or rotary wing alongside a wing. However, the maximum speed is reached when the rotor generates thrust while the wing generates lift force. This fact allows us to categorise these tilt-wing and tilt-rotor (with wings) UAVs in the same group, namely the fixed-wing type.

101 models of the most technically advanced UAVs were removed from the list, among them the fastest UAVs with jet, turboprop, and rocket engines [12]. The fastest model based on relatively widely accessible technology is the Berkut ISR with a piston engine. Its maximum speed is 425 km/h.

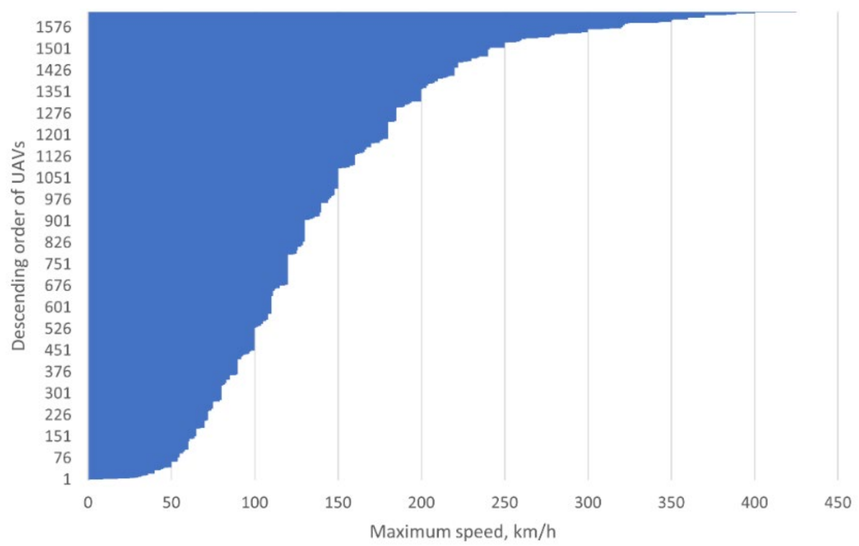

Figure III-1. Distribution of the maximum speed of fixed-wing UAVs.

III.3.2. Rotary-wing type

We analysed and ranked 1,141 rotary-wing UAVs by maximum speed. The 5 models that we defined as highly advanced and fast were excluded from the analysis. Among these were three high-speed compound UAV helicopters: the X2, the HADA and the Jueying-8. We also excluded the Pop.Up Next and the Transporter with turbocharged engines.

After cleaning the data, we built a figure showing the distribution of the rotary-wing UAVs (Figure III-2). The figure shows that the majority of the rotary-wing UAVs have a maximum speed ranging from 50 to 150 km/h. However, a Transporter UAV made by Advanced Tactics features a set of widely available technologies: a quadcopter airframe, four petroleum-powered engines, and primitive flight aerodynamics optimisation for the reduction of drag. Its maximum speed is 321 km/h, which is the maximum speed for the rotary-wing type.

III.3.3. Lighter-than-air type

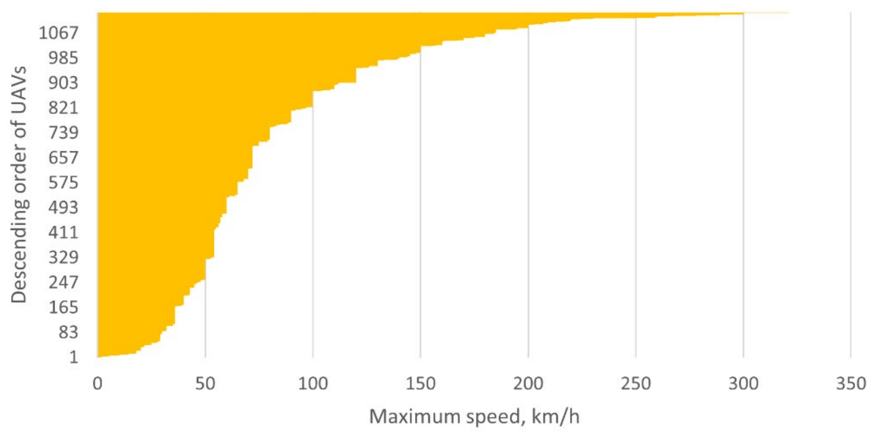

Figure III-2. Distribution of the maximum speed of rotary-wing UAVs.

The lighter-than-air type is exemplified by airships, which tend to have the capability to fly at higher altitudes than rotary-wing and sometimes fixed-wing aircraft. Because of the low air density at altitudes higher than 4,000–6,000 metres, an aircraft can reach its maximum speed. Our study was conducted to assist U-space. Ideally, it is therefore essential to study airships' maximum speeds at a very low airspace level. Since we do not have access to such data, we estimate the airships' maximum speeds with a significant margin of safety. This approach does not affect flight safety; however, we recognise that there is room for further optimisation.

The available database of airships is not large; it only includes 27 models, the fastest of which can reach 150 km/h (Figure III-3).

Not powered by engines or motors, hot air balloons are typically not classified as UAVs and are thus not included in our study.

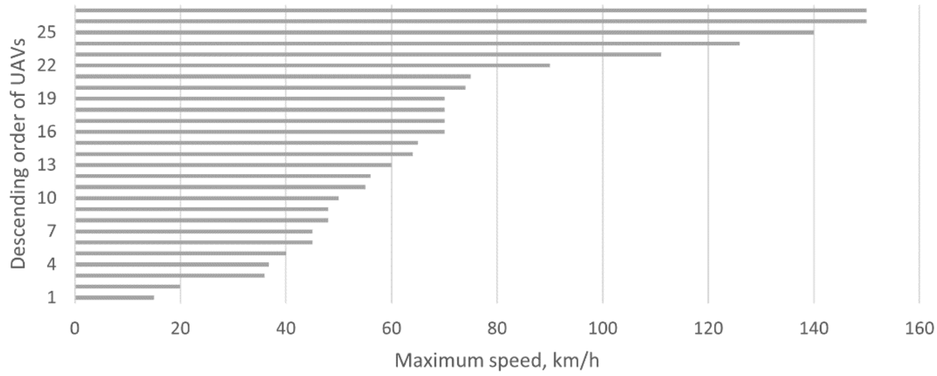

Figure III-3. Distribution of the maximum speed of lighter-than-air UAVs.

III.3.4. Flapping-wing type

Flapping-wing UAVs are among the most rare. In our database, we only have six models, with the fastest one being capable of reaching 125 km/h (Figure III-4).

III.3.5. Parafoil type

Parafoil UAVs, also known as powered parachutes, have a unique design that combines the capabilities of a parachute and propeller-driven aircraft. The lift force is generated by a flexible wing, while thrust is delivered by a propeller-based propulsion system. This type of drone offers a unique mix of payload capacity, stability, and ease of operation. Parafoil UAVs are the slowest of all UAV types; their maximum speed is 80 km/h (Figure III-5).

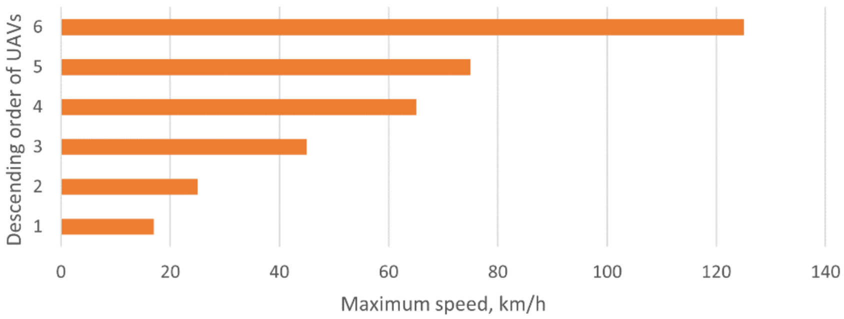

Figure III-4. Distribution of the maximum speed of flapping-wing UAVs.

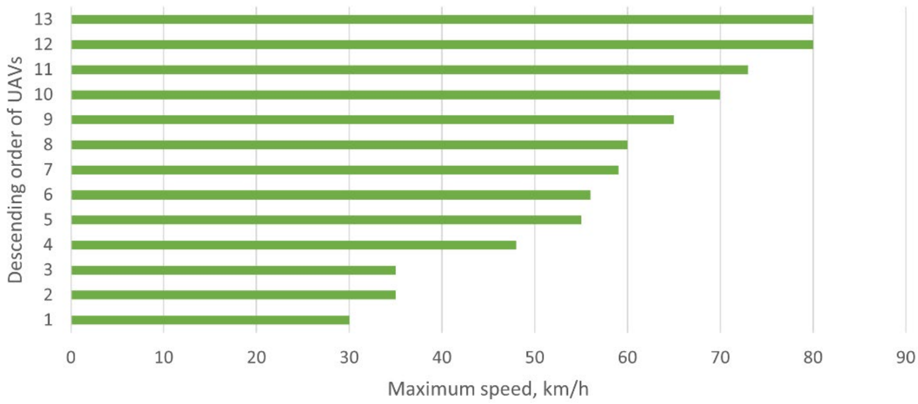

Figure III-5. Distribution of the maximum speed of parafoil UAVs.

III.3.6. Comparison between types

When comparing the various types of UAVs, we see a significant difference in their maximum speeds (Figure III-6). The fixed-wing aircraft, represented by the fastest type, has a maximum speed of more than 400 km/h. Close to this is the fastest rotary-wing UAV, which can fly faster than 300 km/h. Lighter-than-air and flapping-wing UAVs are relatively slow, with speeds ranging up to 150 km/h. Finally, parafoil UAVs are the slowest, with speeds not exceeding 100 km/h. The most common speeds of rotary-wing and fixed-wing UAVs differ by 100 km/h.

The fastest and the slowest types differ up to five times. It means that the classification proposed can lead to up to 5 fivefold optimisations in identifying UDUM maximum speed. Other, more rare types can achieve maximum speeds that are a couple of times slower than the Berkut.

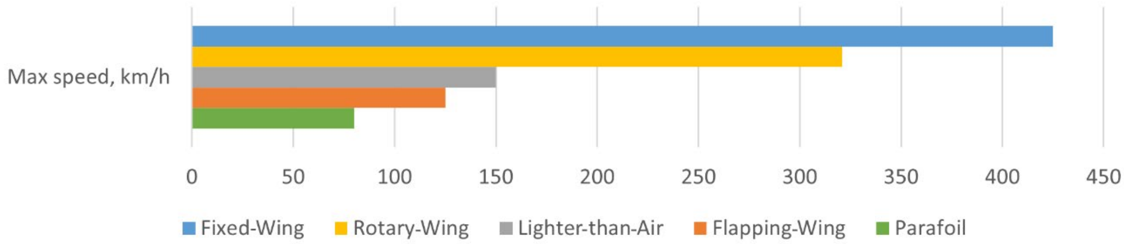

Figure III-6. Comparison between types of UAVs.

Based on the global database analysis, we are able to classify a UDUM's maximum speed according to its type. In the next section, we present a mathematical model for a 4D case.

III.4. Mathematical model

We calculate the separation distance based on a worst-case scenario to minimise the risk of collision with a known-type UDUM. In our worst-case scenario, we assume that the UDUM is the fastest model of its type and that its trajectory is optimised to collide with an ordinary U-space user. In other words, if the autonomous guidance system can plan U-space air traffic based on the worst-case scenario, the chances of a collision with a UDUM can be reduced significantly.

A collision is only possible if two UAVs have violated the minimum separation distance. To prevent the violation, it is essential to plan the CD's trajectory according to the maximum possible speed of the UDUM, which is affected by the possible range of its mass, its drag coefficient, its cross-sectional area and the lift coefficient for winged UAVs. We only analysed a global UAV database with types of UAVs and their maximum speeds (Figure III-6). To predict the range of mass, drag coefficient (C_d), lift coefficient (C_l), and cross-sectional area, a global database with such data and aircraft dimensions is needed. To the best of our knowledge, such a database does not exist. Bearing this in mind, we make calculations using assumptions for the missing data.

If two UAVs are approaching the same coordinates at the same time, there is a potential risk of collision. In this light, we can measure the separation in seconds until the moment of a potential collision. A small adjustment is needed to tackle the problem of aircraft dimensions; an issue we address in the code [18] by adding two aircraft maximum dimensions and dividing the result by two. The deviations here are not very important, since we measure separation distances from the UDUM in the hundreds of metres, while UAV dimensions are only a few to several metres.

There is a significant challenge in making trajectory planning decisions for a CD when the estimated time to potential collision is several minutes. For example, a fixed-wing UAV with a maximum speed of 425 km/h can cover 212.5 km in half an hour. If a UDUM appears, will this mean that the USSP should close this radius of the U-space airspace according to the time of potential approach? As this seems unrealistic, we propose an alternative approach by measuring the time of flight termination for the CD.

III.4.1. Minimum separation distance

For CDs that are not equipped with a parachute, time of flight termination is a variable quantity that depends on the maximum safe descending and landing speed, the current altitude, and the availability of the emergent landing areas. This means that the emergent landing time may vary for each concrete square on the map of a mission. We expect the UAV autonomous guidance system to be able to estimate the time based on information about aircraft performance and geofence information. If a CD is outfitted with a parachute, the flight termination time corresponds to the time required for the parachute to deploy.

Since the intentions and aircraft performance of UDUM remain unknown, CD cannot rely solely on superior manoeuvrability to avoid a collision with dodging manoeuvres. If UDUM is more manoeuvrable and possesses a total mechanical energy advantage over CD, there can be no guarantee of collision-free flight if UDUM's intentions are malicious. Having innovated the MATHryoshka method, we now propose it to find the minimum separation distance, D_{ms}, between a CD and a UDUM. MATHryoshka calculates the distance to a potential collision based on flight time termination.

III.4.2. MATHryoshka method

The MATHryoshka method relies on a simplified, physical mass-point model of a UDUM moving at various angles γ within the range [$-\pi/2$, $\pi/2$]. At the start of the calculation, the UDUM activates maximum thrust, representing the worst-case scenario conditions.

Imagine that we have a scenario with a UDUM rotary-wing type. From our previous analysis, we know that its maximum potential horizontal flight speed is 89 m/s. Its current velocity is 10 m/s, which is detected by sensors. Its mass, cross-sectional area, and drag coefficient are given. Information on air density can be collected from U-space; in our case, we assume that it is 1.29 kg/m3, which is a typical value at sea level.

Given

- UDUM type = rotary-wing.
- Maximum dimension of the UDUM, including width, length and height = 1.5 m.

- Maximum dimension of the CD, including width, length and height = 2 m.
- v_0 = 10 m/s.
- v_{mh} = 89 m/s.
- C_d = 0.2 - drag coefficient for a rotor-wing.
- ρ = 1.225 - air density in kg/m^3 (typical value at sea level).
- A = 0.4 - cross-sectional area, m^2.
- m = 15 kg.
- t = 10 seconds.
- e = 2.71828.
- g = 9.81 m/s^2.

Task

Find the distance travelled (s) by UDUM at various γ in the range [- π /2, π /2] within ten seconds, adding the maximum dimensions of the two aircraft divided by 2. The term 'aircraft maximum dimensions' refers to the highest value among the aircraft's height, width, and length.

Solution using the MATHryoshka method

Figure III-7 illustrates the vector of thrust and the primary aerodynamic forces acting on UDUM.

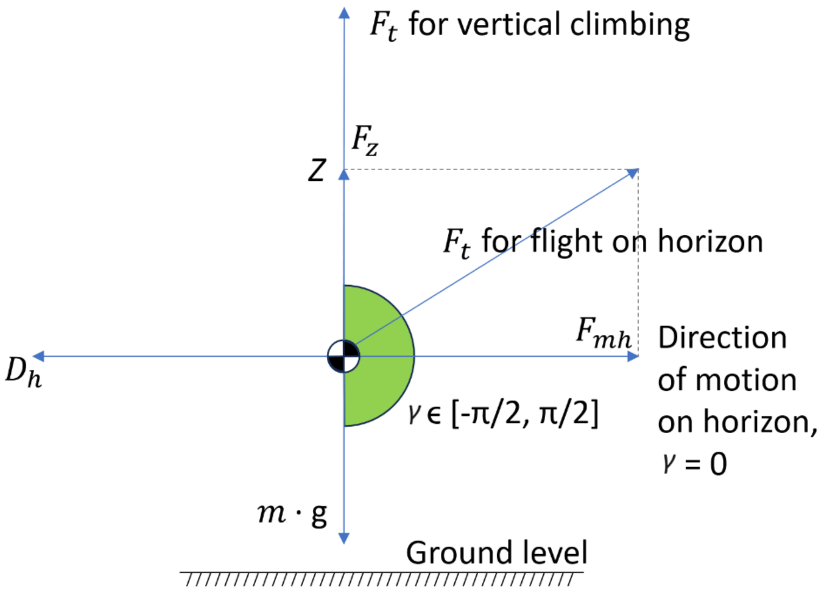

Figure III-7. Vector of thrust and the primary aerodynamic forces.

- D_h - force of drag in horizontal flight with maximum thrust.
- F_{mh} - projection of maximum force of thrust on the horizontal axis X in horizontal flight.
- F_z - projection of maximum force of thrust on the vertical axis Z in horizontal flight.
- γ - flight path angle $x \in$ [- π /2, π /2].
- v_0 - initial velocity.
- m - mass.
- g - gravity.
- F_t - maximum force of thrust.

We use the next model simplifications:

- C_d is constant for any γ .
- C_d is constant at any velocity.
- Moments are ignored.

According to the Newton's law:

$$F = m \cdot a. \tag{1}$$

Where F = total force, and a = acceleration. Now, we introduce a constant b to simplify the calculus (2).

$$b = \frac{1}{2} \cdot \rho \cdot A \cdot C_d. \tag{2}$$

Where ρ = air density, A = cross-sectional area and C_d = drag coefficient. F_{mh} is constant since the UAV flies with maximum thrust in horizontal flight (3).

$$F_{mh} = b \cdot V_{mh}^2. \tag{3}$$

For horizontal flight, F_z is equal to absolute value of $m \cdot g$, consequently:

$$F_t = \sqrt{F_{mh}^2 + (m \cdot g)^2}. \tag{4}$$

The vector of velocity of UDUM can be aligned with F_t only in vertical diving or climbing. Total force generated by rotary-wing propellers acting in the direction of flight can be estimated in the following way. F_{dm} reflects thrust impact in the direction of flight. It is changing from F_{mh} (for horizontal flight) to F_t (for vertical flight). Consequently, it can be expressed as hypotenuse for both F_{mh} and F_t, depending on the respective γ values.

$$F_{dm} = \sqrt{(F_t \cdot \sin\gamma)^2 + (F_{mh} \cdot \cos\gamma)^2}. \tag{5}$$

F represents the main set of forces acting on UDUM at various flight path angles γ . As inertia and moments are not considered, *F* always acts in the direction of aircraft trajectory.

$$F = F_{dm} - m \cdot g \cdot \sin\gamma - b \cdot v^2. \tag{6}$$

Using the Euler method, we find the velocity and distance travelled, where *s* represents the distance travelled in time *t* at a certain angle γ (9).

$$v_{n+1} = v_n + \frac{F_{dm} - m \cdot g \cdot \sin\gamma - b \cdot v_n^2}{m} \cdot dt. \tag{7}$$

$$t_{n+1} = t_n + dt. \tag{8}$$

$$s_{n+1} = s_n + v_{n+1} \cdot dt. \tag{9}$$

To arrive at a practical solution, the next code was written in Python version 3.10.4 - see [18] for the code link. Using this code, we built Figure III-8.

