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Design and Implementation of a Traffic Display System for the Ground Control Segment of an Unmanned Hexacopter

TESI DI LAUREA MAGISTRALE IN Aeronautical Engineering

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Abstract

The prevention of mid-air collision (MAC) has always been a critical safety issue in aviation, and with the ever-expanding presence of unmanned aerial systems (UAS), the airspace is becoming increasingly crowded. As such, it is necessary for any air vehicle to be equipped with the correct surveillance technologies, which allow said vehicle to simultaneously detect the surrounding traffic and to transmit its own presence in the airspace. Automatic Dependent Surveillance-Broadcast (ADS-B) and Flight Alarm (FLARM) constitute part of cooperative surveillance technologies; such techniques rely on aircraft broadcasting their own positions, thus ensuring they maintain spatial distance from other traffic.

In this thesis, a traffic display system is presented, for which both a fusion algorithm and a feasible traffic display have been developed. The former provides integration between three specific position data sources, which are able to receive ADS-B and FLARM broadcasts, while the latter reflects the conventional information gathered from surrounding air vehicles ADS-B is mandatory for commercial aircraft and its coverage is continuously increasing. As such, data fusion between ADS-B and FLARM presents a unique avenue for research. FLARM is commonly used in general aviation and glider operations; over 40,000 manned aircraft and many unmanned aerial vehicles are already equipped with FLARM, and this number is only set to increase.

Thus, a traffic display system validated using the OpenSky Network historical database, which merges both these technologies to consequently display the traffic, offers significant value.

Keywords: UAS, ADS-B, FLARM, Data Fusion, Traffic Display System, Ground Control Segment, Cockpit Display of Traffic Information, Hexacopter



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List of Acronyms

Acronym Description

ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance-Broadcast
ADS-R	Automatic Dependent Surveillance–Rebroadcast
ASL	Above Sea Level
AT	Air Traffic
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
CAS	Collision Alerting System
CDTI	Cockpit Display of Traffic Information
CS	Certification Specifications
CS-ACNS	Certification Specifications and Acceptable Means
	of Compliance for Airborne Communications,
	Navigation and Surveillance
CSMA	Carrier Sense Multiple Access
DAA	Detect And Avoid
DFS	Deutsche Flugsicherung
EASA	European Union Aviation Safety Agency
EFIS	Electronic Flight Instrument System
eID	Electronic Identification
EPU	Estimated Position Uncertainty
EKF	Extended Kalman Filter
ES	Extended Squitter
EU	European Union
FAA	Federal Aviation Administration
FLARM	Flight Alarm

| List of Acronyms

Acronym D		Description			
FLIR		Forward Looking Infrared			
GCS		Ground Control Station			
	GNN	Global Nearest Neighbor			
	GFSK	Gaussian Frequency Shift Keying			
	GNSS	Global Navigation Satellite System			
	GPS	Global Positioning System			
	GVA	Geometric Vertical Accuracy			
	HOD	Hook-On-Device			
	IATA	International Air Transport Association			
	ICAO	International Civil Aviation Organisation			
	IMM	Interacting Multiple Model			
	JPDA	Joint Probability Data Association			
	LTE	Long-Term Evolution			
	LIDAR	Light Detection and Ranging			
	LSN	Least Significant Nibble			
	MAC	Mid-Air Collision			
	MHT	Multiple Hypothesis Tracking			
	MLAT	Multilateration			
	MTOM	Maximum Take-Off Mass			
	MSL	Mean Sea Level			
	MSN	Most Significant Nibble			
	MSLP	Mean Sea Level Pressure			
	NACp	Navigation Accuracy Category for Position			
	NACv	Navigation Accuracy Category for Velocity			
	NAR	Non-Altitude Reporting			
	ND	Navigation Display			
	NED	North-East-Down			
	NIC	Navigation Integrity Category			
	NICbaro	Navigation Integrity Category for Barometric Altitude			
	NMEA	National Marine Electronics Association			

Acronym Description

\mathbf{PF}	Particle Filter
PPM	Pulse Position Modulation
PSR	Primary Surveillance Radar
RA	Resolution Advisory
RF	Radio Frequency
SAA	Sense And Avoid
SDA	System Design Assurance
SIL	System Integrity Level
SIM	Subscriber Identity Module
SNR	Signal-to-Noise Ratio
SPI-IR	Surveillance Performance and
	Interoperability Implementing Rule
SSR	Secondary Surveillance Radar
SV	State Vector
ТА	Traffic Advisory
TCAS	Traffic Collision Avoidance System
TDOA	Time Difference Of Arrival
TIS-B	Traffic Information Service–Broadcast
TOA	Time Of Arrival
UAS	Unmanned Aerial System
UAT	Universal Access Transceiver
UAV	Unmanned Aerial Vehicle
UTC	Coordinated Universal Time
UTM	Unmanned Aircraft System Traffic Management
VS-IMM	Variable Structure Interacting Multiple Model

Introduction

When building and testing a 600kg hexacopter, researchers at the Technische Universität München (TUM) soon realized that data fusion between different position data sources was required. For traffic surveillance purposes, two different cooperative surveillance technologies are needed: Automatic Dependent Surveillance-Broadcast (ADS-B) and Flight Alarm (FLARM). Such techniques allow air vehicles to see the traffic around them and simultaneously transmit their own position.

The aim of this thesis is to develop a traffic display system that achieves data fusion between ADS-B and FLARM, and consequently provides traffic information on a display. Going one step further, the present research suggests a possible design for a traffic display system for the Ground Control Segment of the aforementioned 600kg hexacopter.

The thesis is structured as follows: first, ADS-B and FLARM technologies are described, with emphasis on their main differences, advantages and disadvantages. The position devices are then presented, with particular attention paid to which data are transmitted and received. Section 3 discusses the traffic display system, and is broken down as follows: (i) first, a review of today's traffic displays is presented, together with possible strategies on how to merge different sensor data; (ii) the system design and architecture is then described; and (iii) system implementation is discussed, before functional tests (developed using the OpenSky Network historical database) are presented.

Finally, conclusions and future research avenues are discussed.



In the field of aviation, cooperative surveillance technologies form part of a fundamental structure that allows for safe flight inside the airspace, with the prevention of mid-air collision (MAC) being of critical concern. The International Civil Aviation Organization (ICAO) defines the aviation occurrence category MAC as "Airprox, TCAS [traffic collision avoidance system] alerts, loss of separation as well as near collisions or collisions between aircraft in flight". [1].

In other words, MAC occurs when two (or more) aircraft come in contact with each other while both in flight. This accident category is rare, but is among the most catastrophic. Cooperative surveillance technologies, such as ADS-B and FLARM, are techniques that rely on aircraft broadcasting their positions, thus ensuring they maintain spatial distance from other traffic.

ADS-B coverage is continuously increasing. As reported by the European Organisation for the Safety of Air Navigation (EUROCONTROL), aircraft equipped with ADS-B has risen to more than 96% of total flights. [2]

This growth is mainly due to the European regulatory requirements introduced; in particular, the European Commission Regulation (EU) 1207/2011 (SPI IR) and its subsequent amendments.

FLARM is commonly used in general aviation and glider operations; over 40,000 manned aircraft and many unmanned aerial vehicles (UAVs) are already equipped with FLARM, and this number is rapidly increasing. [3]

In this section, both technologies are analyzed, with a focus on their advantages, disadvantages, benefits and possible critical aspects.

1.1. ADS-B

ADS-B is a surveillance technique that relies on aircraft or airport vehicles broadcasting their identity, position and other information derived from on-board systems (GNSS etc.). This signal can be captured for surveillance purposes on the ground (ADS-B Out) or on board other aircraft to facilitate airborne traffic situational awareness, spacing, separation and self-separation (ADS-B In). [4]

This system architecture is presented in Figure 1.1.

The ADS-B acronym stands for:

- Automatic: information is sent without any interrogation signals.
- Dependent: information is derived from other on-board systems.
- Surveillance: the system provides radar-type data with higher accuracy.
- Broadcast: information is continuously sent and can be received by any suitably equipped aircraft or ground station.



Figure 1.1: ADS-B System Architecture and Protocol Hierarchy [5]

ADS-B allows for the transmission and receival of different data such as: aircraft identification (ICAO address), current position (latitude and longitude), velocity and altitude, along with system status and accuracy of the sent data.

The higher accuracy in position-reporting of ADS-B makes it a critical component of airspace surveillance. Significantly, this technology is cheaper and more reliable than primary and secondary surveillance radar (PSR and SSR), which are relative expensive.

The American Federal Aviation Administration (FAA), as well as its European counterpart EUROCONTROL, named ADS-B as the satellite based successor of radar.

Until today, air traffic control (ATC) relies on interrogation-based SSR - so-called modes - to retrieve an aircraft's identity and altitude.

Figure 1.2. compares the modes A, C, and S, which are in common use for civil aviation. [6]

	Message length	Frequencies (MHz)	Operational mode	Use cases
Mode A	12 bit	1030 (up) 1090 (down)	Independent/Non-selective interrogation	Identification
Mode C	12 bit	1030 (up) 1090 (down)	Independent/Non-selective interrogation	Pressure Altitude Extraction
Mode S	56/112 bit	1030 (up) 1090 (down)	Independent/Selective interrogation	Multiple
ADS-B/1090ES	112 bit	1090	Dependent/Automatic	Multiple

Figure 1.2: Comparison of Civil Aviation Transponder Modes [5]

Radar relies on radio signals and antennas to determine an aircraft's location, while ADS-B uses satellite signals to track aircraft movements. Radio waves are limited to line of site, meaning that radar signals cannot travel long distances or penetrate mountains and other solid objects. ADS-B ground stations are smaller and more adaptable than radar towers and can be placed in locations not possible for radar.

