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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

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AGRADECIMIENTOS

Gracias

TABLE OF CONTENTS

I	Introduction	1
1	Motivation	2
2	Statement of the problem	4
3	Objectives	5
4	Document Structure	6
5	Methodological Framework	7
II	Theoretical Background	10
6	Non-Terrestrial Networks	11
6.1	Geostationary Satellites	11
6.2	Low-Earth Orbit Satellites	11
6.3	High-Altitude Platforms	12
7	Unmanned Aerial Vehicles	14
7.1	Types of Unnamed Aerial Vehicles	14
7.2	Applications of Unmanned Aerial Vehicles	16
8	Deep Learning	17
8.1	Deep Learning Techniques	17
III	State of the art	20
9	Historical Development	21
10	Types & Characteristics	23
10.1	NTN Platforms as Network Users	23
10.2	NTN Platforms as Relays	23
10.3	NTN Platforms as Base Stations	25
10.4	Mixed Architecture Models	25
10.5	Characteristics of Non-Terrestrial Networks	26
11	Modern Trends	27
IV	Methodology	30
12	Requirements	31
12.1	High-level System Requirements	31

TABLE OF CONTENTS

12.2 Unmanned Aerial Vehicle Requirements	31
12.3 Control Station Requirements	32
12.4 Reconnaissance Platform Requirements	32
13 Design	33
13.1 Unmanned Aerial Vehicle	33
13.1.1 Airframe	33
13.1.2 Propulsion System	34
13.1.3 Flight Controller	34
13.1.4 Power System	35
13.1.5 Peripherals	36
13.2 Ground Station	36
13.3 Reconnaissance Platform	37
13.3.1 On-Board Reconnaissance Platform	37
13.3.2 Off-Board Reconnaissance Platform	38
13.4 Communication System	38
13.4.1 On-Board Communication System	39
13.4.2 Off-Board Communication System	39
14 Implementation	40
14.1 Unmanned Aerial Vehicle	40
14.1.1 Airframe	40
14.1.2 Propulsion System	40
14.1.3 Flight Controller	41
14.1.4 Power System	41
14.1.5 Peripherals	41
14.2 Ground Station	42
14.3 Reconnaissance Platform	42
14.4 Communication System	42
15 Testing	43
V Results	45
VI Conclusions	47
16 Conclusions	48
17 Future work	49
18 Socio-economic environment	50
19 Regulatory Framework	51
19.1 Relevant Institutions	51
19.1.1 European Union Aviation Safety Agency (EASA)	51
19.1.2 State Aviation Safety Agency (AESA)	51
19.2 Applicable Legislation	51
19.2.1 Implementing Regulation (EU) 2019/947	51

TABLE OF CONTENTS

19.2.2 Delegated Regulation (EU) 2019/945 52

19.2.3 Regulation (EU) 2024/1689: Artificial Intelligence Act 52

19.3 Operational Categories 52

19.3.1 Open Category 53

LIST OF FIGURES

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]	3
5.1	Methodological framework based on the V-model from INCOSE with the different stages of the project development process[16]	8
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]	13
7.1	Types of UAVs based on their design and intended use [20]. a. Rotary-wing UAV, b. Fixed-wing UAV, c. Hybrid UAV	15
10.1	Different architectures of NTN platforms according to their use case [22].	24
13.1	Rotary-wing designs. Reproduced from [38].	33
19.1	EU Regulations Open Category chart describing the subcategories A1, A2, and A3 with their respective operational limitations [45]	53

LIST OF TABLES

7.1	Comparison of fixed-wing, rotary-wing, and hybrid UAVs across various performance metrics	15
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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.

LIST OF ACROYNMS

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.