In the centre of the diagram, there is the UAV's centre of mass. According to various angles γ , the UDUM can travel a different distance in time *t*. Time *t* is equal to the flight termination time for the CD (we assumed it to be 10 seconds).

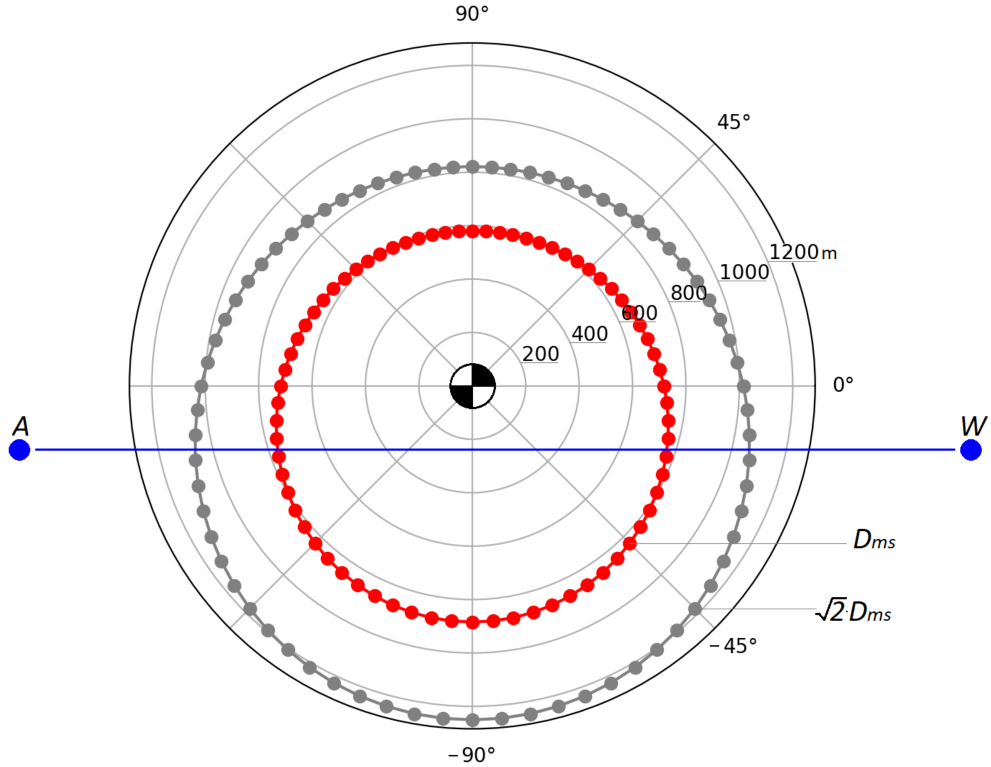

Figure III-8. Distance travelled in 10 seconds for each γ, adding the maximum dimensions of the two aircraft divided by 2. Side view.

Point *A* represents the CD's current position, and *W* is the destination point. Red points represent the minimum separation, D_{ms}, which is the distance travelled by UDUM at various γ in ten seconds, plus two times the aircraft's maximum dimensions divided by 2 (see the code [18]). We consider the impact of aircraft dimensions since it is essential to mitigate the collision threat.

The grey points represent the safety radius, which is D_{ms} multiplied by $\sqrt{2}$ (13), as we explain in the next section.

III.4.3. Minimum separation distance and safety area

One of the key issues in avoiding collisions with UDUMs is the uncertainty regarding their intentions and the lack of information about aircraft performance, including unknown limitations on flight characteristics. The current vector of velocity of a UDUM is essential for tactical deconfliction. Also, the data on UAV performance should be collected in a global UAV database, which, as far as we are aware, does not exist yet. The current vector of velocity is not very reliable since it can change depending on different accelerations and dynamics due to the huge diversity among UAV flight characteristics [19]. In light of these limitations, we propose a multifactor approach that incorporates UDUMs' maximum speed, mass, drag coefficient, cross-sectional area, current vector of velocity and geometric optimality.

Consider a situation where a CD intends to fly from point *A* to a destination, point *W* (Figure III-9). For simplicity's sake, we assume that the CD and the UDUM are at the same altitude. The direct flightpath of the CD intersects with the safety area around a UDUM that has a radius denoted as *r* (10). The position of the UDUM is known and presented in point *I* (Figure III-9).

$$r = \frac{D_{ms}}{\cos\sigma}. \tag{10}$$

A safety area with radius r around point I is essential to ensure an optimal distance between the CD and D_{ms} (Figure III-9) at the moment of approach. The optimal distance is the safety area with radius r, which is equal to the IG segment. There is a fundamental problem in determining the value of r. From one perspective, it must be long enough to maximise the right angle σ – the greater the angle, the less the chance that a new random vector of velocity of the UDUM will be threatening the CD. From another perspective, IG must be sufficiently short to reduce the travelling distance of the CD. Measuring G as a point that the CD can reach faster than the UDUM, based on the current vectors of velocity, is not reliable since the UDUM may have the potential to accelerate or decelerate. If we rely on the UDUM's maximum speed, which is higher than that of the CD, there are instances where point G cannot be found at all. Even employing the standard separation distance between CDs defined by regulation cannot guarantee collision avoidance since the intention of the UDUM is unknown and may even be malicious.

Consequently, we propose to use a geometric optimality logic to find the r value. There are two values that are interconnected (10) – angle σ and value r, since lines $u_1 \perp s$ and $ID = IF = IC = D_{ms}$. Also, $s_1 \parallel s$, $u \parallel u_1$, $C \cap s_1$, $C \cap u$, $F \cap t$, $D \cap u_1$, $D \cap s$, $G \cap n_1$, $G \cap t$, $G \cap s_1$, $G \cap u_1$.

The greater angle σ is, the less potential of collision since the intentions of the UDUM are unknown. Conversely, the greater the value of r, the more U-space airspace is covered by the safety area and the longer distance the UDUM will have to cover to come to W through G. For the sake of optimality, it is essential to determine a value of σ that reflects optimal ratio of σ to r. In that pursuit, we should find a derivative of r and a value of σ that maximises the ratio.

$$\frac{d}{d\sigma}\left(\frac{D_{ms}}{\cos\sigma}\right) = \frac{D_{ms}\cdot\sin\sigma}{\cos^2\sigma}. \tag{11}$$

$$\frac{D_{ms}\cdot\sin\sigma}{\cos^2\sigma} = D_{ms}\cdot\frac{1}{\cos\sigma}. \tag{12}$$

In any case, $\sigma \in (0, \pi/2)$, thus the equation (12) is true when $\sigma = \pi/4$, thus $\frac{1}{\cos\sigma} = \sqrt{2}$, which gives the equation (13).

$$r = \sqrt{2}\cdot D_{ms}\,. \tag{13}$$

The geometric approach may be subject to criticism because it assumes that changing σ is similarly important for trajectory planning as changing the r value. In fact, both are essential, though probably not equally so. We acknowledge the potential for further optimisation in this area. We disregard an error factor that could be essential for addressing delays associated with data collection, computation, and transfer. The error factor may potentially increase the safety radius required.

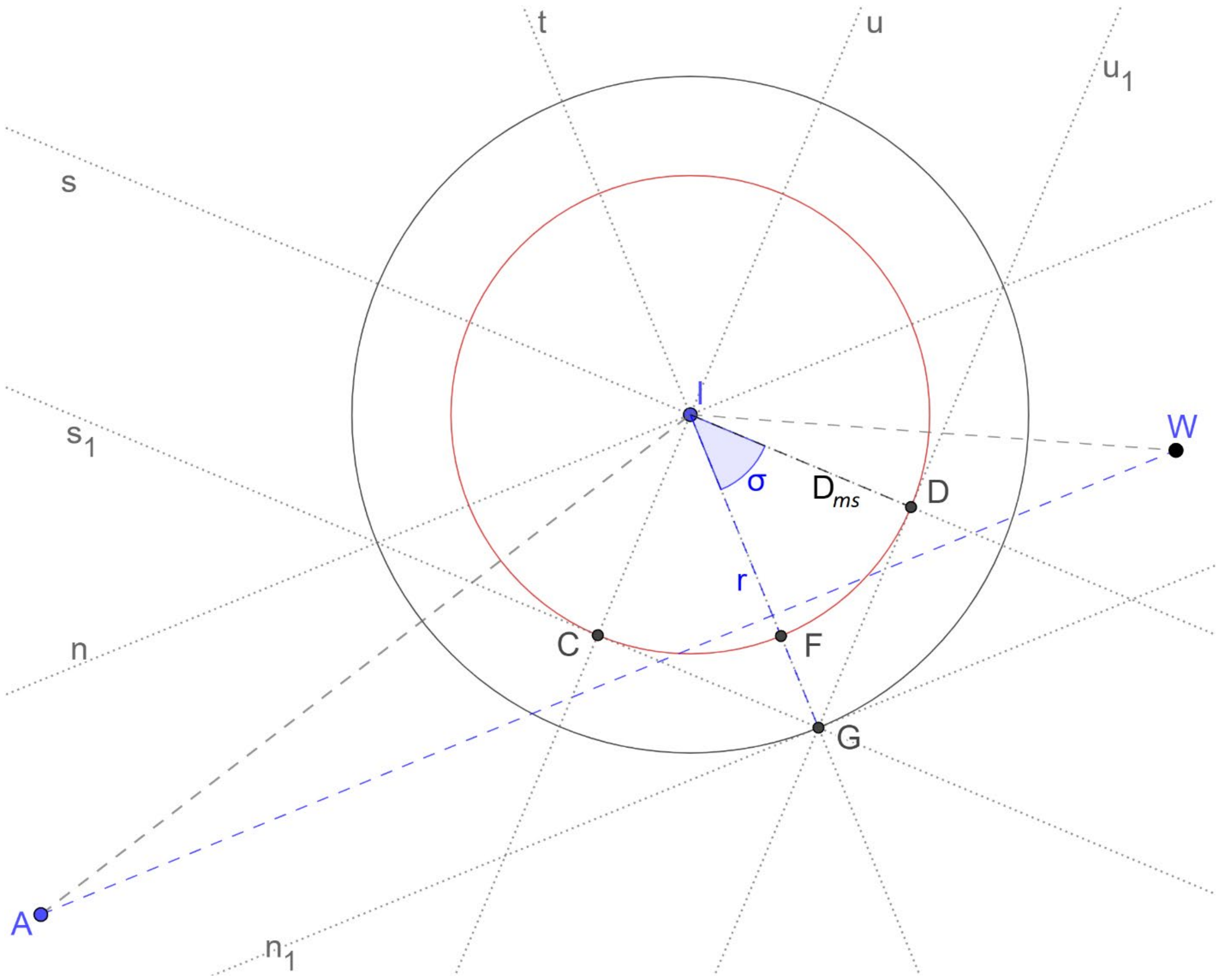

Figure III-9. Minimum separation distance and safety radius for γ = 0°. Above view.

In this section, we analysed the scenario where the CD and the UDUM are at the same altitude, which for the worst-case scenario is γ = 0°. However, in actual airspace, altitudes are likely to differ, for example when the altitude of a UDUM is higher than that of a CD (Figure III-10). Nevertheless, following the same logic, we can multiply D_{ms} by $\sqrt{2}$ to find the safety radius for each value of γ (Figure III-8). For example, for γ = - 45°, D_{ms} = 833.5m and $r = 833.5\text{m} \cdot \sqrt{2} \approx 179\text{m}$.

III.4.4. Some typical scenarios

First, it is essential to identify if the UDUM moves to the location of the CD with the risk of penetrating the safety area. This means that the algorithm of the autonomous guidance system must check if the projection of the vector of velocity of the UDUM, **u**, belongs to the angles ρ_1 or ρ_2 (Figure III-10). If **u** belongs to ρ_1 and not to ρ_2, we suggest avoiding collision by choosing a flight path that is closer to point *K* than point *T*.

To simplify calculations, we moved the X and Y axes in a way such that (see Figure III-11):

- Point $A \in O_y$. Vector **u** ∥ axis O_x. For 3D airspace, **u** is a vector projection of the vector of velocity of the UDUM on the horizontal plane with points *OAW*.
- Points $L, R, N \in O_x$.
- O_x is a tangent line to the safety circle (with radius *r*) in point *N*.
- *q* and t_1 are the tangent lines to the safety circle with radius *r*.
- $t_1 \parallel t_2$.

If **u** ∈ ρ_2 and **u** ∉ t_2 (Figure III-11), the waypoint *L* is a special point that allows the CD to effectively leave the UDUM's direct flightpath, thereby avoiding the safety area of the UDUM. Effectively means that if the two aircraft should move with the same vector of velocity, the CD will reach point *L*. At the same time, point *R* will have the same coordinates as *L* since the UDUM moves in the same direction. Upon reaching point *L*, the CD is not at risk of violating the minimum separation distance if the UDUM continues its movement in the same direction and the CD continues its flight to point *N*. In the next section, we provide a solution for finding the coordinates of point *L*.

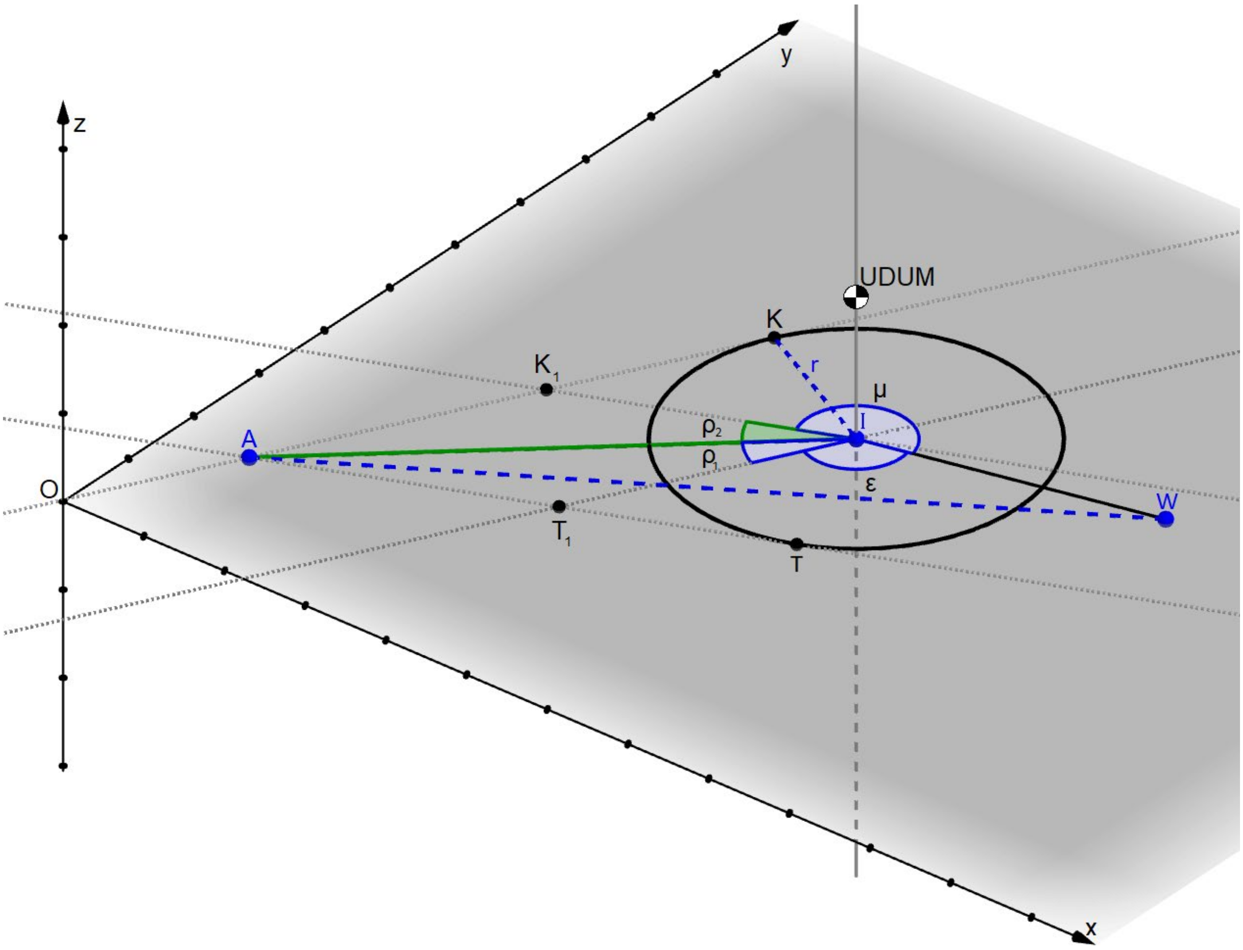

Figure III-10. Front collision hazard, UDUM is higher than CD. Two o'clock view angle.

