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University Degree in Data Science and Engineering and
Telecommunication Technologies Engineering
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Bachelor thesis

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

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ABSTRACT

this is an abstract

Keywords: keyword1, keyword2, keyword3

ACKNOWLEDGMENTS

Thanks

AGRADECIMIENTOS

Gracias

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LIST OF ACROYNMS

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.
EU	European Union.
FPV	First Person View.
GAN	Generative Adversarial Network.
GEO	Geostationary Earth Orbit.
GPS	Global Positioning System.
GPU	Graphics Processing Unit.
HAP	High Altitude Platform.
HetNet	Heterogeneous Network.
INCOSE	International Council on Systems Engineering.
IoST	Internet of Space Things.
IoT	Internet of Things.
ISTN	Integrated Space-Terrestrial Network.
LEO	Low Earth Orbit.
LTE	Long-Term Evolution.
ML	Machine Learning.
MTOW	Maximum Takeoff Weight.
NTN	Non-Terrestrial Network.
QoS	Quality of Service.

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.
VLOS	Visual Line of Sight.
WiFi	Wireless Fidelity.

Part I

Introduction

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.

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 Unmanned Aerial Vehicle (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.

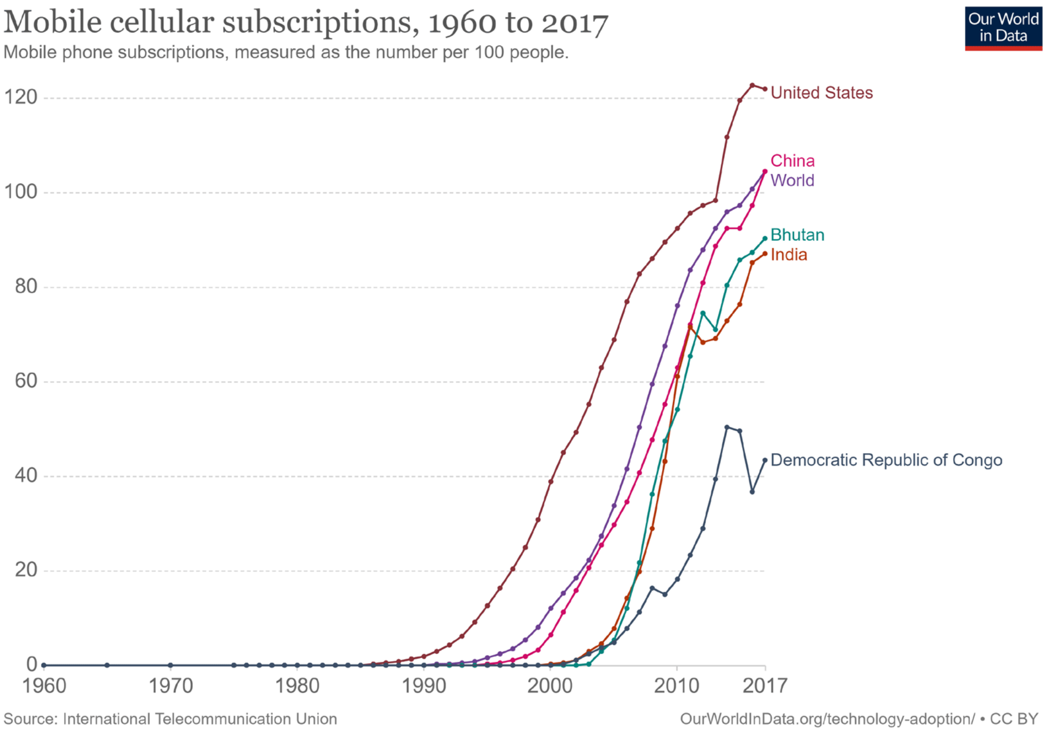

Figure 1.1. *Global Trends in Mobile Cellular Subscriptions (1960–2017): The graph illustrates the exponential growth of mobile subscriptions per 100 people across various regions over recent decades. [2]*

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 ground 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.

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.

4. DOCUMENT STRUCTURE

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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.

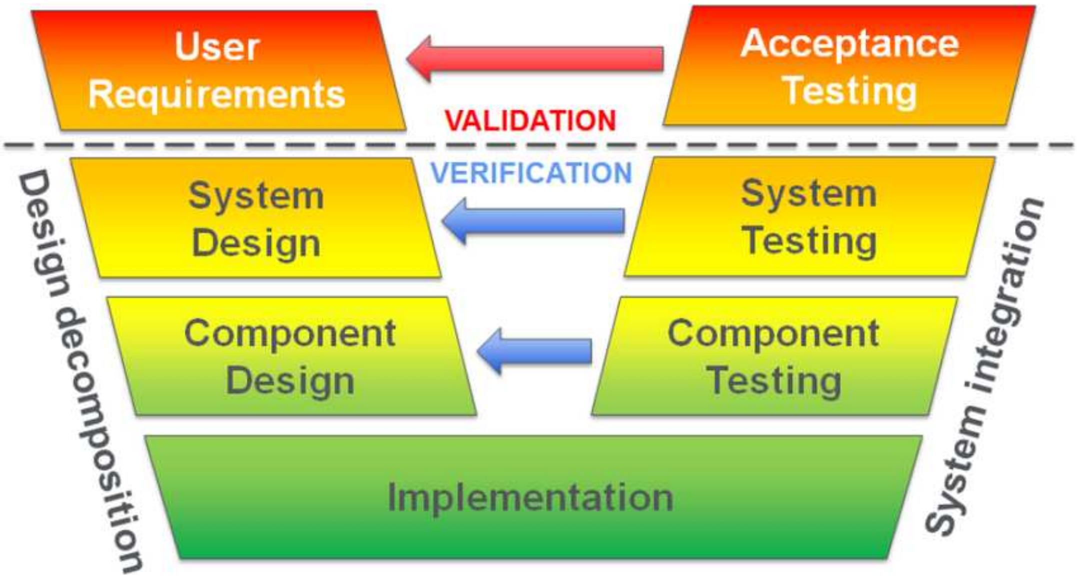

Figure 5.1. *Methodological framework based on the V-model from INCOSE with the different stages of the project development process[16]*

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

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 huge 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 few hundred meters to several 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 ground stations, Internet of Things (IoT) devices, etc.

