D2.5-E-Conspicuity and Automated Separation Algorithms

DELIVERABLE DETAILS			
Deliverable Nr	**Lead Beneficiary**	**Dissemination Level**	**Status**
D2.5	TU-Delft	PU	CONTROLLED
Edition	**Revision**	**Issue**	**Document Code**
01	00	01.00	D2.5_01.00
File Name	D2.5-E-Conspicuity and Automated Separation Algorithms_01.00		
Ref. Template	D0.0-Certiflight Document Template_01.00.dotx		

DOCUMENT HISTORY					
Issue	**Date**	**Status**	**Author**	**Partner**	**Change Description**
00.01	14/04/2023	DRAFT	M.F. Rahman	TU Delft	First Draft
00.02	17/04/2023	DRAFT	J. Ellerbroek	TU Delft	Review and modifications
00.03	30/04/2023	DRAFT	A.Mennella, M. Iadaresta, V.M.Ascione	TOPVIEW	Integration and modifications
01.00	31/05/2023	CONTROLLED	A. Mennella	TOPVIEW	Review
01.01	12/07/2023	CONTROLLED	A.Mennella V.M.Ascione J.Ellerbroek M.F. Rahman	TU Delft TOPVIEW	Integration and modifications according to DRS

APPLICABLE DOCUMENTS		
Ref.	**File Name**	**Description**
AD 1	Grant Agreement-101082484-CERTIFLIGHT	Project Grant Agreement

REFERENCE DOCUMENTS		
Ref.	**File Name**	**Description**
RD 1	SESAR (2022), "U-space ConOps (edition 3.10)	This document presents the concept of operation for U-space
RD 2	FAA & NASA (2020). "UAS Traffic Management Conflict Management Model"	This document presents the concept of operation for UAS traffic management conflict management
RD 3	Commission Implementing Regulation (EU) 2021/664 of 22 April 2021 on a regulatory framework for the U-space	This Regulation lays down rules and procedures for the safe operations of UAS in the U-space airspace, for the safe integration of UAS into the aviation system and for the provision of U-space services
RD 4	Commission Implementing Regulation (EU) 2021/665 of 22 April 2021 on a regulatory framework for the U-space	This Regulation lays down rules and procedures for the safe operations of UAS in the U-space airspace, for the safe integration of UAS into the aviation system and for the provision of U-space services
RD 5	Commission Implementing Regulation (EU) 2021/666 of 22 April 2021 on a regulatory framework for the U-space	This Regulation lays down rules and procedures for the safe operations of UAS in the U-space airspace, for the safe integration of UAS into the aviation system and for the provision of U-space services
RD 6	Jenie, Y. I., Kampen, E. J. V., de Visser, C. C., Ellerbroek, J., & Hoekstra, J. M. (2015). "Selective velocity obstacle method for deconflicting maneuvers applied to unmanned aerial vehicles". *Journal of Guidance, Control, and Dynamics*, *38*(6), 1140-1146.	This journal article presents the implementation of implicit coordination into velocity obstacle method for UAV deconfliction.
RD 7	Fiorini, P., & Shiller, Z. (1998). "Motion Planning in Dynamic Environments Using Velocity Obstacles". The International Journal of Robotics Research, 17(7), 760–772.	This journal article presents the ordinary velocity obstacle method for robots deconfliction
RD 8	Van Wijngaarden, D. Implicitly coordinated Tactical Avoidance for UAVs within a Geofenced Airspace. MSc thesis, TU Delft (2020)	This document discusses the additional constrain the velocity

	http://resolver.tudelft.nl/uuid:4b92f6b0-dc40-4946-a1ae-7efd0df79401	obstacle method considering geofencing
RD 9	Velasco, G. A. M., Borst, C., Ellerbroek, J., Van Paassen, M. M., & Mulder, M. (2015). The use of intent information in conflict detection and resolution models based on dynamic velocity obstacles. *IEEE Transactions on Intelligent Transportation Systems*, *16*(4), 2297-2302.	This journal article discusses the inclusion of intent information in velocity obstacle method
RD 10	Vlaskin, A. “Automatic Dependent Surveillance System for Drones: A Design and Capacity Study” MSc thesis, TU Delft (2022) https://repository.tudelft.nl/islandora/object/uuid:9343ba70-cd9d-4954-bfd6-7d4988a0074e	This document studies automatic dependent surveillance system for drones.
RD 11	EASA (2022), “Technical Specification for ADS-L transmissions using SRD-860 frequency band”	This document presents technical specification for ADS-L, including the data format and typical performance
RD 12	ICAO Annex 11	This document provides the standards and recommended practices for the establishment of air traffic services and communication procedures to ensure safe and efficient global air navigation.
RD 13	ICAO Annex 2	The documents CAO Annex 2 provides the rules of the air and air traffic control procedures that apply to all aircraft operating in international airspace.
RD 14	Commission Implementing Regulation (EU) 2019/947 of 24 May 2019 on the rules and procedures for the operation of unmanned aircraft	This Regulation lays down detailed provisions for the operation of unmanned aircraft systems as well as for personnel, including remote pilots and organizations involved in those operations.
RD 15	ASTM F3411-22 - Standard Specification for Remote ID and Tracking	This specification covers the performance requirements for remote identification (Remote ID) of unmanned aircraft systems (UAS)
RD 16	D2.1 Users’ needs and use cases identification	Use case document
RD 17	A. Tabassum and W. Semke, “UAT ADS-B Data Anomalies and the Effect of Flight Parameters on Dropout Occurrences,” *Data*, vol. 3, no. 2, p. 19, Jun. 2018, doi: 10.3390/data3020019.	The paper discusses message dropout occurrences in ADS-B data

RD 18	Sunil, Emmanuel et al. "Analysis of Airspace Structure and Capacity for Decentralized Separation Using Fast-Time Simulations." Journal of Guidance Control and Dynamics 40 (2017): 38-51.	This journal article presents the variables for safety analysis of decentralized separation
RD 19	J. M. Hoekstra and J. Ellerbroek, "BlueSky ATC Simulator Project: an open Data and Open Source Approach," Proceedings of the 7th International Conference on Research in Air Transportation, no. June, 2016	This paper presents the overview of BlueSky as an ATC simulator tool.
RD 20	J. Hoekstra, R. van Gent, and R. Ruigrok, Designing for safety: the 'free flight' air traffic management concept, Reliability Engineering & System Safety 75, 215 (2002).	This paper proposes the modified voltage potential (MVP) algorithm for conflict resolutions.

This document is part of a project that has received funding from the EUSPA under grant agreement No 101082484 under European Union's Horizon Europe programme.
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Union Agency for the Space Programme ('granting authority'). Neither the European Union nor the granting authority can be held responsible for them.

SUMMARY

LIST OF FIGURES

LIST OF TABLES

Abstract

This document represents the D2.5 contractual deliverable “e-Conspicuity and automated separation algorithms” aimed to analyse, through simulations, possible algorithms for automated separation between GA aircraft and UASs based on the Velocity Obstacle-based methods, which are well-established in the domain of robotics, self-separation for manned aviation, and complexity analysis.

1 Scope of the document

The objective of this document is to analyse and present simulation results of the GNSS-based algorithms for automated separation between GA aircraft and UASs used in the CERTIFLIGHT solution. The employed separation method is based on velocity obstacle theory, which is well-established in the domain of robotics, self-separation for manned aviation, and complexity analysis.

This document is constructed in six parts. Initially, Introduction section outlines the problem definition, research objectives and assumptions and limitations are discussed. Subsequently, a brief overview of communication, navigation, and surveillance systems is presented. The following two sections discuss U-Space and CERTIFLIGHT projects. Then, experiment design is presented containing variables and scenarios of the research. Lastly, the results and discussion conclude the document.

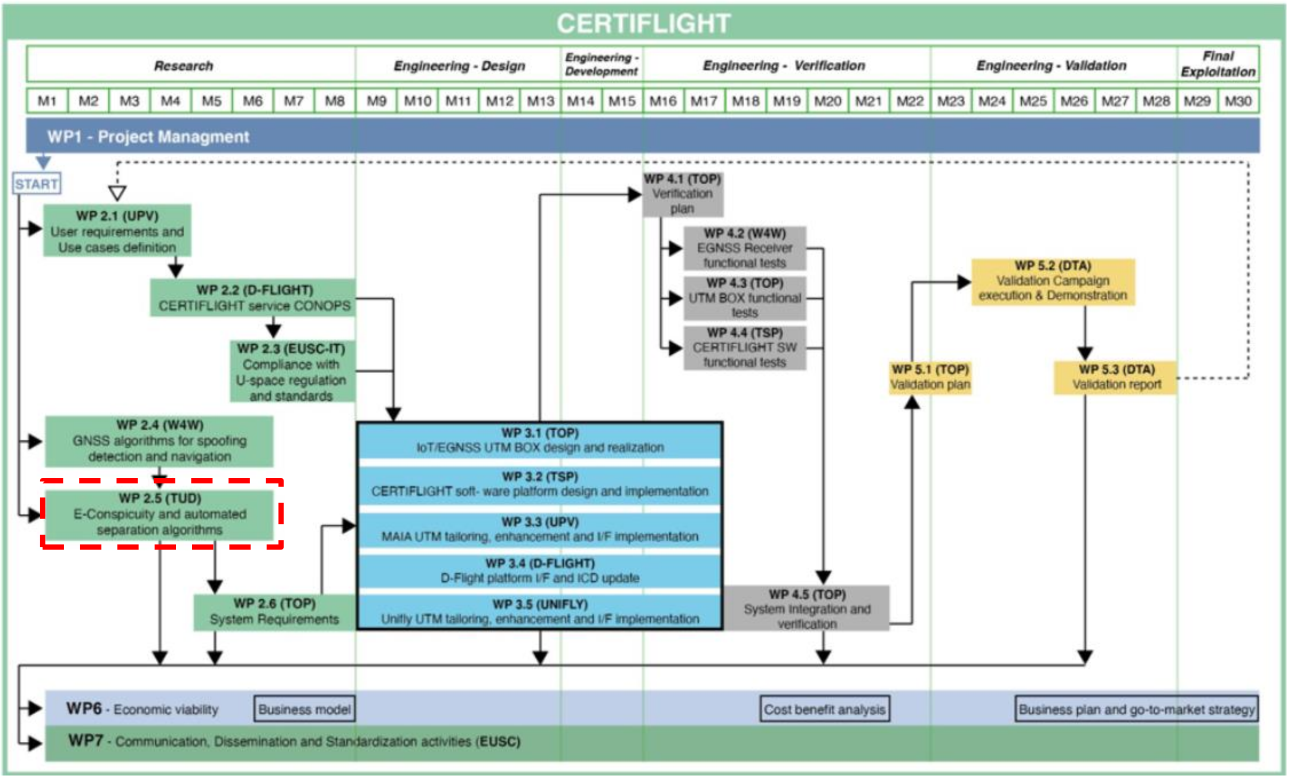


Figure 1-1 Work Breakdown Structure

1.1 Acronyms

A sample of the Acronyms table is below. Please add and/or remove from this list in order to use only the ones needed in each deliverable.