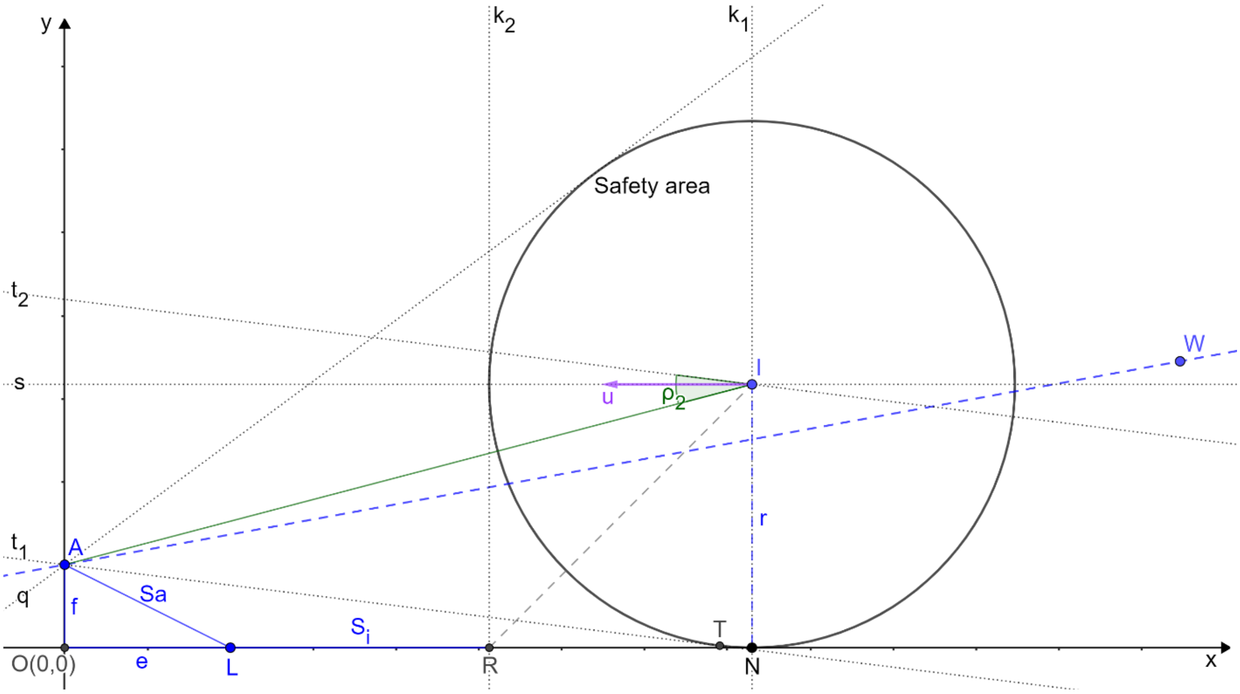

Figure III-11. Rho two problem. Above view.

III.4.5. Rho two problem

Task conditions. Given

- $A(0, y_a)$ - location of the CD.
- $f = y_a$.
- $I(x_i, y_i)$ - projection of location of the UDUM on the horizontal plane OAW.
- $W(x_w, y_w)$ - location of the destination point of the CD.
- r - the safety radius (13).
- **u** – a vector projection of the vector of velocity of the UDUM on the horizontal plane OAW.
- V_i – the projection of the velocity of the UDUM on plane OAW.
- V_a – the velocity of the CD.
- The CD and the UDUM are in simultaneous flight.
- t_1, q – the tangent lines between point A and the safety circle with centre I and radius r.
- $t_1 \parallel t_2$.
- ρ_2 – the angle between line AI and line t_2.
- μ - the exterior angle at the points K_1, I, W.
- ε - the interior angle at the points T_1, I, W.
- $\mathbf{u} \in \rho_2$ and $\mathbf{u} \notin t_2$.
- Line $OLRN \parallel \mathbf{u}$.
- Line $OLRN$ is a tangent line to the circle with radius r and centre I.
- $RN = IN = r$.

Task

Find x coordinates of point L.

Solution

$$x_r = x_i - r. \tag{14}$$

Sa is the travelling distance of the CD from point *A* to point *L*, *OR* = *j*, *OL* = *e*, *AL* = S_a.

$$e = \sqrt{S_a^2 - f^2}. \tag{15}$$

Since V_i and V_a are known, its ratio *k* is a constant. Sa is a distance *AL*, and S_i is a distance *RL*.

$$\frac{V_i}{V_a} = \frac{S_i}{S_a} = k. \tag{16}$$

$$j - k \cdot S_a = \sqrt{S_a^2 - f^2}. \tag{17}$$

$$(k^2 - 1) \cdot S_a^2 - 2 \cdot j \cdot k \cdot S_a + (f^2 + j^2). \tag{18}$$

$$x_l = e = \sqrt{S_a^2 - f^2}. \tag{19}$$

For $S_a > f$, $V_i > 0$. If $V_a \neq V_i$, $k \neq 1$, S_a and S_i can be intersected at two points on the line *x*, thus:

$$S_a = \frac{2 \cdot j \cdot k \pm \sqrt{(-2 \cdot j \cdot k)^2 - 4 \cdot (k^2 - 1)(f^2 + j^2)}}{2 \cdot (k^2 - 1)}. \tag{20}$$

However, for the sake of optimality, the smallest positive value of x_l is needed, thus:

$$x_l = \sqrt{\left(\frac{2 \cdot j \cdot k - \sqrt{(-2 \cdot j \cdot k)^2 - 4 \cdot (k^2 - 1)(f^2 + j^2)}}{2 \cdot (k^2 - 1)}\right)^2 - f^2}. \tag{21}$$

If $V_i > 0$ and $f > S_a$, the CD is at risk of penetrating the UDUM's safety area wherever the CD flies. Mathematically, this means that the discriminant cannot be negative. It means that solutions exist for:

$$k < \sqrt{1 + \left(\frac{j}{f}\right)^2}. \tag{22}$$

If $V_a = V_i$, thus $S_a = S_i$, and $k = 1$, thus:

$$(j - S_i)^2 = S_i^2 - f^2. \tag{23}$$

$$S_i = \frac{j^2 + f^2}{2 \cdot j}. \tag{24}$$

If $V_i > 0$ and $f = S_a$, thus:

$$x_l = 0. \tag{26}$$

If $V_i > 0$, then vector **u** = 0, consequently, point *R* cannot be defined. We suggest heading to point *T* in this case; however, that is a different task.

If **u** ∈ ρ_1 and **u** ∉ ρ_2 and **u** ∉ ε (Figure III-10), and *AW* intersects with the safety area, the task can be solved in a similar way, but by ensuring that the CD heads to the other (right) side of the UDUM.

We assume that the velocity vector of the UDUM and its projection **u** are known in real time. Therefore, recalculating point *L* every few milliseconds (for example) could move its coordinates to a new safe position if the UDUM accelerates. Point *L* can also be moved to a more optimal position if the UDUM decelerates during the flight.

If **u** ∈ μ or **u** ∈ ε and *AW* intersect with the safety area, other challenges arise in which the minimum separation distance D_{ms} and the safety radius r play significant roles in defining the problem and finding a suitable solution. Another example is when *AW* does not intersect with the safety area (Figure III-12), but there is a potential risk that the minimum separation distance may be breached if the UDUM is fast enough. A_1 is the position of the CD, and W_1 is the position of the UDUM. A_1T_2 and W_1T_1 are tangent lines to the circle of the safety area. $A_2I_1 \parallel A_1T_2$, $T_1W_1 \parallel I_1W_2$. $\mathbf{u}_1 \in \rho_3$.

To solve such a task, we need to know the minimum separation distance, D_{ms}, and the safety radius, *r*.

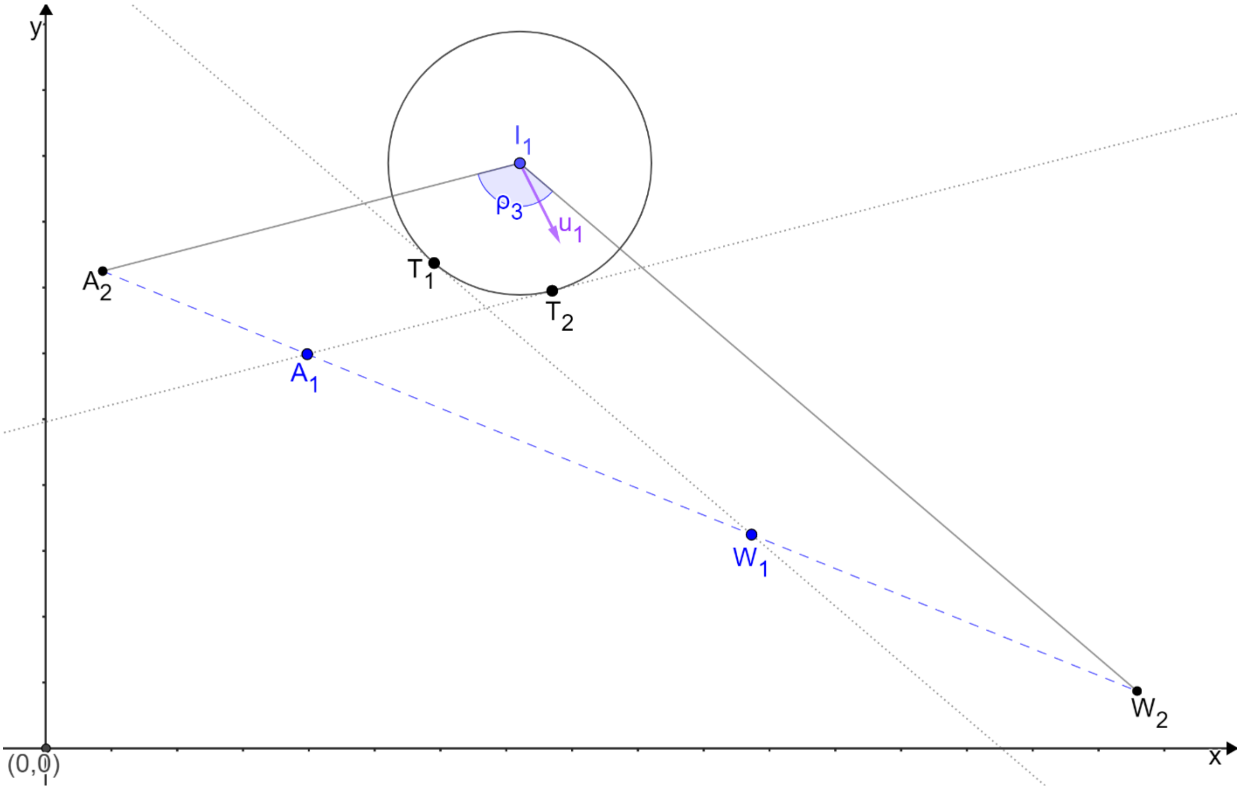

Figure III-12. Trajectory intersection in case of remote positions. Above view.

III.5. Discussion

Additional comments on the impact of UAV dimensions

It is reasonable to examine how the research question regarding the determination of the minimum separation distance and safety radius for UDUMs is addressed through the derived equations (9.1) and (13). Since analytical approaches are limited to calculating the distance travelled at a given time under a set of forces acting on the aircraft, we employed the Euler method (see Equations (7–9)). The final equation for the minimum separation distance is implemented in the code of algorithm [18]. For ease of reference, the equation for the minimum separation distance (D_{ms}) is provided below as equation (9.1).

$$D_{ms} = s(T) + d_{impact} \tag{9.1}$$

Here, *T* is the final simulation time, and *s* is the distance travelled during this time.

$$s(T) = \int_0^T v(t)dt \tag{9.2}$$

d_{impact} represents the influence of the dimensions of both the CD and the UDUM on their separation. This is essential to address, as the mass-point approach is used.

$$d_{impact} = \frac{1}{2}(dim_{cd} + dim_{udum}) \tag{9.3}$$

Here, dim_{cd} refers to the maximum dimension of the CD among height, width, and length. Similarly, dim_{UDUM} refers to the maximum dimension of the UDUM.

The equation for the safety radius of UDUMs is derived in Equation (13). Therefore, the RQ2a is answered and supported mathematically.

Additional comments on equation (12)

In Section III.4.3, it is written: 'For the sake of optimality, it is essential to determine a value of σ that reflects optimal ratio of σ to r'. This statement requires additional clarification. In fact, the intention was to express the idea of finding a value of σ that reflects a balance between a situation where r is expanding too quickly and one where r is changing too slowly. To better understand this, we suggest referring to Figure III-13.

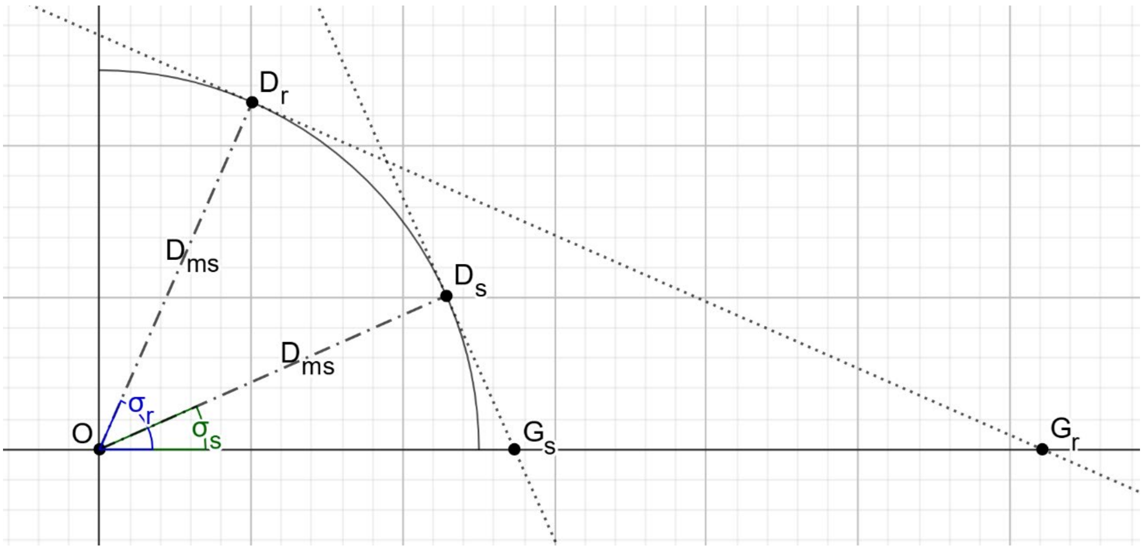

Figure III-13. Trade-off between angle σ and the radius of the safety area.

Figure III-13 contains point O, which represents the UDUM's location in the mass-point approach. D_{ms} is the minimum separation distance. D_r is the point of intersection between the radius of the minimum separation distance and the tangent line from point G_r. The angle σ_r represents the angle D_rOG_r. Point G_r illustrates a case where the CD maintains excessive separation from the UDUM.

Point G_s represents a situation where the CD intends to fly too close to the UDUM, taking an excessive risk of losing the minimum separation distance in the event of the UDUM's movement. D_s is the point of intersection between the radius of the minimum separation distance and the tangent line from point G_s. The angle σ_s represents the angle D_sOG_s.

Figure III-13 demonstrates two use cases where minor changes in angle σ cause rapid or slow changes in r (in this case, r = segment OG_r). To represent the scenario of rapid change, σ_r ($\tan \sigma > 1$) is used. In contrast, when minor changes in angle σ affect r more slowly (i.e., r = segment OG_s), σ_s ($\tan \sigma < 1$) is used.

Since it is necessary to find a trade-off between the rapid and slow change of $r(\sigma)$, we state in equation (12) that r' must be equal to r. In other words, $\tan \sigma = 1$ or $\sin \sigma = \cos \sigma$. This is only possible when $\sigma = \pi/4$, which leads to equation (13).

III.6. Conclusion

This article proposes a novel method for calculating the minimum separation distance and the safety radius for a UDUM whose type was identified by an image. The method includes global UAV database analysis, classification of the existing drones, determination of the fastest UAVs among types, and a mathematical model for estimating the safety radius and the minimum separation distance. To make the method available for the autonomous guidance system, we suggest creating a global UAV database that would allow us to predict the range of drag coefficient, lift coefficient (for UAVs with wings), mass and cross-sectional area based on UAV dimensions.

Relying on the method and the assumptions made, we solved the challenge of collision avoidance when a UDUM approaches a CD, posing a risk of infringement of the minimum separation distance. We also discussed the typical collision hazard patterns for which the method can be used in future research. To quantify the method, we suggest performing the appropriate experiments in a simulated environment.

The continuous development of UAV technologies underscores the importance of maintaining an updated global UAV database. Such an approach could assist in measuring minimum separation distances by using the latest advancements in widely available modern technologies. In this light, the study on UDUM type identification by image or video looks promising.

The findings show that the suggested method allows us to deal with UDUMs whose types were identified by the recognition system. The recommended separation distances measured in hundreds of metres appear realistic and feasible. The significant differences in the maximum speeds among the various types of UAVs reflect the optimisation of the problem.

In case the recognition system cannot identify the UDUM’s type, the UDUM can be classified as the fastest type to guarantee flight safety.

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IV. Gen4jectory 2.0 algorithm – 4-D trajectory planning with minimised flight time for multiple rotary-wing UAVs

This section is written based on the paper, 'Gen4jectory algorithm – 4-D trajectory planning with minimised flight time for multiple rotary-wing UAVs,' available by the following link: I. Panov, M. Boumediene, H. Midtiby, and K. Jensen, "Gen4jectory algorithm – 4-D trajectory planning with minimised flight time for multiple rotary-wing UAVs," presented at the 15th ANNUAL INTERNATIONAL MICRO AIR VEHICLE CONFERENCE AND COMPETITION, Bristol, United Kingdom: IMAV2024, Sep. 2024, pp. 242–252. The link on the publication: https://www.imavs.org/papers/2024/29.pdf

Although some parts of the paper are reproduced here, this section also incorporates substantial changes and additions beyond the original content.

Abstract

Section IV proposes version 2.0 of the innovative Gen4jectory algorithm, which enables the planning of multiple 4-D trajectories, taking into account the unique performance data of uncrewed rotary-wing air traffic. The algorithm calculates trajectories in such a way that Loss of Separation (LoS) incidents are avoided, provided that UAVs adhere to the flight plan. We describe the physical model of drone (Unmanned Aerial Vehicle, UAV) motion, map representation, pathfinding technique, 4-D trajectory planning, LoS checking, experimental setup, and simulation results. Finally, we discuss promising directions for further research.

IV.1. Introduction

The highest level of flight safety in Europe sets a top expectation on unmanned aviation integration in airspace [1]. Simultaneously, U-space and Urban Air Mobility stakeholders expect a high business efficiency of the uncrewed operations where autonomous systems will be able to substitute an expensive labour force. People have limited capabilities in manual planning and managing uncrewed air traffic in congested airspace. These limitations highlight the important need for an autonomous guidance system [2] which will be able to manage U-space and Urban Air Mobility traffic in a safe and efficient way.

However, what is the efficiency of the uncrewed operations? For business applications, the efficiency can be defined as on-time delivery rate, cost per mile, fuel efficiency, vehicle utilisation rate, etc. The metric choice depends on the operation requirements. For example, surveillance operations may require maximisation of endurance; consumer goods delivery and human transportation may require flight time minimization; operation in the night time may require noise limitation; heavy cargo delivery may require energy consumption minimization, etc. Practically speaking, it implies very different approaches to UAV 4-D trajectory planning. For instance, noise limitation could require higher altitudes of operation and avoidance of the noise-sensitive areas, flight time minimisation could require high tilt angles with a high level of thrust during UAV operation.

