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University Degree in Data Science and Engineering and
Telecommunication Technologies Engineering
2024 – 2025

Bachelor thesis

Applications of Autonomous Drones for Non-Terrestrial Networks in Remote Areas

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Leganés, 2025
Madrid, Spain

Abstract

This bachelor thesis presents the design, implementation, and testing of an autonomous drone system for non-terrestrial networks in remote areas. The project aims to provide researchers with an open-source, cost-effective solution for studying and deploying drone-based networks in challenging environments. The system consists of a modular Unmanned Areal Vehicle (UAV), a control station, and a reconnaissance platform. The UAV is designed to be easily customizable, using off-the-shelf components for accessibility and maintainability. It features autonomous flight capabilities and can carry various sensors for different applications. The control station allows real-time monitoring and control of the UAV, while the reconnaissance platform processes data collected by the drone using advanced computer vision and machine learning techniques. The system incorporates a 360-degree camera and on-board processing capabilities, enabling real-time object detection and tracking. Integration with large language models enhances the system's analytical capabilities, providing detailed insights about detected objects. Testing demonstrated the system's ability to fly autonomously, detect and analyze objects in real-time, and communicate data effectively over long distances. With a flight time of 30-40 minutes and a modular design, the developed system offers a versatile platform for applications such as surveillance, search and rescue, and environmental monitoring in remote areas.

Keywords: autonomous drones, non-terrestrial networks, remote areas, unmanned aerial vehicles, reconnaissance platform, object detection, deep learning

Acknowledgments

First and foremost, I would like to express my sincere gratitude to my supervisor, Dr. José Alberto Hernández Gutiérrez, for the opportunity to work with him on this project. His guidance, expertise, and support have been invaluable throughout the development of this thesis.

I would also like to extend my thanks to Tomás Martínez Cortés for his assistance and insights, which have greatly contributed to this work.

My heartfelt appreciation goes to the Telematics Department of Universidad Carlos III de Madrid, especially to David Larrabeiti for his unwavering support since the beginning of my academic journey. I am grateful to all members of the department for creating a nurturing and stimulating environment for research and learning.

Finally, I would like to thank my colleague Carlos de Quinto for his collaboration and support throughout this process. Your camaraderie and intellectual contributions have been instrumental in the completion of this thesis.

To all those mentioned and to the many others who have supported me along the way, thank you for your encouragement, patience, and belief in my abilities. This work would not have been possible without you.

Agradecimientos

En primer lugar, quiero expresar mi más sincero agradecimiento a mi supervisor, el Dr. José Alberto Hernández Gutiérrez, por la oportunidad de trabajar con él en este proyecto. Su orientación, experiencia y apoyo han sido invaluables durante todo el desarrollo de esta tesis.

También me gustaría extender mi gratitud a Tomás Martínez Cortés por su asistencia y perspectivas, que han contribuido enormemente a este trabajo.

Mi más profundo aprecio va para el Departamento de Telemática de la Universidad Carlos III de Madrid, especialmente a David Larrabeiti por su apoyo inquebrantable desde el inicio de mi trayectoria académica. Estoy agradecido a todos los miembros del departamento por crear un ambiente estimulante y enriquecedor para la investigación y el aprendizaje.

Finalmente, me gustaría agradecer a mi colega Carlos de Quinto por su colaboración y apoyo durante todo este proceso. Tu camaradería y contribuciones intelectuales han sido fundamentales para la realización de esta tesis.

A todos los mencionados y a los muchos otros que me han apoyado en el camino, gracias por su aliento, paciencia y fe en mis capacidades. Este trabajo no habría sido posible sin ustedes.

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List of Acronyms

2G	2nd Generation.
3G	3rd Generation.
3GPP	3rd Generation Partnership Project.
4G	4th Generation.
5G	5th Generation.
6G	6th Generation.
AESA	Spanish Aviation Safety and Security Agency.
AI	Artificial Intelligence.
AI Act	Artificial Intelligence Act.
ANN	Artificial Neural Network.
CNN	Convolutional Neural Network.
DL	Deep Learning.
EASA	European Aviation Safety Agency.
ESC	Electronic Speed Controller.
EU	European Union.
FOV	Field of View.
FPV	First Person View.
GAN	Generative Adversarial Network.
GEO	Geostationary Earth Orbit.
GNSS	Global Navigation Satellite System.
GPS	Global Positioning System.
HAP	High Altitude Platform.
HetNet	Heterogeneous Network.
IMU	Inertial Measurement Unit.
INCOSE	International Council on Systems Engineering.
IoST	Internet of Space Things.
IoT	Internet of Things.
ISTN	Integrated Space-Terrestrial Network.

LEO	Low Earth Orbit.
LLM	Large Language Model.
LTE	Long-Term Evolution.
ML	Machine Learning.
MTOW	Maximum Takeoff Weight.
NTN	Non-Terrestrial Network.
PDB	Power Distribution Board.
QoS	Quality of Service.
RED	Radio Equipment Directive.
RF	Radio Frequency.
RNN	Recurrent Neural Network.
SES	Single European Sky.
STP	Standard Temperature and Pressure.
STS	Standard Training Scenario.
TN	Terrestrial Network.
UAS	Unmanned Aircraft System.
UAV	Unmanned Aerial Vehicle.
UE	User Equipment.
USB	Universal Serial Bus.
VLOS	Visual Line of Sight.
VR	Virtual Reality.
WiFi	Wireless Fidelity.

Part I

Introduction

Chapter 1

Motivation

The rapid evolution of cellular users in recent years, refer to Figure 1.1, has significantly increased the demand for high-speed, reliable data connectivity. This growing demand has placed substantial pressure on existing network infrastructures, requiring new solutions to enhance both capacity and coverage. Heterogeneous Networks (HetNets) have been proposed as an effective strategy to address these challenges by creating multi-layered networks that enable efficient data offloading [1]. This improves both the capacity and coverage across the network. However, the dense deployment of these networks also increases energy consumption, which is undesirable in today's environmentally conscious and cost-sensitive world.

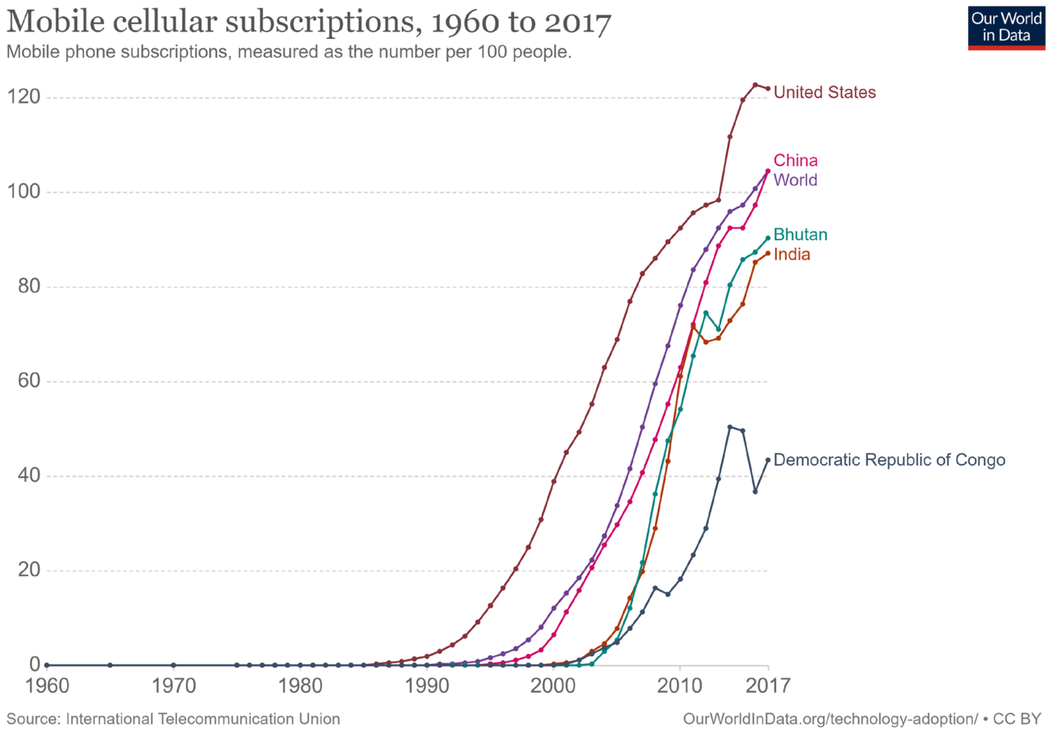


Figure 1.1. *Global Trends in Mobile Cellular Subscriptions (1960–2017): The graph illustrates the exponential growth of mobile subscriptions per 100 people across various regions over recent decades. [2]*

Reducing power consumption while maintaining Quality of Service (QoS) requirements has therefore become a key objective in the deployment and operation of mobile networks [3]. In this context, Non-Terrestrial Networks (NTNs) have emerged as a promising approach to complement Terrestrial Networks (TNs) and expand coverage to regions that have historically been underserved due to the prohibitive costs or logistical challenges of deploying terrestrial base stations [4].

NTNs leverage airborne platforms, including UAV, High Altitude Platforms (HAPs), and satellites, to act as relay nodes or base stations, providing connectivity to end-users across vast geographical areas. Their key advantage lies in the ability to cover expansive regions, including remote and inaccessible areas, where terrestrial solutions are either too costly or impractical. In particular, Low Earth Orbit (LEO) satellites, which orbit at altitudes between 200 and 2000 kilometers, have shown significant potential for providing high-capacity connectivity due to their lower latency and stronger signal strength compared to other satellite types [5]. This proximity to Earth not only enhances performance but also reduces energy requirements, aligning with the broader goal of minimizing power consumption in modern networks.

The emergence of NTNs has further enabled the development of advanced concepts such as the Integrated Space-Terrestrial Network (ISTN) [6][7][8], and the Internet of Space Things (IoST) [9][10][11]. These concepts envision a seamless integration of terrestrial and non-terrestrial components to deliver next-generation communication services, particularly for future 6th Generation (6G) networks. Mega-constellations of satellites, exemplified by networks like Starlink [12] and OneWeb [13], are at the forefront of this transformation. By integrating these networks with terrestrial systems, it becomes possible to connect isolated regions, including rural and oceanic environments, which are otherwise challenging to serve. Furthermore, this integration holds the potential to create a unified communication infrastructure that offers connectivity not only on the ground but also in the air and space.

This research is motivated by the growing need to develop sustainable, cost-effective solutions for extending connectivity to remote areas. NTNs, particularly when integrated with TNs, present a viable path forward in addressing these challenges, thereby supporting the goals of global connectivity and reducing energy consumption in future wireless communication systems. The work is supported by ongoing efforts in NTNs to leverage emerging technologies for the development of 6G networks, with the ultimate aim of delivering ubiquitous, high-quality communication services to all corners of the world.

Chapter 2

Statement of the problem

Current research in the domain of NTN primarily focuses on the development of satellite constellations in Geostationary Earth Orbit (GEO) and LEO [14]. Despite the fact that these satellites offer significant potential, their high costs and limited customizability render them impractical for many research groups and individual researchers. Moreover, the complexity of launching and maintaining satellites in orbit presents a significant barrier to entry for many interested parties.

This work seeks to address the gap by developing a comprehensive, open-source, and cost-effective solution for the deployment of UAVs in remote environments to study and research NTNs. Moreover, this solutions seeks to open the door to a new area of research in the domain of NTN, low altitude UAV-based networks, and to provide a platform for researchers and individuals to explore other potential applications of UAVs in remote areas.

Given the broad nature of this problem, the scope of this thesis will be narrowed to a specific environment and use case, as outlined below:

- **Environment:** The modeled environment will be a remote area with minimal infrastructure, such as a forest, desert, or mountain. Specifically, the case study will involve an esplanade—a flat area devoid of significant obstacles like buildings or trees—allowing the UAV to operate without the risk of collision. Moreover, 4th Generation (4G) or 5th Generation (5G) connectivity will be assumed to be available, enabling the UAV to communicate with a control station.
- **Atmospheric Conditions:** The selected environment will feature a clear sky, with minimal electromagnetic interference from other sources such as UAVs or aircrafts. Additionally, the conditions will approximate Standard Temperature and Pressure (STP) of $15\,^{\circ}\mathrm{C}$ and $1013\,\mathrm{hPa}$.
- **Operational Parameters:** The UAV operations will be confined to Visual Line of Sight (VLOS) and an altitude below $120\,\mathrm{m}$ and the Maximum Takeoff Weight (MTOW) of the UAV will not exceed $25\,\mathrm{kg}$, ensuring compliance with current aviation regulations in Spain and most countries.
- **Hardware:** The UAV will be constructed using commercially available, off-the-shelf components to ensure affordability and ease of replication for other research groups and individuals.

Chapter 3

Objectives

The main objective of this thesis is to offer the research community an open-source, cost-effective solution for deploying drones in remote environments to support the study of NTNs. This project specifically aims to foster new research in the field of NTNs and low-altitude, drone-based networks, providing a platform for further exploration of drone applications in remote areas.

Additionally, the project seeks to develop a reconnaissance platform capable of scouting and detecting individuals, establishing a practical foundation for drone use in applications such as humanitarian aid, environmental monitoring, and disaster response, thereby contributing to public safety and well-being.

To meet these objectives, the following specific goals have been set:

- Design a modular, customizable drone, enabling easy modifications for different applications.
- Use off-the-shelf components for easy assembly, repair, and maintenance.
- Ensure the drone supports autonomous flight, essential for operating in remote areas where manual control is difficult.
- Integrate the latest advancements in drone technology to remain competitive while maintaining cost-effectiveness.
- Develop a customizable reconnaissance platform that can integrate different sensors to gather environmental data and adapt to various tasks.
- Enable real-time data processing and analysis on the reconnaissance platform, providing actionable insights for diverse applications.

Chapter 4

Document Structure

The document structure of this thesis is organized into six main parts, each focusing on a specific aspect of the research on autonomous drones for Non-Terrestrial Networks (NTNs) in remote areas.

The Theoretical Background part, part II, provides the foundational knowledge necessary to understand the core concepts of the thesis. It delves into non-terrestrial networks, explaining different types such as geostationary satellites, low-earth orbit satellites, and high-altitude platforms. This part also covers unmanned aerial vehicles, their types, and applications, as well as an overview of deep learning techniques relevant to the project.

The State of the Art part, part III, explores the historical development of non-terrestrial networks and UAVs, current types and characteristics of NTN platforms, and modern trends in the field. This part provides context for the research and highlights the gaps in existing solutions that this thesis aims to address.

The Methodology part, part IV, forms the core of the thesis, detailing the requirements, design, and implementation of the proposed system. It covers the unmanned aerial vehicle design, control station setup, reconnaissance platform development, and communication system integration. This part provides a comprehensive overview of how the system was built and configured.

The Results part, part V, presents the outcomes of the project, including the testing procedures for individual components and the system as a whole. It discusses the achievements of the implemented system, as well as the challenges encountered during development and how they were overcome.

Finally, the Conclusions part, part VI, summarizes the key findings of the research, reflects on the objectives achieved, and proposes directions for future work. It also includes a discussion on the socio-economic impact of the project and an analysis of the relevant regulatory framework governing UAV operations.

Chapter 5

Methodological Framework

The methodological framework employed in this thesis is grounded in the V-model as established by the International Council on Systems Engineering (INCOSE) [15] for project development. The V-model offers a rigorous and structured method that ensures all project facets are considered, facilitating timely and budget-compliant completion. This is achieved through a comprehensive development process, enabling clear validation and verification of initial requirements at every stage.