Acronyms	Description
ADC	Analogue to Digital Converter
ADF	Automatic Direction Finder
ADS-B	Automatic Dependent Surveillance - Broadcast
ADS-L	Automatic Dependent Surveillance - Light

ATC	Air Traffic Control
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
CD&R	Conflict Detect & Resolution
CNS	Communication, Navigation, and Surveillance
COTS	Commercial off-the-shelf
CPA	Closest Point of Approach
DME	Distance Measuring Equipment
DRI	Direct Remote Identification (service)
EFB	Electronic Flight Bag
EGNOS	European Geostationary Navigation Overlay Service
EGNSS	European Global Navigation Satellite System
FIS-B	Flight Information Services - Broadcast
FPGA	Field-Programmable Gate Array
GA	General Aviation
GNSS	Global Navigation Satellite System
HF	High Frequency
IAB	International Advisory Board
ICAO	International Civil Aviation Organisation
IFR	Instrumental Flight Rules
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IPR	Intrusion Prevention Rate
LPWA	Low Power Wide Area
LoS	Loss of Separation
MVP	Modified Voltage Potential
NB-IoT	Narrow band IoT
NRI	Network Remote Identification (service)
OEM	Original Equipment Manufacturer
OSNMA	Open Service Navigation Message Authentication
RPZ	Radius of Protected Zone
TIS-B	Traffic Information Services - Broadcast
UART	Universal Asynchronous Receiver-Transmitter
UAS	Unmanned Aerial System
UFR	U-space Flight Rules
UTM	Unmanned Traffic Management
VHF	Very High Frequency
VFR	Visual Flight Rules
VLL	Very-Low-Level
VLOS	Visual Line Of Sight
VOR	VHF omnidirectional range
WP	Work Package

Table 1-1 Acronyms list

2 Introduction

The use of Unmanned Aerial Systems (UASs), also known as drones, has been increasing continuously, which challenges the existing air traffic control system. Recently, large research programs such as SESAR and NextGen (USA) have been launched to accommodate the evolving air traffic management, including the integration of UASs into existing airspace [RD1, RD2].

The capabilities of UASs provide new approaches to different industrial sectors. For instance, in last-mile delivery, UAS are considered as economically beneficial as they are not restricted to road infrastructure and can move flexibly in three dimensions. Additionally, UAS can improve the productivity of agricultural sector by automating the crops surveillance or spraying over a large area, using a range of payloads. UAS can also be used to monitor extensive sites such as power plants and distribution centres, often located in rough and extreme terrain. Other industries such as infrastructure, fisheries, and securities can also improve their process by utilizing UASs.

2.1 Problem Definition

Proposed U-Space concepts allow UASs to fly in the existing airspace, thus increasing the likelihood of encountering GA aircraft. EU regulation 2021/664-665-666 considers this event and requires both manned and unmanned aircraft to be electronically conspicuous when operating in U-Space. This concept is called e-Conspicuity [RD 3, RD 4, RD 5]. However, there is no clear separation rule when a potential encounter between GA aircraft and UAS exists. The possibility of mid-air collision will be even higher due to lack of coordination between the two.

Unlike in controlled airspace for manned aircraft, services in U-space airspace have not been standardized yet. For instance, there is no requirement for the update rate of the aircraft's position and the accuracy of the positioning systems. The separation distance between aircrafts is also still undefined for the moment. Two sub-problems that are relevant to this study have been identified in the following sub-sections.

2.1.1 Manned and Unmanned Aircraft Encounter

The differences between manned and unmanned aircraft poses a challenge in the case of possible (near) mid-air collision. The absence of an on-board pilot in unmanned aircraft makes it harder to effectively communicate with manned aircraft. Coupled with the small size and often low visibility of UAS, this reduces situational awareness for the pilot of the GA aircraft. Furthermore, the contrast in flight performance between the two requires a different approach to the existing set of rules applied between aircrafts.

E-Conspicuity increases situational awareness for both manned and unmanned aircraft. The service provides identification of the vehicle as well as its positional data to notify the flying pilot, on board or remotely. However, despite the benefits, there are currently no clear rules or standards to resolve potential conflicts in flight. This can create adverse effects due to lack of guidance. Common rules are required to improve the safety of all aircrafts in the airspace.

2.1.2 Characteristic of the Communication and Navigation Systems

The communication system employed for the e-Conspicuity function can use either direct radio transmission, or an internet-based system. Using direct radio transmission will affect the coverage range of the system and define the situational awareness. When using an internet-based system, the coverage is expected to be global as long as internet is available. The rate of transmission and possible message drop impact the effectiveness of the conflict detection and resolution.

The location of UASs needs to be determined on-board. One can therefore expect the use of Global Navigation Satellite System (GNSS) and inertial sensors. Even though GNSS can directly determine the UASs position on earth, in practice the update rate (limited by computational constraints and communication limits) is limited thus creating inaccuracy especially in a moving object. Inertial sensors can measure the position more frequently and the combination of both can produce a more precise and accurate positioning system. In reality, measurement inaccuracy from both sensors potentially affects the performance of Conflict Detection and Resolution (CD&R) systems.

2.2 Research Objectives

The objective of this deliverable is to study the impact of limitations in accuracy and availability of e-Conspicuity data, on conflict detection and resolution. The conflict detection part considers the characteristic of communication, navigation, and surveillance systems for both vehicles. In case of possible (near) mid-air collision, the conflict resolution shall accommodate the performance and operational difference between the two. The research objective is stated as follows:

Study and analyse the effect of communication, navigation, and surveillance systems characteristic on CD&R algorithm for GA aircraft and UASs encounter.

In the context of this objective, a research activity is described in this deliverable. The activity is **"Evaluate the impact of communication and navigation system limitations on CD&R performance"**. To clearly identify the deliverables, questions are synthesized for these two activities.

Research Activity 1

1. How does data availability affect CD&R performance?
2. How does navigation accuracy affect CD&R performance?

2.3 Assumptions and Limitations

The investigation is done under several assumptions in order to focus on the objectives and reduce the complexity of the research. The following paragraphs express the assumptions within the research scope and limitations of the main keywords of this research.

Assumption 1: The airspace is uncontrolled.

The research considers the G class very low level (VLL) airspace as the airspace. Due to the absence of air traffic controller, the separation is decided by each aerial vehicle by following resolution advisory or autonomously.

Assumption 2: The conflict resolution method will use a horizontal resolution strategy.

This assumption limits the manoeuvre of the aircraft. In terms of speed, the minimum and maximum value depend on the aircraft type and altitude. Even though three-dimensional resolution could be more efficient, this research limits it to horizontal manoeuvre to reduce the complexity considering the resolution might be calculated on-board.

Assumption 3: The conflict resolution method will use implicit coordination.
Aircrafts will use common rules that are implicitly coordinated to avoid adverse manoeuvres. This coordination is preferred over explicit coordination to avoid the wait traps in which vehicles wait for the agreement. Implicit coordination also removes the necessity of direct communication between the vehicles, especially considering the nature of remotely piloted aircraft that adds delay in the process. An example of priority rules that are also implicitly coordinated are the “rules of the air” under the visual flight rules (VFR).

Assumption 4: The conflict resolution method will not use intent information.
To detect potential conflicts, the state of the aircraft will be projected in the future within the look-ahead time. This approach reduces the necessity to transmit trajectory intent information that can fill up the bandwidth and possibly add delay in the transmission.

Assumption 5: Conflicts are only defined pairwise, between two aircrafts.
Even in a high density UASs airspace with randomized setup, it is hard to find multiple aircrafts conflict i.e. multiple conflicts happening to one aircraft at the same time, or otherwise related conflicts are rare and not taken into consideration [RD 6]. Therefore, this research assumes conflict will exists only between two aircrafts, either manned or unmanned.

Assumption 6: No human-in-the-loop evaluation
This study is performed using fast-time simulation. Human-in-the-loop effects are considered out of scope. The main consequence of this is that all manoeuvres done by the aircraft are considered as perfectly conforming to the resolution advisory given by the conflict resolution methods.

Assumption 7: Limited modelling of the communication systems
To simplify the simulation, only limited aspects of the communication systems are considered such as range, resolution, transmission rate, and possibility of message drop. Other factors such as weather, signal noise, interference, and multipath effects are not considered.

3 Communication, Navigation, and Surveillance Systems

To successfully perform autonomous separation depends on a combination of several factors. In this chapter, we present the existing communication, navigation, and surveillance systems in the aerospace sector and their relevance for the autonomous separation implementation on UASs.

3.1 Communication Systems

Communication systems in UASs operate differently from manned aircraft considering the size and its remotely operated nature. The latest developments of relevant system aspects such as data type and employed radio frequencies will be discussed in this sub-chapter.

Based on the data type, communication systems in UAS can be categorized as command and control (C2) and Non C2. C2 communication includes several types of information shared between the pilot and UASs such as telecommand, telemetry of the UAS' state, and navigation aid. These data typically require a high transmission rate and high availability to enable timely pilot reaction to the situation when required. The Non C2 data type is payload-dependent data, and varies between UAS missions such as agriculture, monitoring, or last-mile delivery. Unlike C2, the latter does not impose critical issue if disruption occurs.

Direct radio communication is used in both UAS and manned aircraft but operates on different frequencies. The frequency used in UASs are 2.4 GHz, 5.8 GHz, 900 MHz, and 860 MHz for control signals, telemetry, or payload data transmission. On the other hand, radio communication in manned aircraft uses VHF and HF, enabling communication over a wide area, in contrast to UASs' which covers only a few kilometres. Transmission power, antenna gain, and surrounding terrain profile also affect the communication distance.

Recently, several new communication technologies are explored for UASs operations. Internet-based communication using 4G/5G cellular service potentially enables communication between UAS and U-Space service provider. This will be useful assuming the mobile telephony network is available everywhere throughout the flying area.

3.2 Navigation Systems

Aircraft navigation systems aim to determine the position and heading of an aircraft at any given time during flight. This system is one of the most critical aspects in aviation since it allows the pilot to navigate from the starting point to end point, avoid potential obstacles, and stay on track. Technology advancement allows the evolution of navigation systems from a simple visual reference and compass to the use of advanced radio-based navigation, inertial navigation systems (INS), satellite-based navigation, or a combination of these.

For a radio-based navigation, the most common systems are the automatic direction finder (ADF), VHF omnidirectional range (VOR), and distance measuring equipment (DME). These systems require both airborne and ground-based equipment to communicate on a specific frequency. Since the ground-based infrastructure must be built, this type of navigation systems covers a limited area and is inoperable over the ocean.

Inertial navigation systems (INS) typically use accelerometer and gyroscope measurements to determine the position, velocity, and orientation of an aircraft. The aircraft's state is computed by integrating the sensors information over time and does not require external tools. However, the integrated data is prone to drift over time: an integration error is accumulated over time thus reducing the accuracy. Redundancy is typically introduced to improve the state estimation and ensure data availability in case of sensor failure.

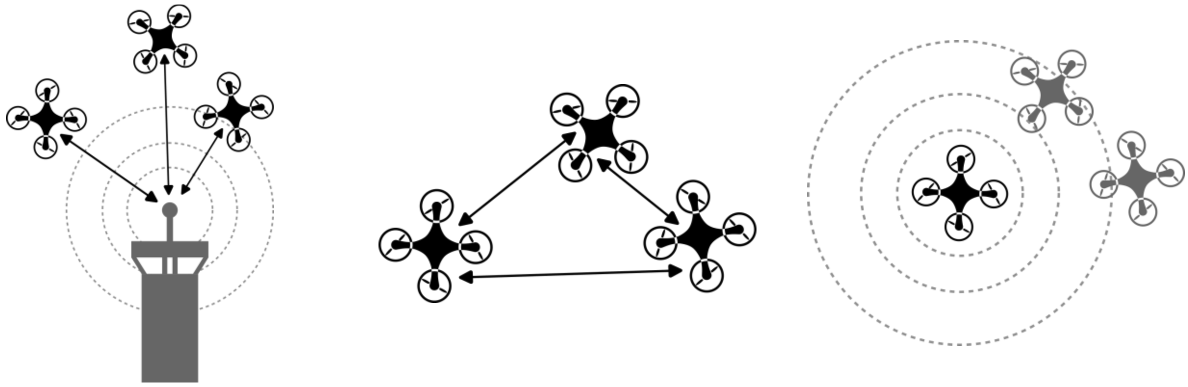
Satellite-based navigation, or global navigation satellite systems (GNSS), utilizes a constellation of satellites to calculate the position of an aircraft. Triangulation is used in the computation by measuring the time it took for the signal to travel to the receiver using at least four satellites. The more satellites are visible to the receiver, the more accurate the positioning will be.