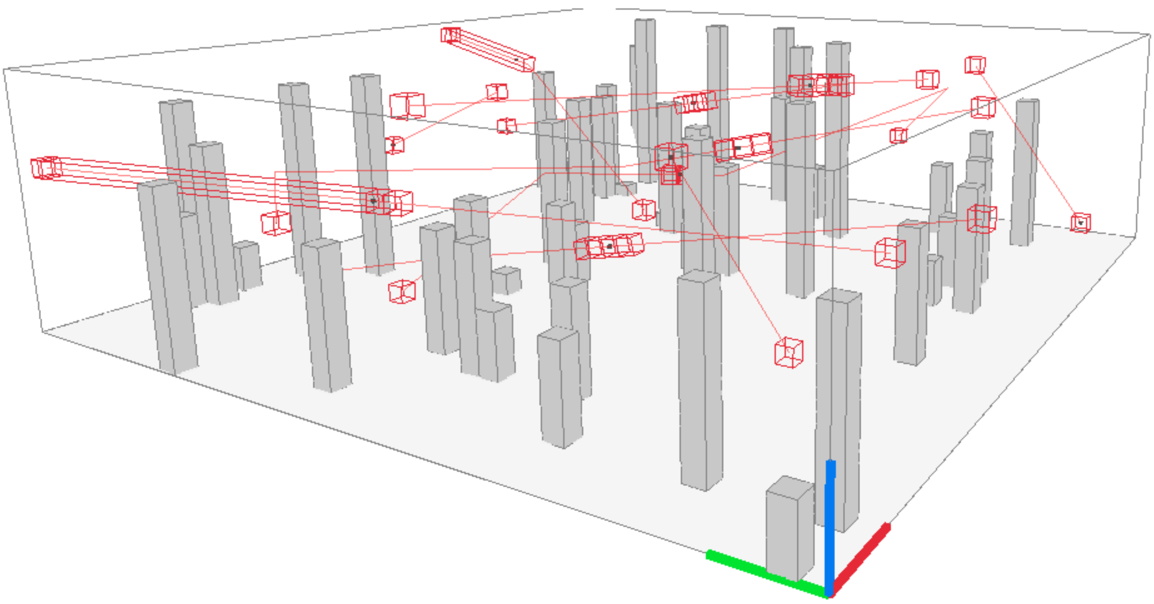

Figure IV-1. Visualization of the Gen4jectory 2.0 algorithm in an urban environment.

According to the forecast given by SESAR [3], delivery and transportation operations will cover about 45% of all UAV operations over Europe by 2050. We expect that delivery and transportation missions will require flight time minimisation in most cases. Bearing this in mind we decided to conduct a research project on uncrewed traffic 4-D trajectory planning focusing on the operations that require flight time minimisation.

4-D trajectory planning is a safety-critical aspect of autonomous UAV operations. It means that the proposed algorithm must exclude LoS for all airspace participants as a result of the operations planning.

The study begins with an abstract and introduction. After that, we discuss our literature review and present the problem formulation. In the section "Algorithm design and methodology", we discuss our physical model of a rotary-wing UAV, the choice of a map representation and pathfinding technique, and an approach for avoiding LoS. Then we discuss the simulation results, which is followed by a conclusion. A list of references finalizes the study.

The main contribution of the Section IV is a novel Gen4jectory 2.0 algorithm that allows planning 4-D trajectories for rotary-wing autonomous UAVs for autonomous uncrewed traffic management systems. (Figure IV-1 provides an example of 4-D trajectory planning in an urban environment (grey 3-D rectangles represent buildings, black points represent UAVs, and red 4-D rectangles indicate separation requirements).

IV.2. Literature review

4-D trajectory planning for air traffic is a classical approach in the field of commercial aviation [4], [5]. However, this approach cannot be completely applied to the Unmanned aircraft system Traffic Management (UTM) as UAVs do flight with no flight corridors and flight levels. Additionally, 4-D trajectory planning for UTM requires a more complex approach as UAVs operate on a very low level facing ground obstacles and other on-surface objects and subjects.

4-D trajectory planning for commercial aviation considers aircraft performance which allows to pre-calculate with sufficient accuracy where and when the aircraft will be. In Europe, this issue is addressed via the Base of Aircraft Data (BADA) database, which incorporates essential aircraft performance data on certified aircraft [6]. The certification process of a commercial airliner is an expensive, well documented process with an obligatory measuring of the aircraft performance data. There is no official demand for U-space air traffic participants to share aircraft performance data as a mandatory condition for operation approval. Therefore, 4-D trajectory planning for U-space is a complex task where alternative approaches must be identified or invented.

We expect that computational methods could help in obtaining quick and low-cost data extraction on aircraft performance based on the 3-D model of a UAV. However, we do not exclude machine learning algorithms that will be able to predict rough aircraft performance data based on a set of images of the UAV. We encourage the scientific community to contribute in this area to fill the gap.

While the issue of collecting aircraft performance data on UAVs remains unresolved, many researchers use assumptions or simply ignore aircraft dynamics constraints within their studies. For example, the authors of [7] proposed a solution for the multi-robot trajectory generation; however, the aerodynamic drag issue was not addressed. Similarly, the authors of [8] proposed the dynamic trajectory planning method missing an essential discussion on aircraft dynamics constraints. The authors of [9] invented a bio-inspired collision-free 4D trajectory generation method that incorporates a set of techniques to plan UAV trajectories like Tau-guidance, geometric, conflict detection, Particle Swarm Optimization, Conflict Detection, and Resolution. Again, the UAV dynamics model was not described in the paper. Similarly, the authors of the papers [10, 11, 12, 13] did not present a satisfactory physical model of the UAV to address 4-D trajectory planning.

In addition to the challenges already discussed for 4-D trajectory planning, path planning in 3-D space for multiple UAVs demands algorithms capable of handling environmental obstacles. A representative example is Theta$*$ [14] and its variants [15, 16]—extensions of the A$*$ algorithm [17]—which have proved effective in 2-D path planning [18] and have been adapted to 3-D environments [19]. Theta$*$ performs line-of-sight checks between the current node and its ancestors, enabling the planner to skip unnecessary waypoints and generate any-angle paths, thereby shortening routes and producing smoother trajectories [14].

Recent studies have explored the use of Theta$*$ and its variants for UAV path planning in 3-D [20, 21], highlighting its ability to generate near-optimal paths while maintaining computational efficiency. For instance, Theta$*$ has been applied in scenarios where UAVs must navigate urban environments with a high density of obstacles [22, 23]. This was done by considering the UAV's ability to move freely in three dimensions.

IV.3. Problem formulation

A precise UAV flight dynamics model is a resolved issue [24]. However, precision requires precise aircraft performance data and costly computation time. For example, mass distribution on the UAV body is essential to estimate the corresponding moments. Obtaining such data for a large number of UAV models is costly and inefficient. In this light, we decided to conduct a research project on a simplified flight dynamics model to allow 4-D trajectory planning for U-space needs. Additionally, we combined our flight dynamics model with the theta-star pathfinding algorithm [25], selected for its superior path quality. We implemented a LoS check that uses 4D collision detection to identify potential conflicts between the spaces reserved by two drones, accounting for both separation volumes in 3-D Euclidean space and their temporal overlap. To manage potential conflicts effectively, we also applied a priority-based resolution strategy.

In this paper, we do not address wind impact, as it is one of the multiple essential constraints in the UAV autonomous guidance [2]. Instead, we focus our study on the fusion of our physical model with the theta-star-based algorithm to test LoS-free flight in our simulation.

The problem of 4-D trajectory planning is a complex multi-factor task with various interconnected constraints [2]. We acknowledge the complexity, and the essentiality of splitting the 4-D trajectory planning problem into the sub-issues. Specifically in this paper, we raise the following research question:

- How to plan 4-D trajectories for the uncrewed air traffic in order to minimise flight time for each consecutive UAV?

In more technical terms, given that each UAV position and all obstacles are known, with no wind present, known air density, and available aircraft performance data, how can 4-D trajectories be planned for the rotary-wing UAVs with zero LoS events?

IV.4. Algorithm design and methodology

To address the research questions, we invented an experimental setup based on the Gen4jectory 2.0 algorithm [26] (Figure IV-2). The algorithm predefined:

- The 3-D workspace is a rectangular airspace whose length and width vary between 350 m and 128 000 m across the different test cases, while the height is fixed at 150 m above ground level. Each experiment therefore uses a map sized L × W × 150 m, where L (length) and W (width) lie in the range [350, 128 000] m, providing a scalable environment for evaluating the planners under progressively larger operating areas.
- We generated the lattice graph by discretising the rectangular airspace into a regular grid. In the horizontal plane, nodes are placed every L/10 and W/10 metres—that is, one-tenth of the current map length and width—while along the vertical axis nodes are spaced at fixed 25 m intervals. Each grid point becomes a vertex, and edges connect neighbouring vertices, forming the 3-D lattice used for path planning.
- The start and goal positions of the UAVs were randomly generated and sampled from a normal distribution within the map's bounds. This allowed us to capture a broad spectrum of potential conflict scenarios, enhancing the robustness of our testing and analysis.
- Separation volumes are modelled as four-dimensional directed rectangular space that extend between successive waypoints along each UAV's trajectory. Every 4-D rectangle keeps a fixed lateral and vertical cross-section of 10 × 10 m, while its longitudinal extent adapts to local traffic density. In high-traffic regions—points lying near the spatial intersection of the straight start–goal lines of any two drones—the 4-D rectangle length is restricted to 30 m, allowing tight control where conflicts are most likely. Outside these zones, where encounters are improbable, the length is enlarged by a factor of 100 to 3 000 m, preventing unnecessary calculations in sparsely used airspace. This traffic-adaptive sizing preserves safety in congested areas while maintaining efficiency across the wider environment. Whenever the prescribed longitudinal span (30 m in dense traffic or 3 000 m in sparse traffic) exceeds the actual distance between successive waypoints, the span is capped at that waypoint separation.

In the next stage, the simulation randomly generates departure and arrival waypoints for all UAVs involved. Also, it generates random values of aircraft performance for rotary-wing UAVs in the realistic range. Specifically, aircraft mass ranged from 2 kg to 500 kg, which covers a large variety of the U-space airspace participants including flying taxis. For each UAV, a drag coefficient is randomly selected from a representative range (0.6 to 1.2) and subsequently treated as constant for that particular UAV throughout its planned trajectory. This assumption is considered appropriate for the purposes of this study, as the flight time estimations are primarily based on segments flown at maximum speed under prevailing conditions. During such phases, the UAV maintains a relatively stable attitude and aerodynamic profile. Accordingly, the use of a representative, constant drag coefficient for these critical flight segments is regarded as adequate for trajectory planning and flight time minimisation, where level or near-level flight predominates. Nonetheless, empirical validation of the algorithm may reveal the need for more refined aerodynamic modelling in vertiport operations, where vertical flight is more prominent.

We chose the range of cross-sectional areas in the range from 0.5 to 4 metres. Additionally, we made cross-sectional areas linearly dependent on aircraft mass. The heavier the UAV, the greater its cross-sectional area. Similarly, maximum thrust depends on aircraft mass, ranging from 20% to 100% reserve over aircraft weight. The standard atmosphere is chosen as a typical baseline in aviation research. However, this variable can be adjusted to any value to reflect the real-life temperature and atmospheric pressure impact on flight dynamics.

Next, the algorithm sequentially calculates the alternative trajectory. This process continues until a safe near-optimal trajectory with minimised flight time is found. We state "near-optimal" because map representation with predefined waypoints corresponded with deviations from optimality. The greater resolution gives the more optimal solution. However, it also implies a greater time complexity as the Theta∗ algorithm requires calculating more potential options to navigate. The optimal balance should be found as a compromise based on operational needs. Similarly, the greater the number of UAVs flying nearby, the more complicated check of LoS is required.

In the next stage, a supplementary algorithm makes a simplified calculation of flight time required to fly from one waypoint to another based on UAV maximum level flight speed. However, to make the maximum speed known, we do pre-calculations based on aircraft performance data and current air density. We cannot rely on the maximum speed given in the flight manual since UAVs can carry extra cargo which affects aerodynamic drag, the air temperature can be far from the standard atmosphere, etc.

In the fifth stage, the simulation runs multiple flight experiments while checking: LoS event, flight time for reaching the destination point based on our main physical model. Finally, the data is recorded and stored in two ".csv" tables which we use for analysis (see folder "stats" in [26]).

IV.4.1. Physical model

IV.4.1.1 Notation

a - acceleration, m/s^2.

C_D - drag coefficient.

Chld - child waypoint in NEU coordinate system.

dp - dot product of ***GP_Par***.

d_{plnd} - distance planned.

g - acceleration due to gravity, m/s^2.

GP - grandparent waypoint in North East Up (NEU) coordinate system.

gp - coordinate of the grandparent waypoint in NEU.

m - UAV mass, kg.

magGPpar - magnitude of ***GP_Par***.

magPar_Chld - magnitude of ***Par_Chld***.

M_{end} - a point of the manoeuvre end.

M_{start} - a point of the manoeuvre start.

Par - parent waypoint in NEU coordinate system.

prnt - coordinate of the parent waypoint in NEU.

S - cross sectional area.

t - flight time, s.

t_{new} - updated time, s.

v - final calculated velocity for a direct section of the flight path, m/s.

v_0 - initial velocity, m/s.

Δ - difference between a vertical component of thrust and UAV weight

γ - flight path angle, degrees.

$\gamma_{\theta lim}$ - flight path angle for flight with angle θ_{lim} and max thrust, degrees.

ε - angle of the flight path change.

θ - UAV tilt angle, degrees.

θ_{lim} - UAV tilt limit, degrees.

θ_{mh} - UAV tilt for flight in horizon with max thrust, degrees.

ρ - air density, kg/m^3.

$\boldsymbol{F_{mh}}$ - vector of maximum force in horizontal flight without drag, N.

$\boldsymbol{F_{net}}$ - vector of maximum net force, N.

$\boldsymbol{F_{netmh}}$ - vector of maximum net force in horizontal flight, N.

$\boldsymbol{F_t}$ - vector of maximum thrust, N.

$\boldsymbol{Ft_{mh}}$ - vector of thrust in horizontal flight, N.

$\boldsymbol{Ft_{min}}$ - vector of minimum thrust for vertical descent, N.

$\boldsymbol{Ft_{\theta lim}}$ - vector of thrust with θ_{lim} angle, N.

$\mathbf{F_{tr}}$ - net force without drag impact, N.

$\mathbf{Ftr_{hc1}}$ - horizontal component of the net force without drag impact before manoeuvre, N.

$\mathbf{Ftr_{hc2}}$ - horizontal component of the net force without drag impact during manoeuvre, N.

$\mathbf{F_x}$ - horizontal component of thrust vector, N.

$\mathbf{F_z}$ - vertical component of a corresponded vector, N.

GP_Par - vector from waypoint *GP* to waypoint *Par*.

Par_Chld - vector from waypoint *Par* to waypoint *Chld*.

Subscript N/E/U stands for North/East/Up coordinate accordingly. We name some values with "$_{red}$" in case the reduced thrust is discussed.

All symbols representing force vectors in this paper we denote by bold letters. The corresponding magnitudes, when referenced, we denote by italic letters without bold formatting.

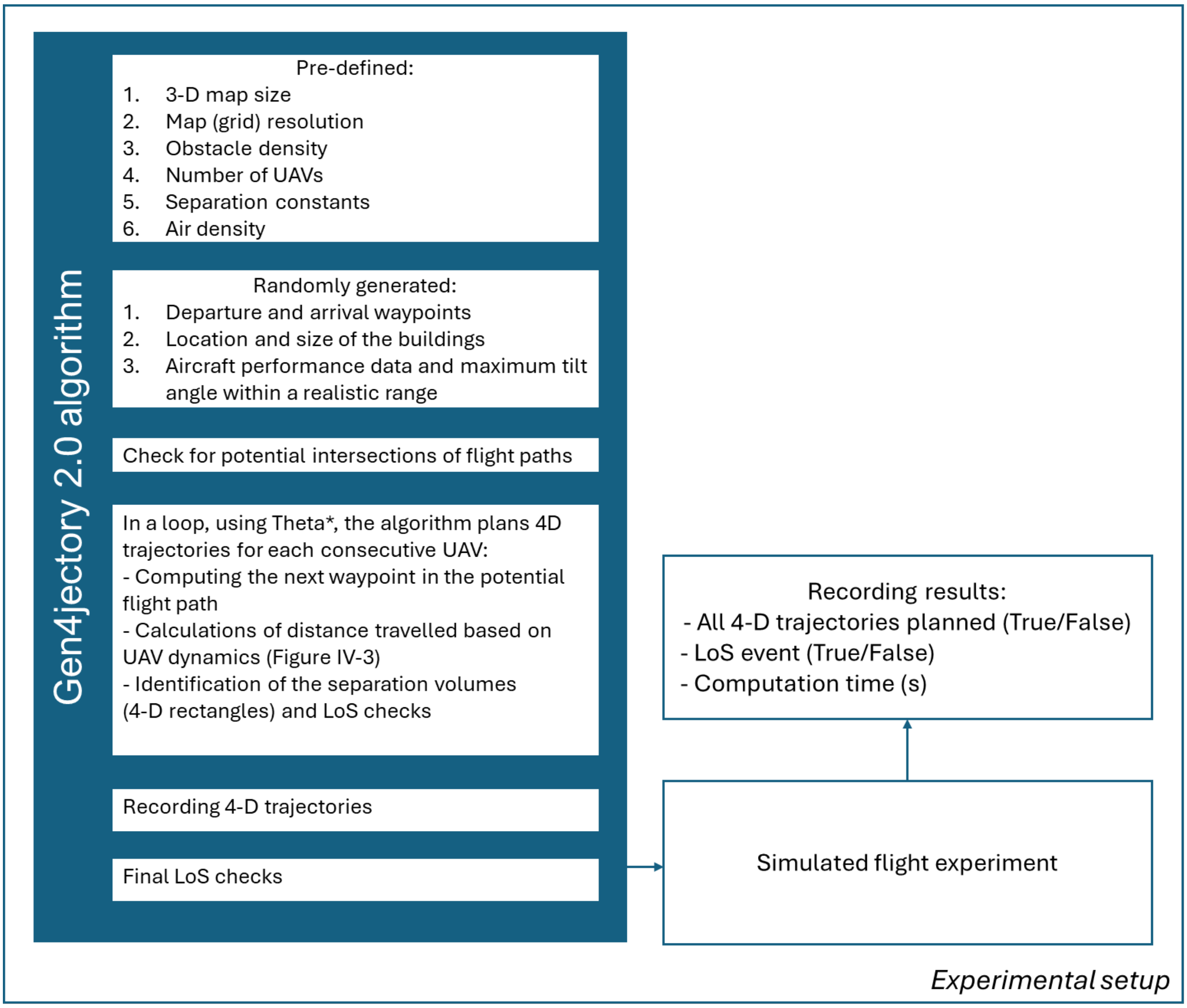

Figure IV-2. Process Diagram of the experimental setup.

IV.4.1.2 Time-dependent UAV motion modelling

In the paper we consider the next conditions:

- NEU Body-fixed coordinate system.

- NEU origin at sea level at some point.

- Mass-point model of UAV.

- Earth curvature is ignored.

- Wind is zero.