The methodology is segmented into seven key components which can be summarized as follows:

1. **Identification of User Requirements**: A detailed analysis of the problem statement is conducted to identify the primary issues and potential solutions. Moreover, the user requirements are defined to ensure that the proposed solution aligns with the objectives of the project.
2. **System Design**: The system architecture is developed based on the user requirements, ensuring that the proposed solution is feasible and aligns with the project's objectives. This phase includes a detailed overview of the system components and their interconnections. Requirements are formulated to satisfy the previously defined solution requirements. This phase includes a high-level overview of the components of the proposed solution, the justification for their selection, and the interconnections among them.
3. **Component Design**: Building upon the high-level architecture of the solution, a more detailed approach is outlined for each component, taking into account their specific power and data transmission needs. This culminates in a comprehensive architecture of the solution. Furthermore, a detailed overview of the components is provided, including the rationale for their selection and the interconnections among them.
4. **Implementation**: The proposed solution is implemented and manufactured utilizing available tools while simultaneously integrating the necessary electrical components. This phase includes a detailed description of the implementation process, including the tools and materials used, as well as the integration of electrical components. The development of software and hardware components is also detailed.
5. **Component Testing**: The functionality of each component is verified in a standalone mode, with detailed information provided regarding the verification process.

6. **System Testing**: The methodology for conducting flight tests and subsequent analyses is elaborated. System integration is performed by assessing communication between module pairs to ensure that data can be transmitted freely and utilized effectively.
7. **Acceptance Testing**: Validation of the initial requirements is conducted to confirm that all solution requirements have been met. This phase also includes preparations for potential future enhancements.

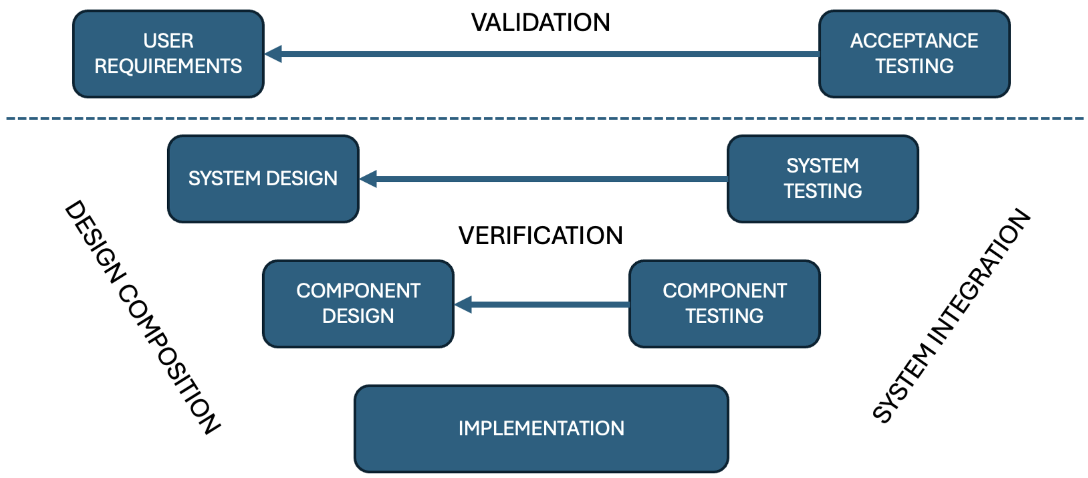


Figure 5.1. *Methodological framework based on the V-model from INCOSE with the different stages of the project development process[16]*

Moreover, a graphical representation of the V-model is provided in Figure 5.1 to illustrate the methodology's structure and the relationship between the various stages.

Part II

Theoretical Background

Chapter 6

Non-Terrestrial Networks

As defined by the 3GPP [17], an NTN refers to a network which partially/fully operates for communication purposes through a spaceborne vehicle (i.e., GEO and LEO satellites, or an airborne vehicle such as HAPs and UAVs). The most important feature that makes NTNs unique is their capability to provide connectivity in unreachable areas (for vessels, airplanes, etc.), or remote areas where a significant investment is required to build a terrestrial infrastructure.

NTNs represent a groundbreaking approach in wireless communication, utilizing aerial and space-based platforms to deliver connectivity services. These platforms can operate at varying altitudes, from a range of a hundred meters to kilometers above ground, offering key advantages over traditional terrestrial networks, such as expanded coverage, increased capacity, and greater flexibility.

NTNs provide a promising solution to meet the rising demand for wireless access in remote and underserved areas. By leveraging aerial and space platforms, NTNs can extend the reach of conventional terrestrial networks, offering connectivity where traditional infrastructure is either difficult or impossible to deploy. In Figure 6.1, we illustrate the different types of NTNs based on altitude and platform type as well as their interaction with other network elements such as User Equipments (UEs), Internet of Things (IoT) devices, etc.

6.1 Geostationary Satellites

GEO satellites operate at an altitude of approximately 36 000 km above the Earth's equator. These satellites maintain a fixed position relative to the Earth's surface, as they orbit at the same rate as the planet's rotation. GEO satellites offer extensive coverage, often spanning entire continents, and are widely used for telecommunications, broadcasting, and weather monitoring.

GEO satellites offer broad coverage and high capacity, making them ideal for applications like direct-to-home television, satellite radio, and broadband internet access. Their capacity to cover large regions makes GEOs integral to global communications infrastructure.

A key advantage of GEO satellites is their ability to support high-capacity services for many users, making them valuable for broadcasting live events, such as sports and concerts, or delivering high-definition video content worldwide. As a fundamental part of the global media and communication ecosystem, GEO satellites are expected to continue playing a vital role in providing connectivity to remote and underserved regions.

6.2 Low-Earth Orbit Satellites

LEO satellites operate at altitudes between 160 km and 2000 km above the Earth. Orbiting at high speeds, these satellites provide global coverage, making them ideal for delivering connectivity to remote and underserved regions. LEO satellites offer numerous advantages over traditional GEO satellites, including lower latency, higher capacity, and reduced infrastructure costs.

Deployed in constellations consisting of hundreds or thousands of satellites, LEO satellites work together to provide continuous coverage. These satellites communicate through inter-satellite links, allowing data to be relayed seamlessly across the constellation. LEO satellites are well-suited for delivering broadband internet access in areas where traditional infrastructure is difficult to establish.

One of the primary advantages of LEO satellites is their low latency, enabling real-time communication and supporting applications that require minimal delay, such as online gaming, video conferencing, and autonomous vehicle systems. Additionally, LEO satellites offer high-speed internet connectivity to users in remote locations, granting access to online services, educational platforms, and e-commerce opportunities. As a critical part of the emerging NTN ecosystem, LEO satellites are expected to play a key role in bridging the global digital divide.

6.3 High-Altitude Platforms

HAPs operate at altitudes ranging from a hundred meters to kilometers above the Earth. These platforms may consist of balloons, airships, or UAVs. They provide unique benefits compared to traditional terrestrial networks, including broader coverage, increased capacity, and lower infrastructure costs. HAPs can be deployed swiftly to offer connectivity in remote or underserved areas, making them an effective tool for reducing the digital divide.

Additionally, HAPs can provide temporary connectivity in disaster-stricken regions or during large-scale events. Rapid deployment allows emergency responders to coordinate efforts efficiently. They can also extend the coverage of existing networks in rural areas, where conventional infrastructure is costly or challenging to install.

Advances in UAV technology have enabled the development of autonomous HAPs equipped with Long-Term Evolution (LTE) or 5G base stations, flying at altitudes of up to 20 km. These platforms cover substantial areas and support a range of applications, making them ideal for remote and underserved locations where deploying traditional infrastructure is not practical.

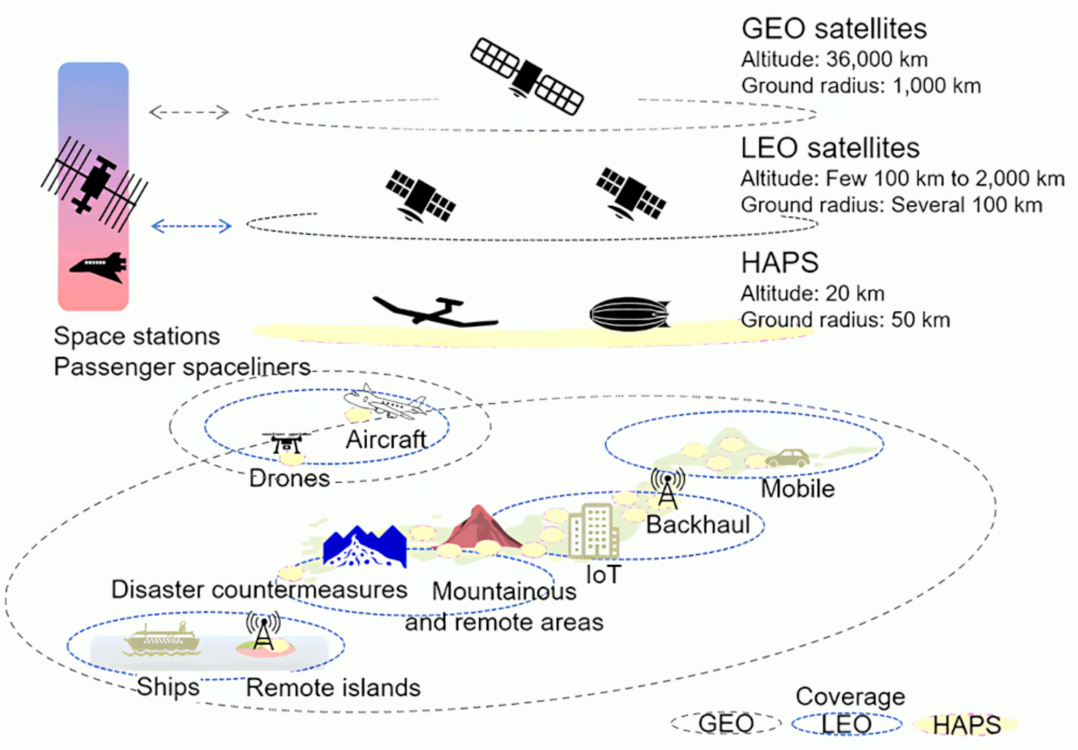


Figure 6.1. *Types of NTNs based on altitude and platform type. HAPs, LEOs satellites, and GEOs satellites interact with other network elements to provide connectivity services. [18]*

Chapter 7

Unmanned Aerial Vehicles

The term UAV encompasses a diverse range of aircraft, from compact quad-copters to larger fixed-wing models. What primarily distinguishes UAVs from conventional aircraft is that UAVs are either remotely piloted or autonomously controlled, whereas traditional aircraft are operated by human pilots. This autonomy enables UAVs to be deployed in scenarios where human presence is either impractical or hazardous, such as military operations or environments with significant risk.

UAVs serve various purposes across multiple industries, including surveillance, reconnaissance, search and rescue missions, and scientific research. Additionally, they have become invaluable in sectors like agriculture, forestry, and environmental monitoring. In recent years, UAVs have gained popularity among hobbyists for recreational flying and personal projects.

7.1 Types of Unnamed Aerial Vehicles

In line with the classification presented by the European Aviation Safety Agency (EASA) [19], UAVs can be categorized into three main types, each based on size, weight, physical design, and operational capabilities:

- **Fixed-wing UAVs:** These aircraft feature fixed wings and function similarly to conventional airplanes. They tend to be larger and designed for long-duration flights, making them suitable for extended missions like surveillance, reconnaissance, and mapping. However, they require runways for takeoff and landing, and cannot hover in place, limiting their versatility in confined spaces.
- **Rotary-wing UAVs:** Equipped with multiple rotors, these UAVs can take off and land vertically. They are typically smaller and more agile, making them ideal for close-range missions like aerial photography, search and rescue, and surveillance. However, their limited range and endurance compared to fixed-wing UAVs restrict their use in long-duration missions.
- **Hybrid UAVs:** Combining the features of both fixed-wing and rotary-wing designs, hybrid UAVs can take off and land vertically like rotary-wing models while achieving greater range and endurance through fixed-wing flight. These aircraft are ideal for missions requiring versatility, such as reconnaissance and mapping. Despite their advantages, they are more complex and costly to operate than single-type UAVs.

Figure 7.1 illustrates the different UAVs types based on their design and intended applications.

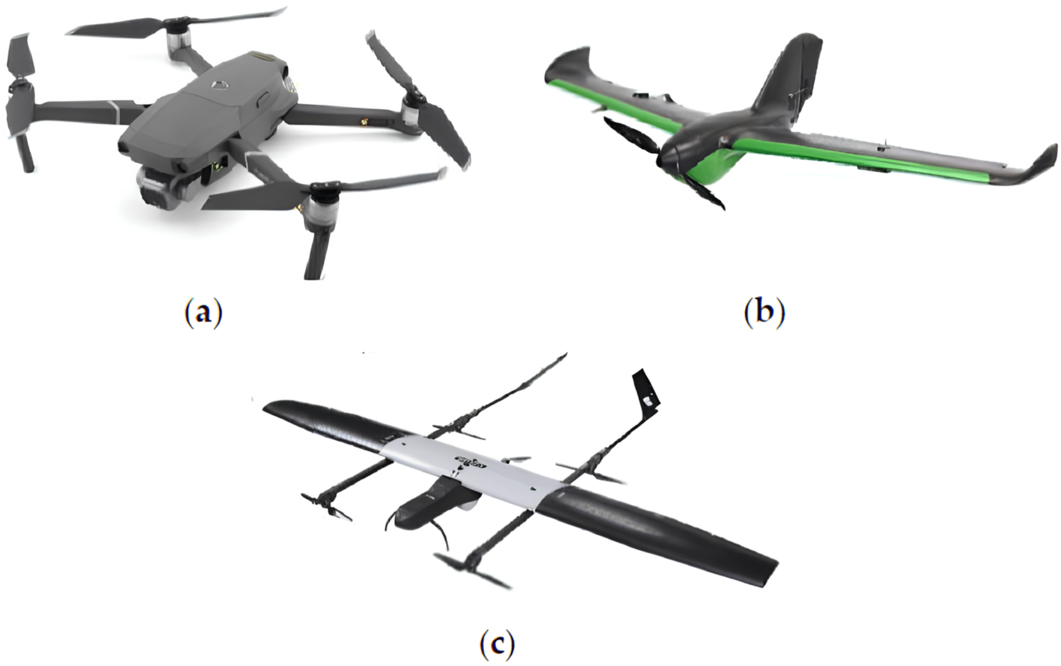


Figure 7.1. *Types of UAVs based on their design and intended use [20].*
a. Rotary-wing UAV, b. Fixed-wing UAV, c. Hybrid UAV

In Table 7.1, a detailed comparison of fixed-wing, rotary-wing, and hybrid UAVs is presented across various performance metrics, including size, range, endurance, cost, and ease of operation. The table provides insights to help in selecting the appropriate UAV for specific mission requirements, depending on factors like payload, range, and maneuverability.