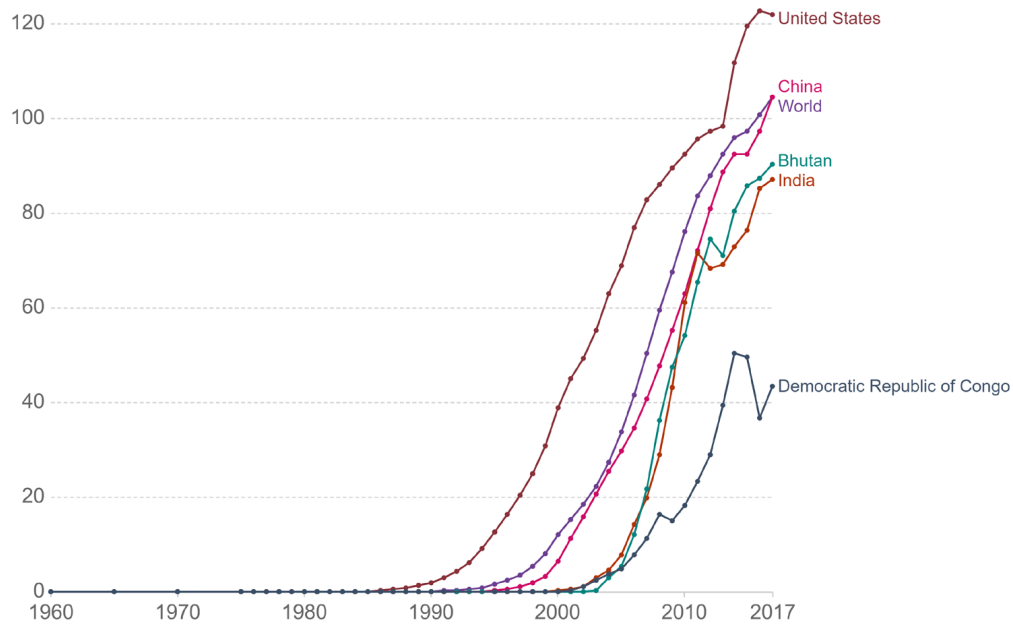
The emergence of NTNs has further enabled the development of advanced concepts such as the Integrated Space-Terrestrial Network (ISTN) [6][7][8], and the Internet of Space Things (IoST) [9][10][11]. These concepts envision a seamless integration of terrestrial and non-terrestrial components to deliver 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.

Mobile cellular subscriptions, 1960 to 2017

Mobile phone subscriptions, measured as the number per 100 people.

Our World
in Data



Source: International Telecommunication Union

OurWorldInData.org/technology-adoption/ • CC BY

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 °C and 1013 hPa.
- **Operational Parameters:** The UAV operations will be confined to Visual Line of Sight (VLOS) and an altitude below 120 m and the Maximum Takeoff Weight (MTOW) of the UAV will not exceed 25 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 NTN. This project specifically aims to foster new research in the field of NTN 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 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 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 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.

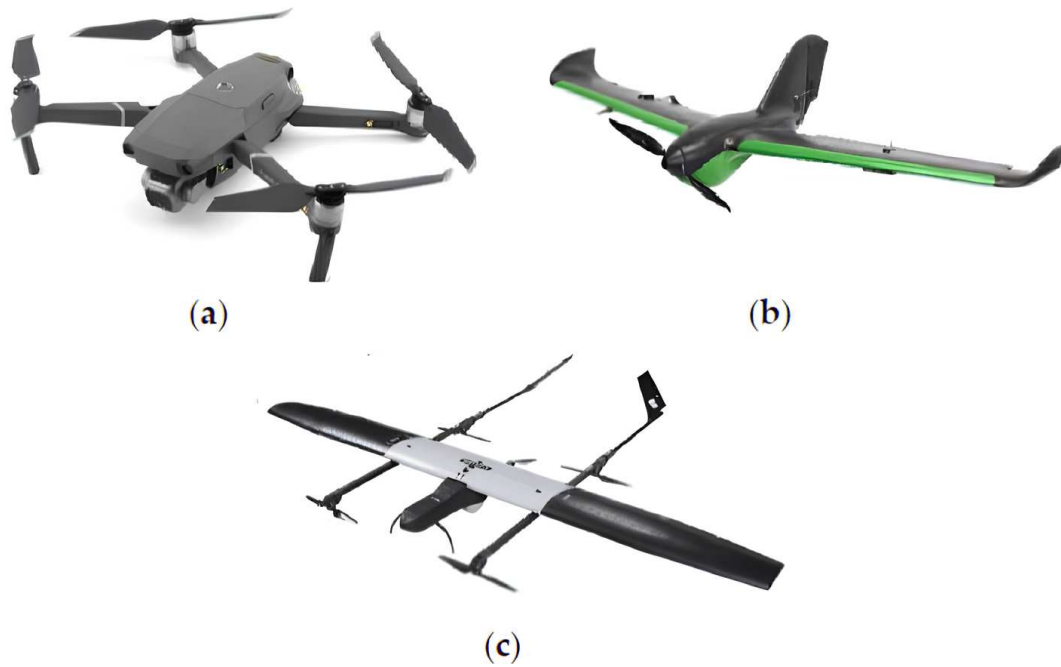


Figure 7.1. Types of UAVs based on their design and intended use [20].
a. Rotary-wing UAV, b. Fixed-wing UAV, c. Hybrid UAV

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 NTN and UAV 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 & 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 User Equipment (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.