A Kalman filter can be used to combine different sensors for navigation. The statistical algorithm calculates the probability of a state given the sensor measurement and the dynamic model of the aircraft and updates the estimation with each measurement. For navigation, satellite-based systems which provide a direct estimation of aircraft position can be combined with the high-rate INS that provide aircraft's acceleration, velocity, and orientation. The combination of these sensors is expected to reduce the uncertainty in the aircraft navigation system.

3.3 Surveillance

Airspace surveillance can be classified into three different types, namely centralized-dependent, distributed-dependent, and independent. The first two are termed as dependent because the aircraft depends on external systems, while the latter is on its own.

A centralized-dependent surveillance (Figure 3-1(a)) receives data from a common source such as air traffic control (ATC) or aviation weather centre (AWC). In manned aircraft, a transponder is used to respond to ground interrogation. A ground radar will be used to determine the aircraft latitude and longitude position, while the altitude is broadcasted by the aircraft to the ATC. However, in unmanned aircraft, it is extremely hard to use radar for the positioning since typical UASs are small in size. This kind of surveillance is also not available for UASs at the moment due to no applicable standard and highly heterogenous systems among the aircraft.



(a) Centralized-dependent (b) Distributed-dependent (c) Independent

Figure 3-1 Different types of surveillance

The second one, distributed-dependent surveillance (Figure 3-1(b)), obtains data directly from the traffic by using cooperative communication. One of the most widely used examples of this type of surveillance is Automatic Dependent Surveillance-Broadcast (ADS-B), which enables aircrafts to receive and broadcast the position, altitude, identity, and other states of its surrounding. Even though ADS-B is common for manned aircraft, most UASs don't have the exact equipment due to the

operational limit. Automatic Dependent Surveillance – Light (ADS-L) is an adaptation of ADS-B, recently being developed to enable similar functionality in U-Space [RD 10, RD 11].
Lastly, independent surveillance (Figure 3-1(c)) uses on-board sensors without requiring any external equipment or communication. For traffic awareness, manned aircrafts are not equipped with such systems since they are expected to communicate through ADS-B. In case of GA aircrafts without ADS-B, pilot uses their vision to recognize surrounding obstacles. For unmanned aircraft, electro-optical and LiDAR sensors are commonly used for obstacle detection and avoidance.

3.4 CNS technologies for e-Conspicuity

The CNS technologies available on the market and envisioned for implementing the e-Conspicuity functionality in Certiflight, are briefly reported in the next subparagraphs.
Flarm, ADS-Light and 4G/5G telephony are the most promising technology in the UAS / GA domain.

3.4.1 Flarm

FLARM (Flight Alarm) is a collision avoidance system designed primarily for use in General Aviation (GA) and light aircraft. It provides an additional layer of safety by helping pilots detect and avoid potential collisions with other aircraft in their vicinity. FLARM operates based on a combination of GNSS, radio transceiver, and collision algorithms. Actually, more than 50.000 manned aircraft and many UASs are already equipped with FLARM and the number is rapidly increasing. FLARM systems are available from several manufacturers for powered airplanes, helicopters, gliders, and drones. With FLARM avionics installed, a pilot is alerted of interfering traffic and potential imminent collisions with other aircraft.

The key components of FLARM technology are the following:

GNSS Receiver:
FLARM uses a GNSS receiver to determine the aircraft's position, altitude, and Ground Speed. This information forms the basis for collision detection and avoidance algorithms. Certiflight aims to go beyond the state of the art of Flarm technology, introducing an OSNMA enabled receiver for providing and authenticated position information.

Radio Transceiver:
FLARM incorporates a radio transceiver that operates on a specific frequency range, typically 868 MHz in Europe. The transceiver allows FLARM-equipped aircraft to communicate with each other by exchanging position and velocity data.

Collision Detection Algorithms:
FLARM employs sophisticated algorithms to detect potential collisions with other aircraft. It takes into account factors such as relative position, altitude, velocity, and direction of nearby aircraft. By continuously analysing this data, FLARM determines the risk of collision and provides timely alerts to the pilot.

Traffic Alerts and Warnings:

When FLARM detects a potential collision threat, it provides visual and audible alerts to the pilot. The system may indicate the direction and relative altitude of the approaching aircraft to aid in situational awareness. FLARM can differentiate between conflicting traffic and non-conflicting traffic to help pilots prioritize their response.

Display and Integration:

FLARM can be integrated into various cockpit displays, including dedicated FLARM displays or multi-function displays (MFDs). Some devices are also available in the form of an Electronic Flight Bag. The information is typically presented in a graphical format, showing the position of nearby aircraft, their altitude, and other relevant data.

Compatibility:

FLARM is designed to be compatible with other avionics systems. It can operate alongside other collision avoidance technologies such as TCAS (Traffic Alert and Collision Avoidance System) and ADS-B (Automatic Dependent Surveillance-Broadcast). FLARM-equipped aircraft can receive and transmit data to both FLARM and non-FLARM aircraft, enhancing overall situational awareness.
FLARM has gained popularity in the GA community due to its effectiveness, relatively low cost, and compatibility with a wide range of aircraft. It is commonly used in gliders, microlights, and other small aircraft, helping pilots detect and avoid potential collisions, particularly in environments with high levels of GA traffic.

Figure 3-2 example of Flarm compatible devices

3.4.2 ADS-B and ADS Light

ADS-B stands for Automatic Dependent Surveillance-Broadcast. It is a surveillance technology used in aviation to enhance situational awareness and air traffic control. It relies on aircraft broadcasting their own precise position, velocity, altitude, and other information at regular intervals. This information is then received by ground stations and other aircraft equipped with ADS-B receivers, enabling more accurate tracking of aircraft and improving collision avoidance.

The key components of ADS-B technology are the following:

Transmitter

An aircraft equipped with ADS-B have a dedicated ADS-B transmitter that periodically broadcasts the aircraft's position, velocity, and other relevant data.

GNSS Receiver

ADS-B relies on a GNSS receiver to determine the aircraft's precise position, altitude, and Ground Speed.

Data Link

ADS-B utilizes a data link to transmit the aircraft's position information. In most cases, it uses Mode S Extended Squitter (1090ES) transmissions in the 1090 MHz frequency band.

Traffic Information Services-Broadcast (TIS-B)

TIS-B is a feature of ADS-B that allows ground-based air traffic control to provide ADS-B-equipped aircraft with surveillance information about other non-ADS-B equipped aircraft in their vicinity. This helps enhance overall situational awareness for pilots.

Flight Information Services-Broadcast (FIS-B)

FIS-B is another feature of ADS-B that provides pilots with real-time weather information, aeronautical information, and other data via the ADS-B data link. This enables pilots to access important flight-related information during their operations.

ADS Light

ADS Light is a new variant of ADS-B that has been developed as a simplified and cost-effective solution for certain types of aircraft operations. It is primarily designed for use in general aviation and light aircraft. ADS Light aims to provide a basic level of situational awareness and enhanced visibility for pilots, particularly in environments with limited or no radar coverage.
Key features of ADS Light include:

Reduced Data Set

ADS Light transmits a reduced set of essential aircraft data compared to traditional ADS-B. It typically includes the aircraft's position, altitude, and velocity.

Lower Data Transmission Rate

ADS Light uses a lower data transmission rate compared to full ADS-B implementations. This helps minimize the impact on bandwidth and reduces power requirements.

Frequency Band
ADS Light operates in the 978 MHz Universal Access Transceiver (978 UAT) frequency band, which is an alternative to the 1090 MHz frequency band used by traditional ADS-B.

Regional Adoption
ADS Light is primarily targeted for specific regions or countries where regulatory authorities have implemented this simplified ADS-B variant as a cost-effective solution for general aviation and light aircraft operations.
ADS Light aims to provide a more affordable and accessible option for aircraft operators, particularly those operating in areas with limited infrastructure or in regions where cost constraints may be a significant factor. It offers a basic level of surveillance and situational awareness, aiding in collision avoidance and improving overall airspace safety.

3.4.3 Mobile telephony

Although originally not designed for such applications, Mobile telephony can be useful for drones' telemetry applications in several ways, considering the wide coverage, the reliable connectivity and the high data rate achievable. In fact, in the last years, several demonstration projects and many UAS operations have demonstrated that the U-space airspace up to 120 m AGL is well covered also with respect to the height by such technology. For Certiflight UTM Box implementation the following protocols are considered:

4G-LTE Narrowband (NB-IoT)
4G-LTE Narrowband, also known as Narrowband IoT (NB-IoT), is a low-power wide-area (LPWA) cellular technology designed specifically for Internet of Things (IoT) applications. It is an evolution of the 4G LTE (Long-Term Evolution) standard and provides enhanced coverage, improved power efficiency, and support for a massive number of IoT devices. Key features of NB-IoT include:

- **Low Power Consumption:** NB-IoT devices are designed to operate on low power, allowing for extended battery life, which is crucial for IoT devices that need to operate for long periods without frequent battery replacements or recharge.
- **Extended Coverage:** NB-IoT offers excellent coverage, especially in hard-to-reach areas such as remote regions. It achieves this through efficient signal penetration (832-862MHz - LTE B20 band) and wide coverage range, enabling IoT devices to communicate reliably over long distances.
- **Cost-Effectiveness:** NB-IoT operates in licensed frequency bands, which ensures better quality of service and reduced interference compared to unlicensed IoT technologies. It also utilizes narrow bandwidth, allowing for cost-effective implementation and efficient utilization of network resources.
- **Scalability:** NB-IoT supports a massive number of devices per cell, making it well-suited for large-scale IoT deployments. This scalability enables efficient management and connectivity of a multitude of IoT devices within a network.

NB-IoT technology is implemented in the actual version of the UTM Box. Thanks to this technology the overall weight of the UTM Box is kept as light as possible (actual version 40 grams), considering the reduction of the weight the battery that can be achieved. The impact of current drain of the new OSNMA GNSS chipset and eventually of other redundant e-Conspicuity mechanisms shall be well assessed for the Certiflight UTM Box.

5G Technology

The added value of the 5G cellular network technology shall be well assessed in the design and development of the new Certiflight UTM Box. In fact, despite the significant improvements in terms of speed, capacity, latency, and connectivity, the 5G modems tend, in general, to consume more power compared to those 4G NB-IoT due to the higher data transfer rates and the increased complexity of the technology.

Being the power consumption (and weight) a key parameter for the UTM Box (in particular for the version to be installed on UAS), a trade-off between these technologies will be considered. In fact, 5G modems are designed to handle significantly higher data throughput, which requires more power to transmit and receive data at faster speeds. On the other hand, 4G NB-IoT modems are optimized for low-power IoT applications and have lower data transfer rates compared to 5G. They are designed to minimize power consumption and prioritize energy efficiency, enabling longer battery life for IoT devices.

On the other hand, features as ultra-Low Latency of 5G networks are very useful for minimizing the delay of the transmission of telemetry data.

The enhanced capacity of the channel for data transmission is considered valuable for Certiflight applications, only in the case of transmitting higher rate IMU data or GNSS observables in real time.

4 U-Space

U-space is a set of services that are based on a high level of digitization and automation of specific functions and procedures designed to support safe, efficient and secure access to airspace for a large number of drones. For this reason, U-space is an enabling framework designed to facilitate any type of routine mission, in all classes of airspace and all types of environments, even the most congested, by addressing an appropriate interface with the manned aviation and air traffic control.