6.1 Geostationary Satellites

GEO satellites operate at an altitude of approximately 35 786 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 several 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 few hundred meters to several kilometers above the Earth. These platforms may consist of balloons, airships, or UAVs. They provide several 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 $20\,\mathrm{km}$. These platforms cover vast areas and support a range of applications, making them ideal for remote and underserved locations where deploying traditional infrastructure is not practical.

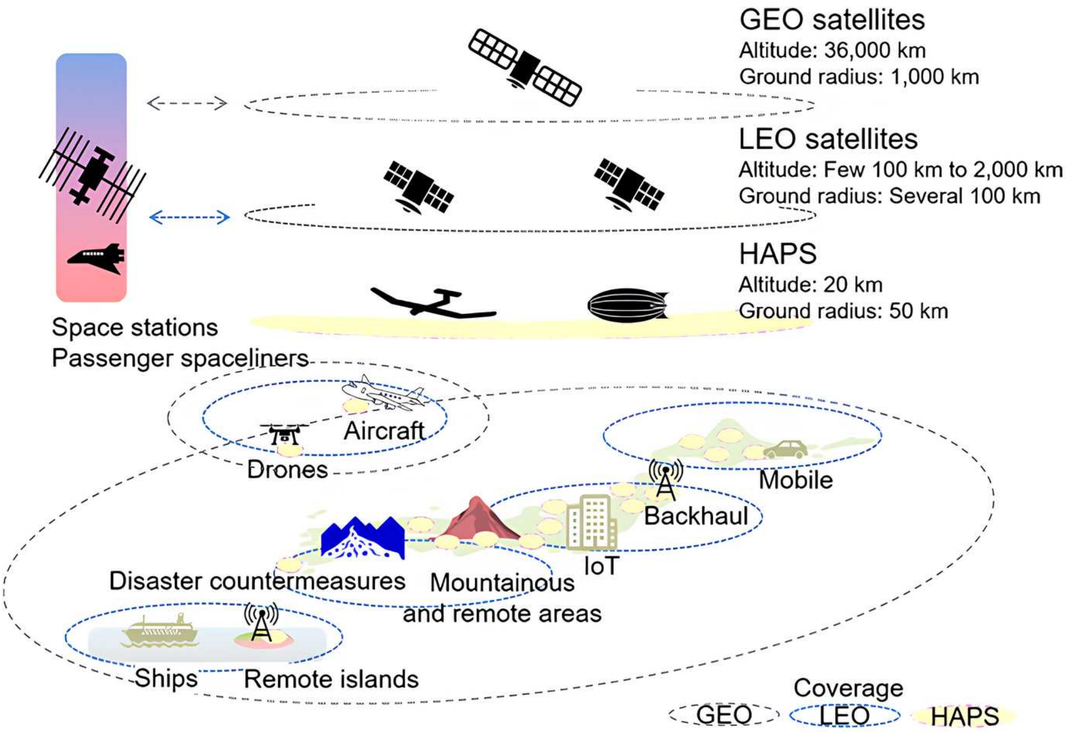

Figure 6.1. *Types of NTNs based on altitude and platform type. HAPs, LEOs satellites, and GEOs satellites interact with other network elements to provide connectivity services. [18]*

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.

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.

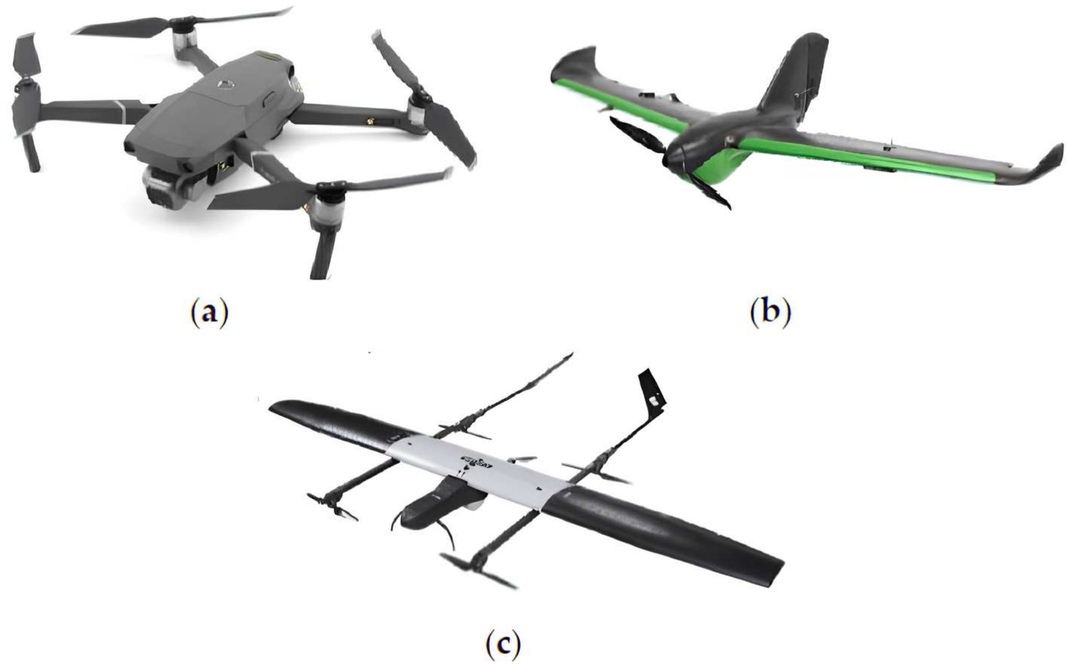

Figure 7.1. *Types of UAVs based on their design and intended use [20].*
a. Rotary-wing UAV, b. Fixed-wing UAV, c. Hybrid UAV

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.