To plan a 4-D trajectory safely, it is essential to reserve a certain volume of airspace at a certain time to avoid the risk of LoS. Vertical, horizontal, and longitudinal separation create a 4-D rectangle, whose sides are normally defined by national regulation. In our implementation this 4-D rectangle is treated as an oriented bounding box (OBB) [27] that is slightly inflated by a fixed safety margin to prevent false negatives in the subsequent collision check. The planner calculates each UAV's position over time—accounting for flight-time, initial and final velocities, and inertial limits—propagates the box accordingly, and then performs an exact OBB-vs-OBB test using the Separating Axis Theorem (SAT) [28]. A separating axis confirms that the reserved volumes never overlap, guaranteeing that no loss of separation can occur. The complete routine is available in our code [26].

Following common practice in aviation research, we assume that the flight takes place under standard atmospheric conditions and, additionally, in the absence of wind. To calculate the flight time required to cover a distance between two waypoints, the physical model has three layers: inputs, calculations, and outputs. We assume that inputs are all given properties of the drone. Among them: mass (m), cross-sectional area (S) and drag coefficient (C_D), the maximum thrust (F_t), the maximal tilt angle of the UAV (θ_{lim}), initial velocity (v_0), air density (ρ), minimum percent of thrust for vertical descending, and delta time for Euler method calculations. The coordinates of the waypoints in the NEU reference system are also known.

Based on the inputs provided, the algorithm transforms Parent (departure) and Child (arrival) waypoints to a vertical plane where the Parent waypoint is placed in the origin. We switch to a body-fixed reference system where the z-axis is pointed up and the x-axis is directed to the Child (next) waypoint. In this case, it is essential to find the coordinates of the Parent and Child waypoint for each straight segment of the trajectory. Once the UAV has reached the area of the arrival point, the algorithm switches through the loop to the next segment, and the Child point is now classified as the Parent point. It happens until the final destination waypoint has been reached.

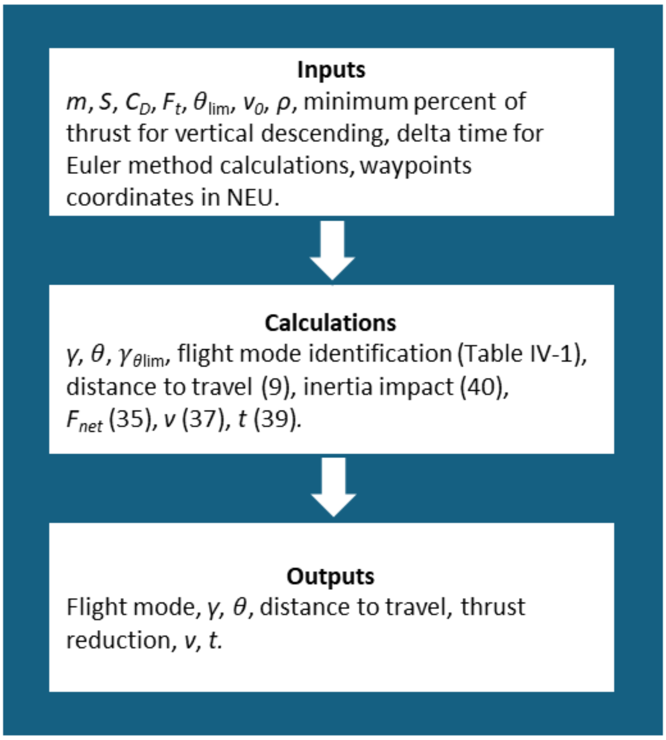

Figure IV-3. The high-level scheme of physical model calculations.

There are a few steps to perform a transformation to the new coordinate system. Firstly, it is essential to select the departure and arrival waypoints that correspond to the segment required. Then we define two vectors corresponding to the departure and arrival waypoints.

$$\mathbf{W}_{chld} = (N_{chld}, E_{chld}, U_{chld}) \tag{1}$$

$$\mathbf{W}_{par} = (N_{par}, E_{par}, U_{par}) \tag{2}$$

A relative position vector can be found:

$$\mathbf{W}'_{chld} = \mathbf{W}_{par} - \mathbf{W}_{chld} \tag{3}$$

We ignore the vertical component and normalise the horizontal component of $\mathbf{W}'_{chld}$, introducing new variables h_s, x_{axis}, Z_{axis}.

$$h_s = \begin{pmatrix} W'_{chldN} \\ W'_{chldE} \\ 0 \end{pmatrix} \tag{4}$$

$$x_{axis} = \frac{h_s}{||h_s||} \tag{5}$$

$$Z_{axis} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \tag{6}$$

Arrival waypoint *x*-coordinate and *z*-coordinate in body fixed coordinate system:

$$w_x = (w_{par} - w_{chld}) \cdot x_{axis} \tag{7}$$

$$w_z = (w_{par} - w_{chld}) \cdot z_{axis} \tag{8}$$

Now the arrival point is transformed to the origin, and accordingly, the destination point has *x* and *z* coordinates.

The basic aerodynamic forces and maximum tilt angle θ have a significant impact on finding a flight mode that allows minimising flight time. With a high thrust-to-weight ratio, the aircraft will be ascending with angle $\gamma_{\theta lim}$ if it has the maximum tilt angle with the maximum thrust.

However, if we significantly increase the weight of UAV, it could lead to a low thrust-to-weight ratio. In this case, the aircraft will be descending with angle $\gamma_{\theta lim}$ at the maximum tilt angle with the maximum thrust. We mark flight modes for the high thrust-to-weight ratio with the capital letter ´A´ and for the low thrust-to-weight ratio with the capital letter ´B´.

Until the UAV has reached $\gamma_{\theta lim}$ it shall fly at maximum thrust to minimise flight time - modes IA, IB, and IIB (Figure IV-4 and Figure IV-5). Exceptions are possible for the aggressive style flight with multiple changes of flight directions. For U-space traffic, we expect mainly direct trajectories with limited manoeuvring.

Once $\gamma_{\theta lim}$ is reached, the descent with γ in range $(-\pi/2, \gamma_{\theta lim})$ is only possible if thrust is decreased - flight modes IIA, IIIA, and IIIB (Figure IV-4 and Figure IV-5).

Table IV-1 identifies the significant differences between the flight modes. For example, vertical ascend and descent imply zero tilt angle. However, the maximum thrust is required for the fastest ascent. In order to maintain aircraft orientation, the minimum thrust can be applied for the vertical descending. Flight modes IA, IB, and IIB imply maximum thrust; however, UAV tilt angle requires calculations. Flight modes IIA, IIIA, and IIIB operate at the maximum tilt angle; however, the level of thrust in Newtons must be calculated.

Table IV-1. Flight modes.

Flight mode	Angle γ	Thrust	Angle θ
Vertical ascent	$\pi/2$	Max	0
IA	$[\gamma_{\theta lim}, \pi/2)$	Max	To find
IB	$[0, \pi/2)$	Max	To find
IIB	$[\gamma_{\theta lim}, 0)$	Max	To find
IIA	$[0, \gamma_{\theta lim})$	To find	θ_{lim}
IIIA	$(-\pi/2, 0)$	To find	θ_{lim}
IIIB	$(-\pi/2, \gamma_{\theta lim})$	To find	θ_{lim}
Vertical descent	$-\pi/2$	As input	0

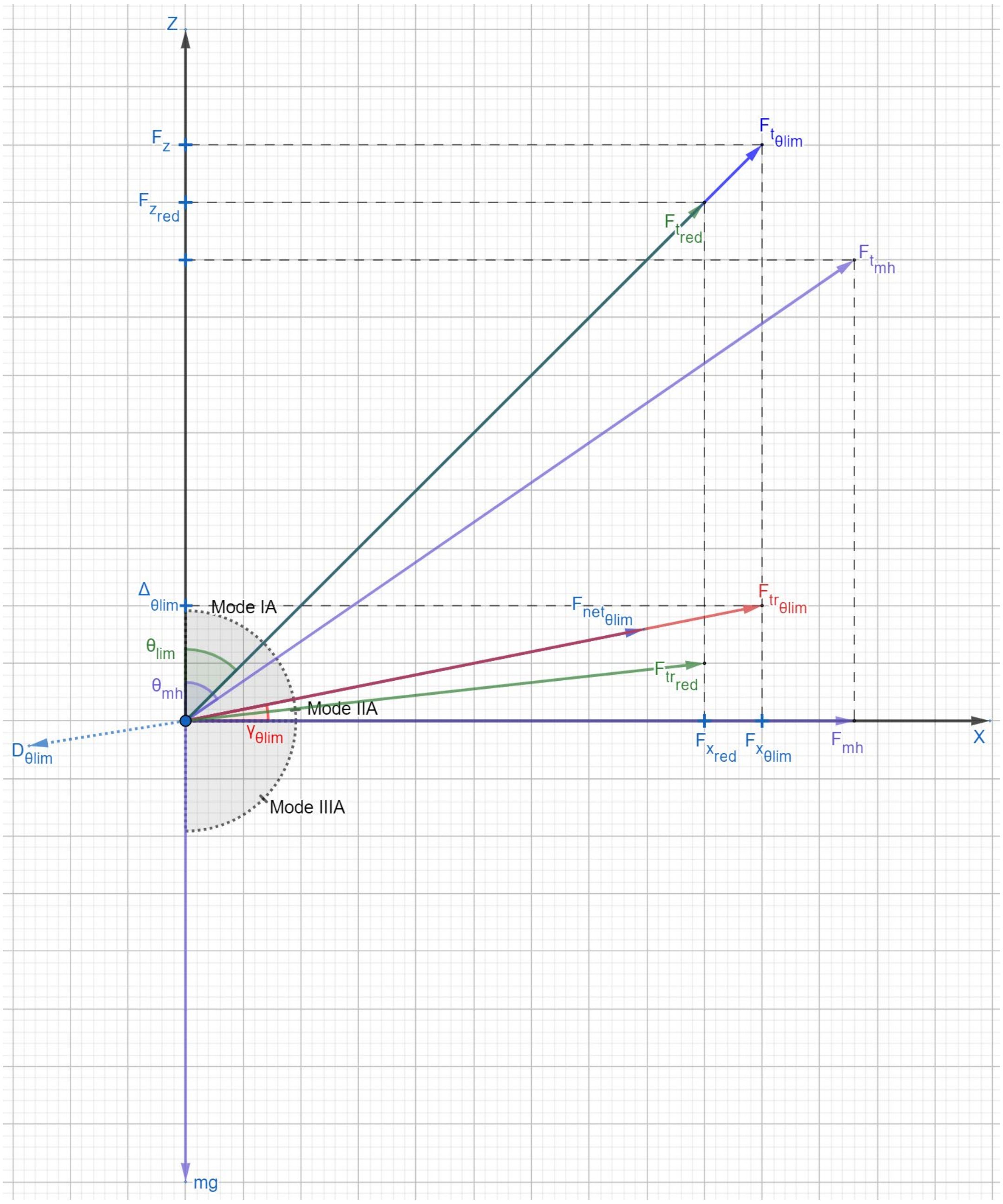

Figure IV-4. Flight modes A. For rotary-wing UAV with a high thrust-to-weight ratio (γθlim ≥ 0).

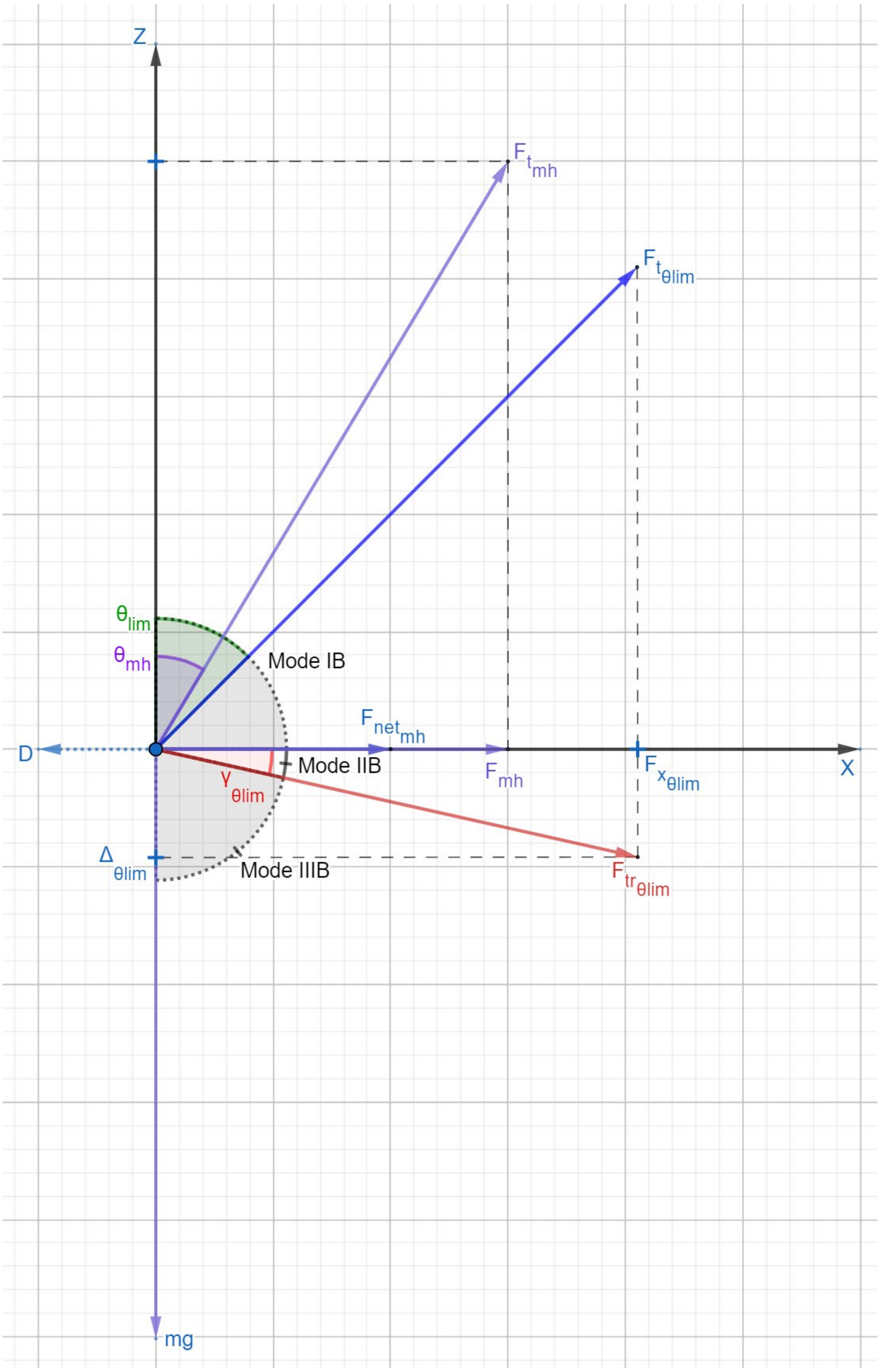

Figure IV-5. Flight modes B. For rotary-wing UAV with a low thrust-to-weight ratio (γθlim < 0).

Travel distance is essential to find the flight time required and the velocity at the end of the segment.

$$d_{plnd} = \sqrt{x^2 + z^2} \tag{9}$$

We propose a new variable *b* to make calculations look simple.

$$b = \frac{1}{2} \cdot \rho \cdot S \cdot C_D \cdot V^2 \tag{10}$$

As waypoint coordinates are given, it is possible to find flight path angle γ:

If $x > 0$, then $\gamma = \arctan(z/x)$.

If $x = 0$ and $z > 0$, then $\gamma = \pi/2$.

If $x = 0$ and $z < 0$, then $\gamma = -\pi/2$.

If $x = 0$ and $z = 0$, then the waypoint is at the origin.

No need to change UAV position. Now γ is known, thus θ can be found which is required for the flight modes IA, IB, and IIB according to Table IV-1. As Δ is a vertical component of $\boldsymbol{F_{tr}}$ and $\boldsymbol{F_x}$ is a horizontal component of $\boldsymbol{F_{tr}}$, then:

$$F_{tr} = \sqrt{\Delta^2 + F_x^2} \tag{11}$$

$$\sin\gamma = \frac{\Delta}{F_{tr}} \tag{12}$$

$$\Delta = \sin\gamma \cdot \sqrt{\Delta^2 + F_x^2} \tag{13}$$

The magnitude of the horizontal force is found.

$$F_x = \sqrt{F_t^2 - (\Delta + \mathrm{m} \cdot \mathrm{g})^2} \tag{14}$$

$$\Delta = \sin\gamma \cdot \sqrt{\Delta^2 + F_t^2 - (\Delta + \mathrm{m} \cdot \mathrm{g})^2} \tag{15}$$

$$\Delta^2 - sin^2\gamma \cdot \left(\Delta^2 + F_t^2 - \Delta^2 - 2 \cdot \Delta \cdot m \cdot g - (m \cdot g)^2\right) = 0 \tag{16}$$

$$\Delta^2 + 2 \cdot sin^2\gamma \cdot m \cdot g \cdot \Delta - sin^2\gamma \cdot F_t^2 + sin^2\gamma \cdot (m \cdot g)^2 = 0 \tag{17}$$

To make the equation look simple, we enter p and c.

$$p = 2 \cdot sin^2\gamma \cdot m \cdot g \tag{18}$$

$$c = -sin^2\gamma \cdot F_t^2 + sin^2\gamma \cdot (m \cdot g)^2 \tag{19}$$

$$\Delta^2 + p \cdot \Delta + \mathrm{c} = 0 \tag{20}$$

$$D = p^2 - 4c \tag{21}$$

$$\Delta_{1,2} = \frac{-p \pm \sqrt{p^2 - 4c}}{2} \tag{22}$$

In the case of flight mode IA and IB $\Delta = \Delta_1$. For IIB $\Delta = \Delta_2$.

$$\cos\theta = \frac{\Delta + m \cdot g}{F_t} \tag{23}$$

$$\theta = \arccos\left(\frac{\Delta + m \cdot g}{F_t}\right) \tag{24}$$

As θ is calculated, it is possible to find the horizontal component of the thrust vector for the modes IA, IB, and IIB:

$$F_x = \sin\theta \cdot F_t \quad (25)$$

And F_{tr} can be found with an equation (11).