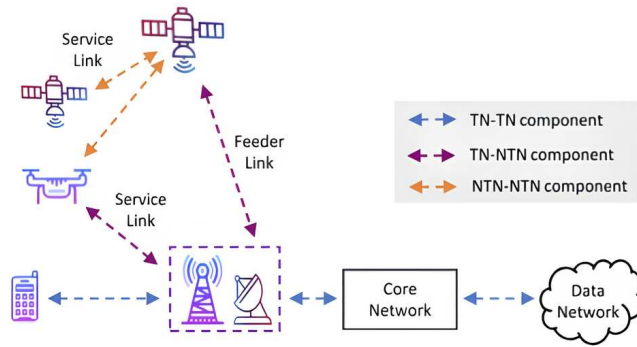
A well-known example is the integration of UAVs into terrestrial networks. The 3GPP has identified UAVs as a unique category of UE [23], leading to research on how to address their specific connectivity challenges [24]. These challenges include maintaining stable connections during flight, managing potential 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 ground 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.

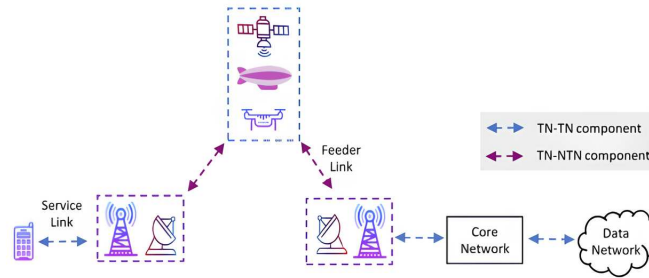
10.2 NTN Platforms as Relays

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.

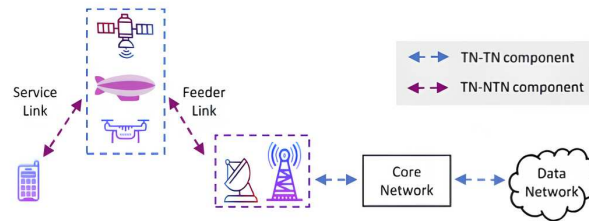
The first configuration involves backhaul connectivity [25], where the NTN platform provides a link between a ground-based base station and the core network. This model is especially useful in remote or hard-to-reach areas where traditional backhaul solutions, such as fiber optic cables, are unavailable or too costly to install. By using satellites or



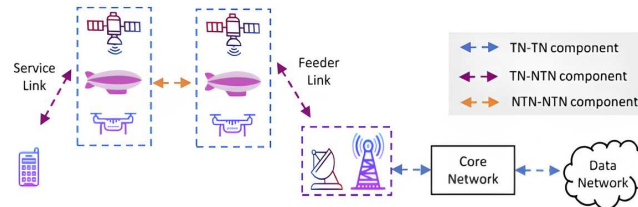
(a) Diagram of NTN Platforms as Network Users where the NTN acts as another UE in the network.



(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].

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.

11. MODERN TRENDS

In recent years, NTN 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, NTN present unique opportunities for various applications, particularly in disaster response, virtual reality, and high-speed internet access. This section explores the modern trends of NTN, 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 NTN 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 NTN 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

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 control station, and the reconnaissance platform.

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 communicate with a ground station in real-time and for long distances, more than 5 km.
- 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 19 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 communicate with a ground station in real-time and for long distances, more than 5 km and function autonomously.
- 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 have a failsafe mechanism, that is it must be able to return to the control station 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.

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 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.

13.1 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.

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 designs are considered, such as fixed-wing, rotary-wing, and hybrid designs as stated in Section 7.1. As one 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 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.