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 convolutional 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 adversari-

ally. 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

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.

10. TYPES, TECHNOLOGIES & CHARACTERISTICS

types of ntns https://arxiv.org/pdf/2103.09156

nice graph to show the structure of ntn https://arxiv.org/pdf/1912.10226

TODO: write this chapter https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=arnumber=9861699, add different types of ntn and the challenges

https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=arnumber=8869712 types of areal platformas, todo add image from it

10.1 Types of Non-Terrestrial Networks

NTNs present a versatile framework for deploying communication infrastructure, utilizing various platform roles tailored to address specific connectivity needs. This section delineates the principal architectural models of NTNs and elucidates the roles they can play within communication networks. These deployment models shed light on the effective utilization of NTNs in diverse scenarios, enhancing coverage, extending network reach, and supporting specialized applications.

TODO: add figure and then reference to each type

10.1.1 NTN Platform as a User

In this configuration, the NTN platform functions as a user, akin to a mobile device or User Equipment (UE) that connects to a terrestrial network. This setup is particularly relevant for platforms such as satellites and UAVs that necessitate connectivity for data transmission. These airborne systems can access existing ground-based communication networks through terrestrial base stations.

A notable instance of this integration is the incorporation of UAVs into terrestrial networks. The 3GPP recognizes UAV as a distinct category of UE, prompting ongoing research to tackle the unique connectivity challenges they pose. These challenges encompass maintaining a stable connection during UAV movement, mitigating potential interference, and ensuring quality of service at varying altitudes. By positioning UAVs as users within the network, terrestrial infrastructure can accommodate a broader spectrum of communication requirements, including applications in surveillance, remote sensing, and logistics.

Moreover, in scenarios where terrestrial ground stations are absent or impractical, satellites can directly communicate with other high-altitude satellites. This strategy obviates the necessity for extensive ground station networks, facilitating direct data transmission between satellites and back to Earth. Such configurations are particularly advantageous for space missions and remote observation, where direct satellite-to-satellite communication can enhance data transmission efficiency and reliability.

10.1.2 NTN Platform as a Relay

Another architectural model involves the NTN platform serving as a relay, functioning as an intermediary that transfers communication signals among different network components. This model can be further divided into two primary configurations based on the location of the relay:

- Connectivity (Connecting the Base Station to the Core Network): In this setup, the NTN platform provides a backhaul link, connecting a ground-based base station to the core network infrastructure. This configuration is especially beneficial in remote regions where traditional backhaul solutions, such as fiber optic cables, are either unavailable or prohibitively expensive to install. Utilizing satellites or HAPs for backhaul connectivity allows the extension of terrestrial networks without necessitating large-scale ground infrastructure.
- Direct Access Relay (Linking Users to the Base Station): In this alternative configuration, the NTN platform acts as a direct relay between ground users and the terrestrial base station. This approach proves advantageous in environments where access to a base station is impeded, such as densely populated urban areas or rugged mountainous terrains. In these scenarios, UAVs or LEO satellites can serve as intermediary nodes, relaying user communication signals to the ground network. This method effectively expands network coverage and improves connectivity in regions that are otherwise difficult to serve with conventional infrastructure.

10.1.3 NTN Platform as a Base Station

When equipped with advanced processing capabilities, the NTN platform can assume the role of a base station. This architecture employs platforms with regenerative payloads capable of processing communication signals onboard, enabling the NTN platform to function as a “flying” or “orbiting” base station. Such systems can manage connections and process data without reliance on terrestrial infrastructure.

- Satellite-Based Base Stations: Satellites, especially those in LEO, can be outfitted with onboard processing units to execute tasks typically managed by ground-based base stations. These tasks may encompass signal processing, traffic routing, and user connection management. Satellite-based base stations are particularly well-suited for providing connectivity in remote locales, such as open seas, deserts, or disaster-stricken areas where terrestrial infrastructure is impractical.
- UAV-Based Base Stations: In addition to satellites, UAVs can be deployed as temporary base stations, providing on-demand network coverage in specific regions. For example, UAVs equipped with 5G communication technology can deliver network services during large events, emergency situations, or military operations. Their ability to operate at relatively low altitudes makes them ideal for applications requiring localized coverage with minimal delay.

10.1.4 Mixed Architecture Models

In practical applications, hybrid configurations that amalgamate different architectural models are common, maximizing the strengths of each platform. Mixed architectures facilitate more flexible deployment strategies by leveraging a combination of platforms with varied roles and capabilities.

- Satellite and UAV Combinations: In certain scenarios, a LEO satellite with base station capabilities may collaborate with UAV acting as relays to extend coverage to ground users. The UAVs, which operate at lower altitudes than the satellites, can enhance connectivity by relaying data to the satellite, which subsequently forwards the information to the core network.

- Multi-Tier Satellite Configurations: Another instance of mixed architecture involves utilizing satellites at distinct altitudes to complement one another. For instance, a GEO satellite can furnish a high-level backhaul connection to the core network, while LEO satellites deliver last-mile connectivity to end users. This multi-tiered approach achieves a balance between low latency (provided by LEO satellites) and extensive coverage (facilitated by GEO satellites).
- HAP Assisted Networks: HAPs, operating approximately 20 km above the Earth's surface, can play a supportive role by bridging the gap between UAVs and satellites. In this configuration, the HAP serves as an intermediate relay point, receiving data from UAVs below and transmitting it to LEO satellites above. This multi-hop communication strategy can significantly enhance data transmission efficiency, particularly in complex environments.