Metric	**Fixed-wing**	**Rotary-wing**	**Hybrid**
Size	Moderate	Small	Large
Range	Long	Short	Moderate
Endurance	High	Low	Moderate
Payload capacity	High	Low	Moderate
Maneuverability	Low	High	Moderate
Ease of use	Moderate	High	Low
Maintenance	Moderate	Low	High
Runway requirement	Yes	No	Yes
Cost	Moderate	Low	High

Table 7.1. *Comparison of fixed-wing, rotary-wing, and hybrid UAVs across various performance metrics*

7.2 Applications of Unmanned Aerial Vehicles

UAVs have a wide range of applications across different industries, leveraging their versatility, maneuverability, and autonomy. Some common applications of UAVs include:

- **Aerial photography and videography:** UAVs equipped with high-resolution cameras are used for capturing aerial images and videos for various purposes, including filmmaking, real estate, and landscape photography.
- **Agriculture:** UAVs are employed in precision agriculture to monitor crop health, assess soil conditions, and optimize irrigation and fertilization practices. They can provide valuable insights to farmers for improving crop yield and reducing resource wastage.
- **Search and rescue:** UAVs equipped with thermal imaging cameras and other sensors are used in search and rescue operations to locate missing persons, assess disaster-affected areas, and deliver essential supplies to remote locations.
- **Infrastructure inspection:** UAVs are utilized for inspecting critical infrastructure like bridges, power lines, and pipelines. They can access hard-to-reach areas and capture detailed images for assessing structural integrity and identifying maintenance needs.
- **Environmental monitoring:** UAVs are deployed for monitoring environmental parameters like air quality, water quality, and wildlife populations. They can collect data in remote or hazardous environments, providing valuable insights for conservation efforts and scientific research.
- **Disaster response:** UAVs play a crucial role in disaster response by providing real-time situational awareness, mapping affected areas, and coordinating emergency operations. They can assist in assessing damage, locating survivors, and delivering aid to disaster-stricken regions.
- **Military and defense:** UAVs are extensively used in military and defense applications for reconnaissance, surveillance, target acquisition, and combat operations. They offer a cost-effective and low-risk alternative to manned aircraft in high-risk environments.
- **Delivery services:** UAVs are increasingly being used for last-mile delivery of goods and services. Companies like Amazon and UPS are exploring the use of UAVs for delivering packages to customers in urban and rural areas.

Chapter 8

Deep Learning

Deep Learning (DL) is a subfield of Machine Learning (ML) that focuses on the development of algorithms and models inspired by the structure and function of the human brain. These algorithms are designed to learn from data, identify patterns and relationships, and make predictions or decisions without explicit instructions. DL algorithms are characterized by their ability to automatically discover and extract features from raw data, enabling them to perform complex tasks such as image recognition, speech recognition, and natural language processing.

DL has revolutionized various industries and domains, including healthcare, finance, transportation, and entertainment. By leveraging the power of DL, organizations can analyze large datasets, extract valuable insights, and automate complex tasks, leading to improved decision-making, enhanced user experiences, and optimized processes. From self-driving cars and virtual assistants to medical diagnostics and fraud detection, DL is transforming the way we interact with technology and the world around us.

Furthermore, DL plays a crucial role in enabling UAV autonomy, allowing drones to perform tasks such as navigation, obstacle avoidance, and object recognition without human intervention. By integrating DL algorithms into UAV systems, researchers and developers can enhance the capabilities and efficiency of drones, enabling them to operate in complex environments and execute sophisticated missions.

8.1 Deep Learning Techniques

DL encompasses a wide range of techniques and architectures that enable machines to learn from data and make decisions. Some of the most common DL techniques include:

- **Artificial Neural Network (ANN):** ANN are computational models inspired by the structure and function of the human brain. They consist of interconnected nodes, or neurons, organized in layers, with each neuron performing a simple computation. ANN can learn complex patterns and relationships in data through a process called back-propagation, where errors are propagated back through the network to adjust the model's parameters. ANN are used in a variety of tasks, such as classification, regression, and clustering.
- **Convolutional Neural Network (CNN):** CNN are a type of ANN designed for processing and analyzing visual data, such as images and videos. They use con-

volutional layers to extract features from input data, pooling layers to reduce spatial dimensions, and fully connected layers to make predictions. CNN are widely used in image recognition, object detection, and image segmentation tasks.

- **Recurrent Neural Network (RNN):** RNN are a type of ANN designed for processing sequential data, such as time series, text, and speech. They have feedback connections that allow information to persist over time, enabling them to capture temporal dependencies in data. RNN are used in natural language processing, speech recognition, and machine translation tasks.
- **Generative Adversarial Network (GAN):** GAN are a type of DL model that consists of two neural networks, a generator and a discriminator, trained adversarially. The generator generates synthetic data samples, while the discriminator distinguishes between real and fake samples. GAN are used in image generation, style transfer, and data augmentation tasks.

These techniques form the foundation of DL and are used in a wide range of applications across various domains, enabling machines to perform complex tasks and make intelligent decisions. In the context of NTN and UAVs, DL techniques can enhance network performance, optimize resource allocation, and enable autonomous operation, leading to more efficient and reliable systems. Furthermore, DL can enable UAVs to perform tasks such as navigation, object detection, and mission planning with high accuracy and efficiency, making them valuable tools for a wide range of applications (e.g., surveillance, monitoring, and disaster response).

Part III

State of the art

Chapter 9

Historical Development

The evolution of NTNs and UAVs has been shaped by technological advances and the increasing demand for global connectivity over the past several decades. Originally, NTNs, encompassing satellite communication networks, HAPs, and UAVs, were developed for specialized applications. These early systems were primarily used for military, navigation, television broadcasting, remote sensing, and disaster management purposes. Due to the high costs and complexities associated with the manufacturing, launching, and maintaining these systems, their deployment was limited to specific sectors and regions, often focusing on government or large corporate projects.

Early satellite communication networks were dominated by GEO satellites, which provided consistent coverage over specific areas of the Earth, particularly for television broadcasting and weather forecasting. However, the high latency and large round-trip time associated with GEO satellites, positioned at approximately 36 000 km from Earth, posed challenges for expanding their use to real-time communication services. Additionally, the prohibitive costs and challenges of deploying and maintaining GEO satellites restricted their usage largely to commercial and government-backed projects.

Throughout the late 20th century, NTNs remained niche solutions, but technological advancements and the growing need for more comprehensive and reliable global connectivity shifted the focus. The limitations of TNs, particularly in rural, remote, and inaccessible regions such as deserts, oceans, and mountainous areas, drove the demand for new approaches. Expanding terrestrial network coverage into these regions posed economic and logistical challenges, making NTNs a critical complementary solution. Satellites became vital to extending coverage beyond the reach of terrestrial infrastructure, filling gaps where ground-based systems were either impractical or uneconomical to deploy.

The 1990s saw the rise of LEO satellite constellations, which were developed to overcome some of the inherent limitations of GEO satellites. LEO satellites, operating at much lower altitudes of 300 km to 1500 km, offered significantly reduced latency and improved spectral efficiency. These benefits made LEO satellites more suitable for supporting new and emerging applications that demanded real-time communication and data transmission. Despite the technological promise of LEO satellites, the initial wave of mega-constellation projects—large networks comprising hundreds to thousands of satellites—stalled, largely due to the high costs of deployment and a lack of sustainable business models.

The late 1990s and early 2000s marked a renewed interest in integrating NTNs with terrestrial systems, particularly as global internet access became a key societal goal. As mobile network generations progressed from 2nd Generation (2G) to 4G, the need for more adaptive network solutions grew. However, it was not until the development of 5G, spearheaded by the 3rd Generation Partnership Project (3GPP), that serious efforts were made to fully integrate NTNs with terrestrial networks. 3GPP's Release 15 [21] in 2018 laid the foundation for 5G networks, and subsequent releases aimed to include NTNs, such as satellite and HAPs, as essential components of the 5G ecosystem. These efforts recognized NTNs' potential to expand the reach of 5G networks into underserved areas and enhance service reliability in mobile broadband and IoT applications.

During the same period, advancements in UAVs also contributed to the development of NTNs. Initially developed for military and surveillance applications, UAVs began to be explored for their potential in civil applications such as disaster management, agriculture, and communications. The rise of 5G networks allowed for UAVs to be integrated into terrestrial networks, enabling beyond VLOS operations that required low-latency, reliable connections for autonomous vehicles, precision agriculture, and more.

As 5G networks continue to evolve, NTNs are becoming increasingly vital in ensuring seamless global connectivity. LEO constellations, in particular, have seen a resurgence, with companies like SpaceX (Starlink) [12] and OneWeb [13] developing large satellite networks to deliver low-latency, high-speed internet services to remote areas. These NTNs are providing the much-needed infrastructure to bridge the digital divide by offering global coverage, enhancing reliability, and addressing specific issues such as network scalability and latency that have traditionally limited satellite communications.

Chapter 10

Types & Characteristics

NTNs are an emerging approach in the field of wireless communication that aims to expand network coverage beyond the reach of traditional terrestrial systems. By utilizing platforms such as satellites, UAVs, and HAPs, NTNs can address the growing demand for global connectivity, particularly in remote or inaccessible areas. NTNs offer a flexible and adaptable infrastructure, supporting a wide range of applications from disaster recovery to rural broadband access.

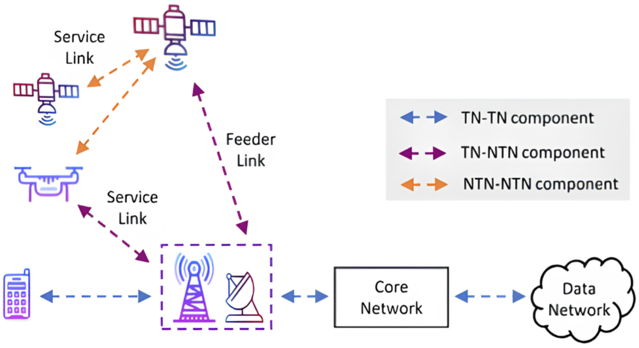
The following sections explore the various types of NTNs, also referred as architectural models, highlighting their roles in enhancing communication networks, the benefits they offer, and the challenges they face. These architectures include platforms functioning as network users, relays, and base stations, along with mixed models that combine different approaches to maximize efficiency and coverage. The diagram of the different architectures of NTN platforms according to their use case is shown in Figure 10.1.

10.1 NTN Platforms as Network Users

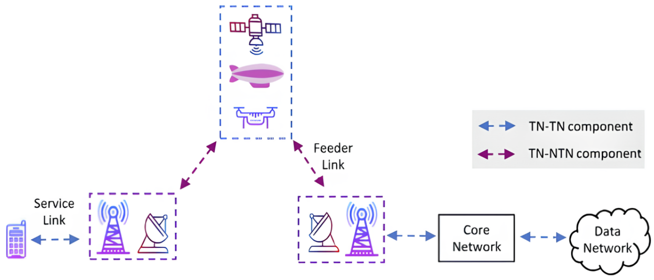
In this architecture, the NTN platform operates similarly to a user device, or UE, connecting to an existing terrestrial network as depicted in Figure 10.1a. This model is particularly relevant for platforms like satellites and UAVs, which need connectivity for data transmission. UAVs, for instance, can access terrestrial networks via base stations located on the ground.

A well-known example is the integration of UAVs into terrestrial networks. The 3GPP has identified UAVs as a unique category of UE [23], leading to research on how to address their specific connectivity challenges [24]. These challenges include maintaining stable connections during flight, managing potential interference, and ensuring service quality at various altitudes. By treating UAVs as network users, terrestrial infrastructure can support a broader range of communication needs, such as surveillance, logistics, and remote sensing.

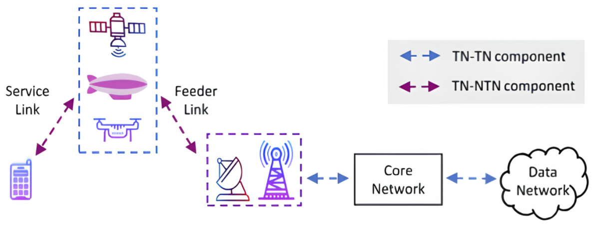
Additionally, in scenarios where terrestrial control stations are unavailable or impractical, satellites can communicate directly with other satellites. This capability eliminates the need for extensive ground infrastructure, improving data transmission efficiency and making it particularly beneficial for space missions and remote observation activities.



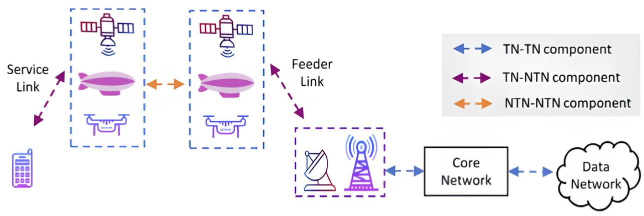
(a) *Diagram of NTN Platforms as Network Users where the NTN acts as another UE in the network.*



(b) *Diagram of NTN Platforms as Relays where the NTN acts as a relay between the UE and the base station.*



(c) *Diagram of NTN Platforms as Base Stations where the NTN acts as a base station for the UE.*



(d) *Diagram of Mixed Architecture Models where the NTN acts as a combination of the above.*

Figure 10.1. *Different architectures of NTN platforms according to their use case [22].*

10.2 NTN Platforms as Relays

NTN platforms can also serve as relays, functioning as intermediaries that transmit signals between different components of the network, refer to Figure 10.1b. This type of architecture can be categorized into two main configurations based on the relay's role within the network.

The first configuration involves backhaul connectivity [25], where the NTN platform provides a link between a ground-based base station and the core network. This model is especially useful in remote or hard-to-reach areas where traditional backhaul solutions, such as fiber optic cables, are unavailable or too costly to install. By using satellites or HAPs as relays, terrestrial networks can be extended without requiring significant ground infrastructure.

In the second configuration, the NTN platform acts as a direct relay between ground users and a terrestrial base station. This setup is particularly effective in environments where access to a base station is limited, such as densely populated urban areas or mountainous regions. UAVs or LEO satellites can serve as intermediary nodes, relaying user signals to the terrestrial network. This approach expands coverage and improves connectivity in areas where traditional infrastructure may not suffice [26].

10.3 NTN Platforms as Base Stations

NTN platforms can also be configured to act as base stations, managing communication networks autonomously. Platforms equipped with advanced processing capabilities, such as regenerative payloads, can process signals onboard and provide connectivity without relying on ground-based infrastructure, as shown in Figure 10.1c. This architecture is particularly useful in scenarios where ground-based base stations are impractical or unavailable.

In the case of satellite-based base stations, satellites in LEO are equipped with onboard processors that handle tasks typically managed by terrestrial base stations, such as signal processing, traffic routing, and user management [27]. This configuration is particularly well-suited for providing connectivity in remote regions, such as open seas, deserts, or disaster-stricken areas where ground infrastructure is impractical or unavailable.

UAVs can also function as temporary base stations, providing localized network coverage in specific areas. For example, UAVs equipped with 5G technology can deliver communication services during large-scale events, emergencies, or military operations. These UAV-based stations operate at lower altitudes than satellites, making them ideal for providing real-time, localized coverage with minimal delay.

10.4 Mixed Architecture Models

In real-world deployments, combining different architectural models is often necessary to create a more flexible and robust network infrastructure [28], as shown in Figure 10.1d. Mixed architecture models leverage the unique strengths of various NTN platforms to optimize communication performance and coverage.

One example of a mixed architecture is a combination of LEO satellites and UAVs. In this configuration, a LEO satellite equipped with base station capabilities can work alongside UAVs acting as relays to extend coverage to ground users. The UAVs, operating at lower altitudes, enhance connectivity by relaying signals to the satellite, which then forwards the data to the core network. This approach ensures a broader coverage area and improved network performance.