With ground stations in place, even in hard-to-reach areas, ADS-B provides better visibility regardless of terrain or other obstacles. [7]

The system can work on two different carrier frequencies: 1090 MHz, which is the default frequency, and 978 MHz, preferred for flying altitudes below 18,000 feet with the aim of reducing the congestion on 1090 MHz at the lowest altitudes. [5]

	ADS-B Main Technical Cha	aracteristics
	Communication type	Broadcast, message based
General features	Transmitter location	Aircraft, UAS, surface vehicles, fixed objects
	Transmission frequency (MHz)	1090 (978 preferred below 18.000 feet)
		A0: 48.5–51.5
	Maximum transmission power (dBm)	A1/A2: 51–54
Physical layer		A3: 53–56
	Maximum physical bit rate (kbps)	1000
	Medium Access Protocol	None. The packets can interfere, alleviated deploying a large number of distributed receivers
	Modulation	Pulse position modulation (PPM)
	Message types	Short squitter (56 bits) for identification, long squitter (112 bits) for identification + data
Message codification	Information encoding resolution	High-integrity GNSS
	Message frequency	0.5 Hz (up to 2 Hz)
	Authentication	No
	Encryption	No
Other features	Error detection	Yes
	Error Correction	Yes

The main characteristics of the ADS-B technology are summarized in Figure 1.3.

Figure 1.3: ADS-B Main Technical Characteristics [5]

1.2. FLARM

FLARM is the proprietary name for an electronic device used to alert pilots of small aircraft, particularly gliders, to potential collisions with other aircraft similarly equipped with the same device. [8]

FLARM presents state-of-the-art traffic information, collision avoidance and remote electronic identification technology used in general aviation, and is installed in over 40,000 manned aircraft and tens of thousands of unmanned aerial systems (UAS). [9]

It is designed for the safety benefit of pilots and small aircraft, as opposed to ATC, airliners or military. Interestingly, while it has been approved by the European Union Aviation Safety Agency (EASA), it is only recommended by EUROCONTROL.

FLARM works by calculating and broadcasting the ownship's future flight path to nearby aircraft. At the same time, it receives the future flight path from surrounding aircraft. An intelligent motion-prediction algorithm calculates a collision risk for each aircraft based on an integrated risk model. When a collision is imminent, the pilots are alerted with the relative position of the intruder, enabling them to avoid a collision. [10]

Each FLARM system determines the aircraft's position and altitude with a sensitive GNSS receiver. Based on speed, acceleration, track, turn radius, wind and other parameters, a precise projected flight path is calculated. This flight path, together with additional information such as a unique identifier, is encoded before being broadcast over an encrypted radio channel. In addition to preventing collisions between aircraft, FLARM can also warn about fixed obstacles. The integrated obstacle collision warning system is kept up to date by installing periodic obstacle database updates. [3]

FLARM obtains its ownship's position from an internal Global Positioning System (GPS) unit and a barometric sensor, which is updated every second.

The data is then broadcast by a low-power radio frequency transmitter (868.2 MHz or 868.4 MHz) along with a 30-second 3D projection of the likely flight path. Its receiver searches for other FLARM devices within range (typically less than 10 kilometers) and processes the information received. [8]

FLARM has certain significant advantages over ADS-B technology, such as a low power consumption and a relatively cheaper cost. Moreover, it presents unique coverage for lower airspace below flight level (FL) 100 outside of airports where ADS-B is nearly nonexistent. [3]

In particular, FLARM plays an important role in the detection of proximity to other similarly equipped and slow-moving aircraft ; a scenario whereby maneuvering is the

main requirement.

FLARM uses its own frequency and radio protocol, optimized for collision avoidance. [11] Since the design of airborne collision avoidance systems (ACAS) is predicated on the need for a safety net for fixed-wing aircraft on relatively stable tracks, it is of little use in preventing gliders from colliding with each other because they are frequently close to each other without being in danger of collision. In these circumstances, ACAS would generate many nuisance alerts, whereas FLARM only gives selective alerts to similarly equipped aircraft posing a collision risk. [8]

Therefore, practical experience shows that ADS-B does not provide sufficiently precise data to warn about aircraft conducting aerial work or glider traffic, where frequent altitude changes and steep turns are common. Thus, to ensure high alert quality, FLARM data should be used to compute alerts for targets that also broadcast ADS-B data. [12]

It is important to underline that FLARM does not transmit any signal detectable by ACAS or ADS-B. This means that small aircraft that rely exclusively on FLARM for collision avoidance will be invisible to aircraft relying on ACAS as a safety net against MAC.

For the sake of clarity, it is important to reiterate that, although ACAS and TCAS are often used interchangeably, there is a difference between the two terms [13]:

- ACAS is typically used when referring to the technical standard or concept;
- TCAS is typically used when referring to a current implementation of the technical standards and concept, which is widely fitted throughout the world.

Regarding the mandatory equipment required by the regulatory agencies, it is important to reiterate that there are two different types of ADS-B: namely, 1090 ES (ES being "extended squitter") and universal access transceiver (UAT). In Europe, EASA requirements concern only 1090 ES. Aircraft with a maximum take-off mass over 5,700 kg are required to have 1090 ES, but may have FLARM in addition.

For light aircraft, FLARM is sufficient. [11]

In the United States, all powered aircraft need either 1090 ES or UAT from year 2020, but may additionally have FLARM.

	FLARM UAS Electronic ID Main	Technical Characteristics	
	Communication type	Broadcast, message based	
General features	Transmitter location	Glider, light aircraft, UAS, sur	face vehicles, fixed obstacles
	Transmission frequency (MHz)	868.4	4 or 868.2
	Maximum transmission power (dBm)		14
	Maximum physical bit rate (kbps)		50
Physical layer	Medium Access Protocol	CSMA without collision detection (random initial wait of 0–1000 ms, random wait after transmission detection of 1 150 ms)	
	Modulation	2-Gaussian Frequency Shift Keying (GFSK)	
	Message types	UAV eID message, o	perator eID message
	Message format and size (in bytes)	Preamble (4B) + Sync (3B) + Payload (24B) + CRC (2B) + Optional signature	
		Timestamp	2 s
Message codification		Latitude	0.000025°
	Information encoding resolution	Longitude	0.000025°
		Altitude	1 m (MSL or WGS84)
	Message frequency	0.33 Hz (or 1 Hz if position de	viation is greater than 30 m)
	Authentication	Optional with external unsp	pecified registration service
	Encryption	Symmetric encryption (same key for all devices)	
Other features	Error detection		Yes
	Error correction		No

The main characteristics of the FLARM technology are summarized in Figure 1.4.

Figure 1.4: FLARM Main Technical Characteristics [5]

1.3. Security Issues

The importance of surveillance technologies, such as ADS-B and FLARM, is significant in terms of enhancing situational awareness and preventing fatal collisions. On a related note, studies on attacks against such communications technologies are equally relevant, helping to preclude possible threats against the whole air infrastructure.

Although ADS-B vulnerabilities have been widely investigated in the past decade [6, 14, 15, 16, 17], technologies used in light aircraft, such as FLARM, currently lack the same attention [18], despite these types of attacks having a real impact on the security (and thus the safety) of air transport aviation.

In their research *Smith et al.* (2020) [19], prove that both short- and long-term trust in a safety system is reduced after a cyber attack. Consequentially, under less optimal circumstances (e.g., bad weather, other instruments malfunctioning), there could be a loss of situational awareness and added stress on the pilot, leading to potentially fatal mistakes.

Smith et al. report that the participants in the simulation test (30 commercial pilots) often have to make a choice between reducing distraction and turning off key systems, or keeping said systems on; this resulted in safety systems being switched off in over a third of cases.

ADS-B vulnerabilities and threats are widely discussed in [6, 14, 15, 17].

Although any passive attacker can record and analyze unencrypted ADS-B messages, an attacker able to actively interfere with ATC communication poses a much more severe threat to security. [6]

Building on this further, it is possible to define the different attack categories for the ADS-B system. [14]

- Message Injection: ADS-B technology does not have an authentication mechanism, meaning attackers can use current technology to construct legitimate fake information and inject fake messages into existing air traffic communications; for example, ground station target ghost injections and aircraft target ghost injections.
- Message Deletion: The attacker could delete any ADS-B message either by generating enough bit errors in the actual message or by producing a synchronization signal with the target ADS-B that is opposite in phase to the target ADS-B signal, so as to partially delete the message.
- Message Modification: An attacker could replace or change a legitimate message by transmitting a high-power signal. Such attacks are the most difficult to combat

since they require modification of messages from legitimate nodes in the network.

• Eavesdropping: This refers to the behavior of an attacker maliciously collecting and analyzing wireless signals. Since ADS-B sends plaintext information over an unencrypted wireless channel, it is naturally open, and any third party can receive its information utilizing a radio frequency transceiver.

As such, eavesdropping is the most direct weakness of ADS-B.

• Jamming: This is a common problem in wireless networks. In a jamming attack, an attacker only needs to send a large amount of high-power data in the same frequency band; a process that can hinder real participation in the communication session. There are two main types of jamming attacks against ADS-B; namely, ground station flood denial and aircraft flood denial. [17]

The purpose of these attacks is to interrupt the monitoring network by jamming the communication channel.

There are several research avenues for security countermeasures, such as physical-layer security, anomaly detection and cryptography. [18]

Physical-layer security is particularly attractive for aviation legacy systems, as attacks on ADS-B have been identified using several different primitives in this field, including Time Difference of Arrival (TDoA), Doppler shifts, and direction of arrival. [16].

Cryptography remains the most effective means to securing communication and is a popular research area in aviation protocols. Despite many proposals posed in the literature, many authors have also pointed out incompatibility with current systems; a major downside of cryptographic countermeasures in a slow-moving industry.

An overview of the possible countermeasures with respect to ADS-B attacks is presented in Figure 1.5.



Figure 1.5: ADS-B Security Solution Classification [14]

Although the FLARM technology produces encrypted messages (something not assured by other wireless aviation communications), the FLARM protocol is still deemed as insecure. [18]

The most critical issue here is the encryption keys; in theory, these should be made available only to partners and other manufacturers hoping to implement compatible FLARM products. However, these keys always subsequently leak or are reverse-engineered, despite FLARM changing them many times over the years in attempt to combat the issue.

FLARM technology has been proven to be vulnerable to spoofing threats. [18]

As such, this study develops a spoofing system that is able to interact with all current FLARM devices, both on aircraft and on the ground.

The general scenario reported in Figure 1.6 shows a system consisting of a sender using an embedded device with radio frequency capabilities. This spoofing system is able to generate signals that are indistinguishable from those of an authentic FLARM device. Such an attack could potentially generate alerts that are barely distinguishable for pilots, thereby causing considerable distractions.