3.6 Advantages and Challenges of Different NTN Architectures

While NTNs present a range of benefits, they also come with specific challenges. Understanding the advantages and limitations of each architecture is crucial for selecting the appropriate model for a given use case. 3.6.1 Advantages

Extended Coverage: One of the primary benefits of NTNs is their ability to provide network coverage in areas that are otherwise unreachable with terrestrial infrastructure. This includes remote regions such as oceans, mountains, and deserts, as well as locations affected by natural disasters where ground networks may be damaged or unavailable.

Rapid Deployment: Platforms such as UAVs and high-altitude balloons can be deployed quickly in response to urgent situations. For example, during a natural disaster, UAVs can be used to reestablish communication networks to support rescue operations and coordinate emergency response efforts.

Flexible Infrastructure: By combining various NTN platforms, it is possible to create flexible network architectures that adapt to changing conditions and requirements. This flexibility allows for tailored connectivity solutions based on the specific needs of different regions and scenarios.

Cost-Effective Solutions: Using NTNs for backhaul or direct relay can reduce the reliance on expensive ground infrastructure, especially in sparsely populated areas where traditional networks would not be economically viable.

3.6.2 Challenges

Latency Concerns: Although LEO satellites offer lower latency compared to GEO satellites, the delay can still be noticeable for real-time applications. This issue is more pronounced in configurations involving multiple satellite hops or inter-satellite communications.

Interference Management: Ensuring clear communication in NTNs can be challenging due to the risk of signal interference, especially when multiple platforms operate at different altitudes and frequencies. Proper spectrum management is necessary to avoid overlapping signals and maintain quality of service.

Power Limitations: UAVs and certain high-altitude platforms have limited onboard power, which can restrict their operational duration and communication capabilities. Energy efficiency is a critical consideration for these platforms to maximize their effectiveness.

Regulatory Challenges: Deploying NTNs, particularly those involving UAVs, often faces regulatory hurdles related to airspace usage, frequency allocation, and compliance with international agreements. Navigating these regulatory requirements can be complex and time-consuming.

3.7 Use Cases for Non-Terrestrial Network Architectures

NTN architectures support a wide variety of applications, providing valuable solutions across different sectors.

Disaster Relief and Emergency Communications: In the aftermath of natural disasters, NTNs can be quickly deployed to restore connectivity for emergency services. UAVs and high-altitude platforms can serve as temporary mobile networks, facilitating communication between rescue teams and enabling coordination of relief efforts.

Environmental Monitoring and Remote Sensing: NTNs are well-suited for environmental monitoring activities, such as tracking forest fires, monitoring wildlife, and studying the effects of climate change. The extensive coverage offered by satellites and high-altitude platforms allows for continuous observation of vast, remote areas.

Maritime and Aviation Connectivity: For ships and aircraft operating in regions without terrestrial network coverage, NTNs can provide essential communication services. LEO satellite constellations, in particular, can offer broadband internet access for passengers on airplanes or crews on ships.

Bridging the Digital Divide in Rural Areas: NTNs can extend internet access to underserved communities, helping to bridge the digital divide. By combining satellites, high-altitude platforms, and UAVs, network operators can deliver broadband services to remote regions where it would be too costly or impractical to build conventional infrastructure.

11. MODERN TRENDS

TODO: write this chapter

https://www.mdpi.com/2504-446X/6/11/334/xml 2. structure of ntns and key technologies, really good

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https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=arnumber=9768113

https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=arnumber=9889300 uav use cases in ntn

https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=arnumber=9681624 uavs and beyond

https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=arnumber=10500741 how uavs can be used in ntn

12. 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.

12.1 Relevant Institutions

12.1.1 European Union Aviation Safety Agency (EASA)

The EASA [22] plays a crucial role in harmonizing aviation safety standards across all European Union (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 [23].

12.1.2 State Aviation Safety Agency (AESA)

In Spain, the Spanish Aviation Safety and Security Agency (AESA) [24] 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.

12.2 Applicable Legislation

12.2.1 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 [23] 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 [25], 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.

12.2.2 Delegated Regulation (EU) 2019/945

The Delegated Regulation (EU) 2019/945 [23] 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.

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

The Artificial Intelligence Act (AI Act) of the EU [26], which came into force on the 1st of August 2024, aims to ensure that Artificial Intelligence (AI) systems are safe, transparent, and ethical, while fostering innovation and protecting fundamental rights as stated in the Delegated Regulation (EU) 2024/1689 [27]. 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.

12.3 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 meters, 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.

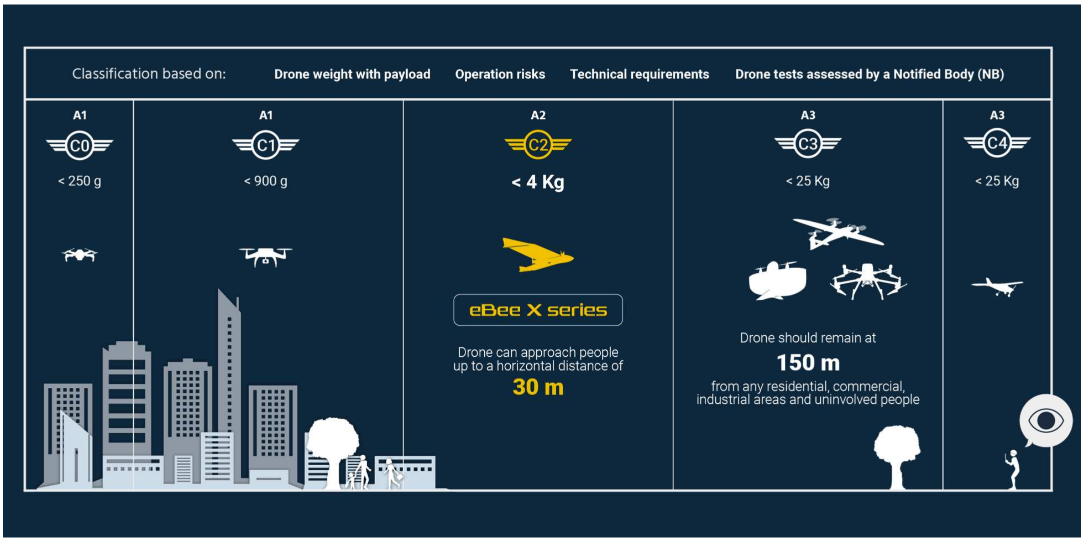

Figure 12.1. *EU Regulations Open Category chart describing the subcategories A1, A2, and A3 with their respective operational limitations [28]*

12.3.1 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 meters (5 meters in low-speed configuration).
3. **A3**: UAS with an MTOW of less than 25 kg that must maintain a horizontal distance of 150 meters from residential, commercial, industrial, or recreational areas.

Check Figure 12.1 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 meters above ground level, as the lower limit for general aviation is 150 meters. This leaves only a 30-meter separation between manned aviation and UAS.
- Operators must always maintain VLOS unless the aircraft is in "follow me" mode or the pilot is using First Person View (FPV) goggles.
- Operators must register if the UAS weighs more than 250 g or if the aircraft is equipped with a camera or sensor.
- 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.

Part IV

Methodology

13. REQUIREMENTS

Based on careful analysis of the conclusions from the current 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 the UAV, control station, and reconnaissance platform.

13.1 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 communicate with a ground station via a 4G or 3rd Generation (3G) connection.
- The system must be cost-effective, with the ability 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, as well as, the scalability of the system to include multiple UAVs working together in a coordinated manner.
- The system must be able to perform reconnaissance tasks autonomously, with the ability to take off, land, and navigate given a set of waypoints.
- The system must comply with the applicable regulatory framework for UAVs in the country of operation, Spain, as well as the EU regulations. See Chapter 12 for more information.

13.2 Unmanned Aerial Vehicle Requirements

The UAV requirements are as follows:

- The UAV must be able to be controlled remotely, with the ability to communicate with a ground station in real-time.
- The UAV must be able to take off, land, and navigate autonomously, with the ability to update its flight plan in real-time.
- The UAV must be able to process data in real-time, with the ability to relay the information to the ground station.
- 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 minutes, without the need for recharging.
- The UAV must be have a failsafe mechanism, that is it must be able to return to the ground station in case of loss of communication or other critical failures.

- The UAV must be able to keep a fixed altitude and position.
- The UAV must comply with the EASA regulations for the Open Category, with a maximum limit set at 25 kg of MTOW and 3 meters of wingspan.
- The UAV must be able to perform reconnaissance tasks, such as mapping, surveillance, and monitoring the environment.

13.3 Control Station Requirements

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 via a 4G or 3G connection.
- 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.
- The control station must have the capability be able to track multiple UAVs simultaneously, with the ability to coordinate their flight plans and tasks.
- The control station must log all telemetry data and flight information, with the ability to analyze the data and generate reports.

13.4 Reconnaissance Platform Requirements

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.
- The reconnaissance platform must be able to be used remotely, with the ability to access the UAVs and the control station via a 4G or 3G connection.
- The reconnaissance platform must be reliable, secure, and easy to use, allowing for the programming of the UAVs to perform specific tasks and the coordination of multiple UAVs in a swarm.
- 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.

14. DESIGN

This chapter outlines the system's design, detailing its components in accordance with the requirements specified in Chapter 13. The system consists of four core components: the UAV, responsible for reconnaissance tasks; the ground station, which oversees real-time monitoring of the UAV; the reconnaissance platform, tasked with processing data from the UAV and delivering actionable insights; and the communication system, enabling real-time data exchange between the UAV, ground station, and the reconnaissance platform.

14.1 Unmanned Aerial Vehicle

For the UAV design, the following components are considered: the airframe, the propulsion system, the flight controller, the power system, and peripherals.

14.1.1 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.

Rotary-wing designs are further divided into multi-rotor and single-rotor designs as seen in Figure 14.1. 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.

For the material of the airframe, a lightweight and durable material is chosen, such as carbon fiber or aluminum. The airframe is designed to be modular, allowing for the integration of different sensors and payloads for different applications. And finally, the airframe is

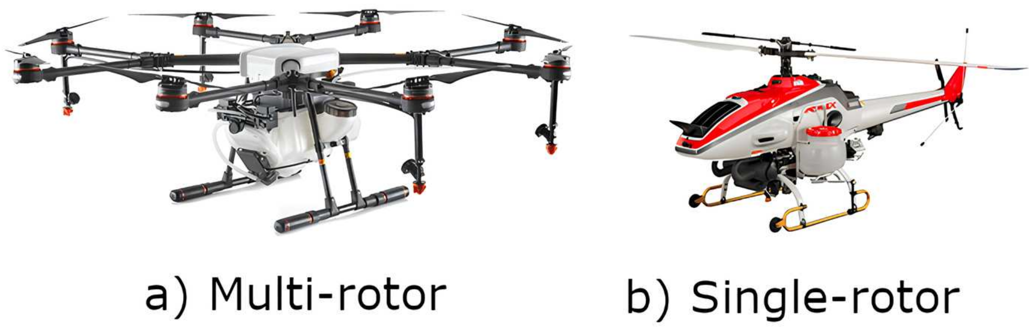

Figure 14.1. *Rotary-wing designs. Reproduced from [29].*

designed to be cost-effective and commercially available, with the ability to be assembled and disassembled easily, and to be repaired and maintained with minimal effort.

For that case the airframe chosen **TODO:** add ref to where we bought it is the **TODO:** add which one. It is a quadcopter design made of carbon fiber, with a wingspan of **TODO:** add size and a maximum takeoff weight of **TODO:** add weight. The airframe is designed to carry a maximum payload weight of **TODO:** add weight, with the ability to adapt to different reconnaissance tasks. Moreover, it has a payload bay that allows for the integration of different sensors and payloads, such as cameras, lidar, and thermal imaging sensors.

TODO: add image of the aireframe chosen

14.1.2 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 a good balance between efficiency, reliability, and low maintenance requirements. The electric propulsion system consists of four brushless motors, four electronic speed controllers, and four propellers. The main requirements of the propulsion system are the ability to provide enough thrust for the UAV to take off, land, and navigate, as well as the ability to carry the maximum payload weight of **TODO:** add weight.

The brushless motors chosen were the **TODO:** add ref to where we bought them, with a maximum thrust of **TODO:** add thrust and a maximum power of **TODO:** add power. The electronic speed controllers chosen were the **TODO:** add ref to where we bought them, with a maximum current of **TODO:** add current and a maximum voltage of **TODO:** add voltage. The propellers chosen were the **TODO:** add ref to where we bought them, with a maximum diameter of **TODO:** add diameter and a maximum pitch of **TODO:** add pitch. This complete propulsion system is designed to provide a thrust-to-weight ratio of **TODO:** add ratio, with the ability to carry the maximum payload weight of **TODO:** add weight which meets the requirements of the UAV design.

TODO: add image of the propulsion system chosen

14.1.3 Flight Controller

The flight controller is the system that controls the UAV during flight. The flight controller 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. 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 ground station in case of loss of communication or other critical failures.

For the UAV design, an autonomous flight controller is chosen, as it provides the ability to take off, land, and navigate autonomously to a set of waypoints. Commercially, there are multiple flight controllers available **TODO:** ref to table and any of them can be used for the UAV design. 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 ground station in real-time. The flight controller chosen was the **TODO:** add ref to where we bought it, as **TODO:** add reasons An image of the flight controller is shown in **TODO:** add ref to fig.

TODO: add table of flight controllers

TODO: add image of the flight controller chosen

14.1.4 Power System

The power system is the system that provides the power required for the UAV to operate. The power system can be of different types, such as batteries, fuel cells, or solar panels. For UAVs, usually batteries are 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 carry the maximum payload weight of **TODO:** add weight.

For the UAV design, a lithium polymer battery is chosen, as it provides a good balance between energy density, power density, and weight. The battery chosen was the **TODO:** add ref to where we bought it, with a maximum capacity of **TODO:** add capacity and a maximum voltage of **TODO:** add voltage. The battery is designed to provide enough power for the UAV to take off, land, and navigate, as well as the ability to carry the maximum payload weight of **TODO:** add weight. The battery is also designed to be modular, allowing for the integration of different batteries for different applications.

TODO: add image of the power system chosen

Moreover, usually the power system is divided into two parts, the power distribution system for the propulsion system and the power management system for the electronics. The main reason for this distinction is that the propulsion system requires a high current and low voltage, while the electronics require a low current and high voltage. However, for the UAV design, the power system is integrated into a single system to reduce weight and complexity and specially the pricing of the system.

Futhermore, in order to provide the required power for the different components of the UAV, a power management system is integrated into the power system. The power management system consists of a battery monitor, a voltage regulator, and a current sensor. The one chosen was the **TODO:** add ref to where we bought it, with a maximum current of **TODO:** add current and a maximum voltage of **TODO:** add voltage. The power management system is designed to provide the required power for the different components of the UAV, as well as the ability to monitor the battery voltage and current in real-time. And finally, a voltage regulator is integrated into the power system to provide the required voltage for the reconnaissance platform and the communication system. The voltage regulator chosen was the **TODO:** add ref to where we bought it, with a maximum voltage of **TODO:** add voltage and a maximum current of **TODO:** add current. The voltage regulator is designed to provide the required voltage for the reconnaissance platform and the communication system, as well as the ability to monitor the voltage and current in real-time.

TODO: add image of the power management system chosen

14.1.5 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, or thermal imaging sensors. For reconnaissance tasks, usually sensors and cameras are chosen, as they provide the ability to collect data and images of the environment. The main requirements of the peripherals are the ability to collect data and images of the environment, as well as the ability to relay the information to the ground station in real-time.

For the UAV design, a Global Positioning System (GPS) module was integrated into the UAV, as it provides the ability to navigate the UAV to a set of waypoints. The GPS module chosen was the **TODO:** add ref to where we bought it, with a maximum accuracy of **TODO:** add accuracy and a maximum update rate of **TODO:** add rate. The GPS module is designed to provide the ability to navigate the UAV to a set of waypoints, as well as the ability to relay the information to the ground station in real-time. An image of the GPS module is shown in **TODO:** add ref to fig.

TODO: add image of the gps module chosen

Moreover, a kill switch was integrated into the UAV, as it provides the ability to stop the motors in case of an emergency. It is a required safety feature for UAVs to prevent accidents and injuries. The kill switch chosen was the **TODO:** add ref to where we bought it.

TODO: add image of the kill switch chosen

Finally, a camera was integrated into the UAV, as it provides the ability to collect images of the environment. The camera chosen was the **TODO:** add ref to where we bought it, with a maximum resolution of **TODO:** add resolution and a maximum frame rate of **TODO:** add rate. The camera is designed to provide the ability to collect images of the environment, as well as the ability to relay the information to the ground station in real-time. An image of the camera is shown in **TODO:** add ref to fig.

TODO: add image of the camera chosen

14.2 Ground Station

The ground station is the control 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 ground 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 ground station is composed of the following components:

For the ground station, two main components are required: the ground control station and the radio controller. The ground control station is the main control station that monitors the UAV in real-time, receives telemetry data from the UAV, has the waypoint planning software, and sends commands to update the UAV's flight plan. The radio controller is a handheld device that allows the operator to take control of the UAV manually in case of an emergency and is the one that connects to the UAV directly and acts as a relay station between the UAV and the ground control station.

The ground control station is composed of a computer, it can be a personal laptop or a desktop computer, with the waypoint planning software installed, in this case, the **TODO:** add software software as it can be seen in **TODO:** ref, and a communication modules to communicate with the UAV in real-time, which will be explained in Section 14.4. The radio controller is a handheld device that allows the operator to take control of the UAV manually, and a communication module to receive telemetry data from the UAV in real-time. For the radio controller, the **TODO:** add ref to where we bought them was chosen, see **TODO:** add figiure, as it provides a good balance between range, reliability, and ease of use as well as a good price-performance ratio.

TODO: figure of the ground control station with the software

TODO: figure of the backup control station with the radio controller

14.3 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 coordinating the flight plans of the UAVs in a swarm, as well as designing the missions for the UAVs to perform specific tasks.

The components chosen for the reconnaissance platform were divided into two main components depending on where they run, the on-board reconnaissance platform and the off-board reconnaissance platform.

14.3.1 On-Board Reconnaissance Platform

The on-board reconnaissance platform is the system that runs on the UAV and is responsible for processing the data collected by the UAV and providing insights to the end-user. The on-board reconnaissance platform is composed of a on-board computer and a communication module to communicate with the off-board reconnaissance platform.

For the on-board computer, multiple options were considered as represented in **TODO:** add table reference. The main use case for the reconnaissance platform is to process the data collected by the UAV in real-time and provide insights to the end-user. For this case, a computer with a high processing power, specially in the Graphics Processing Unit (GPU), is required as deep learning algorithms are used to detect and track objects in the environment. The on-board computer chosen for the reconnaissance platform was the **TODO:** add ref to where we bought them depicted in **TODO:** add figure, as it provides a good balance between processing power, reliability, and price-performance ratio. The reason to choose this on-board computer is that it provides the highest processing power commercially available. Having a stable and reliable on-board computer is crucial for the UAV design, as it allows for the UAV to process the data collected in real-time and provide insights to the end-user. Moreover, it is widely used in the industry and has a large community of developers, which makes it easier to find support and documentation.

TODO: add table with the on-board computer options

TODO: add figure of the on-board computer

For the communication module, a 4G communication module was chosen, as it provides a high bandwidth required to send the data collected by the UAV in real-time to the off-board reconnaissance platform and a simple yet robust communication system. The communication module chosen for the on-board reconnaissance platform was the **TODO:** add ref to where we bought them depicted in **TODO:** add figure, as it provides a good balance between bandwidth, reliability, and price-performance ratio. For the use case of this project, a 4G communication module was enough as the environment where the UAV will operate has a good 4G coverage. On the other hand, if the UAV will operate in remote areas with limited infrastructure, a Radio Frequency (RF) communication module would be more suitable.

TODO: add figure of the communication module

14.3.2 Off-Board Reconnaissance Platform

The off-board reconnaissance platform is the system that runs on a server and is responsible for coordinating the missions of the UAVs in a swarm, as well as generating reports and analyzing the data collected by the UAVs. The off-board reconnaissance platform is composed of a server, a database, and a communication module to communicate with the on-board reconnaissance platform.

For the server, multiple options were considered as represented in **TODO:** add table reference. The main use case for the reconnaissance platform is to process the data collected by the UAVs in real-time and provide insights to the end-user. For this case, a server with a stable and reliable connection is required. Moreover, the server should be able to be accessed remotely from anywhere in the world, as the end-user may be located in a different location than the server. For this the option that was chosen was the **TODO:** add ref to where we bought them as it provides the best price-ease of use ratio. The reason to choose a cloud provider is that it provides a stable and reliable connection, as well as the ability to be accessed remotely from anywhere in the world. Moreover, it is widely used in the industry and has a large community of developers, which makes it easier to find support and documentation.

TODO: add table with the server options

14.4 Communication System

The communication system is the system that allows the UAV to communicate with the ground station in real-time, as well as providing the connection to the reconnaissance platform. The communication system is responsible for sending telemetry data from the UAV to the ground station, receiving commands from the ground station to update the UAV's flight plan, and sending the data collected by the UAV to the reconnaissance platform for further analysis. Different communication systems can be used depending on the use case, such as 4G, 3G, Wireless Fidelity (WiFi), or RF, and the environment where the UAV will operate. The characteristics to consider when choosing a communication system can be seen in **TODO:** add ref to the table in the requirements chapter.

TODO: add table with the communication system options

For this project, two communication systems were chosen the on-board communication system and the off-board communication system.

14.4.1 On-Board Communication System

The on-board communication system is the system that connects the UAV with the ground station in real-time. The on-board communication system is composed of a communication module that sends telemetry data from the UAV to the ground station and receives commands from the ground station to update the UAV's flight plan. The on-board communication system is responsible for providing a stable and reliable connection between the UAV and the ground station, as well as a high bandwidth to send the data collected by the UAV to the reconnaissance platform. The main requirements for the on-board communication system are a high reliability, a low latency, and long range.

For this case, a RF communication module was chosen, as it satisfies the requirements for the on-board communication system as well as not needing a cellular network to operate, thus making it more versatile and ideal to operate in remote areas. The RF communication module chosen for the on-board communication system was the **TODO:** add ref to where we bought them depicted in **TODO:** add figure, as it provides a good balance between reliability, latency, and range. The reason to choose a RF communication module is that 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, as it provides a good price-performance ratio.

TODO: add figure of the communication module

14.4.2 Off-Board Communication System

The off-board communication system is the system that connects the on-board reconnaissance platform with the off-board reconnaissance platform. The off-board communication system is composed of a communication module that sends the data collected by the UAV to the off-board reconnaissance platform for further analysis. The off-board communication system is responsible for providing a stable and reliable connection between the on-board reconnaissance platform and the off-board reconnaissance platform, as well as a high bandwidth to send the data collected by the UAV in real-time. The main requirements for the off-board communication system are a high bandwidth, a secure connection, and the ability to receive data from multiple UAVs simultaneously.

For this case, a 4G communication module was chosen, as it satisfies the requirements for the off-board communication system as well as providing a high bandwidth to send the data collected by the UAV in real-time. The 4G communication module chosen for the off-board communication system was the **TODO:** add ref to where we bought them depicted in **TODO:** add figure, as it provides a good balance between bandwidth, reliability, and price-performance ratio. A 4G communication module was chosen as the environment where the UAV will operate has a good 4G coverage. On the other hand, if the UAV will operate in remote areas with limited infrastructure, a RF communication module would be more suitable.

TODO: add figure of the communication module

15. IMPLEMENTATION

Following the design presented in the previous chapter, 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 stated in the design chapter, refer to Chapter 14, the system is divided into four main components: the UAV, the ground station, the reconnaissance platform, and the communication system. Each component is implemented separately and then integrated into the system as a whole.

15.1 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 ground station. The UAV has multiple subsystems that must be implemented and integrated, in the next subsections, the implementation of each subsystem is detailed as well as the integration of the subsystems into the UAV.

15.1.1 Airframe

For the airframe, the UAV was built using following the instructions provided by the manufacturer. 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 **TODO:** add software software and a **TODO:** add printer 3D printer. 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 **TODO:** add figure.

TODO: add figure of the 3D printed parts

The final assemply of the airframe can be seen in **TODO:** add figure. The final weight of the UAV was **TODO:** add weight and the dimensions were **TODO:** add dimensions.

TODO: add figure of the final assembly of the airframe

15.1.2 Propulsion System

Regarding the propulsion system, the UAV was equipped with four **TODO:** add ref to where we bought them motors, four **TODO:** add ref to where we bought them propellers, and four **TODO:** add ref to where we bought them electronic speed controllers, as stated in the design chapter, refer to Subsection 14.1.2. The motors were attached to the airframe using custom metal brackets, as seen in **TODO:** add figure. The electronic speed controllers were attached to the airframe using **TODO:** add how they were attached, refer to **TODO:** add figure.

TODO: add figure of the motors attached to the airframe

TODO: add figure of the electronic speed controllers attached to the airframe

15.1.3 Flight Controller

The UAV was equipped with a **TODO:** add ref to where we bought them flight controller. The flight controller was attached to the airframe using **TODO:** add how it was attached, refer to **TODO:** add figure. The flight controller was connected the different subsystems of the UAV using **TODO:** add how they were connected. The main software used to configure the flight controller is the **TODO:** add software software, as it provides a user-friendly interface to configure the different parameters of the flight controller. Moreover, it is the defacto standard for UAV flight controllers for hobbyists and professionals, with a large community of developers **TODO:** ref and a large repository of documentation and tutorials **TODO:** add ref to the documentation.

TODO: add figure of the flight controller attached to the airframe

15.1.4 Power System

Powering the UAV is a critical aspect of the design, as the UAV must be able to fly for a long period of time to perform the reconnaissance tasks. Moreover, the power system must be reliable and safe, as any failure in the power system can result in the loss of the UAV and it must be able to power up the different subsystems of the UAV. Regarding the power system, the UAV was equipped with a **TODO:** add ref to where we bought them battery, a **TODO:** add ref to where we bought them power distribution board, and a **TODO:** add ref to where we bought them voltage regulator, as stated in the design chapter, refer to Subsection 14.1.4. The battery was attached to the airframe using **TODO:** add how it was attached, refer to **TODO:** add figure. The power distribution board was attached to the airframe using **TODO:** add how it was attached, refer to **TODO:** add figure. The voltage regulator was attached to the airframe using **TODO:** add how it was attached, refer to **TODO:** add figure.

TODO: add figure of the battery attached to the airframe

TODO: add figure of the power distribution board attached to the airframe

TODO: add figure of the voltage regulator attached to the airframe

15.1.5 Peripherals

The UAV was equipped with the following peripherals, a **TODO:** add gps type GPS module mounted on the top of the airframe with a 3D printed mount to provide with the best reception, and a kill switch mounted on the side of the airframe. The GPS module was connected to the flight controller using **TODO:** add how they were connected, refer to **TODO:** add figure. The kill switch was connected to the flight controller using **TODO:** add how they were connected, refer to **TODO:** add figure.

TODO: add figure of the GPS module attached to the airframe

TODO: add figure of the kill switch attached to the airframe

Furthermore, the UAV was equipped with a **TODO:** add ref to where we bought them camera mounted on the front of the airframe with a 3D printed mount to provide with the best view. The camera was connected to the reconnaissance platform using **TODO:** add how they were connected, refer to **TODO:** add figure. The camera was used to capture images and videos of the environment, as well as to provide the reconnaissance platform with the data needed to detect and track objects in the environment.

15.2 Ground Station

15.3 Reconnaissance Platform

15.4 Communication System

16. TESTING

TODO: write this chapter

Part V

Results

Part VI

Conclusions

17. CONCLUSIONS

TODO: write this chapter

18. FUTURE WORK

TODO: write this chapter

19. SOCIO-ECONOMIC ENVIRONMENT

TODO: write this chapter

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