Urban Air Mobility (UAM) is a new air transportation system for passengers and cargo in and around densely populated and built environments, made possible by vertical take-off and landing electric aircraft (eVTOL) equipped with new technologies such as enhanced battery technologies and electric propulsion. These aircraft will have a pilot on board or be remotely piloted.

The initiative is created to anticipate that the increasing number of UASs flights and that urban air mobility will become more common. This chapter discusses several concepts of U-Space that allow readers to understand E-Conspicuity and automated separation algorithms.

4.1 Phases of Flight

From the U-space concept of operations, five phases of flight have been identified namely strategic – long term, strategic – pre-flight, pre-tactical, tactical, and post-flight. An operator must submit a plan, called U-Plan to operate in U-Space, considering those five phases as seen in Figure 4-1. The strategic – long term consists of activities for authorities and operators of the aircraft such as airspace design, operator licensing, and UAS approval. Next, the pre-flight phase includes planning the flight, risk assessment, seeking permission from the traffic control, preparing the UAS and crew, and contingency planning. Just before the flight, the pre-tactical phase demands airspace capacity balancing and de-confliction for the pre-flight. The tactical part consists of the activation, flight, and termination and will be discussed in detail in the following paragraph. Lastly, the post-flight phase is identified as a phase for logging, reporting, maintenance, and performance assessment.

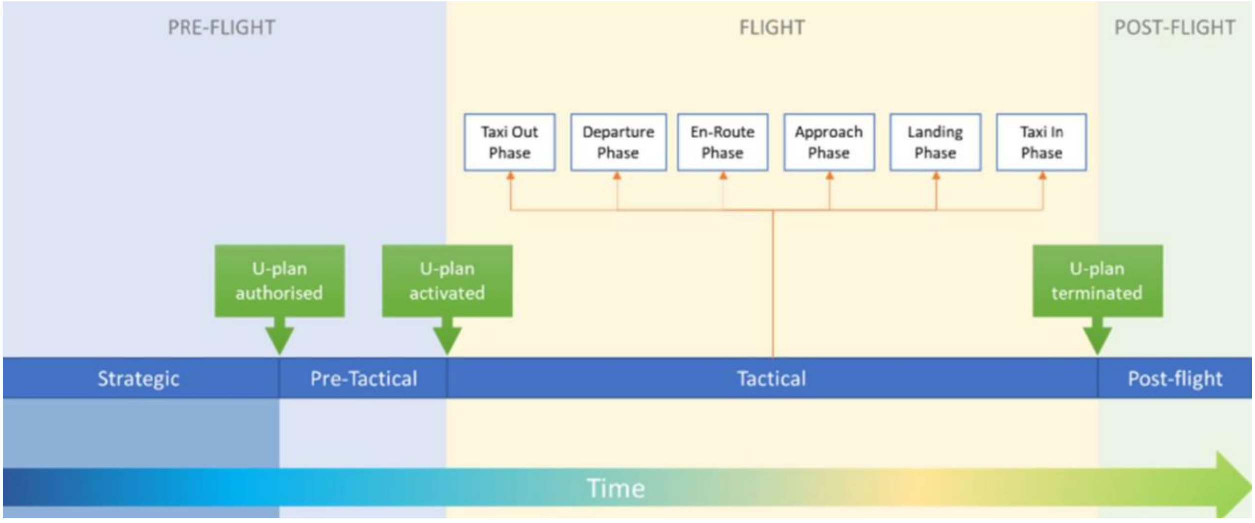


Figure 4-1 Lifecycle of a U-Plan taken from U-Space ConOps [RD 1]

CERTIFLIGHT added value

E-Conspicuity is relevant in the tactical phase. The phase begins when the U-plan is activated and ends when the flight operator confirms the end of the U-plan. During this phase, U-space tactical services are provided such as network identification, conformance monitoring, traffic information, tactical conflict prediction, and emergency management. The flight must conform to the operation plan which may include pre-flight operations, taxi-out, departure, en-route, approach, landing, taxi-in, and parking. Non-conformance can occur due to various factors such as failure, changing conditions, and external events. In that case, contingency plans must be executed, and it requires a situational awareness including the surrounding drone. Thus, e-Conspicuity is helpful.

4.2 Airspace

To accommodate UASs and Urban Air Mobility (UAM), airspace classification by ICAO needs further detailing from local authorities. ICAO annex 11 Section 2.6 [RD 12] defines seven airspace classes (A to G) in terms of VFR and IFR flight rules and services offered. Only subsets of flight rules {VFR, Special VFR, IFR} are permitted in classes A to G. Prohibited and Restricted areas are not part of those classes and can enable air use that is neither IFR nor VFR, as defined is ICAO annex 2 [RD 13]. From those seven classes, Class G airspace is typically an uncontrolled airspace where ATC services are not provided. The European Union specifies several regulations considering UASs operation in the existing airspace. EU regulation 2019/947Article 15 [RD 14] allows the creation of Geographic Zones for the management of UAS traffic, which can be designated U-space airspace. Moreover, EU regulation 2021/664 defines U-space airspace operations and the geographic bounds of U-space airspaces. The air traffic management (ATM) in controlled airspace and uncontrolled airspace is further regulated in EU regulation 2021/665 and EU regulation 2021/666. With these regulations, manned aircrafts are expected to share the airspace with UASs, safely and securely.

E-Conspicuity is discussed in EU regulation 2021/666 to allow manned aircrafts flying in an uncontrolled airspace to safely operate alongside UASs in U-Space airspace. The regulation highlights the importance of every manned aircraft to communicate its position to U-Space service providers. The service enables both manned and unmanned aircraft flying in the airspace to be electronically conspicuous, signalling their presence by means of surveillance technologies.

4.3 U-Space Services

U-Space provides various services including registration, network identification, conflict resolution, and many more. This sub-section aims to briefly discuss the services relevant to e-Conspicuity and automated separation algorithms. The Network Identification service (NRI) meets the objective of providing advice and information useful for the safe and efficient conduct of UAS flights. Aside from position, other information that should be output are UAS operator registration number, unique physical serial number of UAS, the geographical position of the unmanned aircraft and its height above the surface or take-off point, the route course measured clockwise from true north and the ground speed of the UA,, the geographical position of remote pilot or, if not available, the take-off position point, the emergency status of the UAS and the time at which the messages were generated.The Network Identification service also acts as a substitute for Direct Remote Identification (DRI) as in EU regulation 2019/947 [RD 14]. DRI is a system that ensures the broadcasting of information about a UASs in operation so that the information can be accessed remotely. This system allows people to identify a UAS within their line of sight.

The next relevant service is Tactical Conflict Prediction and Resolution, a process of resolving conflict that happen during the flight by changing speed, heading, or altitude. These can be achieved as an advisory or as systems giving instructions. The service requires situation awareness in which reliable positioning of all aircraft is known and frequently updated in the U-Space volume being served.

Additionally, current motion and possibly intent can be considered to predict conflict and alert operators.
To conclude, the tactical conflict prediction and resolution will use data from either direct remote identification or network identification to resolve the conflict. Two key aspects to enable this service are the positioning precision and accuracy and the update frequency. Section 5 below will discuss in detail the implementation of this service.

4.4 Flight Rules

From ICAO Annex 2, rules of the air have been stated to govern aircrafts behaviour during potential mid-air collision [RD 13]. Two distinct flight rules are defined, visual flight rules (VFR) and instrument flight rules (IFR). In case of possible collision, Annex 2 section 3.2 describes the rules of the air related to avoiding collision. In VFR, the pilots of each aircraft are expected to be visually aware of their surroundings.
When the trajectories of the two aircrafts are converging at approximately the same altitude, the aircraft on the right has the right of way. Several exceptions apply, the aircraft must five give way to airships, gliders, balloons, and to aircraft which are towing objects. When an aircraft is being overtaken, it has the right of way, and the overtaking aircraft must stay away by changing its heading to the right. Lastly, two aircrafts are on a head-on situation, both must change their heading to the right.
Within U-space airspace, U-space flight rules (UFR) shall apply uniquely to airspace users in receipt of U-Space services. The aim of UFR is to enable pilots being informed of the relative positions of aircraft by means of e-conspicuity. The rules enable aircraft operations that cannot conform to either VFR or IFR to operate safely. Aircrafts conforming to UFR are required to be electronically conspicuous to the ground system(s) and to other aircraft within the U-space airspace. They are also expected to have air traffic separation service managed by a U-space service.

5 CERTIFLIGHT

The CERTIFLIGHT platform has a primary objective of ensuring data traceability for UAS positioning, avionic, payload, and sensors data. This data, with time and location authentication, can be immensely helpful in a forensic analysis in case of accident or incidents, and in case of airspace infringements. Lastly, the quality assurance of the data provided by CERTIFLIGHT opens new possibilities for U-space services such as smart contract activation with specific conditions related to flight paths, time of flight, or geo-awareness information. Figure 5-1 shows the CERTIFLIGHT preliminary concept.

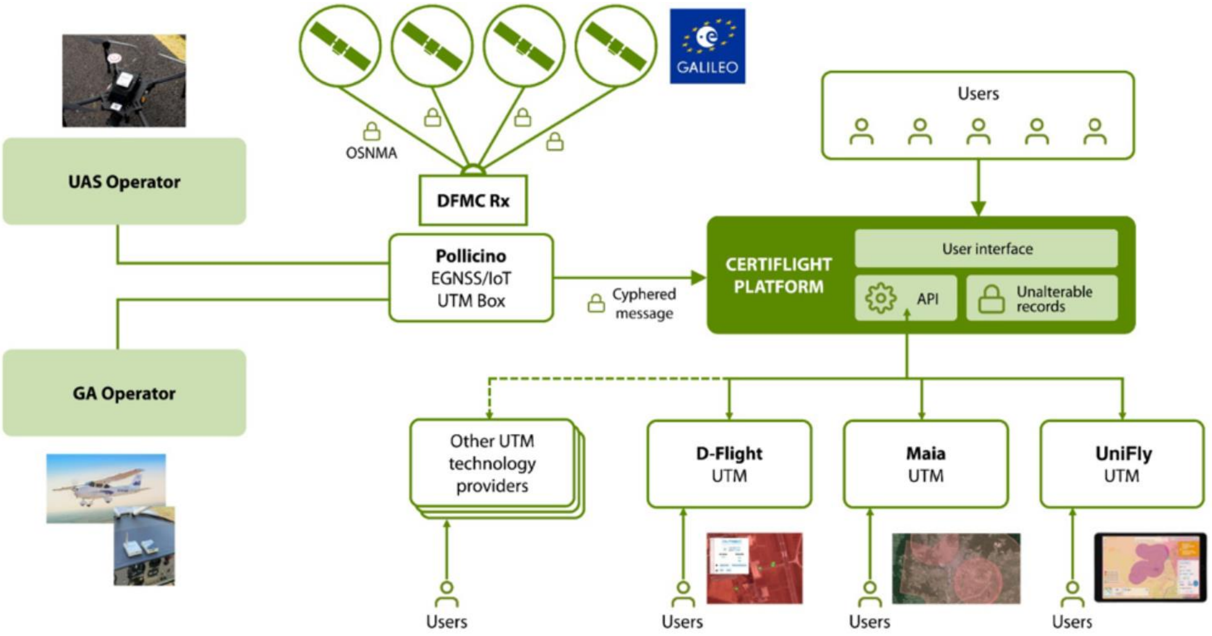


Figure 5-1 CERTIFLIGHT Preliminary Concept

The UTM Box is an EGNSS/IoT transponder mounted on UASs and on GA/Ultralight aircrafts as an add-on (EFB - Electronic Flight Bag). It is the fundamental key enabler for the CERTIFLIGHT solution. The UTM Box will be designed having in mind robustness, reliability, and anti-tampering mechanisms, considering the successful experience of the previous model Pollicino® (self-funded by TopView) with basic tracking functionalities. The UTM Box envisioned for CERTIFLIGHT will be addressed for UAS and GA needs, with the very same electronics, but different HMI (Human Machine Interface).

Figure 5-2 shows the specification of the new UTM Box. The direct remote identification (DRI) and network remote identification (NRI) is in accordance with the EU regulation 2021/664-665-666 for the General Aviation aircraft and UAS situational awareness in the U-space (e-Conspicuity). The positioning system is enabled by EGNSS receiver along with the IMU and barometer integration, resulting in a more precise and accurate estimation. Lastly, warnings to GA aircraft and an optional and advisory autonomous separation for UASs are provided.

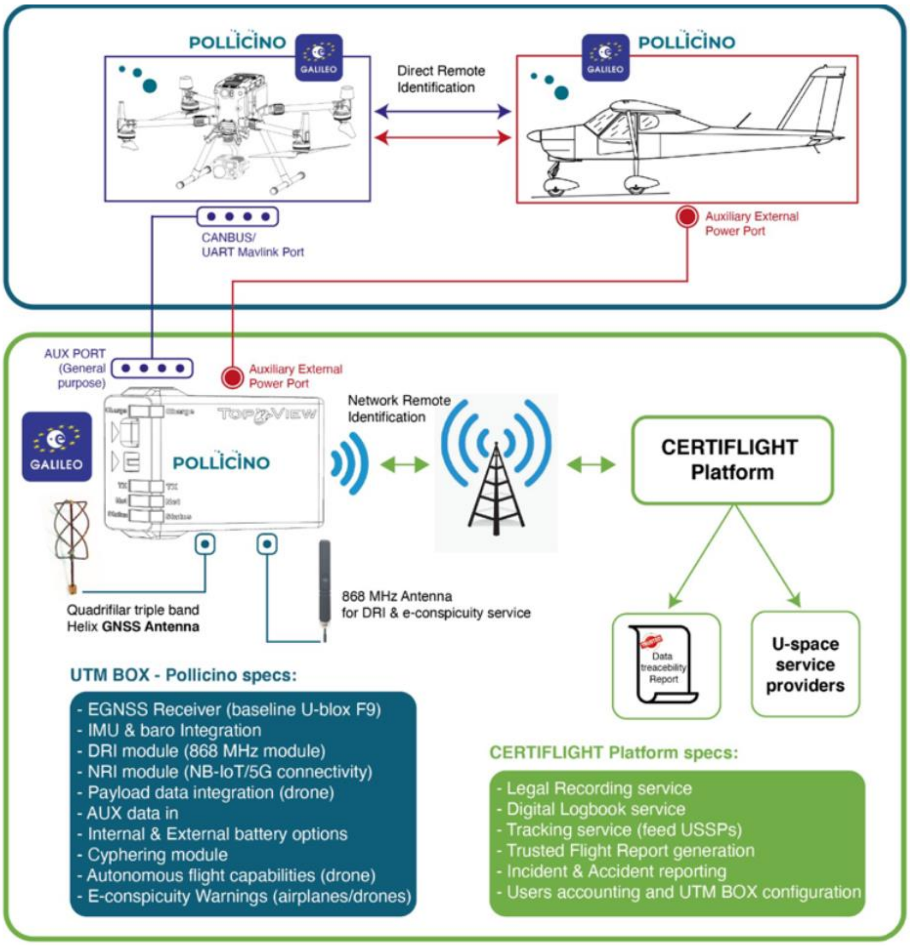


Figure 5-2 UTM Box specification as the next generation Pollicino® UTM Box

The three sub-sections below describe e-Conspicuity available in the CERTIFLIGHT platform, its use cases for UASs and GA aircrafts, and the automated separation algorithm. The e-Conspicuity sub-section includes the DRI and NRI means of communication and frequency update requirement. The use case part provides three main conditions namely, UAS to UAS, GA to UAS, and GA to GA. Lastly, the automated separation algorithm sub-section discusses the priority-based integration of the velocity obstacle method.

5.1 E-Conspicuity

As mentioned in sub-section U-Space Services, direct remote identification and network identification enables aircraft flying in U-space to be electronically conspicuous to its surroundings. The aircraft will provide its position and flight information periodically to both ground system(s) and other aircraft.

CERTIFLIGHT proposes both DRI and NRI communication features. The DRI uses an available ISM frequency band (868 MHz) or new frequency bands allocated specifically for U-space services. With DRI, communication between UASs and GA aircrafts are possible as long as they are within the radio communication range. The second feature is NRI which implement 4G/5G technology. Based on the surveillance type, DRI is categorized as a distributed-dependent type while NRI is a central-distributed dependent type. The combination of both means of communication and surveillance type enables redundancy and wider coverage of the e-Conspicuity.

Several communication characteristics have been discussed through standards and technical specification documents [RD 11, RD 15]. Typically, the transmission rate is expected to be once every second. Using the same criteria as in RD 11, one can expect the minimum transmission rate is once per 5 seconds. Furthermore, data packets should be discarded or flagged if time elapsed after obtaining GNSS fix exceed 1000ms.
Given the means of communication (DRI or NRI) and their characteristics, a maximum limit of the look-ahead time should be defined. The look-ahead time is an important aspect for the conflict resolution method that will be discussed in the next sub-section.

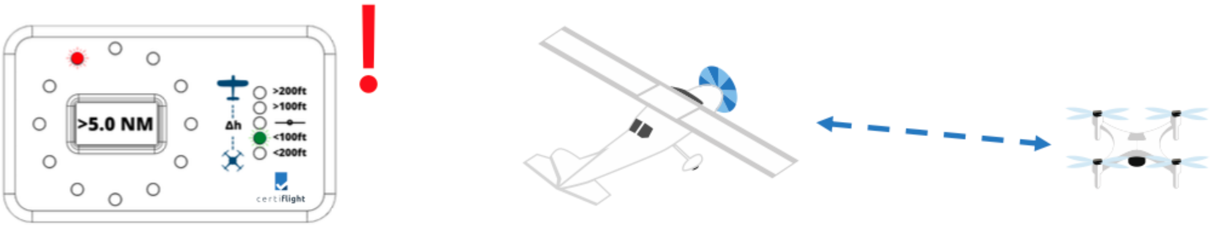


Figure 5-3 Possible mock-up of UTM Box for GA

5.1.1 COTS for e-Conspicuity

Some COTS of particular interest for the project have been already identified by the Consortium for possible integration in the UTM Box. In particular a chipset provided by the polish company Aerobits implementing both Flarm (in-out) and ADS-B (in) protocol has been identified and procured. The chipset is provided with a development board for testing the technology.

ADS-B/ Flarm Chipset and Development Board

TT-SF1 is a high quality and low-price OEM ADS-B/GNSS receiver/FLARM transceiver series operating at 1090MHz and region dependent FLARM frequency. It is based on the proven FPGA-In-The-Loop™ technology, which is a unique combination of a multi-core processor and FPGA. The patented solution allows high-speed RF data processing with significantly reduced number of electronic components.

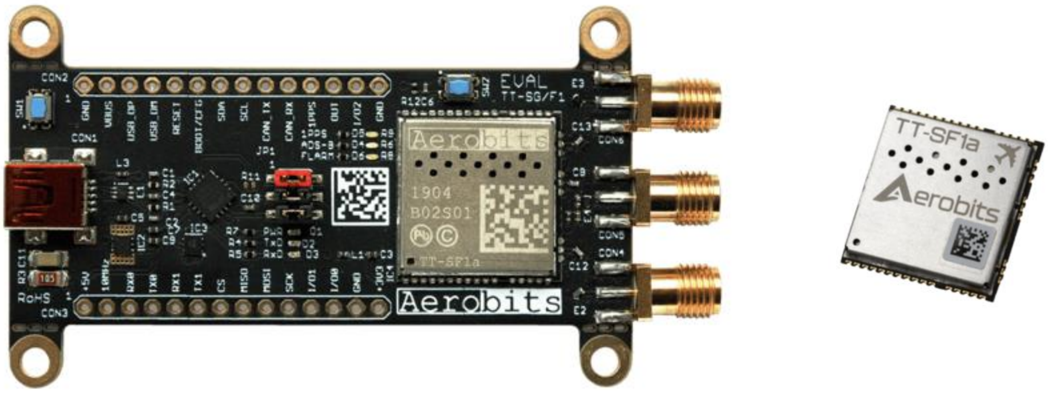


Figure 5-4 Development Board TT-SF1 and Aerobits chipset for Flarm / ADS-B

Simultaneous miniaturization of the module and its OEM nature open a wide range of possible applications, making this chipset suitable for the UTM Box and e-Conspicuity automated algorithms implementation.

The basic version of module offers the possibility of receiving and decoding ADS-B and Mode-A/C/S in different modes. The main features interesting for Certiflight applications are presented:

- Fastest ADS-B implementation on a surface of <4cm2
- Receiving of ADS-B, Mode-A/C/S with RF signal strength/quality analysis
- Time stamp (raw data only) for multilateration
- Multiple supported protocols, i.e. RAW HEX, CSV, AERO, MAVLink, ASTERIX, GDL90
- Integrated high quality GNSS position source (although a dedicated OSNMA chipset will be interfaced, the internal GNSS position source could be also useful for internal PVT comparison purposes)
- Licensed FLARM transceiver
- High-resolution ADC with real-time signal processing; best-in-class aircraft tracking
- High sensitive front-end, jamming and ESD protection (only version b) with ranges over 150 km (open space, 1dBi antenna)
- Simple module integration via UART interface and AT commands
- Scalable OEM solution with enormous customization potential (additional functions or interfaces on request)
- Firmware update capability (uC and FPGA)

ADS-B/ Flarm Ground Station

OGS station is an ADS-B and FLARM Omni-directional receiver station with multi-constellation GNSS sensor to provide best accuracy. LTE connectivity allows usage in all LTE/4G rich environments without the need for any additional cabling to send data. It has been designed to allow quick and easy assemble enclosed in IP67 case for high weather condition resistance. Device comes with all necessary cables and antennas for straight forward installation.

Figure 5-5 Omnidirectional Ground Station - OGS Aerobits for Flarm / ADS-B (in)

The OGS is a perfect solution for permanent installation in open areas for constant airspace monitoring and conducting VLOS/BVLOS operation where safety is critical.

This COTS will be basically used for development and testing activities of the UTM Box (for cross checking e-Conspicuity signal transmission and reception). However, it may have some interesting use also for some use case implementation and for the interface with the U-space service providers.

5.2 Automated Separation Algorithm

Automated separation is a feature that is under development in CERTIFLIGHT to provide a separation assurance and collision avoidance system. This feature benefits from the e-conspicuity to have situational awareness of the surrounding traffic. With that information, potential conflicts between UASs or GA aircrafts can be detected. A resolution advisory will be announced by the UTM Box to guide the pilot, either on-board or remote, to successfully deconflict. Additionally, the advisory can be used to guide UASs for a highly automated deconflict manoeuvre.

Error! Reference source not found. depicts a conflict, indicating that if both UAS continue with their current state, they will get closer than the predefined minimum separation distance. The state projection goes as far as the “look-ahead time”. The value of the protected zone radius may depend on the aircraft type and performance. When both UASs maintain their state and the t_1 becomes the actual time, the UASs are flying within other’s protected zone, this event is called loss of separation (LoS) or intrusion.

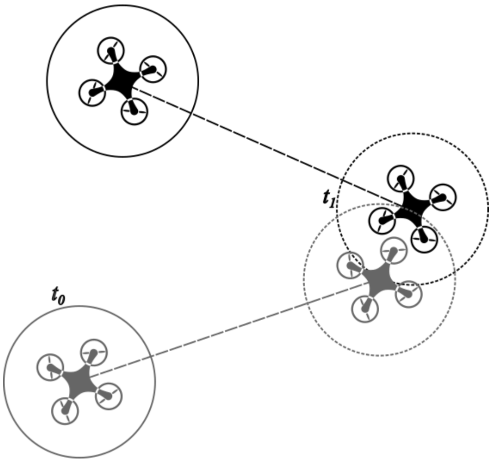


Figure 5-6 Conflict Detected

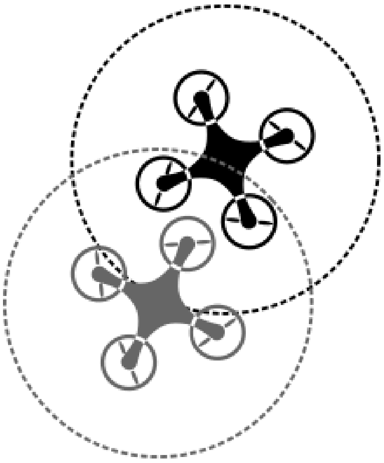


Figure 5-7 Loss of Separation

This research aims evaluate the effect of communication, navigations, and surveillance on the conflict detection and resolutions. The conflict detection uses a state-based approach, projecting the current state into the future and taking into account the communication and navigation uncertainties. Using linear projection of the current state, the time to CPA is calculated as shown in (1).

$$t_{CPA} = -\frac{\vec{d}_{rel}\vec{v}_{rel}}{|\vec{v}_{rel}|} \tag{1}$$

With $\vec{d}_{rel}$ as the cartesian distance vector in meter between the conflicting UASs and the $\vec{v}_{rel}$ is the relative velocity vector in meter per second of the UASs. The distance between aircraft at CPA, in meters, is calculated as shown in (2). Then, when the calculated closest point of approach is smaller then the horizontal spacing, a time interval can be calculated in which the loss of separation will exist if no action is taken. The values are calculated as shown in (3).

$$d_{CPA} = \sqrt{\vec{d}^2{}_{rel} - t_{CPA}^2 . \vec{v}^2{}_{rel}} \tag{2}$$

$$t_{in}, t_{out} = t_{CPA} \pm \frac{\sqrt{}({R_{PZ}}^2 - {d_{CPA}}^2)}{\vec{v}_{rel}} \tag{3}$$

With those equations, a conflict is said to be detected when the d_{CPA} is smaller than RPZ and the t_{in} is smaller than the lookahead time. In this research, both the RPZ and the lookahead time are considered as independent variables since no definitive regulation are established for the moment.

The conflict resolution uses a Modified Voltage Potential (MVP) algorithm as the baseline [RD 20]. On the next deliverable (D3.5), a priority-based rules and velocity obstacle algorithm will be developed as the conflict resolutions and will be compared to the baseline.

6 Experiment Design

6.1 BlueSky

BlueSky is an open data and open-source ATC simulator created by the Faculty of Aerospace engineering at TU Delft [RD 19]. The tool enables the implementation and evaluation of different communication, navigation, and surveillance (CNS) model as well as variety of CD&R method under the same scenario. BlueSky uses aircraft’s performance model to in the simulation. For this research, a DJI M600 model is used due to its wide speed range and commonly used for industrial applications.

6.2 Independent Variables

6.2.1 Conflict Detection

Conflict geometry describes how a conflict will be detected when two aircrafts are flying close to each other. The first variable is the lookahead time, a variable to determine how far the state of aircrafts will be projected in the future, ranging from 6s, 15s, 50s, and 100s. Next, since no regulation exists for the protected zone radius, this variable will be varied between 30 meters and 50 meters for UAS.

6.2.2 Communication systems

A condition where communication is not established for a certain time will be modelled. The communication system will be based on RD 11, having the update rate of once every second or 1 Hz, and a minimum update is once every 5 seconds. To describe the probability of the update for every second, RD 17 is used as a reference. It shows that 97.5% of ADS-B messages are sent within 5 seconds, with 67.5% of it takes less than 3 seconds. The same criteria will be applied in this research.

The approach to the communication model is that the probability of sending the data will remain constant for each one-second step size. For the simulation, each aircraft instance has a variable to count the time elapsed since the last update. Then, a randomised value is compared to the probability of data transmission. Aircraft instances with a random value less than the probability will be updated and the time elapsed is reset. This process can be represented as a Markov Chain and the resulting update interval frequency as shown in Figure 6-1. With this model, approximately 67.5% of the data is sent within 3 seconds, and 80% is sent within 5 seconds. Considering the ADS-L performance will be less than ADS-B, the model is considered as acceptable.

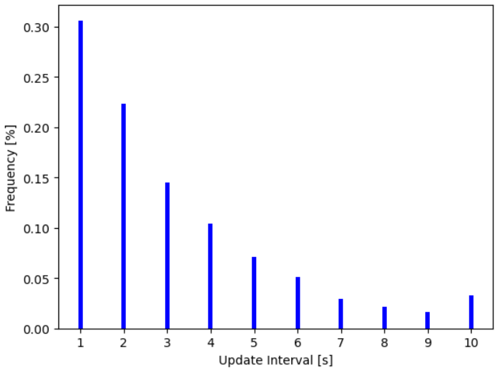


Figure 6-1 Histogram of Update Intervals

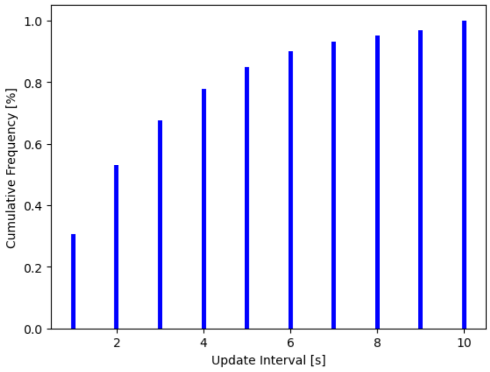


Figure 6-2. Cumulative Frequency of Update Interval

6.2.3 Navigation systems

The navigation system for the CERTIFLIGHT solution will be based on Galileo, Europe's global navigation satellite system. RD 11 categorized the horizontal position accuracy based the 95% accuracy bound to describe the data quality of the navigation system. For instance, a horizontal accuracy bound of 10m means the 95% of the measured position are within 10m of the real position. For this research the accuracy bound will be varied from 3m, 10m, and 30m. For simplicity, the horizontal position will be abbreviated as HPOS.

6.3 Dependent Variables

6.3.1 Precision and Recall

In the presence of uncertainty, the detection algorithm performance can be evaluated by measuring false positives, false negatives, and true positives occurrence. False positives occur when the algorithm predict the conflict occur, or positive outcome, but the actual condition is negative. On the other hand, false negatives happen when the model predicts a negative outcome despite the potential conflict exist in the actual condition. Lastly, true positives mean the algorithm correctly predict the outcome.

Figure 6-3 depicts how the false positives, false negatives, and true positives occur during the conflict detection, with the inner circle represents the RPZ 30 and the outer circle represents RPZ 50. For instance, in an ideal case, the projected ideal state of both Drone 1 and Drone 2 is compared. The conflict is not detected for RPZ 30 while it is considered as a conflict for RPZ 50. In a measured case, suppose the ownship is Drone 1 and the intruder is Drone 2, the projected ideal state of Drone 1 will be compared to the projected measured state of Drone 2. From the figure, it can be observed that both RPZ 30 and RPZ 50 will be considered as a conflict. On the other hand, if we select Drone 2 as the ownship and Drone 1 as the intruder, no conflict will be detected. This is how the false detection in the conflict detection arises.

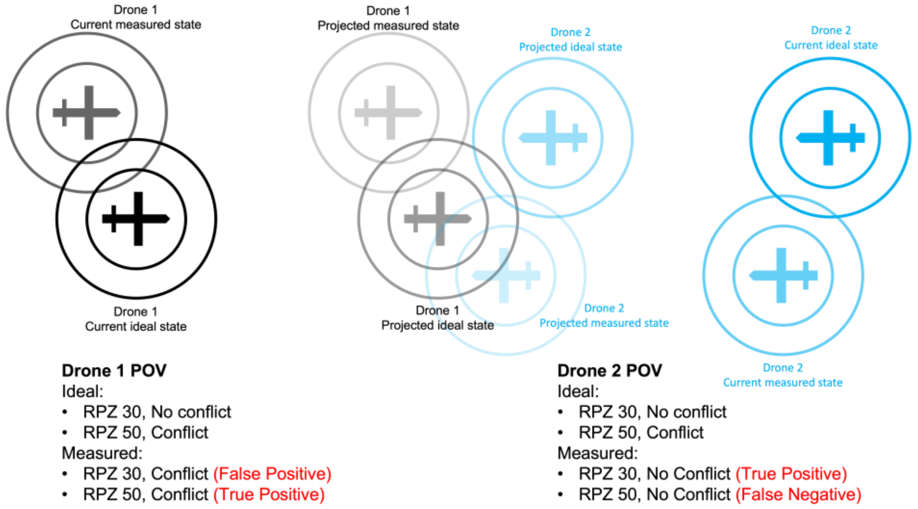


Figure 6-3 False Positive and Negative on Conflict Detection

Two variables can be used to describe both the correct and incorrect prediction. The first one is precision, which captures the proportion of true positives out of all positive predictions, providing insight into how good the algorithm avoids false positives. The next one is recall, which measures the ratio of true positive predictions out of all actual positive instances, indicating the effectiveness of capturing positive instances. The equations for both precision and recall are shown in equation (4) and (5).

$$Precision = \frac{True\ Positive}{(True\ Positive + False\ Positive)} \tag{4}$$

$$Recall = \frac{True\ Positive}{(True\ Positive + False\ Negative)} \tag{5}$$

6.3.2 Safety

Two metrics can be used to measure the safety of the automated separation algorithm. The first is the Intrusion Prevention Rate (IPR) derived by Sunil et al., [RD 18]. This metric describes the number of conflicts (n_{cfl}) that results into intrusion (n_{LoS}), as shown in equation (6). The value range of IPR is between 0 and 100 percent. When none of the conflicts evolve into an intrusion, the IPR is a hundred percent. The higher the IPR, the better the conflict detection and resolution is.

$$IPR = \frac{n_{cfl} - n_{LoS}}{n_{cfl}} \tag{6}$$

The next metric is the loss of separation (LoS) severity. This metric can describe how close the intruder aircraft came to the ownship during a loss of separation, written mathematically as in equation (7). Here, R is the radius of protected zone (RPZ) of the ownship while the d_{CPA} is the closest distance between the conflicting aircraft. The value range of LoS severity is between 0 and 100 percent. When two aircrafts collide in the air, the closest distance between the two is zero thus the LoS severity is a hundred percent. The lower the LoS severity, the better the conflict detection and resolution is.

$$LoS_{sev} = \frac{R - d_{CPA}}{R} \tag{7}$$

6.4 Scenario

Monte Carlo simulation is used in this research to model and analyse the uncertainty and variability of the air traffic. Large random samples from probability distributions are used to simulate multiple possible outcomes. By doing so, the simulation method provides insights into the range of potential outcomes associated with different scenarios.

6.4.1 General Setup

Error! Reference source not found. shows the parameter setup for the Monte Carlo simulation in this research. The safety variables, mentioned in 6.3.2, are evaluated on different horizontal position (HPOS) accuracy, communication model, lookahead time, and radius of protected zone (RPZ). The horizontal position accuracy is considered at three different levels: 3m, 10m, and 30m. Next, the ideal communication model assumes data exchange between UASs happens every 0.05s (i.e., equal to the simulation update rate), whereas ADS-L considers the update rate as 1s, and lastly the ADS-L with delay follows the model as explained in section 6.2.2.

Parameters	Range	Randomization	Unit
Number of vehicles per scenario	800	-	[-]
Number of scenarios	32	-	[-]

Lookahead time	{6, 15, 50, 100}	-	[s]
Radius protected zone, RPZ	{30, 50}	-	[m]
Horizontal position accuracy, HPOS	{3, 10, 30}	-	[m]
Communication Model	{Ideal, ADS-L, ADS-L with Delay}	-	[-]
Initial Closest Point of Approach	[0, 2*RPZ*HPOS]	uniform	[m]
Initial relative heading	[10, 350]	uniform	[deg]
Ground Speed	[15, 35]	uniform	[kts]
Ground speed standard deviation	1.5	normal	[m/s]

Table 6-1 Parameter ranges and randomization

Figure 6-4 shows an illustration for the conflict setup. As mentioned in Table 6-1, the initial closest point of approach (d_{cpa}) will be varied uniformly between 0 and twice the radius of protected zone times the horizontal position accuracy. The initial relative heading ($\Delta\psi$) is set between 10 and 350. Lastly the ground speed can be varied between 15 and 35 kts, with a measurement accuracy of 1.5 m/s.

Potential conflicts between the aircraft are limited to pairwise conflicts. With 800 UASs per scenario this means 400 potential conflict pairs are simulated. The initial states of these conflict geometries and corresponding aircraft, such as closest point of approach, relative heading, and ground speed are randomized for 32 different scenarios, thus producing 12,800 unique potential conflicts for each different set of parameters. Figure 6-5 and Figure 6-6 shows the implementation in BlueSky.

To enable all conflict to be resolved and avoid one aircraft have multiple conflict at the same time, the simulation area and duration are dependent on the lookahead time. The simulation area is an imaginary square with the side set to 6 times the lookahead time multiplied by 35 kts, the maximum speed. The simulation duration is set to 18s, 45s, 100s, and 200s, for each lookahead time respectively, ensuring the potentially in conflict aircraft to diverge.

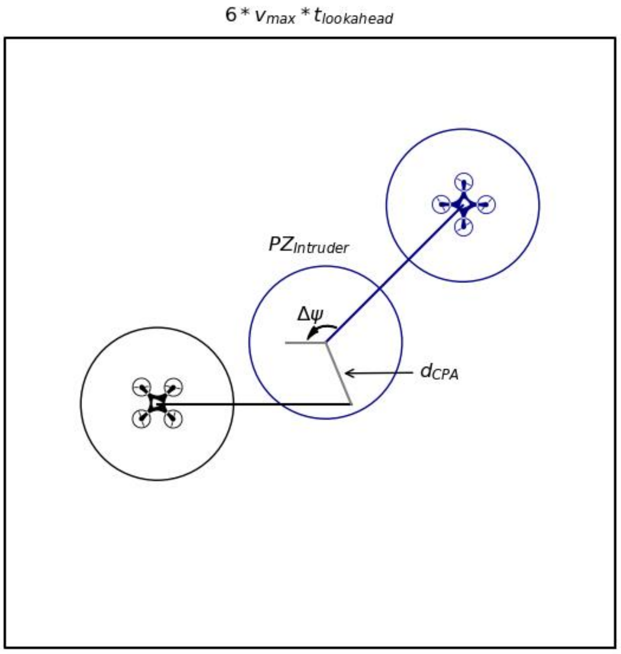
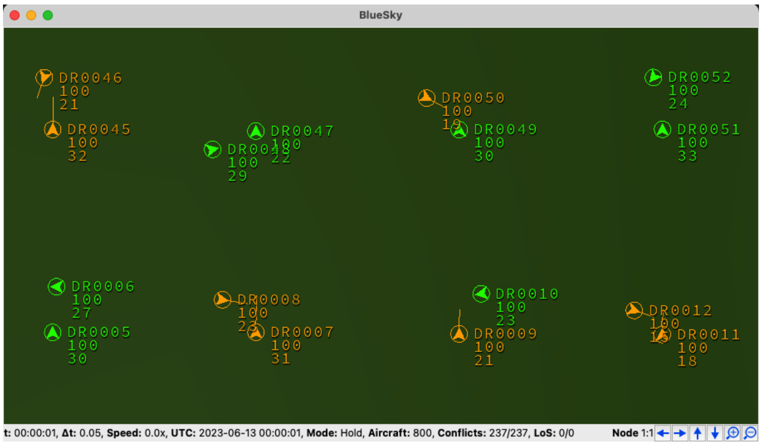
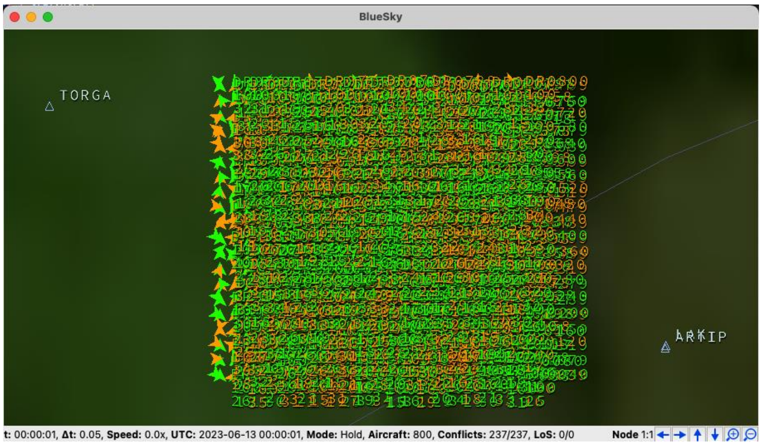


Figure 6-4 Conflict Setup



t: 00:00:01, Δt: 0.05, Speed: 0.0x, UTC: 2023-06-13 00:00:01, Mode: Hold, Aircraft: 800, Conflicts: 237/237, LoS: 0/0

Figure 6-5 Implementation in BlueSky



t: 00:00:01, Δt: 0.05, Speed: 0.0x, UTC: 2023-06-13 00:00:01, Mode: Hold, Aircraft: 800, Conflicts: 237/237, LoS: 0/0

Figure 6-6 One scenario with 800 aircrafts

7 Results and Discussion

The precision, recall, and safety parameters are obtained from the Monte Carlo simulation by having thousands of potential mid-air collisions. All results are discussed throughout the section, first by presenting the precision and recall of the detection in different settings. The next two are the intrusion prevention rate (IPR) and LoS severity, obtained by using MVP as the resolution method.

7.1 Precision and Recall

Figure 7-1 shows the precision of different lookahead time for RPZ of 30m and 50m. When considering highly optimistic navigation with a horizontal positional accuracy of 3m, the lowest lookahead time exhibits the highest precision. However, as positional accuracy decreases, the 15s lookahead time demonstrates the best precision. As explained in section 5.2, Automated Separation Algorithm, the detection considers the relative position and relative velocity between two UASs. The navigation model has both position and velocity error which affecting the detection. Higher lookahead times show lower precision compared to uncertainty when projecting the position by adding the velocity (with a certain error) times lookahead time ahead into the future. Figure 7-2 reveals that recall exhibits a similar characteristic to precision across different lookahead times.
When comparing the two RPZs, it is evident that a higher RPZ leads to increased precision and recall, as the potentially-in-conflict area expands. However, a larger RPZ may result in a greater deviation from the current path, posing a potential trade-off to consider.

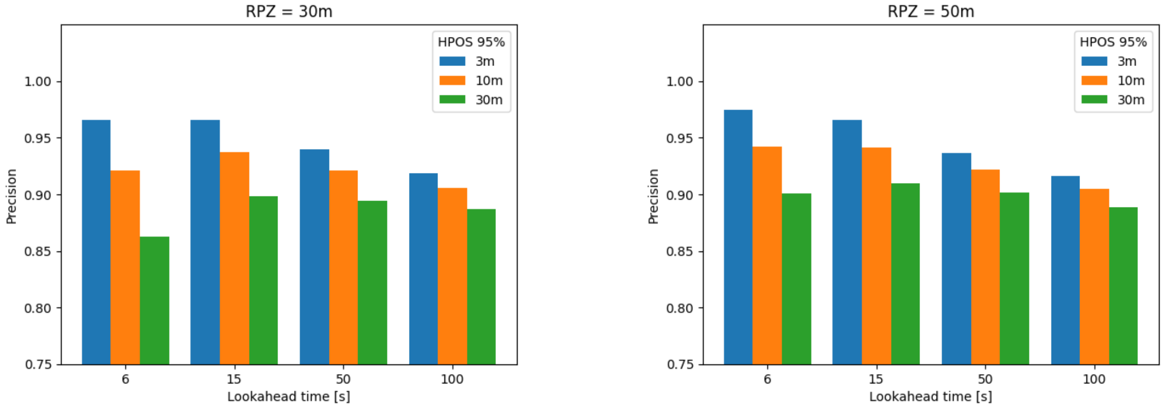


Figure 7-1 Precision

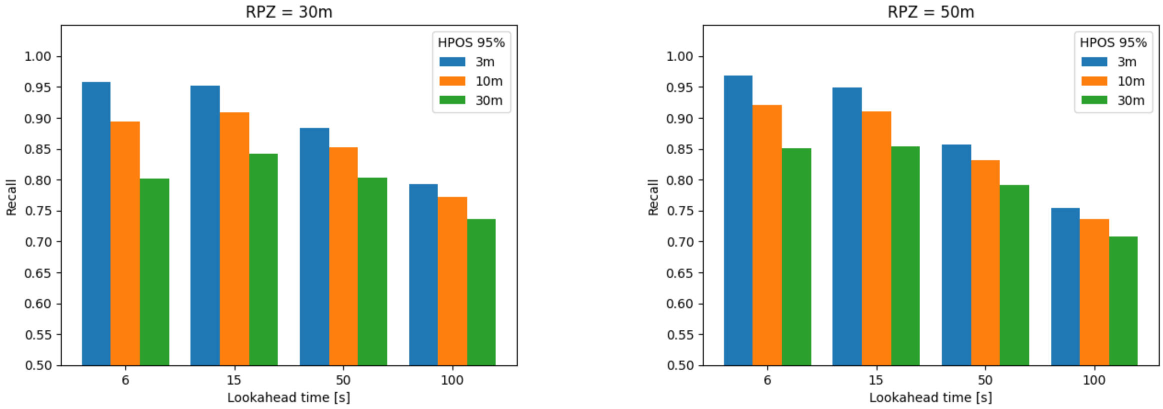


Figure 7-2 Recall

7.2 Intrusion Prevention Rate

The results of the intrusion prevention rate with different set of parameters are shown in Figure 7-3 and Figure 7-4 for RPZ 30m and 50m respectively. From data availability point of view, when data is updated each 0.05s (Ideal), the intrusion prevention rate is nearly 100% for all lookahead time, except for the low lookahead time . When the data update interval is extended to 1s (ADS-L), the conflict resolution performance decreased. Furthermore, ADS-L with delay significantly reduce the conflict resolution performance.

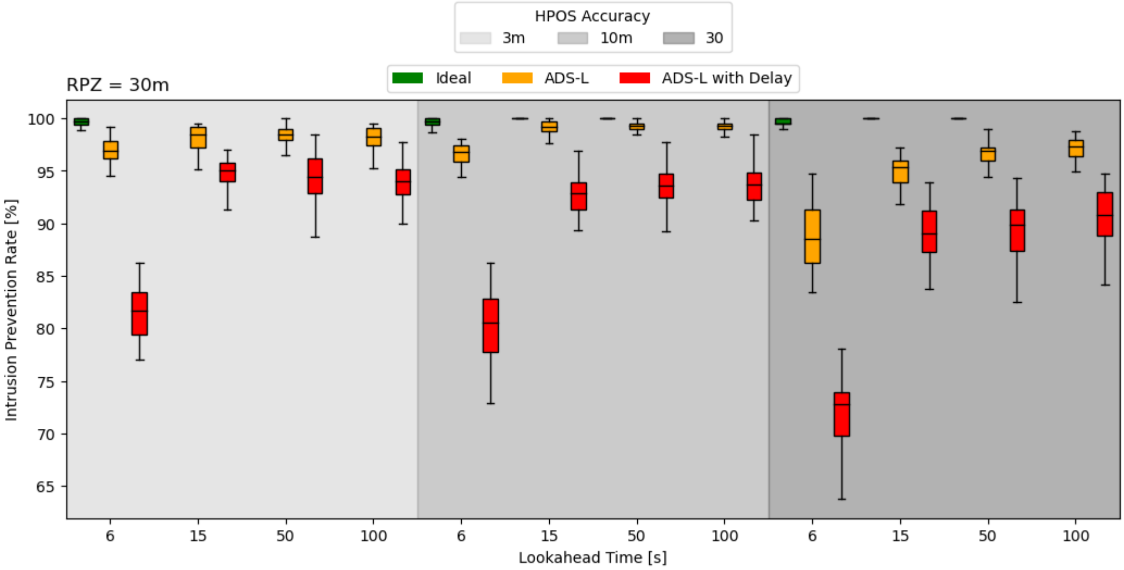


Figure 7-3 Intrusion Prevention Rate, RPZ = 30m

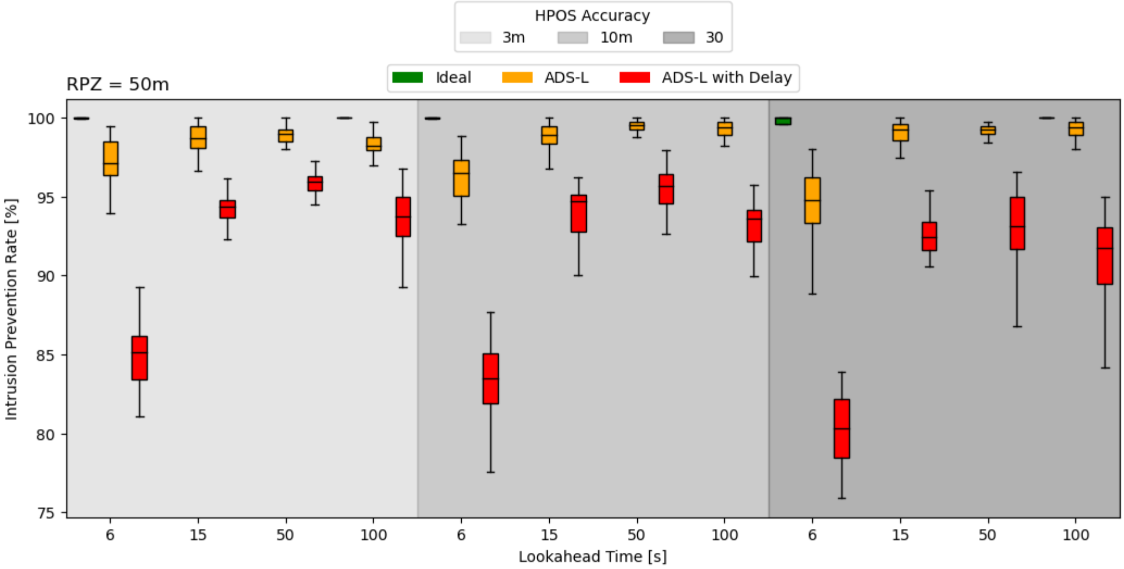


Figure 7-4 Intrusion Prevention Rate, RPZ = 50m

From a navigational uncertainty point of view, the lower HPOS accuracy results in more potential conflict that evolve into a loss of separation. The lowest IPR exists for the lowest HPOS accuracy with the lowest lookahead time, for RPZ values of 30m and 50m. The performance is significantly higher for 15s lookahead time compared to 6s lookahead time, but only slightly improved for 50s and 100s.

Even in the lowest HPOS accuracy, the median for the IPR is higher than 90 percent for lookahead time equals to 15s or more.

7.3 LoS Severity

This section presents the result of the Loss of Separation (LoS) severity for the different parameters mentioned in General Setup. In terms of communication effect, it can be seen from Figure 7-5 and Figure 7-6 that a higher communication rate will result in lower LoS severity. One can also observe that the delay significantly affects the closest point between both aircrafts, as can be seen in Figure 7-5, the higher the delay the higher the LoS severity.

The effect of navigation accuracy shows that the lower the accuracy, the higher the LoS severity is. The severity can be reduced significantly by increasing the lookahead time from 6s to 15s, but the impact is less significant by increasing it beyond 15s. More importantly, the LoS severity can be greatly decresed by changing the radius of protected zone, having the highest LoS severity from 100% for RPZ 30m to slightly more than 50% for RPZ 50m.

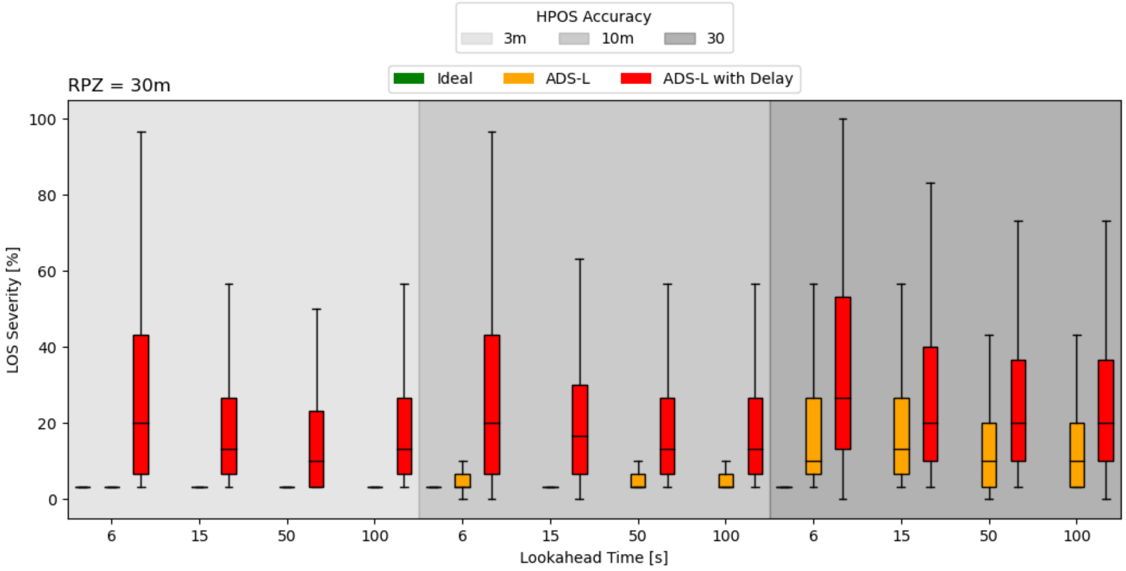


Figure 7-5 LoS Severity, RPZ = 30m

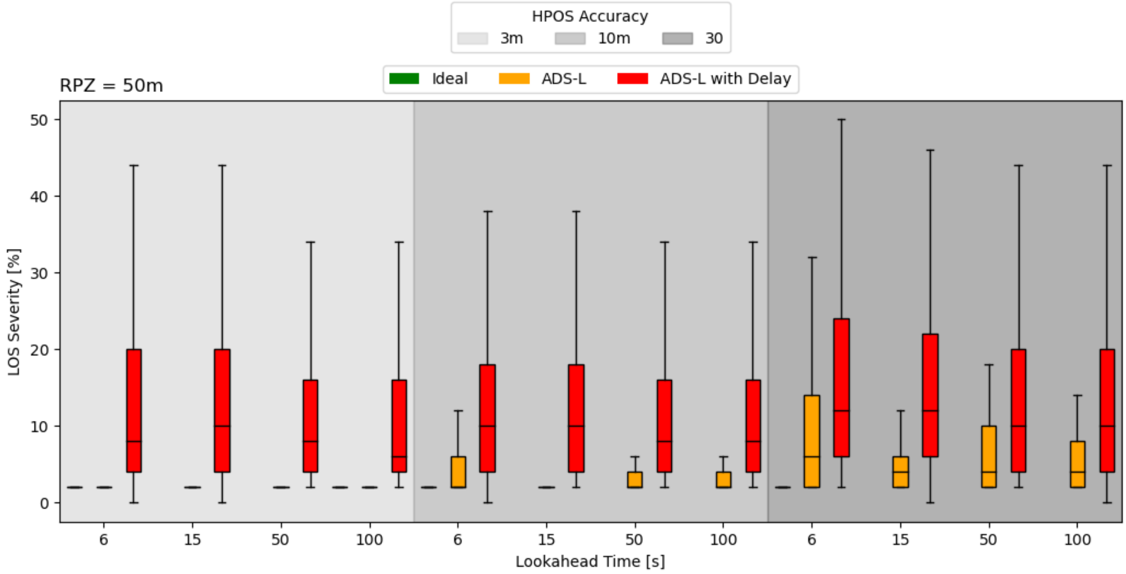


Figure 7-6 LoS Severity, RPZ = 50m

8 Conclusion

To measure the effect of communication delay and positioning accuracy on automated separation algorithms, thousands of potential conflicts between pairs of UASs are simulated in BlueSky. Conflicts are detected by projecting the current state of the UAS into the future, while the conflict resolution uses MVP. Each simulation contains different set of parameters such as lookahead time, radius of protected zone, communication model, and navigation accuracy. Precision, recall, intrusion prevention rate, and loss of separation severity are used to evaluate the performance.

First, the precision and recall of the conflict detection decreases as the uncertainty gets higher. When comparing between different lookahead times, it is seen that a higher lookahead time reduces the precision and recall. This happens because the state, with its uncertainty, is projected further into the future and the error propagates by integration.

For the intrusion prevention rate (IPR) it is observed that a lower update rate and communication delay significantly increase the number of conflicts that evolve into loss of separations (LoS). Moreover, the IPR gets lower as the navigation accuracy decreases. Changing the lookahead time from 6s to 15s effectively improves the results but increasing it from 15s onwards has little impact. Comparing between RPZ values of 30 and 50 meters, it is clear that the wider the radius of protected zone, the higher IPR is since the separation becomes more conservative.

Lower update rate and communication delay have a substantial impact on the severity of loss of separation (LoS) issues, potentially leading to mid-air collisions. Likewise, with lower navigation accuracy there is a clear trend of increased severity. Increasing the lookahead time results in a less severe conflict, with a significant improvement observed when changing it from 6s to 15s or beyond. Expanding the radius of the protected zone from 30m and 50m greatly enhances safety, as it increases the minimum distance between conflicting unmanned aerial systems (UASs) from a mid-air collision to a minimum of 25m.

Through this research activity, we have assessed the impact of communication delay and navigation accuracy on the safety of conflicting UASs. Future research opportunities lie in refining the communication model, investigating additional navigation uncertainty models, and exploring different combinations of lookahead time and radius to determine the optimal configuration for achieving specific safety characteristics. Also, for the next research activity, another conflict resolution method using a priority-based and velocity obstacle algorithm will be developed to enable non-homogenous encounters, such as between UAS and GA aircraft. Lastly, an efficiency metric can be added to evaluate the path deviation due to the CD&R method.