Another example involves multi-tier satellite configurations [29], where satellites at different altitudes work together to provide comprehensive coverage. For instance, a GEO satellite can serve as a high-level backhaul link to the core network, while LEO satellites deliver low-latency connectivity to end users. This multi-tier approach combines the strengths of GEO and LEO satellites, offering both extensive coverage and low-latency communication.

Finally, HAPs can be integrated into NTN networks to act as intermediary nodes between UAVs and satellites. In this configuration, HAPs receive data from UAVs below and transmit it to LEO satellites above, improving data transmission efficiency. This multi-hop communication strategy is particularly useful in complex environments where direct satellite or terrestrial communication is difficult.

10.5 Characteristics of Non-Terrestrial Networks

NTNs offer several benefits, but they also present challenges. One of the primary advantages of NTNs is their ability to extend network coverage to regions where terrestrial infrastructure is either unavailable or impractical [22]. NTNs can provide connectivity in remote areas, including oceans, mountainous regions, and locations affected by natural disasters. Platforms like UAVs and HAPs are especially useful in emergencies, as they can be quickly deployed to restore communication services and support disaster relief efforts.

In addition, NTNs provide a flexible communication infrastructure by integrating different types of platforms. This adaptability makes NTNs suitable for meeting the needs of diverse applications across various regions. Moreover, NTNs are often more cost-effective than traditional networks, especially in sparsely populated areas where building extensive ground infrastructure would be prohibitively expensive.

However, NTNs also face several challenges. Latency is a significant concern, especially in systems that rely on multiple satellite hops or satellite-to-satellite communication. High latency can affect the performance of real-time applications, such as voice or video communication. Signal interference is another issue, as multiple platforms operating at different altitudes and frequencies can lead to overlapping signals. Effective spectrum management is critical to maintaining service quality in NTN deployments.

Power limitations, particularly for UAVs and certain HAPs, can restrict their operational duration [30]. Additionally, regulatory challenges, such as airspace management and frequency allocation, pose obstacles to the widespread deployment of NTNs. For instance, UAV-based NTN platforms must comply with international airspace regulations, while satellite-based NTNs require coordination across different countries to ensure proper frequency usage.

NTNs serve a variety of use cases across different sectors. In disaster recovery scenarios, NTNs can be rapidly deployed to restore communication networks for emergency response teams [31]. NTNs are also valuable for environmental monitoring and remote sensing, providing continuous observation over large areas, such as forests, oceans, and agricultural lands. In the aviation and maritime sectors, NTNs provide reliable connectivity for aircraft and ships, offering essential communication services in regions beyond terrestrial coverage. Finally, NTNs play a crucial role in reducing the digital divide by delivering broadband internet access to rural and remote communities where traditional networks are not viable.

Chapter 11

Modern Trends

In recent years, NTNs have emerged as a significant advancement in the field of wireless communication. These networks utilize platforms as described in previous chapters (e.g., satellites, HAPs, or UAVs), to provide connectivity in areas where traditional communication infrastructure may be lacking or underdeveloped. As the demand for reliable communication continues to grow, NTNs present unique opportunities for various applications, particularly in disaster response, virtual reality, and high-speed internet access. This section explores the modern trends of NTNs, highlighting their importance in enhancing UAV capabilities and addressing contemporary challenges.

One of the most impactful applications of NTN-enabled UAVs is in rescue operations during natural disasters. These drones can serve as critical tools in emergencies such as earthquakes, hurricanes, and floods by establishing essential communication links between affected areas and external agencies. For instance, during the 2015 Nepal earthquake [32], UAVs equipped with NTN technology were deployed to transmit real-time video feeds of devastated regions, allowing emergency responders to assess damage and prioritize resources effectively. Additionally, UAVs can be outfitted with thermal imaging cameras to locate survivors in disaster zones. In the aftermath of Hurricane Harvey in 2017 [33], NTN-enabled UAVs scanned flooded neighborhoods, relaying findings to command centers and guiding rescue teams to those in need. The integration of NTNs with UAVs thus creates a network of aerial assets that optimizes response times and enhances overall disaster management efforts.

Beyond rescue operations, NTN-enabled UAVs are being utilized in innovative applications such as Virtual Reality (VR) experiences and 5G connectivity. By transmitting high-definition video feeds, these drones offer immersive experiences that allow users to engage with their surroundings in unique ways. For instance, during training scenarios for emergency responders, UAVs can capture 360-degree videos of disaster zones, providing trainees with a realistic simulation of on-ground conditions [34]. This not only enhances training effectiveness but also helps responders make informed decisions based on a comprehensive understanding of the situation. Moreover, companies like Nature Eye [35] employ NTN-enabled UAVs to provide live aerial tours of scenic locations, broadening the scope of VR applications and enhancing user engagement.

As NTN technology continues to evolve, the integration of Artificial Intelligence (AI) within UAVs presents opportunities for enhanced operational efficiency and autonomy.

AI algorithms can optimize flight paths, improve communication protocols, and enhance decision-making processes for UAVs in real-time. Companies like Skydio [36] leverage AI to enable their UAVs to autonomously navigate complex environments and avoid obstacles. Moreover, ML techniques can enhance UAVs' ability to analyze data collected from their surroundings. Notably, researchers from the University of Zurich developed an autonomous drone system called Swift [37], which can outperform human champions in First Person View (FPV) drone racing. This achievement represents a significant milestone, highlighting the potential of AI in real-time decision-making and its applications in sectors such as environmental monitoring and precision agriculture.

In conclusion, the modern trends of NTNs in UAV applications demonstrate the transformative impact these technologies can have across various sectors. From enhancing emergency response capabilities to revolutionizing communication infrastructure, NTN-enabled UAVs are poised to play a critical role in shaping the future of wireless communication. Continued research and innovation in this field will unlock new possibilities and applications, ultimately contributing to the advancement of non-terrestrial networks and their integration with terrestrial systems.

Part IV

Methodology

Chapter 12

Requirements

Based on a careful analysis of the conclusions from the modern trends in UAVs outlined in Chapter 11 and the objectives reviewed in Chapter 3, the following requirements are established for the high-level system as well as the detailed requirements for each of the components of the system: the UAV, the drone that will be used for the reconnaissance tasks, the control station, the system that will monitor the UAV in real-time and communicate with it, and the reconnaissance platform, the system that will process the data collected by the UAV and provide insights to the end-user for the different reconnaissance tasks.

12.1 High-level System Requirements

The high-level system requirements are as follows:

- The system must be able to operate in remote areas with limited infrastructure, such as roads, electricity, and internet connectivity.
- The system must be able to be monitored remotely, with the ability to have a communication channel in real-time for long distances, more than 5 km, for the full duration of the mission.
- The system must be cost-effective, with the capability to be assembled and disassembled easily, and to be repaired and maintained with minimal effort.
- The system must be modular, allowing for the integration of different sensors and payloads for different applications, such as mapping, surveillance, and monitoring the environment.
- The system must be able to perform reconnaissance tasks autonomously, with the ability to take off, land, and navigate given a set of waypoints. Moreover, the system must be able to update its flight plan in real-time.
- The system must integrate a real use-case scenario to proof the concept of the system, with the ability to detect and track objects, monitor the environment, and generate alerts and notifications in case of critical events or failures.
- The system must comply with the applicable regulatory framework for UAVs in the country of operation, Spain, as well as the European Union (EU) regulations. See Chapter 20 for more information.

Given the high-level system requirements, the detailed requirements for each of the components of the system are outlined in the following sections.

12.2 Unmanned Aerial Vehicle Requirements

For the UAV, the specifications necessary to meet the high-level system requirements are:

- The UAV must be able to be controlled remotely, with the ability to take off, land, and navigate autonomously given a set of waypoints.
- The UAV must be able to carry different payloads and sensors for different applications up to a maximum payload weight of 2 kg, with the ability to adapt to different reconnaissance tasks.
- The UAV must be able to fly for a minimum of 30 min, without the need for recharging.
- The UAV must be have a failsafe mechanism, that is it must be able to return to the original point of departure in case of loss of communication or other critical failures.
- The UAV must be able to process data in real-time, with the ability to relay the information to the control station and the reconnaissance platform.
- The UAV must comply with the EASA regulations for the Open Category, with a maximum limit set at 25 kg of MTOW and 3 m of wingspan.

12.3 Control Station Requirements

In order to provide an autonomous and reliable control of the UAV, the control station requirements are as follows:

- The control station must be able to receive telemetry data from the UAV in real-time, with the ability to send commands to the UAV to update its flight plan.
- The control station must be able to be used remotely, with the ability to communicate with the UAV over long distances, more than 5 km, and for extended periods of time.
- The control station must be able to create a geofence around the area of operation, with the ability to monitor the UAV's position and altitude in real-time and receive alerts and notifications in case of critical events or failures.
- The control station must log all telemetry data and flight information, with the ability to analyze the data and generate reports.
- The system used for the control station must be reliable, secure, and easy to use, with the addition of a backup control station in case of failure.

12.4 Reconnaissance Platform Requirements

Finally, to provide a use-case scenario for the system, the reconnaissance platform requirements are as follows:

- The reconnaissance platform must be able to run on a variety of operating systems, with the ability to communicate with the UAVs and the control station in real-time and over long distances.
- The reconnaissance platform must be customizable, allowing for the integration of new features and the modification of existing ones, as well as, the addition of new UAVs to the system and different types of reconnaissance tasks.
- The reconnaissance platform must have alerting and notification capabilities, with the ability to send alerts and notifications to the user in case of critical events or failures.
- The reconnaissance platform must have a user-friendly interface, with the ability to display telemetry data and flight information in real-time, as well as, the ability to monitor the UAVs in real-time.

Chapter 13

Design

This chapter outlines the system's design, detailing its components in accordance with the requirements specified in Chapter 12. The system consists of four core components: the UAV, responsible for providing the functionality and mobility, the control station, responsible for monitoring the UAV in real-time and updating its flight plan, the communication system, responsible for enabling real-time data exchange between the UAV, control station, and reconnaissance platform, and the reconnaissance platform, responsible for processing the data collected by the UAV and providing insights to the end-user. The full cost breakdown of the system is detailed in Section 19.4.

13.1 Unmanned Aerial Vehicle

For the UAV design, a simple and cost-effective design is chosen, with the ability to take off and land in remote areas with limited infrastructure. The UAV is designed to be modular, allowing for the integration of different sensors and payloads for different applications. The UAV is also designed to be autonomous, with the ability to take off, land, and navigate to a set of waypoints. The UAV is composed of the following components: the airframe, the propulsion system, the flight controller, the power system, and peripherals. The following sections describe the design of each of the components of the UAV, as well as the reasoning behind the choices made.

13.1.1 Airframe

The airframe is the structure of the UAV that holds all the components together. The airframe must be lightweight, durable, and easy to assemble and disassemble. The airframe must also be able to carry the peripherals and additional components required for the reconnaissance tasks.

For the airframe, different designes are considered, such as fixed-wing, rotary-wing, and hybrid designs as stated in Section 7.1. As on of the main requirements is the ability to take off and land in remote areas with limited infrastructure, a rotary-wing design is chosen for the UAV. The rotary-wing design allows for vertical takeoff and landing, as well as the ability to hover in place, which is useful for reconnaissance tasks making it the most suitable design for the use case.

Rotary-wing designs are further divided into multi-rotor and single-rotor designs as seen in Figure 13.1. Multi-rotor designs are more stable and easier to control, while single-rotor designs are more efficient and have a longer flight time. For the UAV design, a quadcopter design is chosen, as it provides a good balance between stability and efficiency. The quadcopter design consists of four rotors, with two rotors spinning clockwise and two rotors spinning counterclockwise, which provides a stable and efficient flight.

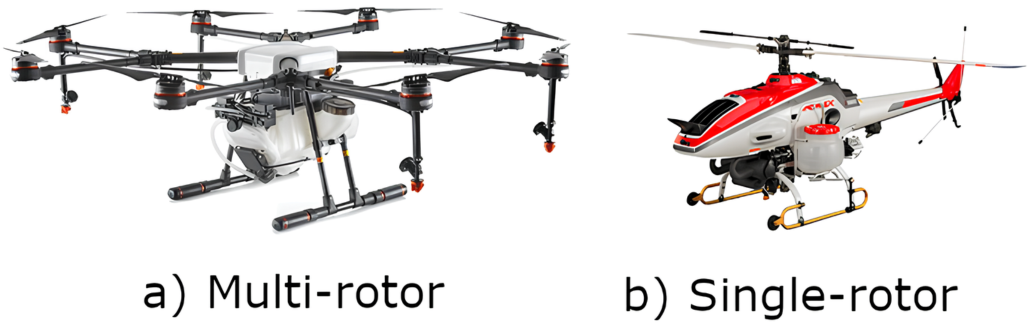


Figure 13.1. *Rotary-wing designs. a. Multi-rotor design. b. Single-rotor design. [38].*

For the material of the airframe, a lightweight and durable material is chosen, such as carbon fiber. For that case the airframe chosen is the Quad plegable Tarot XS690 [39]. It is a quadcopter design made of carbon fiber, with a diameter of 690 mm and a weight of 675 g. The airframe is designed to carry different sensors and payloads, such as cameras, lidar, and thermal imaging sensors.

13.1.2 Propulsion System

The propulsion system is the system that provides the thrust required for the UAV to take off, land, and navigate. The propulsion system can be of different types, such as electric, gasoline, or hybrid. Electric propulsion systems are usually chosen for UAVs due to their efficiency, reliability, and low maintenance requirements. Gasoline propulsion systems are usually chosen for larger UAVs that require longer flight times and higher payloads. Hybrid propulsion systems are usually chosen for UAVs that require both efficiency and long flight times.

For the UAV design, an electric propulsion system is chosen, as it provides the best balance and makes the UAV more reliable and easier to maintain. The electric propulsion system consists of four brushless motors, to generate the rotation, four Electronic Speed Controllers (ESCs), to control the motors, and four propellers, to generate the thrust.

The brushless motors chosen are the Tmotor U7 V2 420KV [40], with a maximum thrust of 3.88 kg at an operating voltage of 22.2 V and a current draw of 28.7 A. The ESCs chosen are the Tmotor FLAME 100A LV 600Hz [41], with a maximum current of 100 A per motor and a maximum voltage of 34 V. The propellers chosen are the Tmotor 17x5.8 V2 [42], with a length of 17 in and a pitch of 5.8 in.

13.1.3 Flight Controller

The flight controller is the system manages the UAV during flight, it is responsible for stabilizing the UAV, controlling the motors, and navigating the UAV to a set of waypoints.

The flight controller can be of different types, such as manual, semi-autonomous, or autonomous. Manual flight controllers are usually chosen for UAVs that require human intervention during flight as they are the simplest to use, require the least amount of training, and are the most cost-effective. Semi-autonomous flight controllers are usually chosen for UAVs that require human intervention for takeoff and landing, but can navigate autonomously to a set of waypoints. Autonomous flight controllers are usually chosen for UAVs that can take off, land, and navigate autonomously to a set of waypoints. One key feature of the flight controller is the *Return to Home* feature, which allows the UAV to return to the original point of departure in case of loss of communication or other critical failures. Finally, the software used for the flight controller is also important. For our case, the software used is ArduPilot [43], an open-source software with a large community of developers and a large number of plugins and extensions to extend the functionality of the flight controller.

The main requirements of the flight controller are the ability to stabilize the UAV, control the motors, and navigate the UAV to a set of waypoints, as well as the ability to communicate with the control station in real-time and the compatibility with the ArduPilot software. The flight controller chosen is the Holybro Pixhawk 6C [44], as it provides the best price-performance ratio. It has multiple redundant sensors, such as accelerometers, gyroscopes, and magnetometers, as well as the ability to integrate different sensors and peripherals for different applications.

13.1.4 Power System

The power system is in charge of providing the power required for the UAV to operate. The power system can be of different types, such as batteries, fuel cells, or electric generators. For UAVs, batteries are usually chosen as they provide a good balance between energy density, power density, and weight. The main requirements of the power system are the ability to provide enough power for the UAV to take off, land, and navigate, as well as the ability to power the different components of the UAV (e.g., Global Positioning System (GPS), camera, communication system, etc.).

For this project, a lithium polymer battery is chosen as it is the most common type of battery used for UAVs and highly available in the market. The battery chosen is the TATTU 22000mAh 4S 14.8V 30C Lipo Battery [45], with a capacity of $22\,000$ mA h and a voltage of 14.8 V. The battery is designed to provide enough power for the UAV to carry the maximum payload weight of 3 kg for 30 min. Note, this flight time can lower if the peripherals and additional components require power to operate.

Furthermore, in order to provide the required power for ESCs of the UAV, a Power Distribution Board (PDB) is integrated into the power system. The PDB is necessary as the UAV requires a high current to operate and a specialized power management system is needed to provide the required power to the different ESCs of the UAV. For this project, the Holybro PM07 Power Module [46] as it supports 4S batteries and provides a maximum current of 90 A. Finally, a voltage regulator is chosen to provide the required voltage for the different components of the UAV. In this case, the HobbyWing 25A HV UBEC [47] is chosen, as it provides a maximum current of 25 A with different voltage outputs, which is enough to power the different components of the UAV such as the flight controller, GPS, and communication system, among others.

13.1.5 Peripherals

The peripherals are the components that provide additional functionality to the UAV. The peripherals can be of different types, such as sensors, geo-location systems, cameras, lidar, thermal imaging sensors, etc. For reconnaissance tasks, usually cameras are chosen, as they provide the ability to collect images of the environment.

For this UAV, a GPS module was integrated into the UAV to provide the ability to navigate autonomously through a set of waypoints. The GPS module chosen is the Holybro M9N GPS GNSS [48] as it provides Global Navigation Satellite System (GNSS) capabilities, a satellite navigation system with global coverage, for a relatively low price. The GPS module is critical for the UAV, as it provides the ability to navigate autonomously through a set of waypoints, as well as the ability to return to the control station in case of loss of communication or other critical failures.

13.2 Control Station

The control station is the station that monitors the UAV in real-time. It is responsible for receiving telemetry data from the UAV and sending commands to update its flight plan. The control station is also responsible for creating a geofence around the area of operation, monitoring the UAV's position and altitude in real-time, and tracking multiple UAVs simultaneously. To perform the tasks mentioned, the control station is composed of a ground control station running a waypoint planning software and a radio controller with a communication module to communicate with the UAV in real-time.

The ground control station is the human-machine interface that allows the operator to monitor the UAV in real-time, receive telemetry data from the UAV, and send commands to update its flight plan. For the ground control station, a personal laptop or a desktop computer is used with the waypoint planning software installed, in this case, the Mission Planner software [49]. For the radio controller, a handheld device is used that allows the operator to take control of the UAV manually in case of an emergency and a communication module to receive telemetry data from the UAV in real-time. The radio controller used is the RadioMaster TX16S MKII Hall V4.0 [50]. For the communication module, the module used is described in Section 13.4.

13.3 Reconnaissance Platform

The reconnaissance platform is the system that processes the data collected by the peripherals and the sensors on the UAV and provides insights to the end-user for the different reconnaissance tasks. The reconnaissance platform is responsible detecting and tracking objects, monitoring the environment, and generating alerts and notifications in case of critical events or failures. The reconnaissance platform is also responsible for managing the different missions of the UAVs with the objectives and constraints defined by the end-user.

The reconnaissance platform is divided into two main components. The on-board reconnaissance platform, which runs on the UAV, is responsible for processing the data collected by the peripherals and the sensors on the UAV, detecting the objects in the environment, and providing insights to the off-board reconnaissance platform. The off-board reconnaissance platform, which runs on a server, is responsible for coordinating the missions of the UAVs, collecting the data of the UAVs, and generating reports and alerts for the end-user.

For the on-board reconnaissance platform, the components chosen were the on-board computer, specifically the NVIDIA Jetson Orin [51] as it provides the best real-time processing power commercially available to run deep learning algorithms, 275 TOPS. The main reason to choose this on-board computer enables the UAV to process the data collected in real-time and reduces the bandwidth required to send the data to the off-board reconnaissance platform. Moreover, a 360-degree camera was chosen to provide a full view of the environment where the UAV is operating and be able to detect and track objects in real-time regardless of the UAV's orientation. The camera chosen was theRicoh Theta X 360 Degree Camera [52]. The reasoning to choose this camera is the only few 360-degree cameras that provide live streaming capabilities and a high resolution, 5.7 K at 30 FPS.

The off-board reconnaissance platform is designed to run on any available server, as it is not required to have a high processing power as the on-board reconnaissance platform. The main requirement for the off-board reconnaissance platform is to have a stable and reliable connection to the on-board reconnaissance platform, as well as the ability to be accessed remotely from anywhere in the world. For this, a cloud provider was chosen, specifically Amazon Web Services [53].

13.4 Communication System

The communication system is the system that allows the UAV to communicate with the control station in real-time, as well as providing to the reconnaissance platform. Different communication systems can be used depending on the use case, such as 5G, 4G, 3rd Generation (3G), Wireless Fidelity (WiFi), or Radio Frequency (RF), and the environment where the UAV will operate. The characteristics to consider when choosing a communication system are shown in Table 13.1.

Communication System	Reliability	Latency	Range	Bandwidth
5G	High	Low	Long	Really High
4G	High	Low	Long	High
3G	Medium	Medium	Medium	Medium
WiFi	Low	High	Short	High
RF	High	Low	Long	Medium

Table 13.1. *Comparison of the different communication systems depending on their characteristics.*

The communication system for the drone is divided into two main subsystems: the communication systems in charge of connecting the UAV with the control station, and the communication systems in charge of connecting the on-board reconnaissance platform with the off-board reconnaissance platform.

For the communication system in charge of connecting the UAV with the control station, a RF communication module was chosen, as it provides a stable and reliable connection, as well as a low latency and long range. Moreover, it is the defacto standard for UAV communication systems to communicate with the control station in real-time. The module chosen to connect the UAV with the control station is the RFD868 TXMOD V2 868Mhz 1W [54], as it is the defacto standard for long-range RF communication systems for UAVs and it is compatible with the EU regulations for RF communication systems, refer to Subsection 20.2.3, and it provides the highest range up to 10 km with a 1 W power output and the given antennas.

Likewise, for the communication system, a 4G communication module was chosen as it provides a high bandwidth to send the data collected by the UAV in real-time. The router chosen is the GL.iNet GL-X750 [55] due to a good price-performance ratio and a low weight and size. Note that a 5G router can also be used but due to the higher cost and the lack of coverage in the area of operation, a 4G router was chosen instead.

Chapter 14

Implementation

Following the design presented in the previous Chapter 13, this chapter lays out the implementation of the system and the integration of the components that compose it, as well as the methodologies and tools used to develop, assemble, and integrate the system. As previously explained, the system is divided into four main components: the UAV, the control station, and the reconnaissance platform. Each component is implemented separately and then integrated into the system as a whole following the V-model methodology described in Chapter 5.

14.1 Control Station

The control station as mentioned in Section 13.2 is the station that monitors the UAV in real-time. It is responsible for receiving telemetry data from the UAV and sending commands to update its flight plan. The control station is also responsible for creating a geofence around the area of operation, monitoring the UAV's position and altitude in real-time, and tracking multiple UAVs simultaneously.

The control station is composed of a ground control station running a waypoint planning software, in this case, the Mission Planner software [49], see Figure 14.1. The radiocontroller is connected to the telemetry module of the UAV to send commands and receive telemetry data via the RF module. The mission planner software is connected to the radiocontroller via a WiFi connection to receive telemetry data and send commands to the UAV by relaying them through the radiocontroller.

14.2 Unmanned Aerial Vehicle

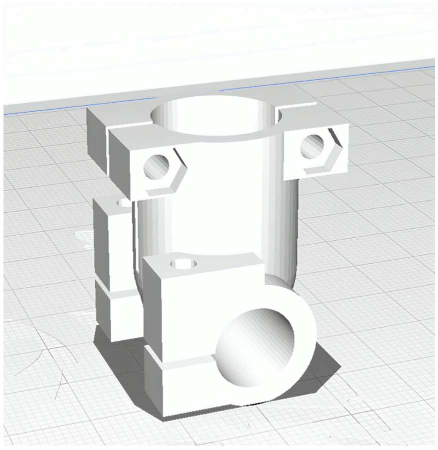
The UAV is the base platform and the main component of the system. For this reason, it is the first component to be implemented. The UAV is responsible for carrying the reconnaissance platform and the communication system, as well as for executing the flight plan generated by the control station. The detailed implementation of the UAV is out of the scope of this thesis and only a high-level overview of the implementation is provided. However, more information about the implementation of the UAV can be found in the [56]. Each subsystem of the UAV described in the Section 13.1 is implemented separately and then integrated into the UAV as a whole.

Figure 14.1. *Control Station setup. On the right, the Mission Planner software running on a laptop. On the left, the reconnaissance platform receiving the video feed. On the bottom center, the RadioMaster TX16S radio controller.*

14.2.1 Airframe

For the airframe, the UAV was built using following the instructions provided by the manufacturer. The airframe can be seen in Figure 14.2a. However, some modifications were made to the airframe to accommodate the additional components using custom 3D printed parts (e.g., the landing gear, the camera mount, and the payload bay). The design and manufacture of the 3D printed parts where made using the FreeCAD software [57] and a Bamboo P1S 3D printer [58]. The reason to use 3D printed parts is that they are easy to design and manufacture, as well as being lightweight and durable. The 3D printed parts were designed to be easily attached to the airframe using screws and nuts, as well as to be easily removed in case of maintenance or replacement. Some of the 3D printed parts used in the airframe can be seen in Figure 14.2b.

(a) *Tarot XS690 airframe [56].*



(b) *3D printed landing gear [56].*

Figure 14.2. *Airframe and 3D printed parts.*

14.2.2 Propulsion System

Regarding the propulsion system, the four motors were attached to the airframe using custom metal brackets, as seen in Figure 14.3a. The ESCs were attached to the airframe using double-sided tape and zip ties, as seen in Figure 14.3b.

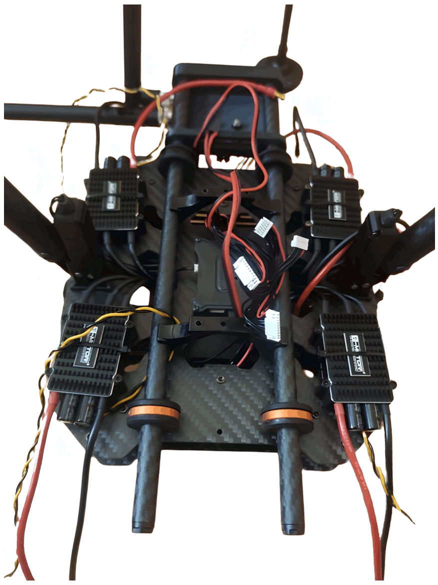
14.2.3 Flight Controller

For the flight controller, it was placed in the middle of the airframe using double-sided tape and zip ties, as seen in Figure 14.4. It is important to note that placing the flight controller in the middle of the airframe provides the best balance and stability for the UAV during flight.

14.2.4 Power System

The power system is the heaviest subsystem of the UAV and must be placed in the center of the airframe to provide the best balance and stability during flight. The battery was attached to the airframe using battery straps, as seen in Figure 14.5a. The PDB, Figure 14.5b, was attached to the airframe using a custom 3D printed mount and places in the middle of the airframe, as seen in Figure 14.5c. Also, the voltage regulator was attached to the top of the airframe using double-sided tape and zip ties, refer to Figure 14.6c.

(a) *Metal motor mount brackets to attach the motors to the airframe (orange brackets) [56].*



(b) *Bottom view of the airframe with the ESCs attached in each corner [56].*

Figure 14.3. *Propulsion system components attached to the airframe.*

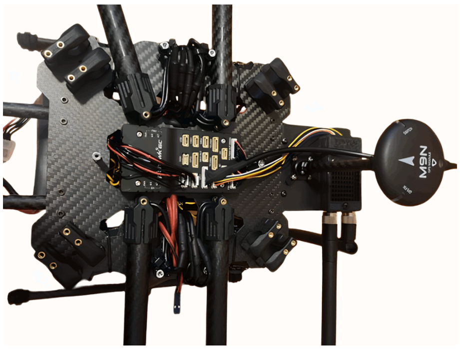
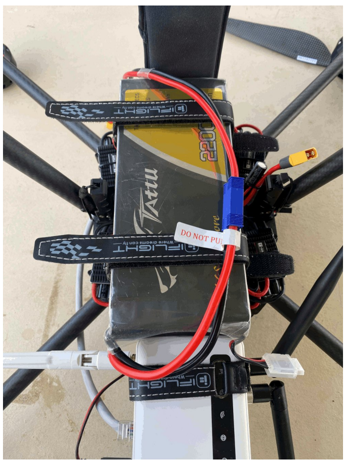
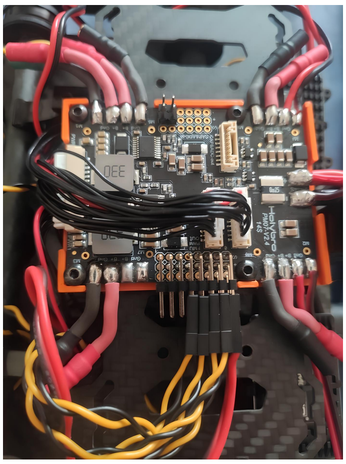


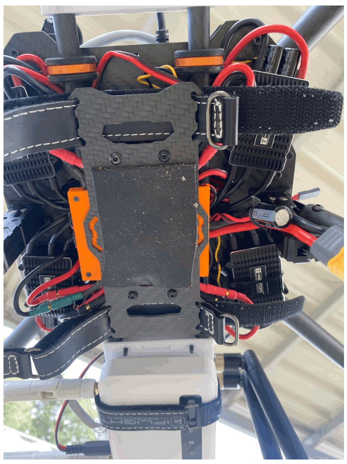
Figure 14.4. *Flight controller attached to the airframe in the middle of the airframe [56].*



(a) *Battery attached to the airframe.*



(b) *PDB attached to the mid plate of the airframe [56].*



(c) *PDB attached to the airframe, orange box in the middle of the airframe.*

Figure 14.5. *Power system components attached to the airframe.*

14.2.5 Peripherals

The GPS was attached to the top of the airframe using a custom 3D printed mount, as seen in Figure 14.6a. A important note is that the GPS module must be placed in a location where it has the best reception, as well as where it is not obstructed by other components of the UAV. It must be place as far as possible from the motors and any carbon fiber components, as they can interfere with the reception of the GPS module.

For the communication system, the RF module was attached to the airframe using the same 3D printed mount as the GPS module, as seen in Figure 14.6a. The 4G module was attached to the airframe along with the RF module and the GPS module.

The camera was attached to the front of the airframe using a custom 3D printed mount in order to provide the best Field of View (FOV), as seen in Figure 14.6b. The camera must be placed in a location where it has the best field of view, as well as where it is not obstructed by other components of the UAV. It must be placed as far as possible from the motors as they can interfere with the camera's FOV.

Finally, for the on-board computer, it was placed in the middle of the airframe using screws and nuts, as seen in Figure 14.6c. It must be placed in a location where air can flow freely to avoid overheating. Depending on the application, the on-board computer can be placed in a different location, as long as it is not obstructed by other components of the UAV, however, it is recommended to place it in the middle of the airframe to provide the best balance and stability during flight.

(a) *GPS module attached to the airframe (circular black module). The RF module is the rectangular black module with two antennas behind the GPS module. The 4G router is the white module below the RF module.*

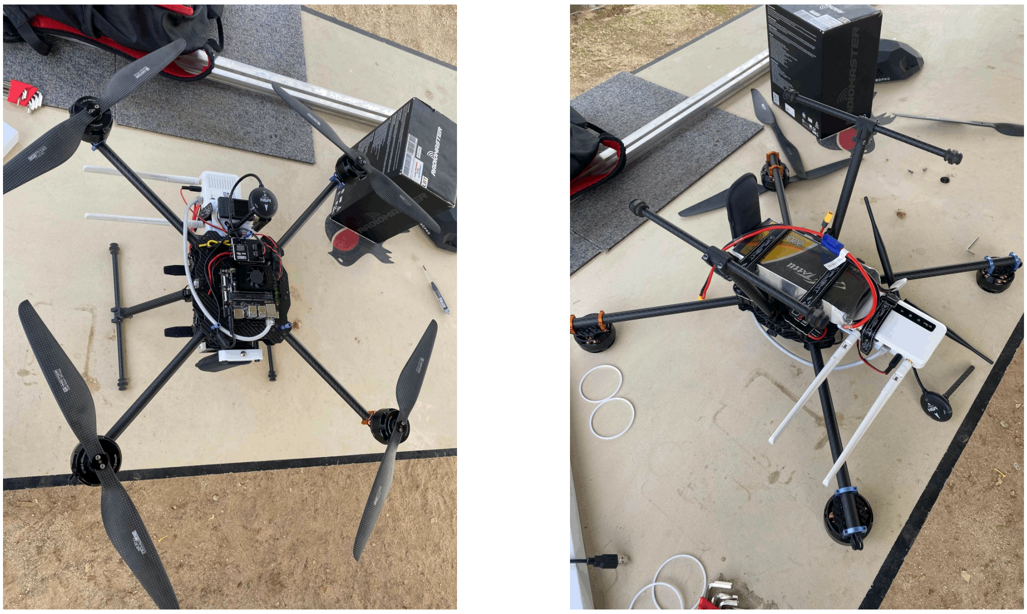
(b) *Camera attached to the airframe using a custom 3D printed white mount.*

(c) *On the center, the on-board computer. On the top side above the fan, the GPS module.*

Figure 14.6. *Peripherals attached to the airframe.*

14.2.6 Final Assembly

After all the components were attached to the airframe, the final assembly of the UAV was performed. The final assembly consists of connecting all the components together, as well as configuring the flight controller and the communication system. The final assembly of the UAV can be seen in Figure 14.7.



(a) *Top view of the UAV assembled.* (b) *Bottom view of the UAV assembled.*

Figure 14.7. *Final assembly of the UAV.*

14.3 Reconnaissance Platform

Finally, to implement the reconnaissance platform, three main components are needed: video capture, video processing, and insights generation. The video capture component is responsible for capturing the video feed from the UAV camera. The video processing component is responsible for processing the video feed to extract relevant information. The insights generation component is responsible for generating insights from the processed video feed. Each different component is implemented separately and then integrated into the reconnaissance platform as a whole.

14.3.1 Video Capture

In order to capture the video from the Ricoh Theta X 360 Degree Camera [52], the camera is connected to the NVIDIA Jetson Orin [51] using a Universal Serial Bus (USB) C cable. The camera is configured to stream the video feed to the NVIDIA Jetson Orin using the Ricoh Theta X 360 Degree Camera API [59]. In order to be able to capture the video feed from the camera, several libraries are used, such as OpenCV [60], GSTThetaUVC [61], LibUVC [62], and V4L2 [63]. It is worth mentioning that the libraries used had to be modified to work with the Ricoh Theta X 360 Degree Camera, as it is not officially supported by the libraries. The video feed is captured in real-time and sent to the video processing component for further processing.

14.3.2 Video Processing

Once the video feed is captured by the Jetson Orin, it is further processed to extract relevant information. The video processing is done using deep learning algorithms to detect and track objects in the environment. The model used for the object detection and tracking is the YOLOv11 [64] as it is the defacto standard for object detection and tracking in real-time. It provides the best performance in terms of accuracy and speed, as well as being able to run on the Jetson Orin. The model used was the YOLOv11-medium with a pixel resolution of 640x640 px and an inference time of 56 ms. In Figure 14.8, an example of the video feed captured by the camera can be seen, note a single frame is showcased.

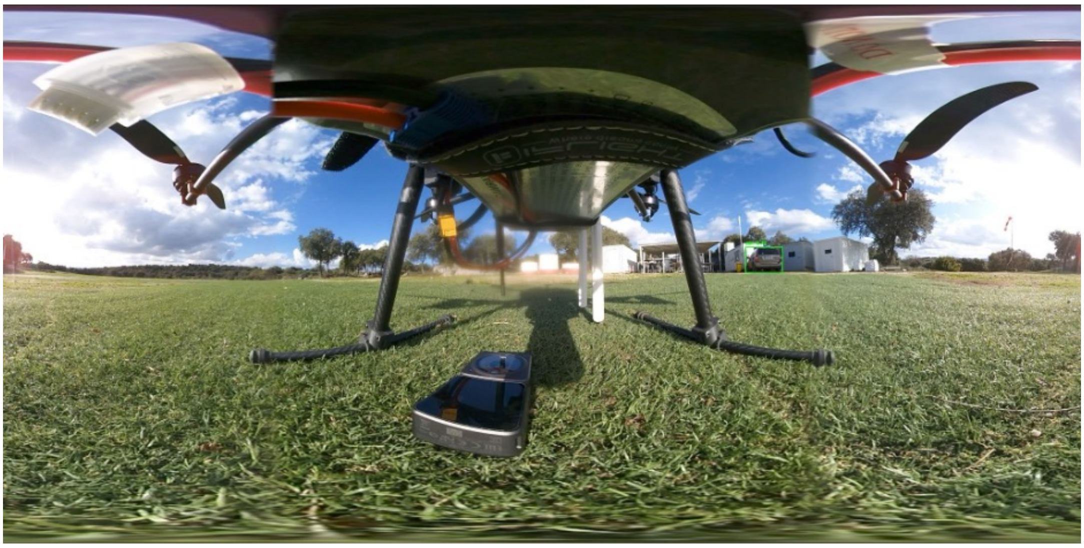


Figure 14.8. *Detection example of the video processing with a YOLOv11. The green box on the middle right side of the image corresponds to the bounding box of the car.*

14.3.3 Insights Generation

Finally, all the detected and tracked objects are sent to the insights generation component to generate insights for the end-user. In order to process the detected and tracked objects, a web application was developed using the NextJS framework [65]. This web application is responsible for displaying the detected and tracked objects in real-time, as well as generating alerts and notifications in case of critical events or failures. The web application is also responsible for managing the different missions of the UAVs with the objectives and constraints defined by the end-user and also handling the user authentication and authorization.

The web application is divided into three main layers: the presentation layer, the application layer, and the data layer. The application layer is responsible for handling the business logic of the web application, such as the user authentication and authorization, the mission management, the rule management, the detection management, the alert management, and the notification management. The presentation layer is responsible for displaying the information to the end-user. The data layer is responsible for storing the information of the web application.

Presentation Layer

The presentation layer is developed using the ReactJS framework [66] for the frontend, Tailwind CSS [67] for the styling, and Prisma [68] for the database handling. In order to provide a responsive and user-friendly interface, the web application is divided into different components, such as the login component, the dashboard component, the mission component, the drone component. Each component is responsible for displaying the information to the end-user and providing the necessary functionalities to interact with the system. The web application is designed to be easy to use and intuitive, as well as to provide real-time updates and notifications to the end-user. In Figure 14.9, a screenshot of the web application can be seen.

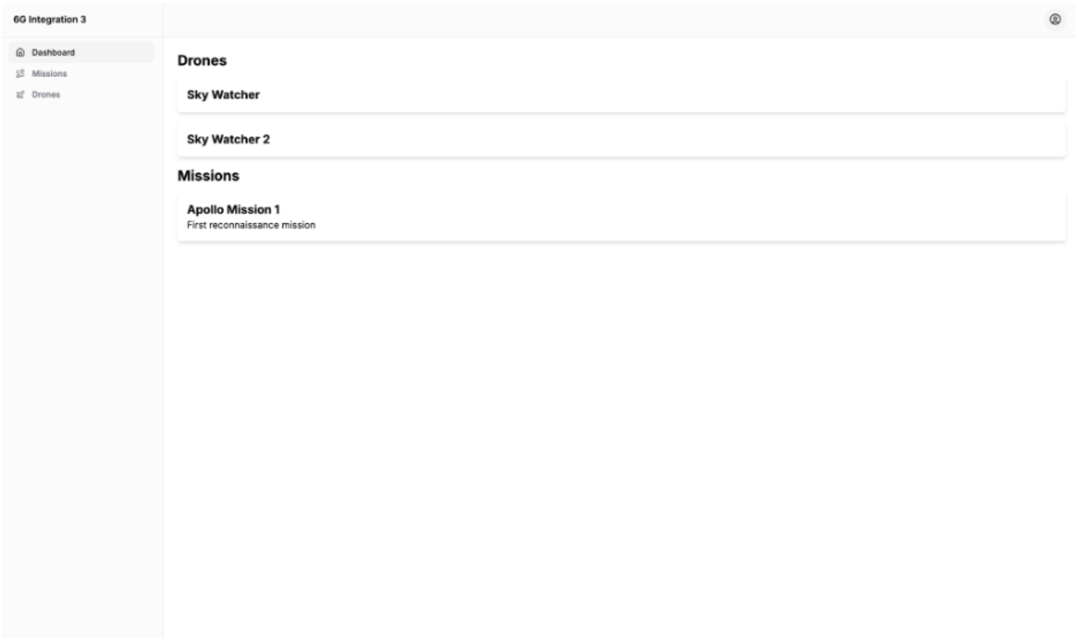


Figure 14.9. *Screenshot of the web application showcasing the dashboard.*

Data Layer

The data layers are divided into two main components: the object storage and the database. The object storage is used to store the video feed captured by the camera, as well as the detected and tracked objects. The object storage used was Amazon S3 [53], as it provides a reliable and scalable storage solution for the web application. For the database, a relational database was used to store the information of the web application. As Prisma [68] was used for the database handling, the database chosen can be any database supported by Prisma, such as PostgreSQL, MySQL, SQLite. This was chosen to provide flexibility and scalability to the system, as well as to be able to easily switch between databases if needed for different use cases such as testing, development, or production. The schema of the database can be seen in Figure 14.10. The schema has six main tables, each one responsible for storing different information:

- User: stores the information of the users of the system that can access the web application. It is used for user authentication and authorization purposes.
- Drone: stores the information of the drones that are connected to the system. It is used to manage the different drones and their missions. Each drone has a unique identifier, and a specific secret token to authenticate with the system and allow the drone to send the data to the system.

- Mission: stores the information of the missions of the drones. It is used to manage the different missions of the drones and group drones together for specific tasks. Each mission can be composed of one or more drones, and each drone can be part of one or more missions. Moreover, users are assigned to missions to have access to the data collected by the drones.
- Rule: stores the information of the rules of a specific mission to generate alerts and notifications. It is used to define the objectives and constraints of a mission, such as the specific objects to detect and track, the specific alerts to generate, and the specific notifications to send.
- Detection: stores the information of the detected objects in the environment by a drone for a specific mission. It is used to store the detected objects and their properties, such as the class, the confidence, the position, the size, and the orientation.
- Alert: stores the information of the alerts generated by the system for a specific mission created by a rule. It is used to store the alerts and their properties, such as the type, the severity, the message, the timestamp, and the status.

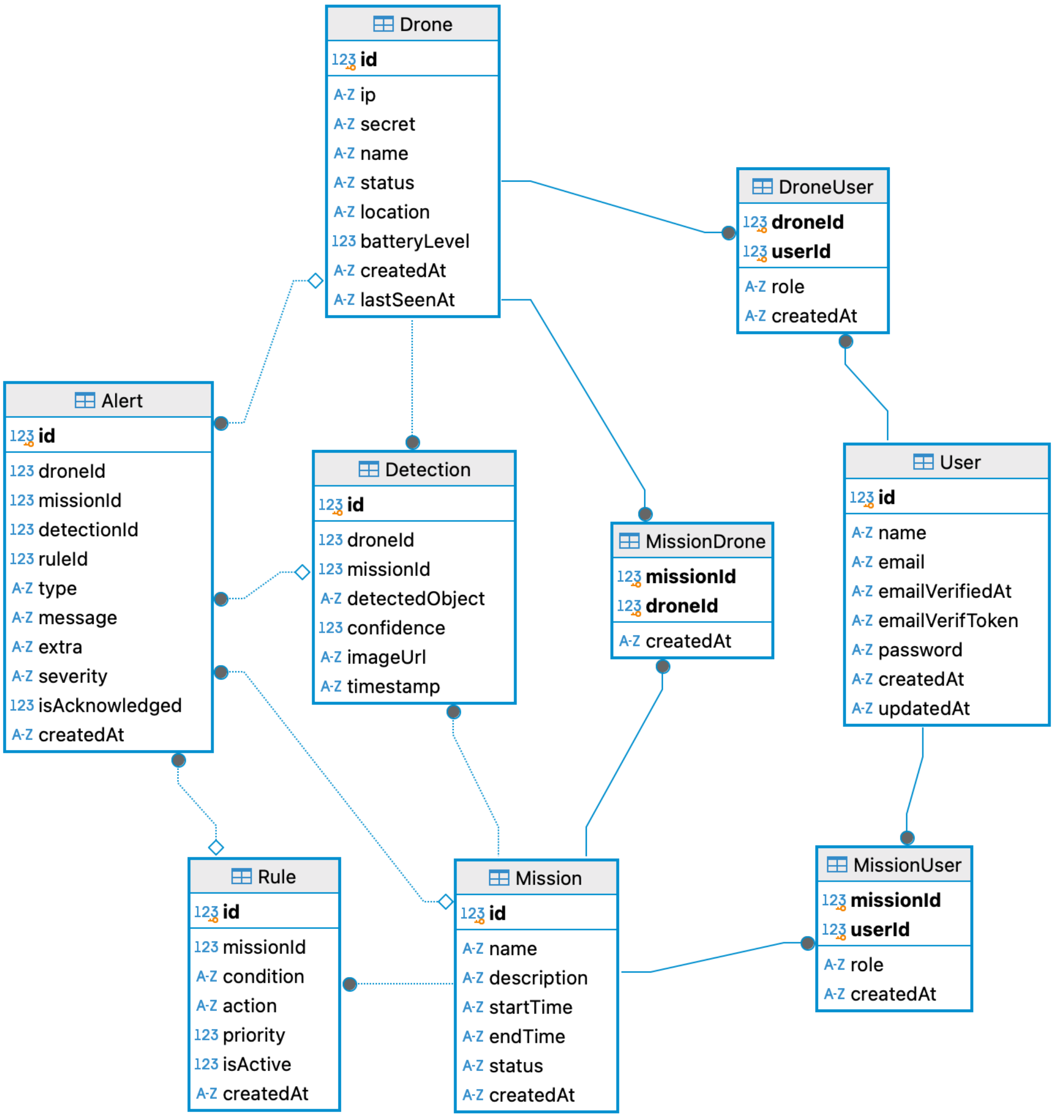


Figure 14.10. *Database schema of the reconnaissance platform.*

Application Layer

The application layer forms the core of the web application, handling crucial business logic and system functionalities. This layer is responsible for managing various aspects of the reconnaissance platform, including:

- User Authentication and Authorization: Implements secure login mechanisms and controls access to different parts of the system based on user roles and permissions. It is done with email password authentication and verification using the NextAuth.js library [69].
- Mission Management: Oversees the creation, modification, and execution of drone missions. This includes defining mission parameters, assigning drones, and monitoring mission progress.
- Rule Management: Allows users to set up and modify rules for generating alerts and notifications based on specific conditions or events detected during missions.
- Detection Management: Processes and organizes the data from detected and tracked objects, making it available for analysis and visualization.
- Alert Management: Generates and manages alerts based on predefined rules, ensuring that critical events are promptly communicated to relevant users.
- Notification Management: Handles the distribution of notifications to users through various channels, keeping them informed about mission status, alerts, and system updates.

The application layer serves as the intermediary between the presentation layer and the data layer, ensuring efficient data flow and processing. It implements the business logic that interprets user actions from the presentation layer, interacts with the data layer to retrieve or store information, and prepares the data for display in the user interface.

LLM Integration

Moreover, the detected and tracked objects are further processed through an Large Language Model (LLM) integration, in this case Llama 3.2 11b Vision [70], using the Groq API to extract additional contextual information and insights. This integration enhances the system's analytical capabilities by providing detailed descriptions, identifying potential relationships between detected objects, and generating natural language summaries of the surveillance data.

The LLM component receives the object detection data from the server with a specific prompt that the server operator wants to send and processes it to provide comprehensive analysis that includes object classification details, behavioral patterns, and potential security implications. This additional layer of intelligence helps operators make more informed decisions by providing context-rich information about the detected objects in real-time. The results from the LLM analysis are stored in the database and made available through the web interface, where they can be accessed alongside the original detection data and visual feeds.

In Figure 14.11, an example of the LLM detection results for a person can be seen.

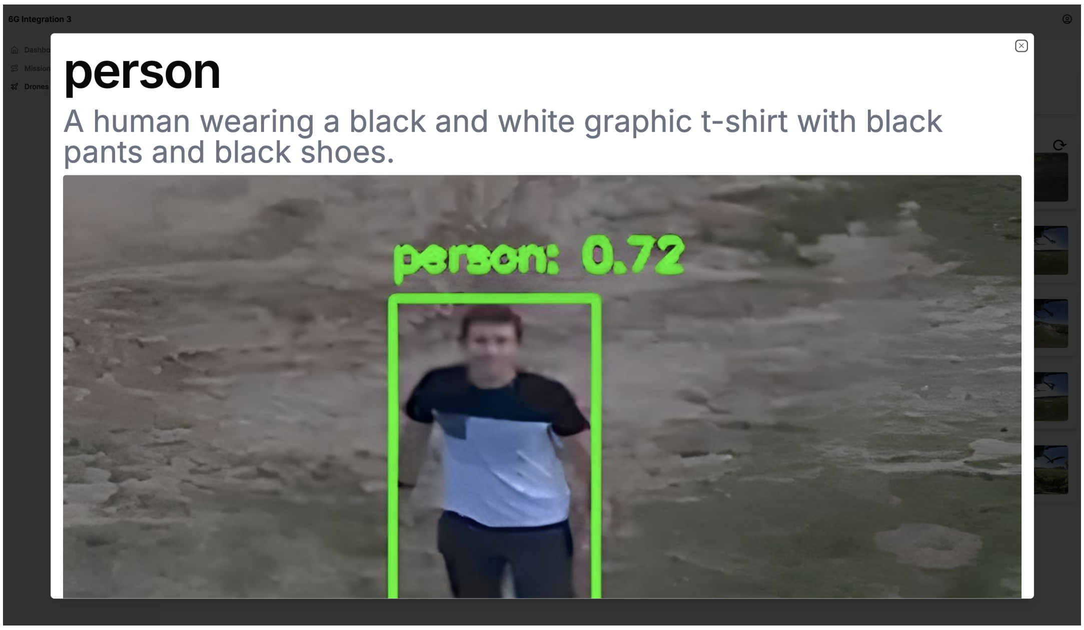


Figure 14.11. *Example of the LLM detection results for a detected object. In this case, the LLM correctly identified the clothes that the person is wearing as the prompt to the image was "What is the person wearing?".*

14.3.4 Integration

Finally, all the different components are integrated into the reconnaissance platform to provide a complete processing pipeline to be able to detect the different objects. In Figure 14.12, the complete architecture and pipeline can be seen and consists of several interconnected components:

- **Drone Component:** Contains two primary elements:
  - 360-degree camera for capturing omnidirectional video feed
  - Object detection system running directly on the drone for initial processing
- **VPN Tunnel:** Provides a secure communication channel between the drone and the server infrastructure, ensuring encrypted data transmission.
- **Server Infrastructure:** Comprises two main processing units:
  - Object Detection module for secondary verification and processing
  - Alert system for generating notifications based on detected events
- **LLM Integration:** The final component in the pipeline that:
  - Processes detected objects through advanced language models
  - Generates contextual insights and natural language descriptions
  - Provides enhanced analytical capabilities for operators

The data flow in this architecture follows a sequential pattern where the video feed from the 360-degree camera is first processed locally on the drone for initial object detection. This data is then transmitted through a secure VPN tunnel to the server infrastructure, where it undergoes additional processing and verification. The server component handles both the object detection confirmation and alert generation based on predefined rules and conditions. Finally, the processed data is passed to the LLM integration component, which provides advanced analysis and insights generation for the end-users through the web interface.

This architecture ensures robust security through the VPN tunnel while maintaining efficient data processing and real-time analysis capabilities. The modular design allows for easy scaling and maintenance of individual components without affecting the overall system functionality.

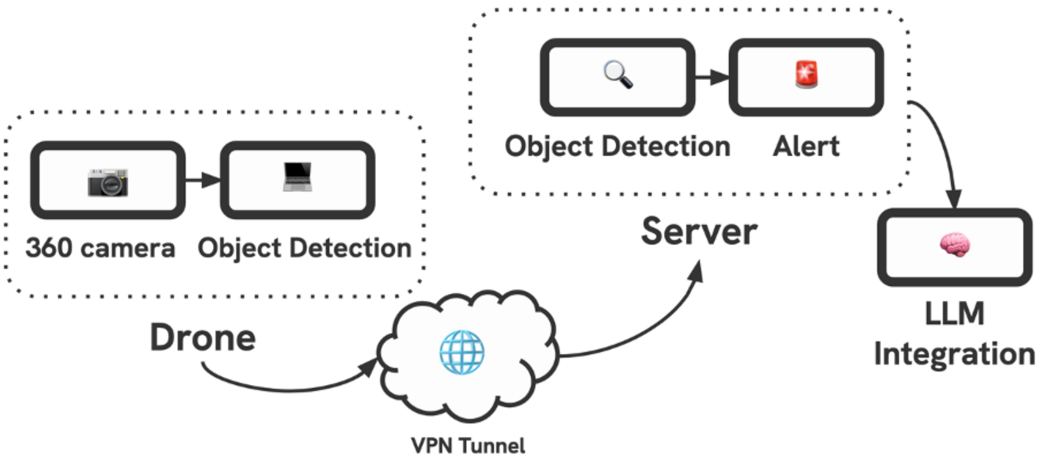


Figure 14.12. *Architecture of the reconnaissance platform.*

Part V

Results

Chapter 15

Testing

In this chapter, the different parts of the systems have been tested following the V-model Chapter 5. In the following sections, the different tests are described and the results are presented.

15.1 Individual Testing

In this section, the components are tested individually to ensure that they are working as expected, that is the drone, the reconnaissance platform, and the communication system.

15.1.1 Drone Testing

In order to test the drone, first static tests where taken and all the electronics was tested individually. For the motors, the ESCs and the flight controller, the first thing is to calibrate them and adjust all ports. This is done through the ArduPilot program [49]. After the configuration is done, the tests are done without propellers as it can be a safty hazard to do the tests with them on, refer to Figure 15.1. Also it is worth noting than whenever the drone is being manipulated, the battery must be disconnected to avoid any unexpected situations.

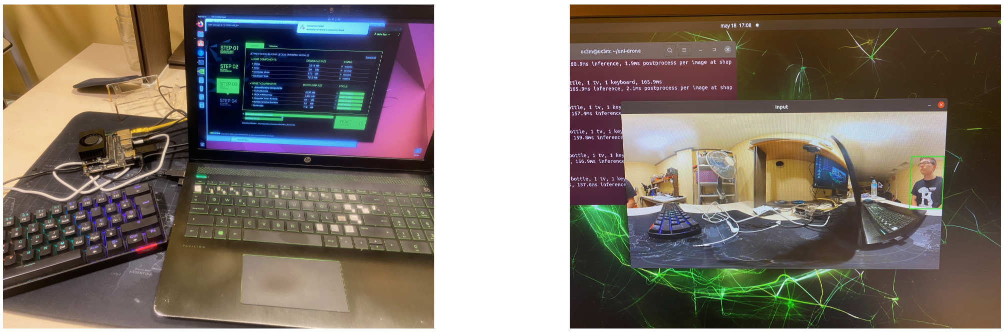
Once the drone is fully working statically, then the next step is to configure all the sensor, GPS and Inertial Measurement Unit (IMU) in this case. Once all the sensors are configured, the next step is to test them individually. The GPS is tested by checking the position in the ArduPilot program and the IMU is tested by checking the orientation in the IMU program.

15.1.2 Reconnaissance Platform Testing

For the reconnaissance platform, the first thing to do is that everything works individually. The camera is tested by connecting it to the computer and checking that the camera is working. The camera is tested by taking a picture and checking that the picture is saved in the computer. The camera is also tested by checking that the camera is working with the Jetson Nano connected, see Figure 15.2.

Moreover, the server developed for the reconnaissance platform is tested by connecting the camera to the Jetson Nano and checking that the server is working. The server is tested

Figure 15.1. *Drone testing without propellers*



(a) *Installation and configuration of the Jetson Nano.*

(b) *Testing the camera with the Jetson Nano.*

Figure 15.2. *Testing of the reconnaissance platform.*

by checking if the system is able to recognize the different objects in the image and if the system is able to send the information to the computer.

15.1.3 Communication System Testing

For the communication system, the tests are done by connecting the RF module and the 4G module to the computer and checking that the modules are working. The RF module is tested by checking that the module is working with the computer and the 4G module is tested by checking that the module is working with the computer.

15.2 General Testing

Once all the individual tests are done, the next step is to test the system as a whole. The system is tested by connecting all the components and checking that the system is working. The system is tested by checking that the drone is able to fly and that the reconnaissance platform is able to recognize the different objects in the image. The system is also tested by checking that the communication system is working and that the system is able to send the information to the computer.

For this, the drone was flown in a controlled environment in a authorized zone to comply with the regulations, see Chapter 20. The tests were performed to test if the system was able to recongize human beings in an area of $10\,\mathrm{km}^2$. Moreover, all videos and images were stored in the computer and the system was able to send the information to the computer. In Figure 15.3, an example of the system detecting a human being is shown. And also in Figure 14.11, the whole system working is shown and the end result of detecting and processing the images is performed.

Figure 15.3. *Human detection during the tests*

Chapter 16

Results

Finally after all the tests were done, the system was validated, and fully working, the results of the systems obtained are:

- The drone is able to fly autonomously and detect objects in the environment.
- The drone is able to communicated and send information to a server to receive real-time information.
- The drone is able to have a 30 to 40 minutes of flight time.
- Integration with LLMs make the system able to adapt to detect different characteristics of objects.
- The drone is modular and can be easily repaired and maintained. Moreover, the drone is able to be easily modified to adapt to different applications.

With all this results obtained, the system checks all the requirements and objectives of the project, refer to Chapter 12 , and the system is able to be used in different applications, such as surveillance, search and rescue, and monitoring of different areas.

For more videos demonstrating the system working, refer to the following links: `https://youtu.be/F1fDpXw-kBg`, `https://youtu.be/kdMgwRRte-8`, and `https://youtu.be/IqNsVOT3uFQ`.

16.1 Problems Encountered

As the project is a proof of concept, there were some problems encountered during the development of the system. The main problems encountered were maily due to the nature of the project, as this project is a proof of concept, there were not previous projects to compare with, and the development of the system was done from scratch.

The first problem encountered was the design and the selection of the components. In order to create a system that is able to detect objects in the environment and more importantly, to be able to have enough flight duration, the selection of the components was crucial. The selection of the components was done based on the requirements of the project, and the components were selected based on the cost, the availability, and the compatibility with the system. One problem was that at first a wrong type of ESC was chosen and it was not compatible to the current set up. And in the end, the correct type was selected, the Tmotor FLAME 100A LV 600Hz, refer to Subsection 13.1.2.

Another problem encountered was the placement of the components in the UAV. As the UAV has limitted space, the components had to be carfully place in order to have space and be stable during flight.

Finally, multiple problems were confronted recarding the integration of all systems and the reconnaissance platform. Here, the libraries used to capture the camera live-feed had to be modified in order to be compatible to the Ricoh Theta X camera. Moreover, custom communication protocols and servers had to be developed in order to be able to send the information from the drone to the server and process the information in real-time.

All in all, after multiple tests and iterations, the system was able to be fully working and the problems encountered were solved.

Part VI

Conclusions

Chapter 17

Conclusions

This thesis presents a comprehensive approach to developing and implementing an autonomous drone system for NTN in remote areas. The project successfully achieved its objectives of creating a modular, cost-effective, and open-source solution that can be easily adapted for various reconnaissance tasks. The implemented system demonstrates the potential of integrating UAVs with advanced communication technologies and artificial intelligence to enhance connectivity and data collection in challenging environments.

The designed UAV platform, equipped with a 360-degree camera and onboard processing capabilities, proved capable of autonomous flight and real-time object detection. The integration of a secure communication system, combining RF and 4G technologies, enabled reliable data transmission between the drone and the control station. Furthermore, the development of a sophisticated reconnaissance platform, leveraging deep learning algorithms and LLMs, showcased the system's ability to provide valuable insights from collected data.

The project's modular approach and use of commercially available components make it accessible for other researchers and organizations to replicate and build upon. This aligns well with the goal of fostering new research in the field of non-terrestrial networks and low-altitude drone-based systems. The successful implementation and testing of the system in a controlled environment demonstrated its potential for applications in humanitarian aid, environmental monitoring, and disaster response.

While some challenges were encountered during the development process, particularly in component selection and system integration, these were ultimately overcome through iterative design and testing. The final system met all specified requirements, including flight duration, autonomous operation, and real-time data processing capabilities.

In conclusion, this thesis contributes a valuable proof-of-concept for autonomous drone systems in non-terrestrial networks, paving the way for future advancements in this field. The developed platform offers a flexible foundation for further research and practical applications in remote area connectivity and reconnaissance.

Chapter 18

Future work

In the future work for this project, several key areas of development have been identified to enhance the system's capabilities and performance. Real-time location tracking will be improved by developing a robust communication protocol between the on-board computer and the off-board server, enabling precise monitoring of the UAV's position throughout its mission. This advancement will significantly enhance the system's ability to track and manage drone operations in real-time. The implementation of swarm intelligence algorithms represents another exciting avenue for future research, allowing multiple UAVs to work collaboratively and efficiently cover larger areas while performing complex tasks. This development could dramatically increase the system's overall effectiveness and scalability.

Further integration of advanced AI capabilities, such as predictive analytics and anomaly detection, will be pursued to enhance the system's autonomous identification of patterns and potential threats. This improvement will make the system more proactive and intelligent in its decision-making processes. To expand the system's operational range, efforts will be made to develop weatherproofing solutions, enabling the UAV to function effectively in various environmental conditions. This enhancement will significantly increase the system's versatility and usability across different climates and terrains. The integration of additional sensors, including thermal cameras and LIDAR, will be explored to broaden the system's detection and analysis capabilities across different spectrums and conditions, providing a more comprehensive understanding of the surveyed environment. Finally, optimizing the on-board processing capabilities for edge computing will be a priority, allowing the system to handle more complex computations locally. This optimization will reduce the need for constant communication with the off-board server, improving real-time performance and efficiency.

Chapter 19

Socio-economic environment

The widespread adoption of UAVs is transforming society and the economy, offering significant benefits while also presenting challenges. This chapter examines the socio-economic factors influencing the deployment of autonomous drones, particularly in NTNs for remote areas. It explores the potential advantages, obstacles, and financial implications of integrating this technology across industries.

19.1 Social Impact

Autonomous UAVs have gained popularity due to their versatility and efficiency, revolutionizing fields like agriculture, construction, and public safety. Their ability to perform complex tasks quickly can greatly enhance societal well-being. For example, UAVs equipped with thermal cameras improve emergency response by locating individuals in burning buildings, while high-resolution cameras can monitor large events. The project demonstrated how UAVs can provide real-time reconnaissance, aiding first responders and improving public safety.

In remote regions, autonomous UAVs facilitate connectivity by delivering essential supplies such as medicine and food. This capability not only improves the quality of life but also bridges the digital divide by providing internet access to underserved communities, thereby enhancing educational and informational resources.

However, privacy and security remain concerns. The extensive data collection by UAVs raises issues of surveillance, while the potential for misuse, such as spying or attacks, underscores the need for clear regulations and ethical guidelines, see Chapter 20.

19.2 Economic Impact

The economic benefits of adopting autonomous UAVs are substantial, with the potential to boost productivity and drive innovation. In agriculture, UAVs enable precision farming through crop monitoring, pest detection, and optimized irrigation, helping farmers improve yields and reduce costs. The construction industry also benefits, as UAVs offer efficient infrastructure inspections, reducing manual labor and associated risks.

Despite these advantages, the costs of adopting UAVs (e.g., purchase, training, maintenance, and insurance) remain significant barriers for small companies and groups. Moreover, the need for skilled operators and the risk of accidents or malfunctions can increase operational expenses which is specially challenging for research groups in NTNs.

19.3 Environmental Impact

Autonomous UAVs can positively impact the environment by reducing fossil fuel usage. Their electric motors are more energy-efficient and produce fewer emissions than traditional vehicles, contributing to lower air pollution and greenhouse gas levels.

Nonetheless, the environmental costs of manufacturing and disposing of UAVs must be considered. The production of lightweight materials like carbon fiber is energy-intensive, and lithium-ion batteries pose recycling challenges. Sustainable design practices are necessary to mitigate these effects.

19.4 Budget Analysis

As previously mentioned, the cost of adopting autonomous drones is a significant hurdle. This section breaks down the expenses associated with purchasing and operating drones, categorized into manufacturing, operating, and additional costs. The analysis includes a detailed assessment of hardware components, maintenance, insurance, and other relevant expenses.

Tables Table 19.1, Table 19.2, Table 19.3, and Table 19.4 provide comprehensive cost breakdowns. The total cost, encompassing all categories, offers a clear picture of the financial investment needed for adopting drones in NTNs applications. For this project, the total cost amounts to 6316 €, which includes the necessary hardware, software, and operational expenses. However, it does not account for human-related costs, such as training and salaries, which are essential for long-term sustainability.

In conclusion, while autonomous drones hold significant promise for remote areas and various industries, careful consideration of social, economic, and environmental factors is essential. Addressing these challenges with appropriate regulations and sustainable practices will maximize their potential benefits.

Item	**Model**	**Quantity**	**Cost (€)**
Airframe	Tarot XS690 [39]	1	199
Motors	Tmotor U7 V2 420KV [40]	4	520
ESC	Tmotor FLAME 100A LV 600Hz [41]	4	360
Propellers	Tmotor 17×5.8 V2 [42]	2	144
Flight Controller	Holybro Pixhawk 6C [44]	1	207
Battery	TATTU 22000mAh 4S 14.8V 30C [45]	1	270
PDB	Holybro PM07 Power Module [46]	1	48
Regulator	HobbyWing 25A HV UBEC [47]	1	58
GPS	Holybro M9N GPS GNSS [48]	1	70
Radiocontroller	RadioMaster TX16S [50]	1	200
RF Module	RFD868 TXMOD V2 868Mhz 1W [54]	1	423
Miscellaneous	Screws, Nuts, Wires, etc.	–	100
Total			2599

Table 19.1. *Manufacturing costs for the UAV.*

Item	**Model**	**Quantity**	**Cost (€)**
On-board Computer	NVIDIA Jetson Orin [51]	1	831
Camera	Ricoh Theta X 360 Degree Camera [52]	1	800
Router	GL.iNet GL-X750 [55]	1	153
4G SIM Card	Orange Prepaid SIM Card (1 month)	1	10
Server	Amazon Web Services (1 month)	1	10
Total			1804

Table 19.2. *Manufacturing costs for the reconnaissance platform*

Item	**Description**	**Cost (€)**
Insurance	Liability Insurance for Pilots	50
Flying Field	Flying Club Membership (1 year)	350
Licensing	Drone Pilot License (1 year)	0
Software	ArduPilot Software License (1 year)	0
Maintenance	Spare Parts	50
Total		450

Table 19.3. *Operating costs.*

Item	**Model**	**Quantity**	**Cost (€)**
Battery Charger	ISDT K4 Dual Charger [71]	1	200
Lipo Bags	Lipo Safe Bags (Large) [72]	1	13
Tools	Screwdriver Set, Pliers, etc.	–	50
Solders	Soldering Iron, Solder, etc.	–	200
3D Printer	Bamboo P1S [58]	1	1015
3D Filament	PLA Filament (1kg)	1	30
Total			1508

Table 19.4. *Other costs.*

Chapter 20

Regulatory Framework

The regulatory framework governing drones is a complex and dynamic area, influenced by various laws and regulations that differ from country to country. Generally, drone operations are regulated by aviation authorities responsible for ensuring safe and responsible usage.

20.1 Relevant Institutions

20.1.1 European Union Aviation Safety Agency (EASA)

The EASA [73] plays a crucial role in harmonizing aviation safety standards across all EU member states. Its primary objective is to maintain a consistent and high level of safety in civil aviation operations throughout the EU. EASA achieves this through the establishment and enforcement of common regulations applicable to all member states. Notably, for the standardization of Unmanned Aircraft System (UAS), EASA has implemented Regulations (EU) 2019/947 [19] and (EU) 2019/945 [74].

20.1.2 State Aviation Safety Agency (AESA)

In Spain, the Spanish Aviation Safety and Security Agency (AESA) [75] serves as the national regulatory authority, overseeing compliance with civil aviation standards within the aerospace sector. AESA plays a critical role in promoting the development and application of aviation legislation, ensuring that the Spanish civil aviation system upholds the highest safety, quality, and sustainability standards. In instances of non-compliance with aviation regulations, AESA possesses the authority to enforce sanctions.

20.2 Applicable Legislation

20.2.1 Implementing Regulation (EU) 2019/947

The Implementing Regulation (EU) 2019/947 [19] establishes the operational rules and requirements for UAS within the EU. It provides a legal framework for the utilization of UAS across various operational categories, outlining requirements for operational authorizations and risk assessments where applicable. The regulation sets standards for remote pilot competency, operational procedures, and safety management to conduct UAS flights safely and effectively.

Additionally, it integrates with the Delegated Regulation (EU) 2019/945 [74] by defining operational requirements related to the UAS classes established within it. The regulation details specific operational limitations and conditions for each UAS class, including the management of UAS in classes C0 through C4. It also includes provisions for the safe integration of newly introduced UAS classes under Delegated Regulation (EU) 2020/1058 [76], specifically classes C5 and C6.

Moreover, this regulation addresses the procedures for UAS operators from third countries (non-EASA member states) wishing to operate within the Single European Sky (SES) airspace, ensuring alignment with EU standards and safety regulations.

20.2.2 Delegated Regulation (EU) 2019/945

The Delegated Regulation (EU) 2019/945 [74] defines the rules and standards for UAS within the EU. It specifies the types of UAS that require certification regarding design, production, and maintenance. This regulation also provides guidelines for the commercialization of UAS intended for use in the Open category, as well as for remote identification accessories (e.g., Drone Remote ID). Furthermore, it outlines the requirements for the design and manufacture of UAS intended for operations defined in the Implementing Regulation (EU) 2019/947.

20.2.3 Regulation (EU) 2014/53: Radio Equipment Directive

The Delegated Regulation (EU) 2014/53 [77] establishes the Radio Equipment Directive (RED), which sets essential requirements for radio equipment within the EU. This directive aims to ensure the efficientuse of the radio spectrum, prevent interference, and promote the safety and health of users and consumers. The RED applies to all radio equipment, including UAS radio frequency systems, ensuring compliance with specific power limits and technical standards to guarantee safe and reliable operation. For UAS, the RED regulates the use of radio frequencies of 2.4 GHz, 5.8 GHz, and 868 MHz, limiting power output to 25 mW, 100 mW, and 25 mW, respectively. These regulations also cover data privacy, emergency service access, and interoperability, ensuring that UAS operate safely within shared airspace.

20.2.4 Regulation (EU) 2024/1689: Artificial Intelligence Act

The Artificial Intelligence Act (AI Act) of the EU [78], which came into force on the 1st of August 2024, aims to ensure that AI systems are safe, transparent, and ethical, while fostering innovation and protecting fundamental rights as stated in the Delegated Regulation (EU) 2024/1689 [79]. The AI Act categorizes AI systems by risk, imposing strict requirements on high-risk applications, particularly in aviation, which may affect public safety and fundamental rights. These requirements encompass robust risk management, transparency, human oversight, and data governance, ensuring that AI systems are reliable and secure.

The AI Act introduces significant compliance obligations that could escalate development costs and timelines. High-risk systems must adhere to stringent standards to access the EU market, potentially challenging innovation but ultimately aiming to build trust and facilitate broader adoption of AI technologies within the EU.

20.3 Operational Categories

The Regulation (EU) 2019/947 [19] classifies UAS into three distinct categories:

- **Open Category:** The least restrictive category, designed for low-risk operations, includes activities such as recreational flying and commercial operations posing minimal risk to people and property. Operators must adhere to specific limitations (e.g., flying below 120 m, maintaining VLOS). UAS must weigh under 25 kg, and pilots must ensure that the drone does not fly over people or in restricted areas. No prior authorization is required, though registration and remote pilot training are compulsory for all operations, except for drones weighing less than 250 g that lack a camera or sensor.
- **Specific Category:** This category covers medium-risk operations necessitating a more detailed assessment. It includes operations that may involve flying over people or in restricted areas, provided mitigation procedures are in place. Operators must conduct a risk assessment and obtain an operational authorization known as Standard Training Scenario (STS) from AESA. Requirements for UAS and pilot qualifications may vary based on the specific risk assessment and operational procedures defined within it.
- **Certified Category:** Designed for high-risk operations, this category involves stringent requirements comparable to those for manned aviation. UAS must meet specific certification standards and operators must comply with strict safety regulations. This category often includes advanced training requirements and operational procedures similar to those for commercial air transport.

20.3.1 Open Category

This work will focus on civil UAS that fall under EASA's Open Category, although some findings may be applicable to other categories with appropriate regulatory adjustments. Within the Open Category, three subcategories differentiate based on associated risk, aircraft weight, and operational limits:

1. **A1**: UAS with a MTOW of less than 250 g that can fly over people but not over assemblies of people.
2. **A2**: UAS with an MTOW of less than 4 kg that can fly close to people but must maintain a horizontal distance of 30 m (5 m in low-speed configuration).
3. **A3**: UAS with an MTOW of less than 25 kg that must maintain a horizontal distance of 150 m from residential, commercial, industrial, or recreational areas.

Check Figure 20.1 for a visual representation of the Open Category subcategories.

Moreover, additional rules applicable to all three subcategories include:

- The maximum height must not exceed 120 m above ground level, as the lower limit for general aviation is 150 m. This leaves only a 30 m separation between manned aviation and UAS.
- Operators must always maintain VLOS unless the aircraft is in “follow me” mode or the pilot is using FPV goggles.
- Operators must register if the UAS weighs more than 250 g or if the aircraft is equipped with a camera or sensor.

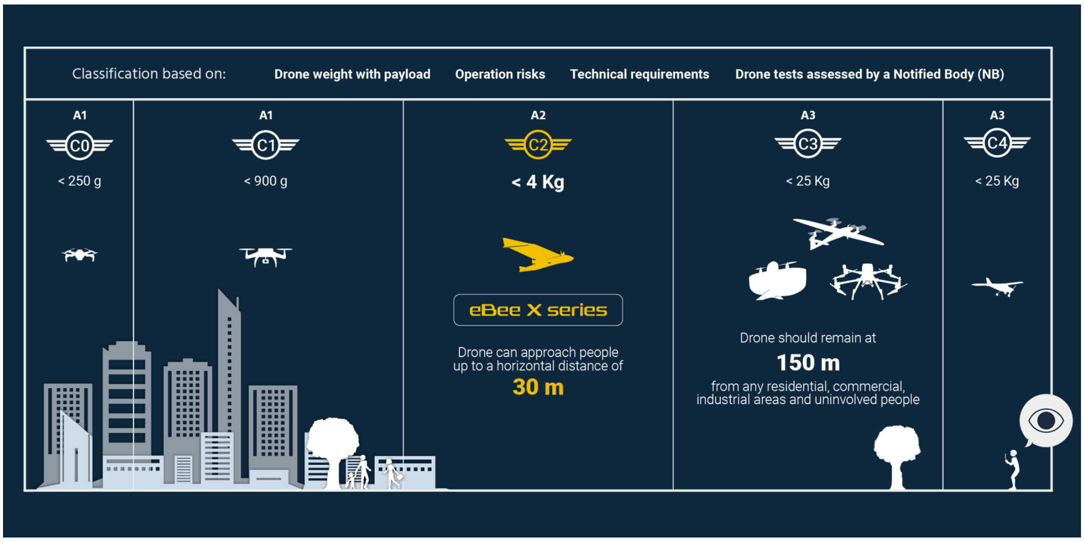


Figure 20.1. *EU Regulations Open Category chart describing the subcategories A1, A2, and A3 with their respective operational limitations [80]*

- The aircraft must possess a remote identification ID, which is standard in all C1-C6 categories, with the exception of C4 and privately built aircraft.

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