In this work two anomaly detection approaches are proposed. It was observed that while sanity checks can provide a first line of defense, physical-layer countermeasures such as those based on a signal-to-noise ratio (SNR) can be more useful for effectively detecting spoofing attacks.

One advantage regarding the implementation of countermeasures, with respect to ADS-B technology, could be the actual proprietary of FLARM. In fact the company can iterate much more quickly than the global standards that are used in commercial aviation could.



Figure 1.6: Overview of the Attack Scenario on FLARM Technology [18]

A summary of ADS-B and FLARM technologies is presented in Table 1.1.

In conclusion, it is important to reiterate that FLARM should not be confused or used interchangeably with ADS-B. The purpose of the latter is to relieve the crowded 1090 MHz frequency and to give ATC more accurate data for separation purposes. However, FLARM, unlike ADS-B, is a collision-avoidance technology similar to TCAS. Even though many FLARM devices also receive transponder and ADS-B Out traffic, ADS-B has limitations when it comes to collision avoidance.

	ADS-B	FLARM
Transmitter Subjects	Aircraft, UAVs, Surface vehicles, Fixed objects	Gliders, Light and small aircraft, UAVs, Surface vehicles, Fixed obstacles
Data Broadcasts	Identity, Position, Speed, Altitude, Equipment capabilities, System status	Identity, Position, Speed, Altitude, Flight path, Status flags
Transmission Frequency	1090 MHz or 978 MHz	868.2 MHz or 868.4 MHz
Range	180-200 nautical miles	Typically less than 6 nautical miles
Advantages	Improved safety and situational awareness, spacing efficiency, higher accuracy (not dependent on range from ground stations) and integrity with respect to radar technology	Low power consumption and relatively cheaper than ADS-B, coverage where ADS-B is not present, can incorporate ADS-B, able to give selective warnings in close range
Disadvantages	Dependent on on-board avionics	Transmits only to similarly-equipped aircraft
Security Issues	Ground Station flooding, Ghost aircraft injection/flooding, Aircraft Spoofing, Message deletion/injection	Spoofing threats

Table 1.1: Summary of ADS-B and FLARM Co-operative Surveillance Technologies

The aforementioned hexacopter from TUM is equipped with three different position devices.

These instruments allow the drone to transmit its presence in the airspace as well as to receive information about the surrounding traffic. In this section, the three instruments are examined through different aspects: how each one works and which data are received/sent.

A brief summary is presented in Table 2.1.

	Data Transmitted	Data Received
MXS-NC Transponder	Mode-S replies and ADS-B OUT	ADS-B IN and Mode-S replies
AT-1	Ownship's GPS position via FLARM	1090 MHz Mode-S transponder replies, 1090 MHz ADS-B and FLARM broadcasts
HOD4track	Ownship's GNSS position via LTE	ADS-B and FLARM broadcasts

Table 2.1: Summary of Transmitted and Received Instruments' Data

2.1. MXS-NC Transponder



Figure 2.1: MXS-NC Transponder

The MXS-NC is an installed equipment on Unmanned Aircraft Systems (UAS) providing transponder functions within the Secondary Surveillance Radar (SSR) system.

The SSR system provides situation awareness to Air Traffic Control (ATC) and the remote pilot. [20]

The MXS-NC transponder performs the following basic functions:

- Transponder:
 - Interacts with air traffic control (ATC) by transmitting and receiving standard secondary surveillance radar pulses per ICAO requirements. The transponder replies to ATCRBS interrogations with a squawk code and pressure altitude data.
 - Provides Mode S replies (includes data such as ICAO address and call sign) and is capable of being selectively interrogated.
- ADS-B In:
 - The MXS-NC receives Automatic Dependent Surveillance-Broadcast (ADS-B)
 In Extended Squitter messages (ES) that have been transmitted automatically
 from surrounding planes and the Air Traffic Control (ATC) system.
 - ES messages report Position, Velocity, Identification and Category, Target State and Status, and Aircraft Operational Status. From this data, MXS-NC

generates ADS-B, TIS-B and ADS-R reports for delivery to the flight computer which communicates the data to the user.

- Transponders with ADS-B In are useful for sense and avoid applications by providing the user with surrounding traffic information with a nominal range of 120 nautical miles (NM).
- ADS-B Out:
 - Provides host computer-controlled Automatic Dependent Surveillance-Broadcast (ADS-B) Out capability.
 - Transmits Extended Squitter (ES) and Acquisition Squitter messages at regular intervals, providing Position, Velocity, Identification and Category, Emergency/Priority Status, Target State and Status, Aircraft Operational Status, and other aircraft data.
- Altitude Encoder:
 - Computes ownship's barometric altitude with an integral pressure sensor and encoder.

The MXS-NC accomplishes these functions by communicating with ATC, surrounding aircraft, the aircraft flight computer, external GPS, and discrete inputs from the aircraft. Extended Squitter messages received by the MXS-NC report Position, Velocity, Identification and Category, Target State and Status, and Aircraft Operational Status. To output this data, the MXS-NC generates ADS-B, TIS-B and ADS-R reports for delivery to the host system which processes the data as required.

The ADS-B State Vector Report Message, shown in Figure 2.2 is one of several message types sent by the MXS-NC to report data on an ADS-B In participant, including position, velocity, and other information.

Payload Index	Message Field	Bytes
00	Report Type and Structure ID	3
03	Validity Flags	2
05	Participant Address	3
08	Address Qualifier	1
09	Report Times of Applicability	6
15	Latitude	3
18	Longitude	3
21	Geometric Altitude	3
24	N/S Velocity	2
26	E/W Velocity	2
28	Ground Speed While on Surface	1
29	Heading While on Surface	1
30	Barometric Altitude	3
33	Vertical Rate	2
35	NIC	1
36	Estimated Latitude	3
39	Estimated Longitude	3
42	Estimated N/S Velocity ¹⁹	2
44	Estimated E/W Velocity 19	2
46	Surveillance Status	1
47	Report Mode	1

Figure 2.2: ADS-B State Vector Report Message Payload Structure Overview -MXS-NC Transponder [20]

The description of each message field from the ADS-B State Vector Report Message, presented in Figure 2.2, is provided below:

• Report Type and Structure ID: The first part identifies the report as a State Vector Report. The remaining data constitutes the Structure ID, which indicates the fields that are being reported in the current message. If the bit for the field is set to "ONE", then the data field is available and included in the current report. If the bit is set to "ZERO", this indicates that the field is not reported for the current message and the State Vector message will not include that field. The State Vector Message will concatenate the next field to be included into the report, following the previous

reported field. This is performed for each data field that is reported.

- Validity Flags: These flags indicate whether the data contained in the specified field is valid or not. If the bit is set to "ONE" then the data field contains valid information. If the bit is set to "ZERO" then the data field contains invalid information.
- Participant Address: Contains the address of the transmitting installation. These fields contain up to six (6) hex characters. This can be the ICAO address or some other type of address.
- Address Qualifier: Indicates the type of participant address reported and what the emitter category is set to for the given participant.
- Report Times of Applicability: Contains time stamps created when an ADS-B message is received by the message processor or when the message processor updates the State Vector (SV) report. The time stamp is based on the Transponder's established receiver unit time. Each time of applicability (TOA) is formatted in units of 1/128 second.
- Latitude: Sent as 24-bit 2's complement number representing a range of possible values from -90 Degrees to +90 Degrees.
- Longitude: Sent as 24-bit 2's complement number representing a range of possible values from -180 Degrees to +180 Degrees.
- Geometric Altitude: Sent as 24-bit 2's complement. The first bit indicates the sign, zero is positive and one is negative by 2's complement. The geometric altitude is sent in feet with a resolution of 0.015625 feet.
- N/S Velocity: Formats the North/South (N/S) Velocity in the target's State Vector into a 16-bit 2's complement number, and stores the result in the N/S Velocity field of the State Vector report.
- E/W Velocity: Formats the East/West (E/W) Velocity in the target's State Vector into a 16-bit 2's complement number, and stores the result in the E/W Velocity field of the State Vector report.
- Ground Speed While on Surface: The data specifies the status of the "Movement" of the ADS-B transmitting subsystem (aircraft or surface vehicle) while on the surface.
- Heading While on Surface: The data is sent as an 8-bit 2's complement number. The first bit indicates the sign, zero is positive and one is negative by 2's complement. The heading is sent in degrees with a resolution of 1.40625 degrees.

- Barometric Altitude: Sent as 24-bit 2's complement. Barometric Altitude is decoded the same as Geometric Altitude. It is relative to a standard pressure of 1013.25 millibars (29.92 in Hg).
- Vertical Rate: This the altitude rate of change of the reported ADS-B participant. This is either the rate of change for the barometric or the geometric altitude; whichever one is in the State Vector Message. The first bit indicates whether the data is positive or negative. If the first bit is set to "ONE" then the data is negative, and the direction is down; if set to "ZERO" then the data is positive, and the direction is up. The Vertical Rate is sent in feet per minute with a resolution of 1.0 feet per minute.
- NIC: The Navigation Integrity Category (NIC) field specifies radius of containment for the ADS-B participant.
- Estimated Latitude: Latitude position is estimated when an Airborne Velocity message is received. The estimated latitude is decoded the same as the latitude.
- Estimated Longitude: Longitude position is estimated when an Airborne Velocity message is received. The estimated longitude is decoded the same as the longitude.
- Estimated N/S Velocity: The MXS-NC does not transmit Estimated Velocity.
- Estimated E/W Velocity: The MXS-NC does not transmit Estimated Velocity.
- Surveillance Status: This field reports two sets of data. The most significant nibble (MSN) reports the surveillance status of the ADS-B participant. The least significant nibble (LSN) reports the Intent Change Flag of the ADS-B participant.
- Report Mode: This field is used to indicate the current reporting mode of the ADS-B participant.

The ADS-B Mode Status Report Message, shown in Figure 2.3 is another of the several message types sent by the MXS-NC to report data on an ADS-B In participant, including aircraft/vehicle information, such as call sign and emitter category.

Payload Index	Message Field	Bytes
00	Report Type and Structure ID	3
03	Validity Flags	1
04	Participant Address	3
07	Address Qualifier	1
08	Report Times of Applicability	2
10	ADS-B Version	1
11	Call Sign	8
19	Emitter Category	1
20	A/V Length & Width Code	1
21	Emergency/Priority Status	1
22	Capability Class Codes	3
25	Operational Mode	2
27	SV Quality - NACp	1
28	SV Quality - NACv	1
29	SV Quality – SIL	
	SV Quality – SIL Supplement	
	SV Quality – System Design Assurance	
30	SV Quality - GVA	1
31	SV Quality – NIC _{baro}	1
32	Track/Heading and Horizontal Reference Direction	1
33	Vertical Rate Type	1
34	Reserved	2

Figure 2.3: ADS-B Mode Status Report Message Payload Structure Overview -MXS-NC Transponder [20]

The description of each message field from the ADS-B State Vector Report Message, presented in Figure 2.3, is provided below:

• Report Type and Structure ID: The first part identifies the report as a Mode Status Report. The remaining data constitutes the Structure ID, which indicates the fields that are being reported in the current message. If the bit for the field is set to "ONE", then the data field is available and included in the current report. If the bit is set to "ZERO", this indicates that the field is not reported for the current message

and the State Vector message will not include that field. The State Vector Message will concatenate the next field to be included into the report, following the previous reported field. This is performed for each data field that is reported.

- Validity Flags: These flags indicate whether the data contained in the specified field is valid or not. If the bit is set to "ONE" then the data field contains valid information. If the bit is set to "ZERO" then the data field contains invalid information.
- Participant Address: Contains the address of the transmitting installation. These fields contain up to six (6) hex characters. This can be the ICAO address or some other type of address.
- Address Qualifier: Indicates the type of participant address reported and what the emitter category is set to for the given participant.
- Report Times of Applicability: Contains time stamps created when an ADS-B message is received by the message processor or when the message processor updates the State Vector (SV) report. The time stamp is based on the Transponder's established receiver unit time. Each time of applicability (TOA) is formatted in units of 1/128 second.
- ADS-B Version: Indicates the formats and protocol used by the ADS-B participant.
- Call Sign: Indicates the aircraft identification used by the ADS-B participant. Data is sent as unsigned ASCII characters.
- Emitter Category: Indicates the type of aircraft or vehicle of the ADS-B participant.
- A/V Length & Width Code: Indicates the length and width of the vehicle or aircraft of the ADS-B participant. Aircraft and vehicles that exceed a width of 90 meters and a length of 85 meters shall use the code of 0x0F.
- Emergency/Priority Status: This data indicates whether or not Emergencies/Priorities are present.
- Capability Class Codes: These flags indicate the capabilities of the ADS-B participant. If a bit is set to "ONE", then it indicates that the service is supported. All reserved bits should be "ZERO".
- Operational Mode: These flags indicate the operational mode of the ADS-B participant. A bit is set to "ONE" indicates that the mode is true. All reserved bits should be "ZERO".
- SV Quality NACp: The Navigation Accuracy Category for position (NACp) field
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reports the level of accuracy of the geometric position being reported. Estimated position uncertainty (EPU) is defined as the radius of a circle that is centered on the ADS-B participant and indicates the probability of being inside the circle is 95%.

- SV Quality NACv: The Navigation Accuracy Category for velocity (NACv) field reports the horizontal velocity error with 95% certainty.
- SV Quality SIL: The Source Integrity Level (SIL) provides the probability of the ADS-B participant exceeding the radius of containment specified by the NIC field.
- SV Quality SIL Supplement: Provides whether the SIL probability is based upon a per sample or per hour probability of exceeding the radius of containment. If bit 2 is set to "ONE" then the probability of exceeding the radius of containment is based upon "per sample". If bit 2 is set to "ZERO" then the probability of exceeding the radius of containment is based upon "per hour".
- SV Quality System Design Assurance (SDA): Defines the failure condition that the position transmission chain can support.
- SV Quality GVA: This data indicates the Geometric Vertical Accuracy.
- SV Quality NICbaro: This data indicates whether or not the barometric altitude has been cross-checked against another source of pressure altitude and whether or not it is based on a Gilham-coded source.
- Track/Heading and Horizontal Reference Direction: This data indicates the nature of the horizontal direction information reported in the "Heading While on Surface" field in the State Vector report.
- Vertical Rate Type: This data indicates whether the Vertical Rate in the State Vector Report is the rate of change of barometric pressure altitude or the rate of change of geometric altitude.
- Reserved: These bytes are reserved for future use and are not output by the MXS-NC.

2.2. Air Traffic (AT-1)



Figure 2.4: Air Traffic (AT-1)

AT-1 is a small, lightweight traffic/electronic conspicuity system based on FLARM and ADS-B technology. It detects the position of surrounding air traffic and transmits the ownship's position to other aircraft that are equipped with compatible systems. It transfers traffic data and warning messages to compatible cockpit display systems, annunciators, and other avionics systems using various data interfaces. [21]

AT-1 uses 1090 MHz Mode-S transponder replies, 1090 MHz ADS-B broadcasts, and FLARM broadcasts to determine positions, flight vectors, and threat levels of other air traffic.

AT-1 broadcasts the ownship's GPS position via FLARM to other FLARM-equipped aircraft or ground stations. [12]

The AT-1 performs the following functions [12]:

- The ADS-B In capability allows the AT-1 to receive traffic data through a built-in 1090 MHz Extended Squitter (1090 ES) receiver. AT-1 processes all received ADS-B messages, including those from equipment with no source integrity or design assurance levels (SIL=0, SDA=0). Therefore, it is also processing information from ADS-B transmitters with non-certified GPS data sources. The ADS-B messages inlcude: identity (Flight ID/Tail Number, ICAO registration number, etc.), ground track, ground speed, pressure altitude, indications of equipment capabilities, and emergency status.
- AT-1 receives and processes replies sent by Mode-S transponders on the 1090 MHz transponder frequency band. Mode-S transponder replies do not contain position reports. Therefore, AT-1 is not capable of determining the exact position of the replying target. It estimates the target's distance using the field strength of the received signal. These estimations have very limited precision. Targets detected using this method are commonly referred to as "bearingless targets", as their relative

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bearing is unknown.

• AT-1 receives FLARM broadcasts, which contain GPS data, identity, altitude, and several status flags. In particular, based on GPS and a pressure sensor, FLARM predicts the short-term future flight path and continuously broadcasts this to nearby aircraft by means of a digital radio message. To ensure high alert quality, AT-1 does not use ADS-B data to compute alerts for targets that also broadcast FLARM data. Instead, it will rely exclusively on the target's more precise FLARM data.

The AT-1 ADS-B and FLARM messages are reported in the Preliminary Dataport Specification manual [22]. Both messages are sent in output once per every second in a NMEA data protocol. The field names are described for both messages in Figure 2.5 and Figure 2.6.

Fieldname	Description
ModeSAddress	6-digit hexadecimal value.
	Official 24-bit Mode-S aircraft address (e.g. '3A45BC').
FlightID	String value with a maximum length of 8 characters.
-	Company callsign for commercial aircraft operating with flight plan.
	Aircrafts registration for non commercial operating aircraft.
	Depends on data entered into the aircrafts transponder.
EmitterCategory	2-digit hexadecimal value.
c ,	Aircraft category value as described in DO260.
ModeASquawkCode	4-digit octal value.
	Mode-A squawk selected on aircrafts transponder.
Latitude	Decimal value. Range: from -90.0 to 90.0.
	Aircrafts latitude in degrees. Southern latitudes use a negative sign.
Longitude	Decimal value. Range: from -180.0 to 180.0.
-	Aircrafts longitude in degrees. Western longitudes use a negative sign.
AltitudeWGS84	Decimal value.
	Aircrafts altitude above the WGS84 ellipsoid in meters.
AltitudeQNE	Decimal value.
-	Aircrafts pressure altitude above 1013.25hPa pressure level in meters.
Track	Decimal value. Range 0.0 to 360.0.
	Aircrafts true ground track in degrees.
GroundSpeed	Decimal value.
	Aircrafts ground speed in m/s.
ClimbRateWGS84	Decimal value.
	Aircrafts vertical speed in the WGS84 reference system in m/s. Positive
	values indicate a climbing aircraft.
ClimbRateBaro	Decimal value.
	Aircrafts barometrical vertical speed in m/s. Positive values indicate a
	climbing aircraft.
SignalStrength	Decimal value.
5	Strength of received signal in dBm.
PositionTimestamp	Decimal integer value. Range 0 to 86399999.
	Time of reception of the latest ADS-B position information in ms since last
	midnight UTC.
VelocityTimestamp	Decimal integer value. Range 0 to 86399999.
	Time of reception of the latest ADS-B velocity information in ms since last
	midnight UTC.
ModeSTimestamp	Decimal integer value. Range 0 to 86399999.
	Time of reception of the latest Mode-S signal in ms since last midnight
	UTC.
ADSBVersionNumber	Decimal integer value. Range 0 to 2.
	ADS-B version number, used by aircrafts transponder.
QualityIndicator	Maximum 8-digit hexadecimal value.
	ADS-B quality indicators transmitted by transponder according to ADS-B
	version.

Figure 2.5: Absolute ADS-B Target Data - AT-1 [22]

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Fieldname	Description
IDType	Decimal integer value. Range: from 0 to 2.
	Defines the interpretation of the following <id> field.</id>
	0: Random ID, configured or if stealth mode is activated.
	1: Official 24-bit Mode-S aircraft address.
	2: Fixed FLARM ID (chosen by FLARM).
ID	6-digit hexadecimal value.
	Aircrafts ID. Interpretation is dependent of IDType (e.g. '3A45BC').
FlarmAcftType	1-digit hexadecimal value.
	Aircrafts type:
	0: reserved
	1: glider/motor glider (turbo, self-launch, jet) / TMG
	2: tow plane/tug plane
	3: helicopter/gyrocopter/rotorcraft
	4: skydiver, parachute (Do not use for drop plane!)
	5: drop plane for skydivers
	6: hang glider (hard)
	7: paraglider (soft)
	8: aircraft with reciprocating engine(s)
	9: aircraft with jet/turboprop engine(s)
	A: reserved
	B: balloon (hot, gas, weather, static)
	C: airship, blimp, zeppelin
	D: unmanned aerial vehicle (UAV, RPAS, drone)
	E: reserved
	F: static obstacle
Latitude	Decimal value. Range: from -90.0 to 90.0.
	Aircrafts latitude in degrees. Southern latitudes use a negative sign.
Longitude	Decimal value. Range: from -180.0 to 180.0.
5	Aircrafts longitude in degrees. Western longitudes use a negative sign.
AltitudeWGS84	Decimal value.
	Aircrafts altitude above the WGS84 ellipsoid in meters.
Track	Decimal value. Range 0.0 to 359.0.
	Aircrafts true ground track in degrees.
GroundSpeed	Decimal value.
	Aircrafts ground speed in m/s.
ClimbRateWGS84	Decimal value.
	Aircrafts vertical speed in the WGS84 reference system in m/s.
NoTrack	Decimal integer value. Range: from 0 to 1.
	The target's configured no track setting
	Targets with a NoTrack value of '1' express their intention to remain private
	Data from these targets may not be persisted in any way (e.g. in database)
	If the data is transmitted to a third party system (e.g. a server) then the
	implementer must make sure the third system also respects this rule
Timestamn	Decimal integer value Range 0 to 86399999
mestamp	Time of message recention in ms since last midnight LITC
	The of message reception in this since last midnight of C.