For the modes IIA, IIIA, and IIIB, the UAV flies at θ_{lim} and the reduced thrust shall be calculated. In this case, Δ is different.

$$\sin(\theta_{lim}) = \frac{F_{x_{red}}}{F_{t_{red}}} \quad (26)$$

$$\tan(\theta_{lim}) = \frac{F_{x_{red}}}{m\cdot g + \Delta_{red}} \quad (27)$$

$$F_{x_{red}} = \tan(\theta_{lim}) \cdot (m \cdot g + \Delta_{red}) \quad (28)$$

$$\tan\gamma = \frac{\Delta_{red}}{F_{x_{red}}} \quad (29)$$

$$F_{x_{red}} = \frac{\Delta_{red}}{\tan\gamma} \quad (30)$$

$$\tan(\theta_{lim}) \cdot (m \cdot g + \Delta_{red}) = \frac{\Delta_{red}}{\tan\gamma} \quad (31)$$

$$\Delta_{red} - \tan\gamma \cdot \tan(\theta_{lim}) \cdot m \cdot g - \tan\gamma \cdot \tan(\theta_{lim}) \cdot \Delta_{red} = 0 \quad (32)$$

$$\Delta_{red} = \frac{\tan\gamma \cdot \tan(\theta_{lim}) \cdot m \cdot g}{1 - \tan\gamma \cdot \tan(\theta_{lim})} \quad (33)$$

$F_{x_{red}}$ is known, see equation (28).

$$F_{tr_{red}} = \sqrt{\Delta_{red}^2 + F_{x_{red}}^2} \quad (34)$$

Table IV-2 summarises the similarities and differences in the calculations in finding the vector of net force without drag impact. For example, vertical ascend and descent imply known thrust. Minimum thrust is essential for vertical descent. Flight modes IA, IB, and IIB have commonality in finding F_x and F_{tr}, but IIB differs in finding Δ and θ. Flight modes IIA, IIIA, and IIIB have the same line of calculations.

Table IV-2. Comparison of flight modes.

Flight mode	Similarities	Differences
Vertical ascend	F_t is given	
IA	(11), (25)	$\Delta = \Delta_1$, $\theta = \theta_1$
IB		
IIB		$\Delta = \Delta_S$, $\theta = \theta_2$
IIA	(28), (33), (34)	
IIIA		
IIIB		
Vertical descend	Given F_t and F_{t_red}	

F_{tr} has been calculated for each mode, and the net force can be found via this equation:

$$F_{net} = F_{tr} - \frac{1}{2} \cdot \rho \cdot S \cdot C_D \cdot V^2 \quad (35)$$

The acceleration can be found through Newton's law.

$$a = \frac{F_{net}}{m} \tag{36}$$

Finding flight time between waypoints and final velocity, position update, and time update can be calculated via Euler's method.

$$v_{t+\Delta t} = v_t + a_t \cdot \Delta t \tag{37}$$

$$x_{t+\Delta t} = x_t + v_t \cdot \Delta t \tag{38}$$

$$t_{new} = t + \Delta t \tag{39}$$

Now, the travelling time between two waypoints can be calculated.

The calculations we did so far considered only two waypoints - Parent and Child. That is not an issue for the first direct segment of the 4-D trajectory because we assume that the initial velocity is known, and it is zero (the UAV takes off from a vertiport). However, in case of changing flight path direction, the inertia gets the higher impact the greater the angle of manoeuvre. Since we intend to plan a 4-D trajectory based on limited information about the UAV, a simplified model of inertia is required. In this light, we have to consider three waypoints - Grandparent (*GP*), Parent (*Par*), and Child (*Chld*). If we put a plane on the three waypoints, then it is possible to draw the manoeuvre in 2-D space which is simple for understanding. One of the cases is a horizontal manoeuvre in the vicinity of the Parent waypoint (Figure IV-6). Since rotary-wing UAVs have a small turning radius in comparison to separation requirements, it is possible to neglect the more precise calculations of the 4-D trajectory and accept the corresponding deviations.

Figure IV-6 gives an example of a 90-degree manoeuvre in a plane based on the initial three waypoints. The model implies minor deviations due to simplification: The UAV travels with a cutting angle and does not reach the Parent point precisely. The strong side of this approach is the simplicity of addressing inertia with having limited data on the rotary-wing UAV.

To simplify the calculation, we assume that a UAV approaching the Parent's waypoint vicinity can turn on the angle ε in advance (Figure IV-6) - in the point M_{start}. Due to inertia, the UAV will continue moving in its current state of motion, but aerodynamic drag will gradually decelerate it, potentially causing the UAV to move towards the Parent-Child segment. It is not necessary to find the precise position of M_{start}; this point is essential just for understanding how the issue of inertia can be addressed in a simplified way. However, angle ε is essential to calculate as it has a high impact on the initial velocity for the Parent-Child segment. For example, for very small ε, the final velocity for the Grandparent-Parent segment will be almost equal to the initial velocity of the Parent-Child. For $\varepsilon = \pi$, the initial velocity of the Parent-Child segment will be equal to the negative meaning of the final velocity for the Grandparent-Parent segment.

Since v is the final calculated velocity for a direct section of the flight path, and v_0 is the initial velocity, the next equation can be used as a simplification of the manoeuvre for any angle ε.

$$v_0 = \cos\varepsilon \cdot v \tag{40}$$

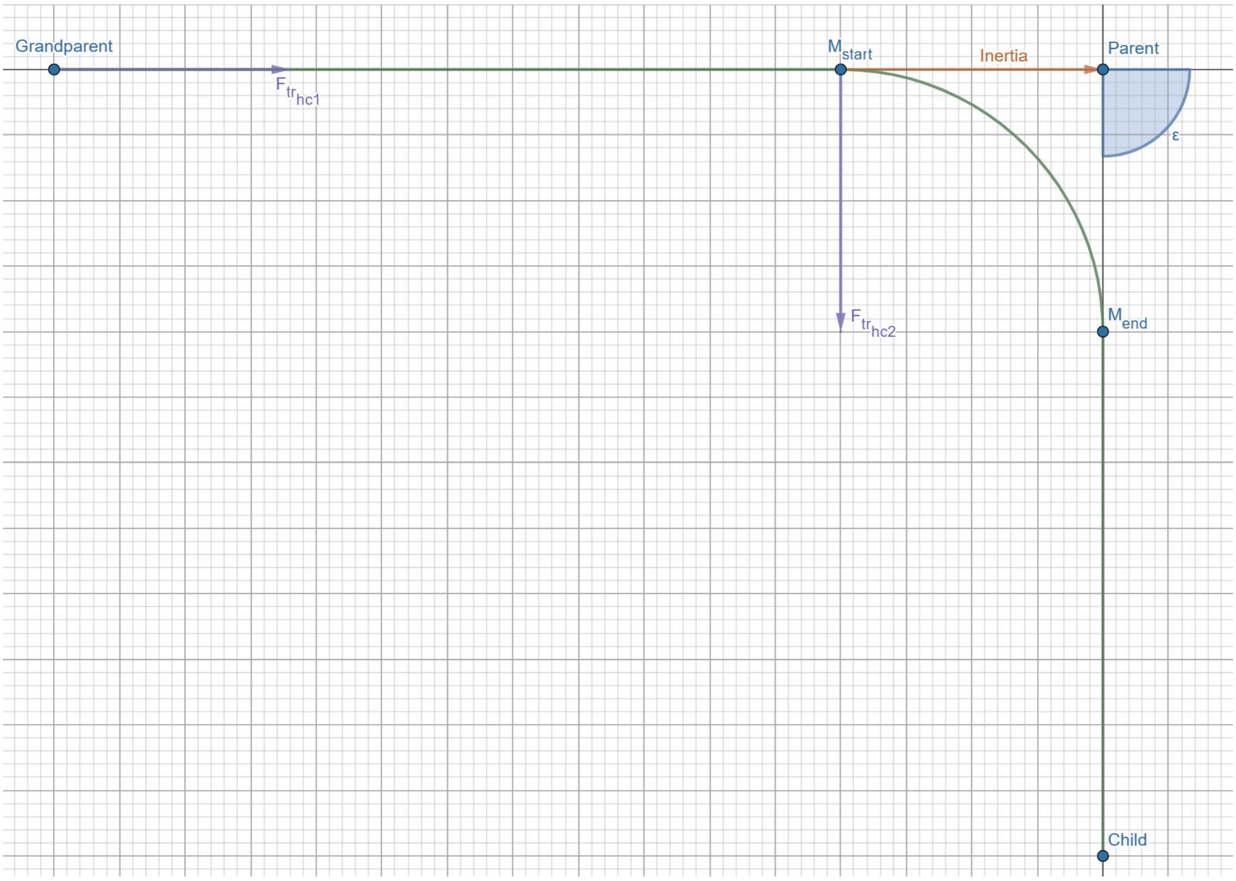

Figure IV-6. Manoeuvre at 90 degrees on the constant altitude. View from above.

To find the angle ε, some calculations are required. The coordinates of three waypoints in NEU are known.

$$GP = [gp_N, gp_E, gp_U] \tag{41}$$

$$Par = [prnt_N, prnt_E, prnt_U] \tag{42}$$

$$Chld = [chld_N, chld_E, chld_U] \tag{43}$$

To compute vectors from point:

$$\boldsymbol{GP\_Par} = [prnt_N - gp_N, prnt_E - gp_E, prnt_U - gp_U] \tag{44}$$

$$\boldsymbol{Par\_Chld} = [chld_N - prnt_N, chld_E - prnt_E, chld_U - prnt_U] \tag{45}$$

To find dot product:

$$dp = GP\_Par_N \cdot Par\_Chld_N + GP\_Par_E \cdot Par\_Chld_E + GP\_Par_U \cdot Par\_Chld_U \tag{46}$$

To find magnitudes:

$$mag_{GP\_Par} = \sqrt{GP\_Par_N^2 + GP\_Par_E^2 + GP\_Par_U^2} \tag{47}$$

$$mag_{Par\_Chld} = \sqrt{Par\_Chld_N^2 + Par\_Chld_E^2 + Par\_Chld_U^2} \tag{48}$$

To find angle ε:

$$\cos \varepsilon = \frac{dp}{mag_{GP\_Par} \cdot mag_{Par\_Chld}} \tag{49}$$

$$\varepsilon = \arccos(\cos \varepsilon) \tag{50}$$

IV.4.2. Map representation

The 3-D workspace is a bounded rectangular airspace whose length L and width W vary between 350 m and 128000 m across the different test cases, while the height is fixed at 150 m. To manage pathfinding in this scalable environment, we construct a graph.

- Horizontal discretisation. Nodes are placed every L/10 m along the x-axis and every W/10 m along the y-axis, giving a resolution that automatically adapts to the current map size.
- Vertical discretisation. Along the z-axis nodes are spaced at a constant 25 m interval, independent of L and W.

Each grid point becomes a vertex, and edges connect neighbouring vertices to form the 3-D lattice.

Start and goal positions are sampled from a normal distribution over the continuous map and then inserted into the graph as additional vertices; each is connected to its nearest lattice neighbours to ensure seamless integration. This combination of an adaptive grid and probabilistically chosen endpoints yields a wide variety of flight paths and conflict scenarios, providing a robust basis for evaluating our 4-D trajectory-planning and collision-avoidance algorithms. We add randomly placed cuboid buildings, each with random heights between 5 m and 150 m. Obstacle density is defined as the total volume of obstacles (cumulative building volume) divided by the total volume of airspace. In our experiments, this ratio is fixed at 1.75%, while a second test set uses 0% (no buildings).

IV.4.3. Pathfinding technique

For efficient pathfinding in the 3D environment, we employ the Theta∗ algorithm—an any-angle extension of A∗ adapted to three-dimensional grids. In classic A∗, a node may connect only to its immediate lattice neighbours, so the resulting route 'stair-steps' along grid edges. Theta∗ lifts this restriction by performing a line-of-sight test between vertices: if the straight segment from the current node to an earlier ancestor is unobstructed, the two are linked directly. This operation—commonly referred to as cutting a corner—skips intermediate waypoints and removes right-angle turns, producing a route that more closely follows the true Euclidean shortest path.

Within our study, an efficient path is one that minimises total distance while remaining feasible for the vehicle. A shorter distance reduces flight time and energy consumption, and fewer turns yield smoother motion that respects limits on climb rate, turn radius, and acceleration.

To ensure feasibility, the planner couples Theta∗ with a lightweight flight dynamics model that enforces these kinematic bounds. The resulting trajectories are therefore near-optimal in length and directly executable by real UAVs when navigating around buildings, terrain, and other aircraft.

The algorithm realises the principle of first-come, first-served. This implies that the earlier a UAV requests a 4-D trajectory, the more optimal the resulting trajectory will be.

IV.4.4. LoS check

Each UAV reserves a separation volume represented as a 4-D rectangle aligned with the motion segment between two consecutive waypoints. The rectangle has a fixed 10x10 m cross-section, while its longitudinal side adapts to local traffic density: 30 m inside high-traffic corridors (i.e. near the spatial intersection of start–goal lines) and 3 000 m elsewhere, but it is capped at the actual waypoint-to-waypoint distance. This traffic-aware sizing keeps buffers tight where encounters are likely and avoids unnecessary conservatism in sparsely used airspace, all while honouring national separation minima.

During path generation, Theta∗ proposes straight edges between grid nodes, together with their traversal windows derived from the UAV's kinematic model. Before collision checking, each candidate 4-D rectangle is isotropically inflated by a small safety margin (0.6 m in our experiments) to account for numerical error. The planner then performs an exact OBB-vs-OBB intersection test, based on the Separating Axis Theorem, against every rectangle already reserved by previously planned vehicles. If a separating axis exists, the edge is accepted and the new rectangle is committed to the global reservation table; otherwise, the edge is discarded and Theta∗ continues its search. This procedure ensures that the resulting 4-D trajectories are mutually conflict-free, preventing any loss of separation (LoS).

IV.5. Simulation results

We conducted a simulation-based study across map side lengths ranging from 350 m to 128 000 m (height fixed at 150 m) and fleet sizes from 1 to 200 rotary-wing UAVs. For every map–fleet pairing, we created two obstacle-density conditions:

- An obstacle-free scenario (0 % density).
- An urban scenario in which cuboid buildings collectively occupy 1.75 % of the map's total volume (obstacle-dense scenario). The number and dimensions of individual buildings were drawn so that their combined volume matches the prescribed fraction.

The experiments were conducted on a desktop PC equipped with a 13th Gen Intel i9 16-core CPU and 32 GB of RAM, running Windows 11. All simulations were implemented in Python 3.12.5. The experimental data collection can be found in the folder "stats" in [26].

Number of agents and computation time. Obstacle-free scenarios

To analyse experimental data, it is essential to investigate how computation time depends on the number of drones (agents). In this light, we assume that:

$$T_{comp} = a_{int} \times N_{ag}{}^{p_{scale}} \tag{51}$$

Here, T_{comp} is mean computation time. N_{ag} is number of UAVs (agents), and p_{scale} is a line slope in power-law scaling analysis terms [29]. a_{int} - intercept of the straight-line fit.

We then take natural logarithms of both sides, which gives:

$$\ln T_{comp} = \ln a_{int} + p_{scale} \times \ln N_{ag} \tag{52}$$

Using experimental data [26] and a power-law scaling approach, we obtain Table IV-3. In this table, R^2 represents the coefficient of determination, which reflects a numerical summary of how well the power-law model is fitted. Since R^2 is very close to 1 (R > 0.96), it is possible to argue that almost all the variability in $\ln T_{comp}$ is captured by the straight-line fit. In other words, the power-law assumption previously made (51) is a very good descriptor. The exponent p_{scale} varies between approximately 1.7 and 1.9, which implies a near-quadratic relationship as described by (51). This statement is further supported by Figure IV-7. Influence of map resolution on computation time in obstacle-free scenarios. In this figure, the whiskers represent minimum and maximum values, which is a more practical approach for flight safety matters. Boxes on the figure represent the 25th percentile for the bottom and the 75th percentile for the top. With each successive doubling of the number of agents, the spread increases significantly—by more than a factor of two in absolute terms. Each time the number of agents doubles, the median grows by a near-quadratic factor. Simultaneously, the variability increases significantly in absolute terms.

The near-quadratic relationship is an important outcome of the analysis, revealing the scalability limitations of the algorithm as the number of drones increases.

Table IV-3. Power-law scaling for obstacle-free scenarios.

Map size, m³	Exponent p_{scale}	Coefficient of determination R^2
(350 x 350 x 150)	1.91	0.998
(8 000 x 8 000 x 150)	1.86	0.976
(16 000 x 16 000 x 150)	1.85	0.968
(32 000 x 32 000 x 150)	1.81	0.966
(64 000 x 64 000 x 150)	1.77	0.961
(128 000 x 128 000 x 150)	1.73	0.976

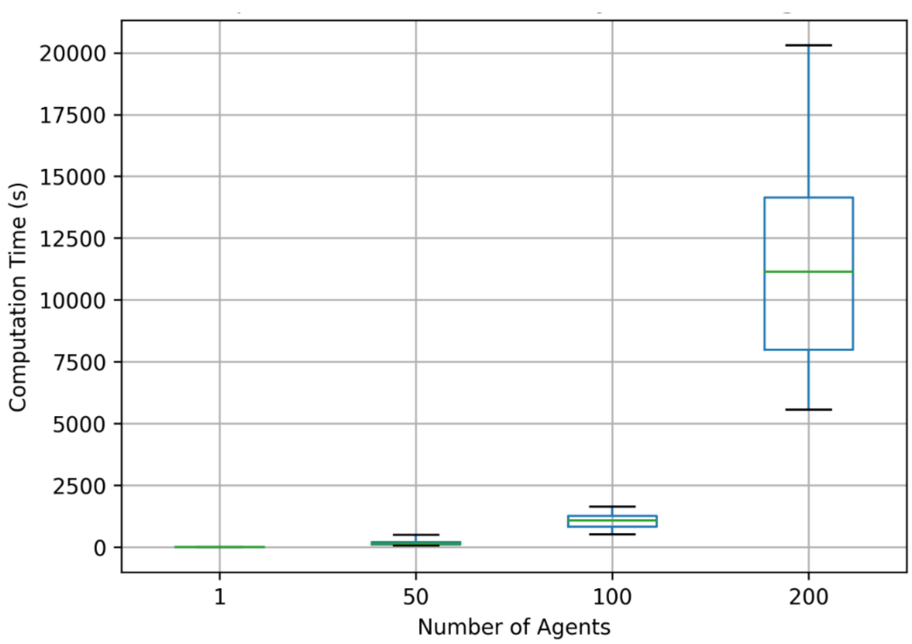

Figure IV-7. Influence of number of agents on computation time in obstacle-free scenarios.

For flight safety purposes, it is also beneficial to examine the following hypothesis: "The more agents on a map, the greater the uncertainty in the algorithm's computation time performance."

First, it is important to clarify how uncertainty is measured. For example, the absolute value of the standard deviation provides limited insight into the variability dynamics. Therefore, a relative measure is more appropriate. The coefficient of variation — defined as the ratio of the standard deviation of computation time to its mean — serves this purpose well.

Based on this reasoning, Table IV-4 was generated.

Table IV-4. Computation time statistics for different numbers of agents in obstacle-free scenarios.

Number of agents	Number of experiments	Mean computation time, s	Standard deviation, computation time, s	Coefficient of variation
1	30	0.43	0.30	0.70
50	30	185.82	120.07	0.65
100	30	1068.24	288.52	0.27
200	25	11568.63	4260.62	0.37

To analyse the behaviour of the coefficient of variation as the number of agents increases, all experiments were consolidated into a single table, thereby extending the number of trials for each group of agents (1, 50, etc.). Since identical map sizes were used within each group, we summarised the experimental data across various maps by comparing the total counts.