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

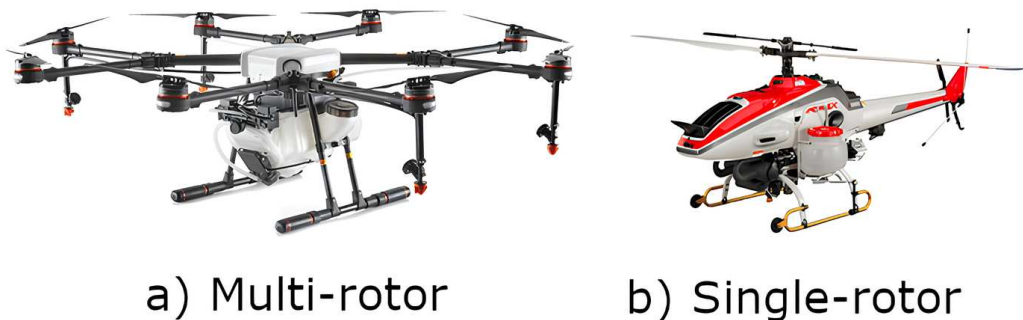


Figure 13.1. *Rotary-wing designs. Reproduced from [38].*

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 airframe chosen

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 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

13.1.3 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 re-

turn 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

13.1.4 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

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, or thermal imaging sensors. For reconnaissance tasks, usually cameras are chosen, as they provide the ability to collect images of the environment. But other sensors can be integrated into the UAV to provide additional functionality, such as geo-location systems for navigation, lidar for obstacle avoidance, or thermal imaging sensors for monitoring the environment.

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

13.2 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 13.4. 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 figure**, 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

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

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

13.3.1 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

13.3.2 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

13.4 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, 3rd Generation (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.

13.4.1 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

13.4.2 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

14. 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 13, 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.

14.1 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.

14.1.1 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 were 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 assembly 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

14.1.2 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 13.1.2. 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

14.1.3 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

14.1.4 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 13.1.4. 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

14.1.5 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.

14.2 Ground Station

14.3 Reconnaissance Platform

14.4 Communication System

15. TESTING

TODO: write this chapter

Part V

Results

Part VI

Conclusions

16. CONCLUSIONS

TODO: write this chapter

17. FUTURE WORK

TODO: write this chapter

18. SOCIO-ECONOMIC ENVIRONMENT

TODO: write this chapter

19. 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.

19.1 Relevant Institutions

19.1.1 European Union Aviation Safety Agency (EASA)

The EASA [39] 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 [40].

19.1.2 State Aviation Safety Agency (AESA)

In Spain, the Spanish Aviation Safety and Security Agency (AESA) [41] 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.

19.2 Applicable Legislation

19.2.1 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 [40] 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 [42], 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.

19.2.2 Delegated Regulation (EU) 2019/945

The Delegated Regulation (EU) 2019/945 [40] 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.

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

The Artificial Intelligence Act (AI Act) of the EU [43], 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 [44]. 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.

19.3 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.

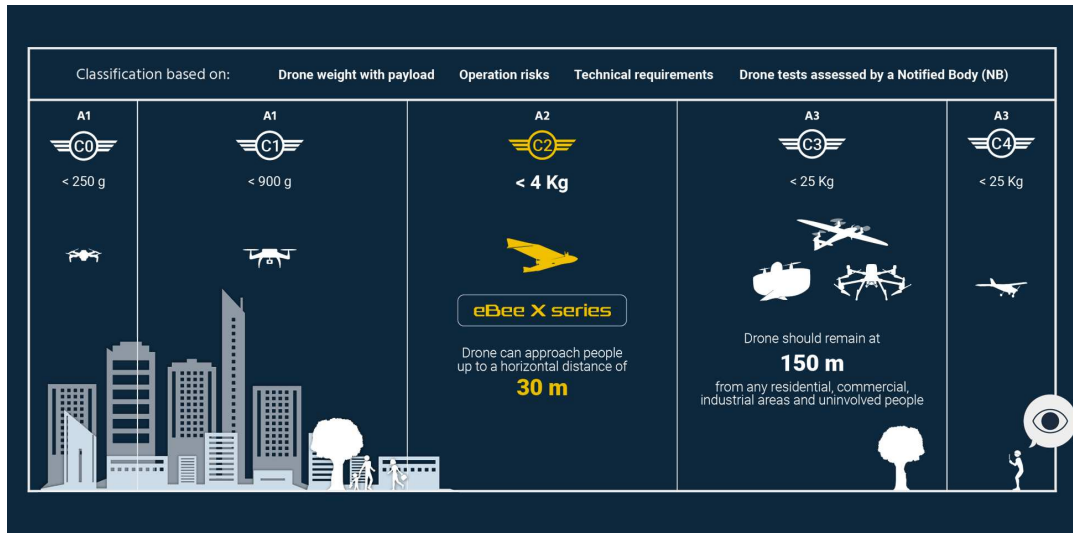


Figure 19.1. *EU Regulations Open Category chart describing the subcategories A1, A2, and A3 with their respective operational limitations [45]*

19.3.1 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 19.1 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.
- 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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