Figure 2.6: Absolute FLARM Target Data - AT-1 [22]

2.3. Hook-On-Device V2XT (HOD4track)



Figure 2.7: Hook-On-Device V2XT (HOD4track)

The Hook-on-Device (HOD) is a device used for transmission of the ownship's position data for UAS and other aircraft. Thanks to its low weight, the HOD can be attached to any aircraft.

It contains an LTE modem and a SIM card. The device transmits its current GNSS position via LTE to the UAS Traffic Management (UTM) system of DFS and it makes itself visible for other aircraft also via FLARM. [23]

In addition, the HOD4track receives FLARM and ADS-B signals from surrounding air traffic, and outputs the traffic data locally — including its own position — via MAVLINK before sending it to the Droniq UTM. [24]

MAVLink is a very efficient and reliable messaging protocol for communicating with drones (and between on-board drone components). [25]

The HOD4track ADS-B and FLARM data received from other traffic are converted into absolute positions and then sent through the MAVlink #246 ADSB_VEHICLE message, as shown in Figure 2.8. [26]

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ADSB_VEHICLE (#246)

[Message] The location and information of an ADSB vehicle

Field Name	Туре	Units	Values	Description
ICAO_address	uint32_t			ICAO address
lat	int32_t	degE7		Latitude
lon	int32_t	degE7		Longitude
altitude_type	uint8_t		ADSB_ALTITUDE_TYPE	ADSB altitude type.
altitude	int32_t	mm		Altitude(ASL)
heading	uint16_t	cdeg		Course over ground
hor_velocity	uint16_t	cm/s		The horizontal velocity
ver_velocity	int16_t	cm/s		The vertical velocity. Positive is up
callsign	char[9]			The callsign, 8+null
emitter_type	uint8_t		ADSB_EMITTER_TYPE	ADSB emitter type.
tslc	uint8_t	S		Time since last communication in seconds
flags	uint16_t		ADSB_FLAGS	Bitmap to indicate various statuses including valid data fields
squawk	uint16_t			Squawk code

Figure 2.8: ADSB_VEHICLE message - HOD4track [26]

It is important to note that, since the same message structure exists for both ADS-B and FLARM reports, it is not possible to determine whether the message delivered by the HOD has been transmitted via ADS-B or FLARM technology solely by examining the ADSB_VEHICLE messages.

Finally, Figure 2.9, reports on the cooperative surveillance technologies that each position data source is capable of transmitting as output information.



Figure 2.9: ADS-B and FLARM Technologies for the Position Data Sources

A traffic display system depicts the position of nearby traffic on a plan position indicator, relative to the ownship. It indicates the relative horizontal and vertical position of other aircraft based on the replies from their position data sources.

ADS-B is mandatory for commercial aircraft and its coverage is continuously increasing. [2] As such, data fusion between ADS-B and FLARM presents a unique avenue for research. FLARM is commonly used in general aviation and glider operations; over 40.000 manned aircraft and many UAVs are already equipped with FLARM, and this number is set to increase rapidly. [3]

Thus, a traffic display system that merges both of these technologies to consequently display the traffic offers significant value, in that such a system has the potential to detect the majority of air vehicles. Of course, here the air traffic under discussion is cooperative and thus equipped with this type of surveillance technology.

This section presents the traffic display system developed in this study. It begins by reviewing the state of the art regarding current traffic displays and data fusion strategies, before presenting the system design and architecture and then the developed algorithm.

3.1. State of the Art

In this section, two fundamental aspects of a generic traffic display system are analyzed. Firstly, current traffic displays and the information commonly shown are examined. Secondly, a review of possible data fusion methods, reported around the literature, is presented.

3.1.1. Traffic Display

When the term "traffic display" is used in this paper, reference is being made to such devices as the TCAS traffic display and the cockpit display of traffic information (CDTI). These systems are capable of displaying position information of nearby aircraft and, in the case of TCAS, can also indicate proximate, traffic advisory and resolution advisory status.

In very few words, these alerts provide two types of advisories to the pilots:

- Traffic Advisories (TAs) to prepare the pilots for a potential resolution advisory and aid the visual acquisition of the intruder aircraft;
- Resolution Advisories (RAs) which provide vertical collision avoidance guidance to the pilots. An RA can be issued against a single threat or multiple threats.

Even though TCAS plays a crucial role in aviation safety, this system has limited bearing accuracy, with the traffic display potentially showing inaccurate positions of other aircraft. Typically, the error is no more than 5 degrees, but this has reached 30 degrees in some cases. Ultimately, the display accuracy depends on the selected scale. [13]

The bearing displayed by ACAS is not sufficiently accurate to support the initiation of horizontal maneuvers based solely on the traffic display. Furthermore, the reference for the traffic display is the ownship's position, which can lead to misinterpretation of relative motion of other traffic on the display. Consequently, horizontal maneuvers based solely on information displayed on the ACAS traffic display are prohibited. [13]

On a related note, the display of the FLARM collision alerting system, shown in Figure 3.1, has also presented some issues, such as that the display lacks indications about the system's limitations. [27]

The results of this research show that errors in the initial search direction for traffic increases whenever the ownship does not fly straight and level. These errors have been attributed to a misunderstanding of the system's indications.



Figure 3.1: FLARM Display [27]

As can be observed in the following figures, the minimum required information in a common traffic display is as follows:

- Ownship position and track
- Surrounding traffic position, relative altitude and vertical trend

Additional information could be shown depending on the particular display, i.e., aircraft identifier, predicted and previous aircraft position, and surrounding traffic track.





Figure 3.2: Navigation Display on Airbus A320/330 [19]



Figure 3.3 presents a CDTI used in conjunction with ADS-B applications.

Figure 3.3: Example of Cockpit Display of Traffic Information [28]



Other examples of traffic displays are shown in Figure 3.4, Figure 3.5 and Figure 3.6.

Figure 3.4: Example of Dedicated Traffic Display [13]



Figure 3.5: Electronic Flight Instrument System (EFIS) [29]



Figure 3.6: Actual Traffic Display Implementation on Boeing 737-800 [13]

On the other hand, when UAS are considered, the detect and avoid (DAA) system plays a critical role, being able to provide the pilot-in-command with the capability to selfseparate from (i.e., remain well clear of), and avoid collisions with, other aircraft. [30] This sense and avoid (SAA) capability is intended to compensate for the UAS pilot being at a ground control station as opposed to an aircraft cockpit by aiding the pilot with the capacity of self-separation and collision avoidance from other aircraft. [31]

Even though the DAA system notionally consists of both hardware and software components, this study focuses specifically on the display of traffic information, with the aim of showing the differences compared to previous displays.

An advanced implementation of the basic informative display (Figure 3.7a) is shown in the "Banding Display" (Figure 3.7b). [31]



(a) Basic Informative SAA Display



Figure 3.7: Basic Informative and Banding SAA Displays [31]

In DAA displays, the information shown is similar to that previously described for a generic traffic display, but with some extras and particularities; for example, the option to see the history trail of the surrounding traffic and supplementary information for possible intruders.

Regarding the advanced banding display, one can observe the color-coded arc and altitude tape, together with a text-based recommended maneuver, so as to prevent conflicts with intruders.

3.1.2. Data Fusion

Data fusion from different sensors is a crucial aspect of aviation navigation and safety. In particular, data fusion has the advantage of being able to extract the main benefits of each surveillance technology, be it cooperative or non-cooperative.

Some UAVs are equipped with ADS-B or with the portable collision avoidance system (FLARM); both are powerful tools for air traffic management.

Although it was not feasible to explore further during the course of this project, the robust detection of non-cooperative intruders in the airspace is a crucial aspect in the development of DAA systems and in surveillance. In this scenario, it is necessary to use several kinds of sensors, the characteristics of which compensate the weaknesses of the others.

For instance, while thermal sensors visualize heat, an optical camera that captures images is not aware of thermal energy; radars are able to measure distances, while individual visual sensors cannot. [32]

Data fusion and object tracking are important aspects of a robust collision avoidance system. Typically, this task is performed by data association and mapping, followed by tracking filters. For data association purposes, ellipsoidal gating functions, Global Nearest Neighbor or Joint Probabilistic Data Association can be used. These data association functions assign the data to the most likely track, and follow this with track updates and object-tracking filters with an extended Kalman filter or interacting multiple model (IMM). [33]

Kalman filters are employed to obtain the states of the tracked obstacles; they are used to predict the trajectory in a given time horizon. One of the main advantages of this approach is its ability to integrate a large number of sensors and its low computational cost. Although the majority of problems of interest are non-linear, and uncertainties of process and measurements cannot always be as well modeled as Gaussian distributions, the Kalman Filter has widespread applications in the field of aircraft tracking. [34]

The IMM model offers a different approach, being a state-of-the-art tracking algorithm for when the behaviors of multiple kinematics are to be considered. Using this model, the state vector of the intruders is determined and this is propagated to predict the future trajectories using a probabilistic model. This algorithm consists of a set of Kalman filters that run in parallel and concur to match a target model.

Although IMM is designed to handle the behaviors of multiple kinematics, its performance deteriorates as the number of competing models increases. Information gathered by the sensors is not limited to major models; rather, it diffuses across multiple models. As such, the "Variable-Structure IMM" is well suited for sensor data fusion. The basic idea here is to design supervision, over the IMM, which is able to select the most appropriate models and parameters according to the current situation. [35]

It is possible to determine two different approaches in data fusion: centralized and decentralized data fusion. In the former, the combination of observations (measurements) of each sensor are combined to give an improved global estimate over that obtained with the use of only one measurement. In this type of data fusion architecture, the central processor generates optimum global state estimation and error covariances based exclusively in its previous estimate and in measurements provided by each Kalman filter-implemented sensor.

A track-level fusion method (decentralized data fusion) exploits the fact that each sensor, using its own measurements, can perform its own preprocessing to obtain a first state estimation through which local tracks are generated. In this kind of approach, each sensor must have its own algorithm to perform data processing and memorization. The tracks of each sensor are then transmitted to a central data processor responsible for the fusion process.

The fact that this central processor uses a set of information from different sources means it is able to provide a more accurate state estimation. [34]

An example of the centralized parallel filter approach is presented in the work of *Lu et al.* (2014) [36]. In particular, a fusion between ADS-B and MLAT [multilateration] is carried out to achieve high accuracy and precision. MLAT allows the targets to be located by accurately computing the TDoA of a signal emitted from that object to three or more receivers. The TDoA is a positioning methodology that determines the difference between the time of arrival of radio signals.

In their work $d'Apolito \ et \ al.$ (2019) [33] propose an approach for data fusion and tracking of sensor data based on the multiple hypothesis tracking (MHT) algorithm.

The advantage of this method is a better data fusion performance with sensor ambiguities compared to classical approaches. In this case, the data assignment is not performed continuously with each incoming data update; rather, as soon as intruders are detected, several hypotheses for data associations are formulated. The decision on the right datato-track assignment is deferred until a preordained number of scans are available.



Figure 3.8: Flow Diagram of the Multiple Hypothesis Tracking Algorithm [33]

Figure 3.8 shows the flow chart of the conventional MHT algorithm. In general, new measurements are considered as new tracks and evaluated with a gating process. This process determines whether the new observation shall be also considered as part of an existing track. The computational complexity for the evaluation of the hypothesis is exponential. This leads to reduced performance of the computing architecture and memory consumption. Therefore, a minimum number of hypotheses are processed for computational effectiveness.

Compared to conventional approaches, the MHT performs better with inaccurate data, but further testing in an air-based environment is required.

A novel data fusion algorithm was proposed by $d'Apolito \ et \ al.$ (2022) [32].

This approach is composed of two parts: a data association algorithm and a tracking filtering stage. More specifically, the implemented methodology combines the MHT algorithm for the data association and the particle filter (PF) for tracking. Figure 3.9 shows the flow chart of the implemented MHT-PF algorithm.



Figure 3.9: Flow Diagram of the Multiple Hypothesis Tracking and Particle Filter Algorithm [32]

The aim of this combination is to merge the strength of the MHT for data association (even in the presence of close space targets and false detection) with the robustness of the particle filter against noise and missed detection. One of the most effective filtering algorithms, particle filtering is a Monte Carlo method that sequentially uses incoming measurements to maintain a set of particles distributed across the surveyed state space. Each particle consists of a state and an associated weight and is interpreted as a state hypothesis. When particles are high in number and their sum-normalized weights are known, their ensemble can be interpreted as a state-discrete approximation of the posterior probability density function of the true origin of a target that is causing the received detections.

This joint approach has been validated with the use of simulated data and has shown robustness, with a good variance reduction.

3.2. System Design and Architecture

The traffic display system designed for the 600kg hexacopter is a simplified version of the display and data fusion algorithms presented above in Section 3.1.

This is primarily attributed to the fact that, at least in the context of this first build, there is no need, resources, or requirements to develop a system of such high complexity. However, the developed system presented in this study is of great interest as it meets certain safety requirements of the hexacopter. Furthermore, it allows for the fusion of data from three different position data sources, which are based on similar yet significantly different technologies, such as ADS-B and FLARM.

The main requirement of the developed traffic display system is the capacity to simultaneously merge incoming data from the three position data sources and to display the surrounding traffic.

To achieve this goal, the system has been designed in four different areas:

- 1. Inputs, which include the messages received by the three position data sources.
- 2. Algorithm, which consists of all the processes that analyze the messages and produce the outputs.
- 3. Outputs, 20 Aircraft structures that include position data information.
- 4. Display, which provides actual representation of the outputs through a conventional traffic display.

The architecture of each area is presented in the following passage, while the actual implementation is discussed in Section 3.3.

The inputs represent all the messages received by the three position data sources (as described in Chapter 2).

The architecture of the inputs is presented in Figure 3.10. As previously mentioned, there are 5 different messages: ADS-B messages sent by the MXS-NC Transponder, ADS-B and FLARM messages sent by the AT-1, and ADS-B and FLARM messages sent by the HOD4track.

For the sake of simplicity, the MXS-NC Transponder's ADS-B State Vector and Mode Status Report messages are processed as one single message in this work. This is mainly due to the fact that considering two different messages would add an unnecessary complexity to this first project.

The architecture of each message is described in Table 3.1, 3.2, 3.3, 3.4: we report only

the inputs that are actually used inside the algorithm, together with a short description, the unit of measurement and the data type of each field.

For fields and details of all the messages, the reader should refer to Chapter 2.



Figure 3.10: Architecture of the Algorithm's Inputs

	Field name	Description	Units of measure	Data type
	Participant Address	Contains the address of the transmitting installation. This field contains up to six (6) hex characters. This can be the ICAO address or some other type of address.	-	uint32
	Latitude	A range of possible values from -90 degrees to $+90$ degrees.	deg	double
	Longitude	A range of possible values from -180 degrees to $+180$ degrees.	deg	double
	Geometric Altitude	The WGS-84 GNSS height above the ellipsoid and has a resolution of 0.015625 feet.	ft	single
	N/S Velocity	North/South Velocity, + for North to South and - for South to North.	kn	single
	E/W Velocity	East/West Velocity, + for East to West and - for West to East.	kn	single
-NC Transponder	Vertical Rate	The altitude rate of change of the reported ADS-B participant. This is either the rate of change for the barometric or the geometric altitude; whichever one is in the State Vector Message. The Vertical Rate has a resolution of 1.0 feet per minute.	ft/min	single
MXS	NIC	Specifies radius of containment for the ADS-B participant.	-	uint8
	NACp	Reports the level of accuracy of the geometric position being reported. Estimated position uncertainty is defined as the radius of a circle that is centered on the ADS-B participant, when the probability of being inside the circle is 95%.	-	uint8
	NACv	Reports the horizontal velocity error with 95% certainty.	-	uint8
	SIL	Provides the probability of the ADS-B participant exceeding the radius of containment specified by the NIC field.	-	uint8
	SDA	Defines the failure condition that the position transmission chain can support.	-	uint8
	Validity Flags	These flags indicate whether the data contained in the specified field is valid or not.	_	single

Table 3.1: MXS-NC Transponder ADS-B Message Architecture

	Field name	Description	Units of measure	Data type
	ModeSAddress	6-digit hexadecimal value. Official 24-bit Mode-S aircraft address.	-	uint32
	Latitude	Decimal value. Range: from -90.0 to 90.0. Aircraft's latitude in degrees. Southern latitudes use a negative sign.	deg	double
	Longitude Decimal v Aircraft Ion	Decimal value. Range: from -180.0 to 180.0. Aircraft's longitude in degrees. Western longitudes use a negative sign.	\deg	double
F AltitudeWGS84 Track GroundSpeed ClimbRateWGS84	AltitudeWGS84	Decimal value. Aircraft's altitude above the WGS84 ellipsoid in meters.	m	single
	Track	Decimal value. Range 0.0 to 360.0. Aircraft's true ground track in degrees.	deg	single
	GroundSpeed	Decimal value. Aircraft's ground speed in m/s .	m/s	single
	ClimbRateWGS84	Decimal value. Aircraft's vertical speed in the WGS84 reference system in m/s. Positive values indicate a climbing aircraft.	m/s	single

Table 3.2: AT-1 ADS-B Message Architecture

	Field name	Description	Units of measure	Data type
	ID	6-digit hexadecimal value for the aircraft's ID. Can be a random ID, the official 24-bit Mode S aircraft address or a fixed FLARM ID (chosen by FLARM).	-	uint32
	Latitude	Decimal value. Range: from -90.0 degrees to 90.0 degrees. Southern latitudes use a negative sign.	\deg	double
AT-1	Longitude	Decimal value. Range: from -180.0 degrees to 180.0 degrees. Western longitudes use a negative sign.	\deg	double
	AltitudeWGS84	Decimal value. Aircraft's altitude above the WGS84 ellipsoid in meters.	m	single
Track		Decimal value. Range 0.0 to 360.0. Aircraft's true ground track in degrees.	deg	single
	GroundSpeed	Decimal value. Aircraft's ground speed in m/s .	m/s	single
	ClimbRateWGS84	Decimal value. Aircraft's vertical speed in the WGS84 reference system in m/s. Positive values indicate a climbing aircraft.	m/s	single

Table 3.3:	AT-1	FLARM	Message	Architecture
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	Field name	Description	Units of measure	Data type
	ICAO_address	Contains the ICAO address of the transmitting installation.	-	uint32
	Latitude	Latitude of the transmitting installation.	degE7	int32
	Longitude	Longitude of the transmitting installation.	$\mathrm{degE7}$	int32
HOD4track	Specify the altitude type reported the Altitude field. If 0, Altitude reported from a Baro source usin QNH reference, or if 1, Altitude reported from a GNSS source.		ft	uint8
	Altitude	Altitude (ASL) of the transmitting installation.	mm	int32
	Heading	Heading is considered as the actual Track of the transmitting installation.	cdeg	uint16
	Hor_velocity	Ground speed of the transmitting installation.	m cm/s	uint16
	Ver_velocity	Vertical velocity of the transmitting installation. Positive is up.	m cm/s	int16
	Flags	Bitmap to indicate various statuses including valid data fields.	-	uint16

Table 3.4: HOD4track ADS-B and FLARM Messages Architecture



Figure 3.11: Algorithm's Flow Chart

Figure 3.11 presents a simple and reduced illustration of the algorithm processes, reporting only the high-level functions.

Analyzing it with a top-down approach, one can notice the inputs together with the process and decision blocks. At the ends of the branches, terminal and display blocks are presented.

The flow chart symbolizes an iterative process; the algorithm itself manages the inputs received on every time step, allowing the system to properly merge and display traffic data.

All of the most important functions are described in Section 3.3.

The outputs are fused in a structure referred to as *Traffic*: a Simulink bus structure that encloses the outputted 20 *Aircraft* structures.

This architecture is presented in Table 3.5. The *Traffic* structure consists of the processed position data about the surrounding traffic.

An *Aircraft* structure has the same architecture as the *Traffic* structure, the only difference being that the *Traffic* structure contains all of the 20 *Aircraft* structures inside.

	Field name	Description	Units of measure	Data type
	ICAO_address	Contains the 20 ICAO addresses of the surrounding traffic.	_	uint32
	Latitude	Contains the 20 latitudes of the surrounding traffic.	deg	double
	Longitude	Contains the 20 longitudes of the surrounding traffic.	deg	double
Traffic	Altitude	Contains the 20 geometric altitudes of the surrounding traffic.	$^{ m ft}$	single
Track		Contains the 20 tracks of the surrounding traffic.	deg	single
	GroundSpeed	Contains the 20 ground speeds of the surrounding traffic.	kn	single
	ClimbRate	Contains the 20 vertical speeds in the WGS84 reference system of the surrounding traffic.	ft/s	single

Table 3.5: Architecture of the Algorithm's Outputs - Traffic Structure

The outputs are further reworked and sent to the display. The display is designed through the Ansys SCADE Display software, which is a specialized tool for modeling humanmachine interfaces (HMI). The SCADE Display facilitates embedded graphics, display and HMI development, and certified code generation for safety-critical displays. [37] The actual display implementation is further presented in Section 3.3.5.

3.3. System Implementation

This section presents the algorithm and illustrates the fundamental actions that the system is able to achieve. The most important functions and processes are explained in detail in the following passages.

The algorithm's implementation through MATLAB Simulink software is presented in Figure 3.12 and an overview of the main function, named *Traffic Steps*, is illustrated in Figure 3.13.



Figure 3.12: Algorithm's Implementation and Overview



Figure 3.13: Traffic Steps Subsystem Overview

3.3.1. Inputs

To start, the messages sent in output from the three different position data sources are processed inside the *Inputs* subsystem represented in Figure 3.12.

As can be noted from Table 3.1, 3.2, 3.3, 3.4, units of measurement differ from each other for similar fields across the different messages. Thus, a unit conversion is initially required to prevent inconsistencies, whereby data are converted into units defined in the *Traffic* structure, as shown in Table 3.5.

For the FLARM and ADS-B HOD messages, the *Flags* field is checked; if an inconsistency is observed, the message is cleared and ignored by the algorithm.

The MXS-NC Transponder messages require an additional preprocessing step, whereby the N/S Velocity and E/W Velocity fields are converted to the associated Track and GroundSpeed fields. This is achieved through trigonometric and geometric relations.

FMXS-NC Transponder messages are analyzed through the Validity Flags field and the commonly referred to quality indicator fields, such as NIC, NACp, NACv, SIL and SDA. In fact, in addition to checking the Validity Flags field (so that if an inconsistency is observed, the message can be cleared and ignored by the algorithm), the quality indicator fields are also analyzed, so as to understand if they comply with EASA requirements. The EASA provides standards for 1090 MHz ES ADS-B Out installations, and this is reported in the Certification Specifications and Acceptable Means of Compliance for Airborne Communications, Navigation and Surveillance (CS-ACNS) Issue 4. [38]

In this certification specification the agency defines a summary of the minimum horizontal position data requirements. These conditions, illustrated in Figure 3.14, are checked by they algorithm for every MXS-NC Transponder message.

Quality Parameter	Requirement
Position Accuracy (NACp)	NACp<=185.2 m (0.1NM) (i.e. NACp>=7) for both 3 NM and 5 NM separation
Position Integrity Containment Radius (NIC)	3 NM Sep: NIC<=1 111.2 m (0.6 NM) (i.e. NIC>=6) 5 NM Sep: NIC<=1 852 m (1 NM) (i.e. NIC>=5)
Source Integrity Level (SIL)	SIL=3: 10 ⁻⁷ /flight-hour
System Design Assurance (SDA)	SDA=2: 10 ⁻⁵ /flight-hour - allowable probability level REMOTE (MAJOR failure condition, LEVEL C software and design assurance level)
Velocity Accuracy (NACv)	NACv<=10 m/s (i.e. NACv>=1)

Figure 3.14: Minimum Horizontal Position and Velocity Data Quality Requirements

The algorithm incorporates the option to either include or exclude messages after checking the EASA requirements on ADS-B quality indicators. This decision depends on the specific utilization of the system and is subject to operator discretion. Making this choice is not trivial, as it involves a trade-off between prioritizing, on the one hand, the widest possible coverage and surveillance of surrounding traffic, and prioritizing high-quality messages over complete coverage on the other hand.

For this study, only the geometric altitude (altitude above the WGS84 ellipsoid) is analyzed, compared and then displayed. This is primarily attributed to the fact that comparing and displaying both geometric and barometric altitude would be challenging and could possibly end in the displayed altitude being misunderstood.

Only the MXS-NC and AT-1 sources send the barometric altitude for the same reference, where the altitude reported is relative to a standard pressure of 1013.25 millibars (29.92 in Hg). On the contrary, the HOD source outputs the barometric altitude as the altitude reported from a barometric source using QNH reference, which is the mean sea level pressure derived by reducing the measured pressure at ground level to mean sea level using the specifications of the ICAO standard atmosphere.

For these reasons, only the geometric altitude is considered and thus the *Altitude_type* field is checked for the HOD source: if the altitude reported is the barometric one, the *Altitude* field is cleared.

Alongside this choice, in the scenario in which one of the sources is sending in output where the barometric altitude or the geometric altitude field is empty, the algorithm handles the message as a non-altitude reporting aircraft, or non-altitude reporting target. [13]

In this case, the aircraft is simply displayed through the other information available but without the altitude tag.

3.3.2. Aircraft Identification

After the incoming messages are properly processed, the algorithm analyzes each *Address* field. Messages in which this field is empty are ignored by the system.

This process is performed in the *Aircraft Identification* subsystem (Figure 3.13). For every incoming message, the algorithm compares the *Address* field with the ones that are already present in the *Traffic* structure, so as to understand if the message belongs to a new or an existing aircraft.

For the sake of simplicity, during this work, the aircraft identification is carried out assuming that the address present in each *Address* field is the ICAO address (or an equivalent FLARM official address). This is mainly due to the fact that other ways to identify the

aircraft—such as through the call sign or track-based recognition—are not considered crucial aspects and would add complexity to this preliminary work.

Messages having the same *Address* field are assigned to the same *Aircraft* structure, and thus an allocated slot inside the output *Traffic* structure is selected.

This procedure is continually achieved by comparing the *Address* field of the incoming messages with the already existing *ICAO_address* from the *Traffic* structure. This particular process is carried out in the *Aircraft Function* subsystem (Figure 3.13).

3.3.3. "Updated-message" Algorithm

In the next step, the algorithm needs to understand the last message of every aircraft; doing so allows it to determine which messages have delivered the updated position of each aircraft sending traffic data. To do this, the system executes the so-called "updatedmessage" algorithm. This approach consists of verifying that the incoming messages truly reflect an updated position of the aircraft. This process is of crucial importance; having three different position data sources indicates that messages sent from the surrounding traffic are received multiple times and realistically processed by the algorithm in different time steps. Thus, the system needs to understand which message reflects the updated position and subsequently display the information included in that particular message. Ideally, this procedure could be achieved simply by comparing the different time stamps inside each message. Unfortunately, this approach is not feasible as the three position data sources have three different time scales that are not directly comparable. Thus, a

self-developed algorithm is essential. The process is described as follows:

1. For each stored aircraft inside the *Traffic* structure, the algorithm processes the latitude, longitude and altitude, and subsequently transforms the position in a North-East-Down (NED) frame. This is necessary because comparing just the latitude and longitude of different messages would be too strong an assumption, which would result in low accuracy for long distances. For this reason, the position is converted into a NED frame with a fixed origin point.

Figure 3.15 presents such a reference compared to the latitude and longitude coordinates.



Figure 3.15: North-East-Down Frame [39]

This process is performed for every incoming message that has the same identifier as one already present in the *Traffic* structure.

2. The next step consists of comparing the new and old positions; respectively, the NED position of the received message, and the NED position of the stored and observed aircraft inside the *Traffic* structure.

This process is summarized in Figure 3.16 and, as can be observed, the angle between the new position and the old track is computed (angles α and β , respectively in Figure 3.16a and Figure 3.16b). The algorithm determines whether the new message reflects an updated position or not by comparing this angle with the half-plane (defined by adding and subtracting 90 degrees to the old track of the aircraft). Figure 3.16a shows the scenario in which the computed angle α lies in the range defined by the described half-plane; in this case, the algorithm accepts the new message as an updated position. In Figure 3.16b, however, the message is considered an old version of the actual aircraft's position, because the computed angle β lies outside the prescribed half-plane and thus the message is not deemed as carrying an aircraft's updated position.



Figure 3.16: "Updated-message" Algorithm - Standard Scenario

3. Simultaneously, the algorithm performs certain checks on the vertical scale. Here, the climb rate is another criterion that has been used: if a stored aircraft inside the *Traffic* structure has a positive climb rate (i.e., a situation in which the aircraft is climbing), updated messages should include an altitude that is greater than the older one stored inside the *Traffic* structure. The same applies in the opposite scenario in which the climb rate is negative.

Therefore, the message is accepted as an updated position of the aircraft only in cases where both the vertical and horizontal checks are satisfied.

4. Some issues could emerge in the scenario in which the flying object maintains flight around the "zero-point" in one or both of the vertical and horizontal axes. In fact, when the climb rate reported inside the message is oscillating around the zero value, the algorithm would inadvertently discard many of the incoming messages. To prevent this from happening, a threshold has been imposed on the climb rate value, under which the algorithm bypasses the vertical check on the message.

The same could happen when the ground speed exhibits small values. In scenarios whereby the flying object is almost hovering and quickly changes its track, the algorithm could mistakenly discard messages that actually reflect the real updated position of the aircraft.

For this reason, when the ground speed lies under a fixed threshold, the algorithm bypasses the half-plane check described in step 2 and performs another kind of validation. In these scenarios, the system builds a sphere around the aircraft's position in the NED frame and subsequently verifies whether or not the position of the new message lies inside the constructed sphere, so as to understand if the message represents an updated position or not. The radius is chosen taking into consideration the maximum acceleration that a generic aircraft can have. This approach is presented in in Figure 3.17.



Figure 3.17: "Updated-message" Algorithm - Sphere Scenario

If the algorithm does not receive any more messages from a specific aircraft, identified by a unique identifier, for a certain amount of time (15 seconds), it proceeds to the next step. This involves removing the allocated slot, which is the *Aircraft* structure inside the bigger *Traffic* structure, associated with that certain aircraft. This choice is largely used in this kind of application [40], where it is necessary to avoid overcrowding on the display, especially with aircraft that no longer transmit position information. Therefore, after the "updated-message" algorithm is performed, the system assigns the gathered data to each pre-allocated *Aircraft* structure inside the output *Traffic* structure.

The whole procedure described in this Section is performed in the *Updated Message Al*gorithm subsystem, which is presented in Figure 3.13. It is important to clarify that no inconsistency is reported when the different position data sources refer to terms such as *Heading* and *Track*. These two terms, in fact, despite theoretically representing two different concepts (as reported in Figure 3.18) often convey the same information; namely, the projection of an aircraft's path on the earth's surface at a clockwise angle from the geographic north, so as to define the track itself. Conceptually, the heading of an aircraft may be different than its track due to the wind; this difference is called drift angle.



Figure 3.18: Heading, Track and Drift Angles [41]
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3.3.4. Outputs

The outputted *Traffic* structure is subsequently processed and sent to the display, as can be noted in the *Traffic To Display* subsystem shown in Figure 3.12. The data sent to the display are represented in Table 3.6, where two new fields can be noted.

The *LatitudePredicted* and *LongitudePredicted* fields contain a simplified version of the estimated latitude and longitude of the 20 aircraft. Here, the algorithm processes the actual position, track and velocity of each aircraft, and predicts the new position for up to the next 10 seconds.

This is achieved under the assumption of uniform linear motion of each aircraft.

Subsequently, the system receives this information and displays a straight line for each aircraft, each one characterized by an origin (the actual position of the aircraft), an end point (the predicted position of the aircraft) and a direction (the actual track of the aircraft).

A potential issue could occur in scenarios in which messages are received from a flying object such as an almost hovering drone, which is characterized by small ground speed and high maneuverability (resulting in a highly variable track). In this case, the situation displayed would represent a straight line that is "rolling" and that changes direction with a high frequency.

To prevent this from happening, the algorithm computes the predicted latitude and longitude and sends them to the display only if the aircraft's ground speed is above a certain value.

Field name	Description	Units of measure	Data type
Latitude	Contains the 20 latitudes of the surrounding traffic.	deg	double
Longitude	Contains the 20 longitudes of the surrounding traffic.	deg	double
Altitude	Contains the 20 geometric altitudes of the surrounding traffic.	m	single
Track	Contains the 20 tracks of the surrounding traffic.	deg	single
ClimbRate	Contains the 20 vertical speeds in the WGS84 reference system of the surrounding traffic.	m m/s	single
LatitudePredicted	Contains the 20 predicted latitudes of the surrounding traffic.	deg	double
LongitudePredicted	Contains the 20 predicted longitudes of the surrounding traffic.	deg	double

Table 3.6: Position Data Sent to the Display

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3.3.5. Display

The display has been implemented through the Ansys SCADE Display software. As can be observed in Figure 3.19, the display is designed with the position of the hexacopter fixed in the middle, which rotates together with the hexacopter heading.



Figure 3.19: Traffic Display Implementation

Every surrounding aircraft's position analyzed by the algorithm is reported, together with its track, vertical trend, predicted position and relative altitude with respect to the hexacopter altitude. In particular, as described in Section 3.3.1, every non-altitude reporting target is displayed with a different color and without altitude information. The hexacopter position and altitude is reported in the bottom left of the display.

3.3.6. System Limitations

The algorithm has some limitations, which are described as follows:

- 1. The *Traffic* and *Aircraft* structures: since the *Traffic* structure contains all the 20 *Aircraft* structures, the actual display can output up to only 20 aircraft. This choice has been made to prevent both high computational cost and an overcrowded display. Despite this significant limitation, the algorithm can be easily scaled up to higher dimensions.
- 2. The MXS-NC Transponder input message: in this project, the MXS-NC Transponder's ADS-B State Vector and Mode Status Report messages are processed as one single message. This is mainly because of complexity issues; additional preprocessing would be required to properly merge two messages when belonging to the same aircraft.
- 3. Aircraft identification: understanding whether different messages belong to the same aircraft (and thus have the same identifier) is based on the assumption that the address present in each *Address* field is the ICAO address (or an equivalent FLARM official address). Although this choice inhibits scenarios in which different types of address are sent, it is ultimately justified by avoiding the necessary higher complexity that such an implementation would require.
- 4. Altitude type: only the geometric altitude is analyzed in this study. Therefore, scenarios in which only the barometric altitude is reported represent a potential limitation of the system. This issue could possibly be resolved by analyzing and displaying only the barometric altitude, but with the warning that one of the position data sources is sending the barometric altitude to a particular reference that differs from the standard pressure reference.
- 5. Predicted latitude and longitude: each aircraft's predicted position is computed under the assumption of uniform linear motion. Although this is a strong assumption and not always verified, such a choice is justified by the increased awareness it brings to the display.
- 6. The "updated-message" algorithm: as already described in Section 3.3.3, the system needs to be able to understand and choose whether new delivered messages truly depict the updated position of each aircraft or whether they are simply duplicates or characterize an older aircraft's position. To accomplish this task, the "updated-message" algorithm has been developed. Despite being a fundamental aspect of the process, it has certain limitations when analyzing scenarios in which the ground

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speed is low and the air vehicle is rapidly changing its track, or where the climb rate is oscillating around the zero value. These system limitations may result in actually valid messages being misunderstood as old ones, resulting in them being discarded without updating the aircraft's position. Some countermeasures have been

implemented to partially prevent these issues and are presented in Subsection 3.3.3.



4 Functional Tests

The traffic display system has been tested with the aid of the historical database provided by the OpenSky Network platform. [42, 43]

ADS-B data have been gathered through OpenSky-related tools provided by the online community [44, 45, 46], with the aim of testing the algorithm's performance and accuracy by feeding the collected messages into the system.

Traffic data were collected by searching the database on a specific day and time, and in a particular region. This information was retrieved on 7 June 2023, from 15:45 to 16:00 UTC, in the vicinity of Franz Josef Strauss International Airport (IATA: MUC, ICAO: EDDM). A total of 15 aircraft were examined, and their respective ADS-B message broadcasts were analyzed by the algorithm. Specifically, the path and call sign of each aircraft are illustrated in Figure 4.3 and Figure 4.4. Considering the time instant after 300 seconds from the beginning of the simulation, the corresponding display representing the surrounding traffic is reported in Figure 4.1.. It can be observed that the system accurately processes and represents information about every aircraft broadcasting either ADS-B or FLARM data. The algorithm generates aircraft paths that reflect the real-time traffic situation, as depicted, for instance, on the known Flightradar24 or reported through the OpenSky Network historical database, as can be clearly seen in Figure 4.2.

In particular, the system has also been tested in scenarios where the algorithm analyzes incorrect messages, or rather messages that represent an outdated position of the aircraft. Therefore, the algorithm has demonstrated proper behavior by not considering such messages as representing an updated position of the respective aircraft. Testing the system in these scenarios offers significant value as such scenarios represent potential real-life situations, as well as the most likely scenario that the hexacopter could encounter during normal operation.



Figure 4.1: Traffic Display after 300 seconds of simulation



Figure 4.2: 15 Aircraft Path Gathered through the OpenSky Network Historical Database



Figure 4.3: 15 Aircraft Path Computed by the Algorithm



Figure 4.4: 15 Aircraft Path Computed by the Algorithm - Zoom on MUC Airport



5 Conclusions and Future Developments

The results of this work have been considered overall satisfactory and compliant with the hexacopter requirements; the algorithm is able to properly achieve data fusion between ADS-B and FLARM messages, which have been designed with the same architecture described inside each of the three data sources.

Moreover, the system is capable of displaying the processed information on a standard traffic display, together with additional scenarios in which aircraft do not send altitude data.

The developed traffic display system is believed to be a crucial and fundamental aspect for every flying object that employs cooperative surveillance technology (such as ADS-B and FLARM), since this is the primary system responsible for the surveillance of the surrounding traffic. In particular, the algorithm has been designed for the 600kg hexacopter of TUM. The functionality of the system has been systematically tested and validated across a wide range of conceivable scenarios within a generic airspace. Experimentation on the algorithm used the historical database of the OpenSky platform; this has shown satisfactory results, consistent with the real-world situation as reported, for example, in software such as Flightradar24.

The system has effectively met the predetermined objectives and purposes, owing in part to the successful integration of a sub-algorithm that recognizes and verifies the validity of new messages compared to those already stored within the algorithm.

However, stemming from the inherent need to simplify certain aspects of the process, the system does exhibit some limitations, which calls for further development of the traffic display system described in this study. For example, the employment of non-cooperative surveillance technologies (such as LIDAR, FLIR or visual cameras) could further enhance the coverage and surveillance of the airspace. In addition, the process of aircraft identification for each incoming message could be further improved. In the present study, the algorithm is capable of assigning a new message to an already existing identifier only if the ICAO address or an equivalent FLARM offical address is transmitted. For this reason,

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a possible development could be through identifying the aircraft by analyzing its track, whereby the aim is to cover scenarios in which the reported address is either empty or differs from the official ICAO address.

The display itself could be also optimized to include more information about the ownship and the representation of the surrounding traffic through specific symbols determined by the study of the emitter-type field. Moreover, the implementation and following integration of a collision avoidance system (such as a similar TCAS or a DAA/SAA system) together with the developed algorithm would further improve security inside the airspace. In summary, the validation and successful implementation of the traffic display system in the ground control segment marks a significant milestone in enhancing airspace surveillance for the 600 kg hexacopter and ensuring safer flight operations.

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