The only exception is that the simulation setup could not accommodate 200 drones on the smallest map, which prevented five experiments under those conditions. As a result, Table IV-4 contains 25 experiments for the 200-agent case, rather than the full set of 30.

The extension of the total number of experiments should decrease the level of noise and is likely to reveal the trend. The coefficient of variation provided in Table IV-4 shows the trend, although likely with some noise impact. Specifically, it has a high value at the beginning (0.70) and slowly decreases towards the end, by almost half (0.37). However, there is a small leap that slightly breaks the trend (0.27). It appears to be noise, which is reasonable to expect with 115 experiments in total. Nevertheless, analysis of the coefficient dynamics allows us to state that the more agents are on a map, the higher the uncertainty in algorithm computation time performance in absolute terms, but the lower the uncertainty in relative terms.

Number of agents and computation time. Obstacle-dense scenarios

This section provides statistical analysis of 113 experiments under high obstacle density (1.75%) conditions [26]. Similar to the no-obstacle cases, the simulation setup was not able to place 200 drones on the smallest map, which prevented five experiments. Also, the algorithm was not able to find trajectories for 200 agents on the largest map in one scenario. This occurred because the specific set of random positions led to exceptionally high traffic density, which prevented a collision-free assignment of separation volumes during planning. Another test failure occurred on the smallest map for 100 agents in one scenario, as the experimental setup was not able to allocate non-overlapping positions for the drones. The remaining 113 experiments, involving various numbers of drones in different-sized maps, were computed successfully (Table IV-5, Table IV-6).

In this subsubsection, the values of p_{scale}, the coefficient of determination R^2, standard deviation, coefficient of variation, and other data reflect the experimental results with a 1.75% obstacle density.

R^2 is very close to 1 ($R \geq 0.98$), which implies that almost all values of $\ln T_{comp}$ are located in the vicinity of the straight line (Table IV-5). This allows us to state that the power law (51) is a very good descriptor of the algorithm's performance. The exponent p_{scale} varies between 1.6 and 1.77, which implies a superlinear, sub-quadratic relationship for equation (51). In Figure IV-8, for the sake of flight safety, the whiskers reflect the minimum and maximum values of the data. Boxes on the figure represent the 25th percentile at the bottom and the 75th percentile at the top. The figure shows that deviations in data distribution can be high, and maximum values can be relatively far from the quartiles and the median.

Table IV-5. Power-law scaling at 1.75% obstacle density.

Map size, m^3	Exponent p_{scale}	Coefficient of determination R^2
(350 x 350 x 150)	1.60	0.995
(8 000 x 8 000 x 150)	1.77	0.985
(16 000 x 16 000 x 150)	1.72	0.982
(32 000 x 32 000 x 150)	1.68	0.980
(64 000 x 64 000 x 150)	1.63	0.980
(128 000 x 128 000 x 150)	1.65	0.985

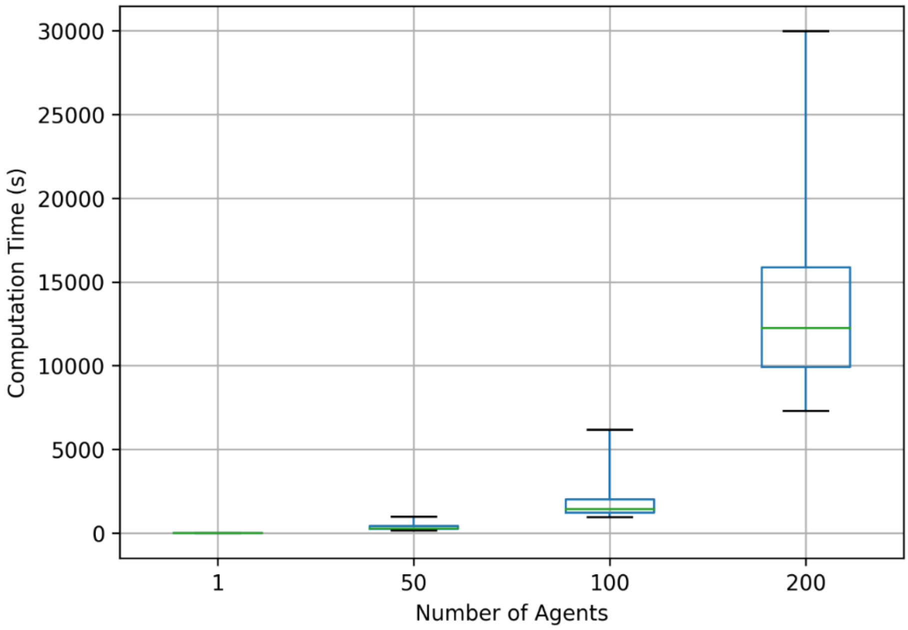

Figure IV-8. Influence of number of agents on computation time at 1.75% obstacle density.

Following the logic of the previous subsubsection, Table IV-6 was computed for 1.75% obstacle density. The standard deviation increases with the duplication of agents, which implies higher uncertainty in absolute terms. However, the coefficient of variation tends to decrease with each subsequent duplication of agent numbers, implying lower computation time uncertainty for larger numbers of agents in relative terms. An exception is the coefficient of variation for 100 agents, which is unexpectedly high and may reflect noise due to the limited number of experiments (113 in total).

Table IV-6. Computation time statistics for varying numbers of agents at 1.75% obstacle density.

Number of agents	Number of experiments	Mean computation time, s	Standard deviation, computation time, s	Coefficient of variation
1	30	1.25	2.04	1.63
50	30	384.13	219.93	0.57
100	29	2124.55	1621.55	0.76
200	24	13952.66	5918.62	0.42

It is difficult to determine what specific time planning limitations will be accepted as standard in the future. Real-world flight data may provide empirical evidence to help answer this question. However, the authors expect that acceptable computation time for 4-D trajectory planning will not exceed a few minutes for urgent missions and may extend to a few hours for operations planned well in advance.

Map resolution and computation time.

Map resolution may have a significant impact on computation time, as more potential waypoints require more calculations. To test this hypothesis, six types of map resolution were used in the experiments, following the logic explained in Section IV.4.

Figure IV-9 indicates that, in obstacle-free cases with up to 100 agents, map resolution has a minor impact within the range of 35 to 12 800 resolution points. Resolution points refer to the number of points used in the horizontal dimensions (North and East). For example, on a 350 x 350 x 150 map, we used 35 x 35 x 7 main waypoints; on an 8 000 x 8 000 x 150 map, 800 x 800 x 7 main waypoints were used (see Section IV.4).

The blue, orange, and green lines show only slight changes with each duplication of map resolution. However, the red line, which represents 200 agents, shows a smooth and consistent increase. Notably, duplicating the number of map-resolution waypoints on the red line leads to an almost linear rise in computation time.

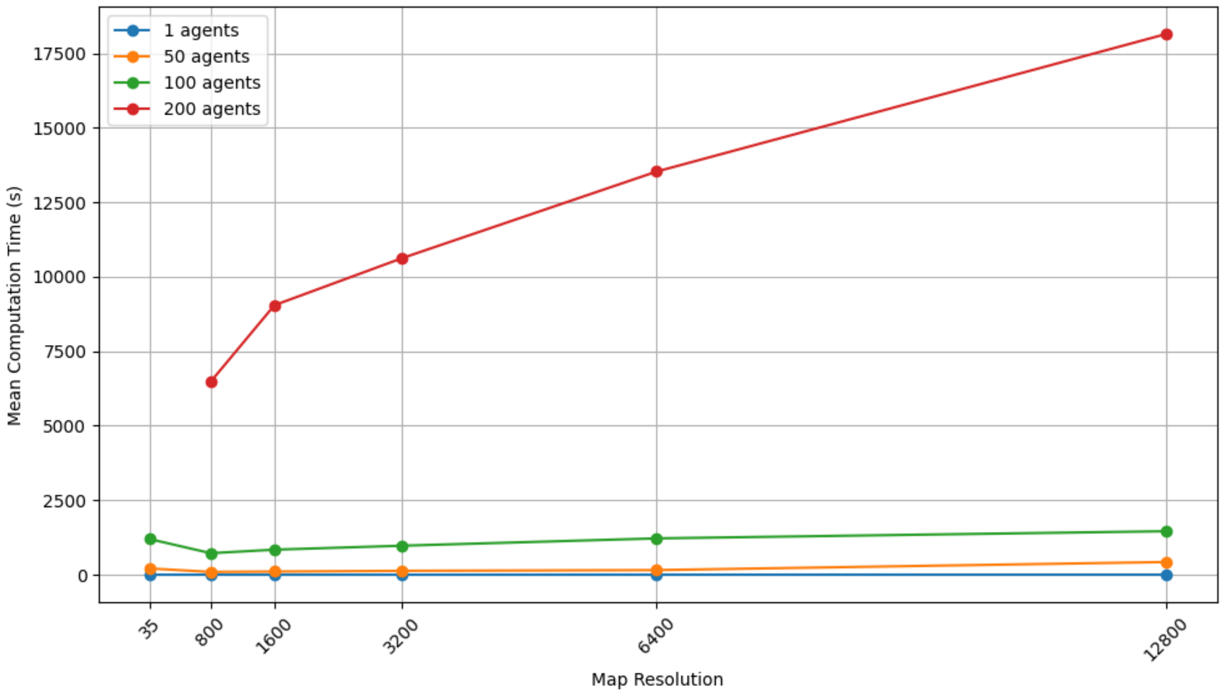

Figure IV-9. Influence of map resolution on computation time in obstacle-free scenarios.

With high obstacle density (1.75%), the situation is roughly similar (Figure IV-10). The highest rise is observed in the case of 100 agents, when computation time becomes roughly twice as long if the map resolution is doubled from 6 400 to 12 800 points.

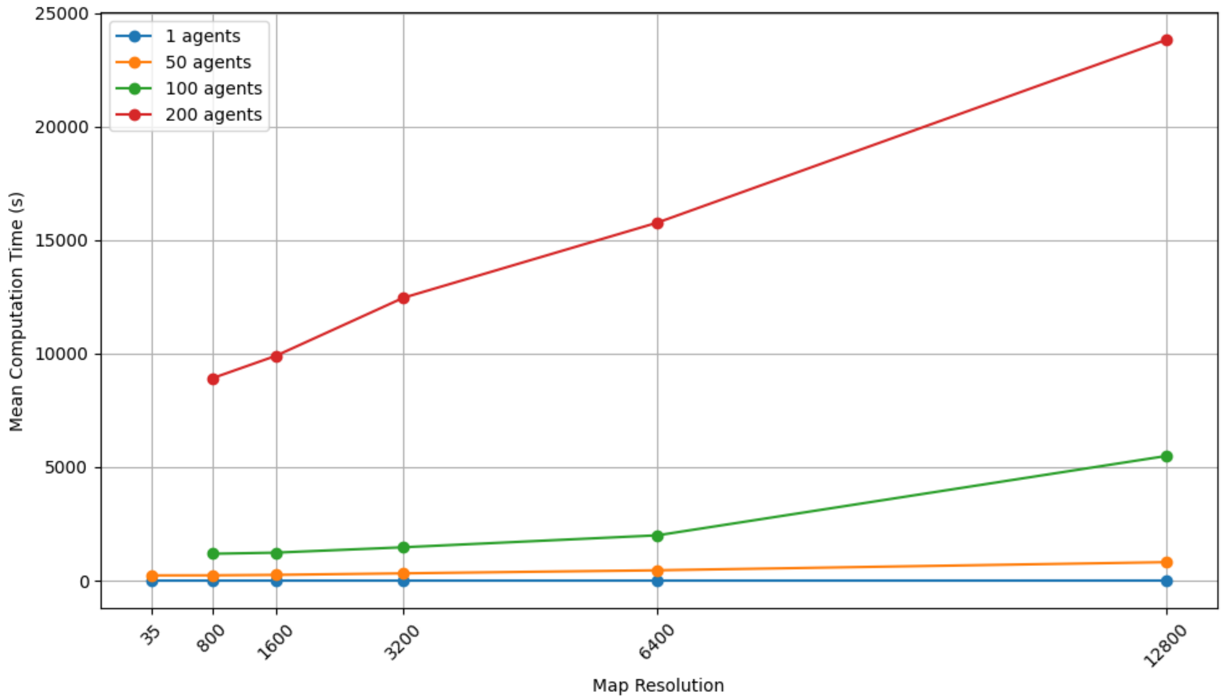

Figure IV-10. Influence of map resolution on computation time. 1.75% obstacle density.

The key insight from the analysis is that, under the experimental conditions, the algorithm shows low sensitivity to the number of drones when this number is 100 or fewer. The only exception is the transition between 6 400 and 12 800 points. In cases with high obstacle density and 200 agents, the algorithm becomes resolution-limited once agent interactions dominate.

IV.6. Conclusion

Based on the experimental results, we conclude that the Gen4jectory 2.0 algorithm can plan 4-D trajectories for rotary-wing UAVs, even in congested urban environments, within the assumptions made and the limitations identified. The algorithm calculates trajectories without loss of separation (LoS) in a near-optimal manner, taking into account the unique performance data of each drone.

Computation time ranged from a near-quadratic dependency on the number of drones in obstacle-free cases to superlinear sub-quadratic at 1.75% obstacle density. This implies significant practical limitations for operations involving hundreds of drones, but also confirms the algorithm's potential for managing up to one hundred UAVs.

The algorithm can be dependent on map resolution especially if many drones are presented. To aid better computation time, the density of waypoints is reduced for larger maps, which may, in theory, result in an inability to find a trajectory in highly congested environments. This presents an opportunity for further optimisation of the algorithm.

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V. Discussion and Perspectives

V.1. Scientific novelty and significance

In general, the PhD thesis contributes to addressing safety-critical matters to allow UAV autonomous guidance within U-space.

V.1.1. Reflection on addressing RQs in information provision

In particular, the research on information provision (section II) delivered an essential analysis of the existing constraints, information needs, and U-space services planned according to the Concept of Operations of U-space [1]. The study built upon previous research from the European projects DREAMS [2] and IMPETUS [3] on information provision for U-space, contributing with new knowledge specifically to the information provision needs of the final (U4) stage of U-space development. Uncrewed air traffic cannot operate safely and efficiently if essential information flows are not clearly defined, and the corresponding services fail to collect and share this information properly. In light of this, the research contributes significantly by creating a reliable foundation for designing U-space final stage services according to the information provision essential needs.

Additionally, the research's novelty and essentiality were recognised by The Federal Aviation Administration which requested a presentation of the findings to support further UTM research and development in the United States. This is not surprising since the concept of operations of the American UTM did not sufficiently address the essential information needs for autonomous uncrewed operations either [4], [5]. Finally, the Danish national cluster for robot, drone and automation industry, Odense Robotics, also expressed their interest in the research findings and invited the first author of [6] to present the results at the International Drone Show 2025.

However, the dissertation acknowledges the limitations associated with TRL 2 and encourages the scientific community to continue research through the methodology explained in section II.4. Practical testing of the current findings may reveal insights into previously unidentified issues that might still remain unresolved.

V.1.2. Reflection on addressing RQs in safe separation with UDUM

Section III addresses the issue of identifying a safety separation with uncooperative drone of unknown model but known type (RQ2a). This problem was revealed through the findings obtained in section II. Specifically, information needs regarding the position and classification of airspace intruders, including wildlife, were identified as a gap. This information is safety-critical because without it, flight in the vicinity of a rogue drone is associated with an unpredictable risk of a LoS event or even a midair collision. Section III proposes a fundamental method for using uncooperative drone classification and positioning to determine safe separation distances, enabling collision-free 4D trajectory planning in the event of a rogue drone occurrence.

Additionally, section III deals with the issue of planning horizontal manoeuvres to avoid a LoS with an uncooperative drone. RQ2b was raised to show how measuring a safe separation distance can be used in practical scenarios. Since the horizontal manoeuvre is a classical approach to collision avoidance in the field of manned aviation, the RQ2b formulation reflected this viewpoint.

The strong side of the method proposed is that it gives a novel concept, supported by mathematical reasoning, that excludes LoS cases with an uncooperative drone if all systems and procedures have been performed properly. The fundamental novelty of the approach is associated with the global UAV database usage and the extraction of valuable knowledge of the limitations of each type of drone.

The arguable side of the study is that it assumes that there is a global UAV database on aircraft performance, which does not exist yet – at least to the authors' best knowledge. Presently, the actual data on UAV performance is fragmented and belongs to various entities – manufacturers, research institutions, and regulatory bodies. As a result, the lack of data availability significantly slows the research and development of UAV technology for commercial use. Therefore, in section III, the assumptions were made – with the hope – that scientific and business requests would motivate the creation of a UAV performance global database. Nevertheless, the situation resembles the classical 'chicken-and-egg problem' — something must come first to catalyse progress. In light of this, the study highlighted the essential need for an accessible and global UAV performance database.

The research concludes at the TRL 3 stage where the method was demonstrated analytically through mathematical modelling. However, real operations can be influenced by data bias because of sensor noise and other technical limitations of situational awareness. For example, night-time can potentially limit video camera capabilities in rogue drone-type identification. In this case, the uncooperative drone must be assumed as the fastest of all known models, and the night-time separation should be increased accordingly. The practical side of the problem of safe separation from the rogue drone is complex because various factors have essential impacts. Therefore, researchers could split the problem into sub-problems and start addressing them by using realistic assumptions and the findings of others. The iterative nature of the design science research cycles should lead to more practical solutions at the later TRL stages.

V.1.3. Reflection on addressing RQs in 4-D trajectory planning

The uncrewed air traffic 4-D trajectory planning problem is fundamental for U-space (UTM). The Concept of Operations of U-space directly relies on 4-D trajectories as an essential element of uncrewed air traffic management [1]. Among other potential requirements to trajectory planning, a flight time minimisation algorithm looks like one of the most promising since fast delivery is associated with better business efficiency (higher rate of UAV usage) and better customer experience (for example, quick food delivery is essential to keep it hot). The literature analysis performed in sections II and III revealed the essentiality of addressing the issue of planning 4-D trajectories for uncrewed air traffic to minimise flight time.

Addressing RQ3 led to the development of the Gen4jectory 2.0 algorithm which uses the UAV performance data and theta-star pathfinding algorithm. The Euler method is a part of its calculation instruments.

The set of simulation experiments demonstrated the ability of the Gen4jectory 2.0 algorithm to resolve the uncrewed air traffic trajectory planning, specifically its ability to plan 4-D trajectories for multiple UAVs in a congested urban environment with minimised flight time (under assumptions taken and identified constrains). The algorithm planned 4D trajectories for the UAVs, taking into account various aircraft performance parameters. In all instances where planning was successfully completed, there were no cases of loss of separation (LoS). Challenges in completing the planning for all agents were observed in a very small number of test cases, either due to extremely high agent density on the largest map or restrictive initial setup constraints on the smallest map. This fact gave a good foundation for further research, maturing the algorithm from the modelling stage to real-world flight tests and commercial usage. The Gen4jectory 2.0 algorithm development reached the TRL 4 stage (section IV) and requires further research and development efforts to be ready for practical implementation.

V.1.4. General perspective

The PhD thesis delivered essential progress in advancing uncrewed air traffic autonomy for U-space. Specifically, addressing RQ1a, RQ1b, and RQ1c contributes significantly to understanding the complexity of autonomous operations. The research revealed constraints and essential gaps in information provision that must be fulfilled to allow the fourth stage (U4) of U-space. The limitations associated with TRL 2 motivated proposing a high-level methodology to identify, measure, and close the gaps, where real-world testing of the findings will likely contribute by offering measurable parameters. This new knowledge is valuable progress, not only from the industrial perspective, but also because it offers directions for further research to allow autonomous operations of UAVs.

The findings in sections III and IV revealed the essentiality of the global UAV database availability for the research community. Even if the classical approaches to obtaining aircraft performance data are costly and time-consuming for small drones, the alternative methods (for example, computational fluid dynamics (CFD)) have the potential to address this problem. However, this requires additional research. Addressing this issue will likely allow UAV motion planning in 4-D space and will give an understanding of the limitations associated with each type of uncooperative drone (to find the safe separation distance).

The methods proposed in sections III and IV do not consider wind impact during the flight. This limits the practical implementation of the methods proposed. However, the modelling of the wind is just one of the constraints among many [6]. Therefore, it was decided to conduct the research with a prime focus on the research questions with a typical baseline in the field of aviation – standard atmosphere, no wind conditions, etc. The baseline is essential as it gives a universal approach for the controlled comparison of studies and the results obtained.

In conclusion, it is important to note that all three publications (sections II, III, and IV) address issues of significant scientific and industrial relevance. They all contribute with valuable knowledge to advance uncrewed aircraft flight safety and business efficiency for autonomous operations.

V.2. Relevance of the study for industry and society

For the Danish and European societies, the PhD thesis signifies an advance in the integration of autonomous uncrewed air traffic into daily business life. However, what does this mean in practice? For example, for the end-user, it means a new level of convenience through new business-to-customer services. For the business community, it means new business opportunities, new markets, and services. For example, business-to-business services have the potential to decrease the time and cost of goods delivery for remote areas. Denmark is a country of hundreds of islands, and in such a geographical area, aerial autonomous robots can offer delivery of medical samples, medicine, consumer goods, hot food, surveillance, inspection of wind turbines, agricultural operations, etc. Finally, human transportation with uncrewed autonomous aerial vehicles is a fast and convenient way of travelling with high speed and potentially a high degree of freedom.

In terms of global competitiveness, the practical implementation of the dissertation's findings helps make Danish businesses more competitive in the global market, reinforcing Denmark's renowned traditions in the field of robotic technologies. Scientific and technical groundwork in the field of U-space and urban air mobility implies a higher degree of competitiveness for the Danish aviation and robotics industries by creating new highly skilled and well-paid jobs. This, in turn, supports the Danish government's efforts to increase national economic prosperity. New attractive workplaces can bring higher satisfaction in society and contribute to increased revenues for the public budget.

The greater the degree of economic success and technological advancement of a Danish high-tech industry, the higher the positive impact it has on the European Union's scientific and business cooperation. In this light, the dissertation supports the significant efforts of the European Commission in advancing U-space, specifically by contributing to U4-stage research and development.

V.3. Suggestions for future research

V.3.1. Ground infrastructure

U-space will likely have a hybrid system, i.e., a mix of centralised and decentralised UTM systems. This expectation is based on the reasoning behind the potential optimisation of the ground infrastructure deployment (a set of sensors and communication channels). If demand for UAV operations is high, then investments in the essential ground infrastructure are more likely. This can be relevant for big cities or industrial centres. However, a remote island with a small village has a lower chance of getting the expensive ground system deployment. Therefore, it is reasonable to expect that U-space will encounter varying levels of information availability depending on the area of operation. This may require further research into conducting autonomous operations in areas with limited ground infrastructure and, consequently, limited information provision.

V.3.2. UAV performance data collection

Different models and types of aircraft behave differently in airflow since they normally differ in drag coefficient, lift coefficient (for the fixed-wing), cross-sectional area, thrust, etc. Even if the maximum velocity of a UAV is given in a flight manual, its acceleration, climb, and real velocity (in case of extra cargo) may remain unknown. Therefore, it is essential to possess data on aircraft performance to plan uncrewed air traffic accordingly.

Drones are often (though not always) smaller and cheaper than commercial or general aviation aircraft. As a result, comprehensive and costly testing of UAVs in aerospace centres may be economically unfeasible. In light of this, an alternative approach to UAV performance data collection is essential. For example, CFD modelling could provide a simplified and cost-efficient estimate of aircraft performance data for UAVs. However, this requires extensive research into how to collect such data quickly and cost-effectively across different UAV models, as well as what levels of precision can be achieved.

V.3.3. Technological limitations

The problem of early TRL is associated with a potential risk of the inability of the technologies to deliver the required results. For example, section II provides an analysis of the information needed to allow autonomous guidance of UAVs. In the scientific literature, we found evidence of what technologies could help with collecting the information needed. However, it is only a preliminary analysis. The practical implementation could, potentially, show that some systems or sensors are not accurate enough, or they work too slowly, or the costs of the system integration, deployment, and maintenance are unacceptably high. Similarly, the methods proposed in sections III and IV are dependent on the sensor's availability and accuracy, quality of communication, computation time, etc. This implies that even if the algorithms work properly in modelling and simulations, practical deployment could still require corrections to the initially proposed algorithms.

In the worst-case scenario, technological limitations could significantly constrain the applicability of findings from the early TRL stages. This reflects the 'early TRL risk', a common challenge in the research and development of complex systems. Therefore, the practical testing of the findings is important for advancing through the TRL ladder.

V.3.4. Practical tests

It might be beneficial to compare the findings with the alternative approaches that already exist. Specifically, the Gen4jectory 2.0 algorithm could be compared with other 4-D trajectory planners that already exist or will likely appear in the future. The Gen4jectory 2.0 algorithm is novel, it relies on the theta-star pathfinding technique, aircraft performance data, and the most essential forces that act on an aircraft, allowing multiple rotary-wing UAVs to plan their collision-free trajectories even in a congested urban airspace. However, these advantages are not the only essential points. The practical testing and comparison may reveal an optimal trade-off of the trajectory precision and computation time acceptable to plan and replan 4-D trajectories efficiently. Such a comparison could shed light on the optimal algorithm selection.

Generally speaking, the findings presented in this dissertation should be tested in practice within designated test zones and, following essential corrections, assessed in real-world autonomous operations.

V.4. Personal meaning

Three years of the research journey resulted in a fruitful transformation of industrial experience, acquired knowledge, and the author's vision into a valuable peer-reviewed scientific contribution. The new knowledge presented provides humanity with a deeper understanding of the essential information required for autonomous guidance of uncrewed air traffic, the safe separation of uncooperative drones of unknown models, and the planning of 4-D trajectories with minimised flight times for multiple rotary-wing UAVs in urban areas. This achievement marks the culmination of a period of hard work during the PhD study, involving significant intellectual effort, bringing great satisfaction with the results achieved, and motivating the application of new knowledge to advance U-space in Europe.

The PhD journey cultivated an invaluable fundamental skill set in research methodology, including the formulation of research questions, conducting literature reviews, and developing novel algorithms. For example, performing the systematic literature review revealed a situation where the volume of the existing papers (in terms of reading time) associated with the research topic was much larger than an ordinary human lifetime. In this situation, it was important to find a proper strategy of study, focusing on addressing the research questions and mitigating unnecessary details. Additionally, an iterative process involving the selection of research methodologies, discussions with the supervision team, and extensive review of relevant literature facilitated significant progress in developing a robust research design. With that, the primary objective of the educational process of the PhD programme was achieved and a new skill set was acquired which is necessary to conduct independent, rigorous research.

The author of the PhD thesis is a seasoned member of the European network of U-space stakeholders guided by EUROCONTROL. The group unites European and American scientists, industrial representatives, and officials. The regular discussions on the experience obtained in the different European U-space test zones provided an invaluable understanding of the essential challenges that must be resolved. This provided a valuable overview of the existing research issues and helped significantly in formulating the relevant research questions. At the time of writing, with the research now complete, the author reflects on the published papers with deep satisfaction, recognising their relevance and the essentiality of the study to the advancement of U-space.

Among other advantages, the PhD study helped the author master the subject. The author gained a new level of understanding of U-space issues, existing solutions and technologies, the associated limitations of UAV autonomous guidance, and how the scientific community is attempting to address some of them. One of the most valuable findings is a deep understanding of the complexity involved in planning and realising the final stage of U-space (U4).

Another positive aspect of the study was engagement with the academic community through participation in conferences, seminars, discussions with supervisors, and the peer-review process. The author recognises the crucial role of the supervision team whose guidance and expertise were invaluable. Furthermore, prolonged and constructive communication with peer reviewers significantly sharpened the articles and provided valuable experience in the field of scientific publishing.

Mastering problem-solving through addressing complex research questions exemplifies how the PhD study contributed to the author's professional development. Rigorous research requires a solid theoretical and philosophical foundation. The author acknowledges significant progress in integrating theory and philosophy with research question formulation, appropriate methodology selection, and comprehensive literature reviews.

Critical thinking is an important skill in the scientific approach. This allows seeking the problematic areas and essential inaccuracies in the research questions, methodologies, scientific literature, findings, etc. Criticism itself is invaluable in questioning existing and new knowledge in order to find better, more efficient, and more optimal solutions. The PhD journey contributed significantly to the author's development in this regard.

Furthermore, the PhD journey provided valuable experience in practising time management and working under the pressure of deadlines associated with research, study, dissemination, and publishing responsibilities. It also helped develop the important skill of writing logically structured papers in precise and formal language.

One of the most important achievements associated with the PhD study was the PhD courses, which provided a significant boost in collecting new knowledge. For example, a course on aircraft performance from Delft University of Technology provided a solid foundation for the development of the Gen4jectory 2.0 algorithm. A course on machine learning techniques provided an important background to the invention of the method for finding safe separation with uncooperative drone.

The PhD study at Aarhus University includes teaching and supervision of Master's programme students. Lecturing and working closely with the students gave the thesis author valuable experience, providing a wider picture and deeper understanding of the interconnection of the elements and problems of the autonomous guidance in U-space.

As a result, the author has transformed into a more capable individual with advanced professional and analytical skills, enriched by scientific methodologies and valuable new experience in the practice of science.

V.5. Techno-optimism and cautions

In his article about techno-optimism, Königs raises the question of whether we should be optimistic or pessimistic about technology [7]. The author of this PhD thesis believes that positive expectations regarding the use of autonomous drones are likely to be realised. In the coming decades, people will likely experience fully autonomous transport and various commercial and public services associated with autonomous aerial robots.

However, the autonomous aerial vehicles can also pose potential hazards. For example, malicious successful hacking attempts could result in endangering human lives in the area of UAV operations. Furthermore, the use of autonomous UAVs for terrorist purposes could pose a serious threat to critical infrastructure, such as airports or nuclear plants, as well as to people gathered in crowds, for example, at stadiums or demonstrations. The autonomous vehicles do not require a person onboard or in control, which makes it harder to detect and identify the lawbreaker with malicious intentions.

Another significant issue is privacy. For example, if a family is relaxing in the countryside or in a private garden, how might they react if a UAV were to record them simply by flying overhead? Should this be considered an interference with private life? However, if the UAV executes a surveillance mission or uses video cameras for navigation, then what kind of trade-off can be acceptable for society? What measures are required to protect privacy to a certain level? These questions require answers and regulatory updates.

Finally, if artificial neural networks are responsible for safety-critical and security aspects of U-space, would it be sufficient to rely solely on the statistical analysis of their efficiency without a comprehensive understanding of how the system works? This issue becomes especially relevant if strong AI emerges in the future. In this light, the author cautions the scientific community that it is essential to pay close attention to the problem of human control over autonomous vehicles and to develop solutions that ensure human safety and security.

V.6. Conclusion

From a general perspective, this PhD dissertation contributes by analysing the essential constraints, information provision needs, and identified gaps in comparison with the latest version of the U-space Concept of Operations. The findings revealed a significant mismatch between the actual needs and the U-space services planned. Additionally, the findings offer a high-level methodology for measuring and addressing the gaps, which points the way for further research.

Another contribution of the research is a novel method that offers an approach regarding how to calculate a safe separation with an uncooperative drone of unknown model. Further development of the method (advancing through the TRL ladder) is likely to lead to a practical solution capable of addressing the safety risks associated with rogue drone interference in U-space airspace.

Finally, the novel Gen4jectory 2.0 algorithm created a fundamental foundation for 4-D trajectory planning with minimised flight time for multiple rotary-wing UAVs in urban airspace. The algorithm considers the aircraft performance constraints and uses a highly advanced Theta* pathfinding technique, representing a promising balance between essential forces acting on the UAV and reasonable simplifications of the motion model. Comprehensive testing and comparison of Gen4jectory 2.0 with other existing approaches can help identify the most efficient one for practical implementation. This opens a venue for future research and development to allow autonomous guidance for uncrewed air traffic in U-space.

These findings were made possible through close collaboration with the SDU UAS Center in Odense. This invaluable synergy united expertise in flight mechanics, robotics, and computer science, fostering interdisciplinary research and generating new knowledge. The outcomes of this study are expected to contribute meaningfully to the scientific and engineering communities, paving the way for a novel industry of autonomously guided UAVs.

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Appendix

Declaration of Generative AI and AI-assisted technologies in the writing process

Statement: During the preparation of this work, the author used ChatGPT 4o in order to strengthen readability. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the thesis.

Co-author statements

AARHUS BSS
SCHOOL OF BUSINESS AND SOCIAL SCIENCES
AARHUS UNIVERSITY

Declaration of co-authorship[1]

Date: 07/04/2025

This declaration concerns the following article/manuscript:

Title:	A Critical Review of Information Provision for U-space Traffic Autonomous Guidance
Authors:	Ivan Panov, Asim Ul Haq

The article/manuscript is:

☒ Published, state full reference: Panov, I.; Ul Haq, A. A Critical Review of Information Provision for U-Space Traffic Autonomous Guidance. Aerospace 2024, 11, 471. https://doi.org/10.3390/aerospace11060471
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A. Research idea: Identifying, developing, specifying, and formulating the overarching research question and aim.
B. Theory: Organizing theoretical perspectives, developing arguments and hypotheses, specifying theoretical model.
C. Research design: Developing and planning design for test or exploration of the research question.
D. Data collection: Preparing and organizing data collection, data collection, preparing data for analysis and storage.
E. Data analysis: Application of empirical techniques to analyze or synthesize study data including providing support for interpretations such as visualizations etc.
F. Writing: Drafting and revising manuscript presenting the research idea and results

of this article/manuscript as follows:

4 Has essentially delivered this part.
3 Major contribution
2 Equal contribution
1 Minor contribution
0 Did not contribute to this part.

[1] Attribution of authorship should be based on criteria a-d adopted from the Vancouver guidelines (see also rules and guidelines from Aarhus University) and all individuals who meet these criteria should be recognized as authors. The co-author has contributed:

a) to the conception or design of the work, or the acquisition, analysis, or interpretation of data for the work, *and*
b) drafting the work or revising it critically for important intellectual content, *and*
c) to the final approval of the version to be published, *and*
d) agrees to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

N/A Not relevant or not applicable

Table 1. Individual contributions and signature of each co-author[1]

Author	Extent of contribution (4-0) per element (A.-F.)						Signature of the author[2]
	A. Research Idea	B. Theory	C. Research Design	D. Data Collection	E. Data Analysis	F. Writing	
Ivan Panov	4	4	4	4	4	4	
Asim Ul Haq	0	0	0	1	1	1	

[1]More rows can be added for additional authors.
[2]All authors must confirm the declaration either by signature or email.

If relevant, you may add more information on the work and collaboration such as open science practices or more detailed specifications of authors' contributions here:

Declaration of co-authorship[1]

Date: 07/04/2025

This declaration concerns the following article/manuscript:

Title:	A method for determining the safe separation to an unknown-model uncooperative UAV in U-space
Authors:	Ivan Panov, Jes Jepsen, Mirko Presser and Kjeld Jensen

The article/manuscript is:

☒ Published, state full reference: I. Panov, J. Jepsen, M. Presser, and K. Jensen, "A method for determining the safe separation to an unknown-model uncooperative UAV in U-space," presented at the 15th ANNUAL INTERNATIONAL MICRO AIR VEHICLE CONFERENCE AND COMPETITION, Bristol, United Kingdom: IMAV2024, Sep. 2024, pp. 208–217. [Online]. Available: https://www.imavs.org/papers/2024/25.pdf
☐ Accepted, state journal:
☐ Invited for revision, state journal:
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☐ In preparation

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Ivan Panov	4	4	4	4	4	4	
Jes Jepsen	0	0	0	0	1	1	Jes Jepsen
Mirko Presser	1	0	0	1	1	0	
Kjeld Jensen	1	1	0	1	1	1	Kjeld Jensen

[1]More rows can be added for additional authors.
[2]All authors must confirm the declaration either by signature or email.

If relevant, you may add more information on the work and collaboration such as open science practices or more detailed specifications of authors' contributions here:

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AARHUS UNIVERSITY

Declaration of co-authorship[1] Date: 07/04/2025

This declaration concerns the following article/manuscript:

Title:	Gen4jectory algorithm – 4-D trajectory planning with minimised flight time for multiple rotary-wing UAVs
Authors:	Ivan Panov, Mouad Boumediene, Henrik Skov Midtiby, Kjeld Jensen

The article/manuscript is:

☒ Published, state full reference: I. Panov, M. Boumediene, H. Midtiby, and K. Jensen, "Gen4jectory algorithm – 4-D trajectory planning with minimised flight time for multiple rotary-wing UAVs," presented at the 15th ANNUAL INTERNATIONAL MICRO AIR VEHICLE CONFERENCE AND COMPETITION, Bristol, United Kingdom: IMAV2024, Sep. 2024, pp. 242–252. [Online]. Available: https://www.imavs.org/papers/2024/29.pdf
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Mouad Boumediene	1	2	2	2	2	2	
Henrik Skov Midtiby	0	1	1	0	2	1	Henrik Skov Midtiby
Kjeld Jensen	0	2	1	0	1	1	Kjeld Jensen

[1]More rows can be added for additional authors.
[2]All authors must confirm the declaration either by signature or email.

If relevant, you may add more information on the work and collaboration such as open science practices or more detailed specifications of authors' contributions here: