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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

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Gracias

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Part I

Introduction

1. MOTIVATION

2. STATEMENT OF THE PROBLEM

The current research area in non-terrestrial networks is focused on the development of satellites based on Geostationary Earth Orbit (GEO) or Low Earth Orbit (LEO) constellations [1]. This devices have a high cost and are not easily customizable, therefore, they are not suitable for most research groups and individuals. On the other hand, drones are a more affordable and customizable solution, but they have a limited range and are not suitable for long-term missions.

The main problem that drones have currently is that there is no widely available solution that allows the creation of a drone that can perform autonomous missions in remote areas. The current solutions are either expensive, closed-source drones that are not customizable, or require a lot of infrastructure to operate, such as a ground station, a high-speed internet connection, etc. This limits the potential applications of drones in remote areas, where infrastructure is limited or non-existent.

The main problem that this work will address is the lack of comprehensive, open-source, and affordable solutions for the development of drones that can perform autonomous missions in remote areas.

As the scope of this problem is broad, it needs to be narrowed down to a specific problem that can be solved in this thesis. The environment that will be modeled in this thesis will have the following characteristics:

- The environment will be a remote area with limited infrastructure, such as a forest, a desert, or a mountain. In this case study, the environment will be a esplanade, that is a flat area with no obstacles such as buildings, trees, or mountains. This will allow the drone to fly freely without the risk of crashing into obstacles.
- The environment will have a clear sky, with no interference from other drones, airplanes, or other sources of electromagnetic interference. Furthermore, the environment will have a low level of electromagnetic interference and a temperature close to the standard temperature and pressure (STP) conditions of 15°C and 1013 hPa.
- The type of operations that the aircraft will engage in will always be withing Visual Line of Sight (VLOS) of the operator and below 120 meters of altitude. Moreover, the drone designed will not exceed 25 kg of Maximum Takeoff Weight (MTOW). This is to comply with the current regulations in Spain and most of the world.
- The hardware that will be used in the drone will be off-the-shelf components that are widely available and affordable. This will allow the drone to be easily replicated by other research groups and individuals.
- The work will be focus on human rescue operations, such as searching for missing people, locating survivors in disaster areas, or monitoring the environment for signs of danger. This is not the only application of drones in remote areas, but it is a promising one that can have a positive impact on society.

3. OBJECTIVES

The main goal of this thesis is to develop a open-source, modular and customizable drone that can be used in remote areas. The drone will be able to fly autonomously and will be able to communicate with a ground station. The drone will be able to be controlled remotely and will be able to be programmed to perform specific tasks. The drone will be able to be used in a variety of applications, such as reconnaissance, surveillance, agriculture, humanitarian aid, etc.

Moreover, a software platform will be developed that will allow the drone to be programmed to perform reconnaissance tasks and the software will be designed to support multiple drones to create a swarm of drones that can be used to perform reconnaissance tasks in a coordinated way.

The drone will be designed to be easy to assemble and disassemble and will be designed to be easy to repair and maintain. The drone will be designed to be cheap and will be designed to be easy to customize and modify.

4. DOCUMENT STRUCTURE

5. METHODOLOGICAL FRAMEWORK

The methodological framework employed in this thesis is grounded in the V-model as established by the International Council of System Engineering (INCOSE) [2] 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.

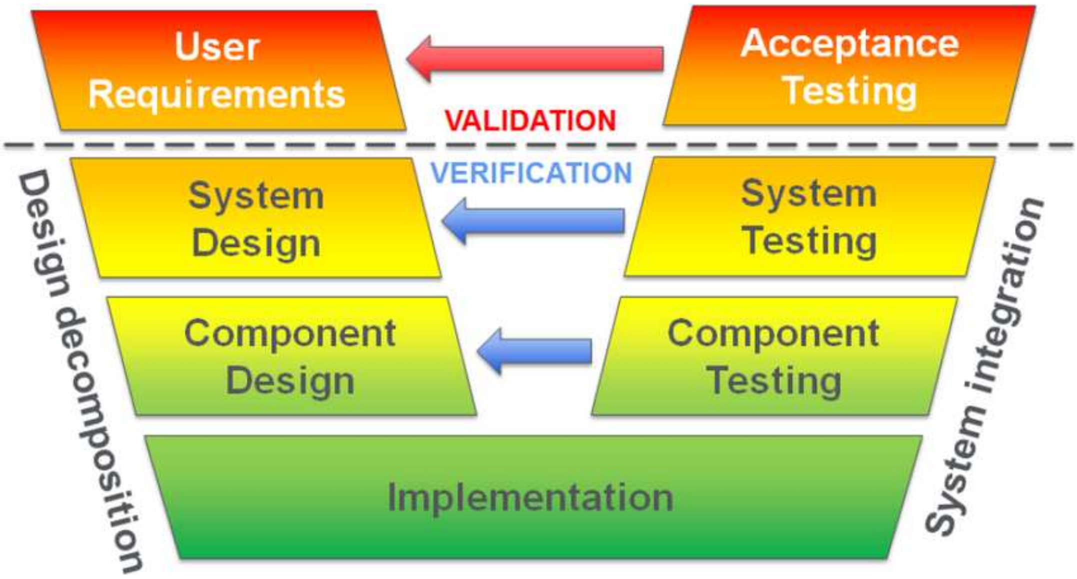

Figure 5.1. *Methodological framework based on the V-model with the different stages of the project development process[3]*

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

State of the art

6. OVERVIEW OF UNMANNED AERIAL VEHICLE SYSTEMS

7. HISTORICAL DEVELOPMENT

8. TYPES & TECHNOLOGIES

9. MODERN TRENDS

10. 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.

10.1 Relevant Institutions

10.1.1 European Union Aviation Safety Agency (EASA)

The European Union Aviation Safety Agency (EASA) [4] 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 European Union. EASA achieves this through the establishment and enforcement of common regulations applicable to all member states. Notably, for the standardization of Unmanned Aerial Systems (UAS), EASA has implemented Regulations (EU) 2019/947 [5] and (EU) 2019/945 [6].

10.1.2 Spanish Aviation Safety and Security Agency (AESA)

In Spain, the Spanish Aviation Safety and Security Agency (AESA) [7] 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.

10.2 Applicable Legislation

10.2.1 Implementing Regulation (EU) 2019/947

The Implementing Regulation (EU) 2019/947 [5] establishes the operational rules and requirements for UAS within the European Union. 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 [6] 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 [8], 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.

10.2.2 Delegated Regulation (EU) 2019/945

The Delegated Regulation (EU) 2019/945 [6] defines the rules and standards for UAS within the European Union. 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.

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

The Artificial Intelligence Act (AI Act) of the European Union [9], 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 [10]. The 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.

10.3 Operational Categories

The Regulation (EU) 2019/947 [5] classifies UAS into three distinct categories:

- **Open Category:** The least restrictive category, designed for low-risk operations, includes activities such as recreational flying and commercial operations posing minimal risk to people and property. Operators must adhere to specific limitations (e.g., flying below 120 meters, maintaining Visual Line of Sight). 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 Scenarios (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.

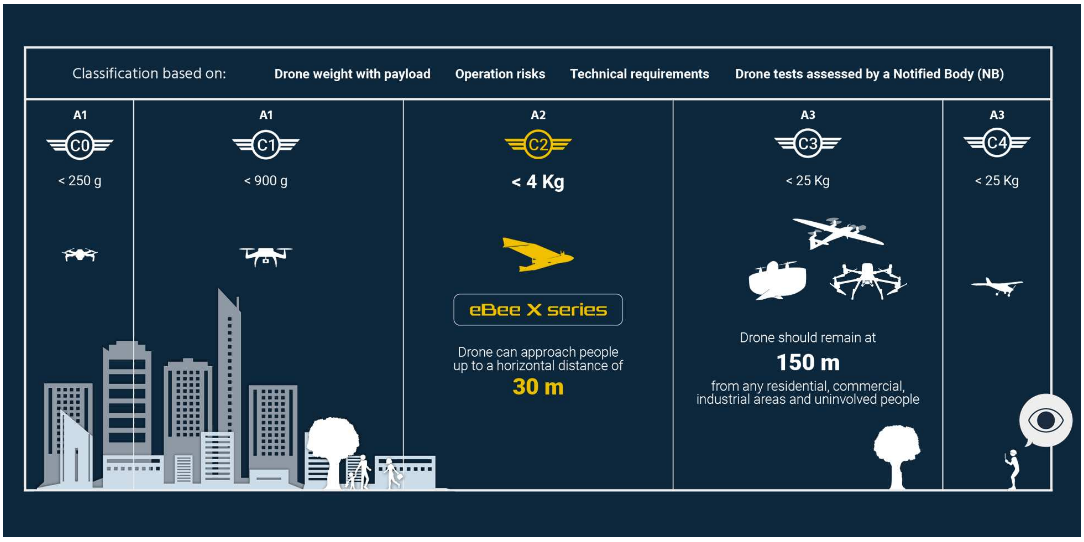

Figure 10.1. *EU Regulations Open Category chart describing the subcategories A1, A2, and A3 with their respective operational limitations [11]*

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

Check Figure 10.1 for a visual representation of the Open Category subcategories.

Moreover, additional rules applicable to all three subcategories include:

- The maximum height must not exceed 120 meters above ground level, as the lower limit for general aviation is 150 meters. This leaves only a 30-meter separation between manned aviation and UAS.
- Operators must always maintain Visual Line of Sight (VLOS) unless the aircraft is in "follow me" mode or the pilot is using First-Person View (FPV) goggles.
- Operators must register if the UAS weighs more than 250 g or if the aircraft is equipped with a camera or sensor.
- The aircraft must possess a remote identification ID, which is standard in all C1-C6 categories, with the exception of C4 and privately built aircraft.

Part III

Methodology

11. REQUIREMENTS

Based on careful analysis of the conclusions from the current trends in UAVs outlined in Chapter 9 and the objectives reviewed in Chapter 3, the following requirements are established for the high-level system as well as the detailed requirements for the UAV, control station, and software platform.

11.1 High-level System Requirements

The high-level system requirements are as follows:

- The system must be able to operate in remote areas with limited infrastructure, such as roads, electricity, and internet connectivity.
- The system must be able to be monitored remotely, with the ability to communicate with a ground station via a 4G or 3G connection.
- The system must be cost-effective, with the ability to be assembled and disassembled easily, and to be repaired and maintained with minimal effort.
- The system must be modular, allowing for the integration of different sensors and payloads for different applications, as well as, the scalability of the system to include multiple UAVs working together in a coordinated manner.
- The system must be able to perform reconnaissance tasks autonomously, with the ability to take off, land, and navigate given a set of waypoints.
- The system must comply with the applicable regulatory framework for UAVs in the country of operation, Spain, as well as the European Union regulations. See Chapter 10 for more information.

11.2 UAV Requirements

The UAV requirements are as follows:

- The UAV must be able to be controlled remotely, with the ability to communicate with a ground station in real-time.
- The UAV must be able to take off, land, and navigate autonomously, with the ability to update its flight plan in real-time.
- The UAV must be able to process data in real-time, with the ability to relay the information to the ground station.
- The UAV must be able to carry different payloads and sensors for different applications up to a maximum payload weight of 2 kg, with the ability to adapt to different reconnaissance tasks.
- The UAV must be able to fly for a minimum of 30 minutes, without the need for recharging.
- The UAV must be have a failsafe mechanism, that is it must be able to return to the ground station in case of loss of communication or other critical failures.

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

11.3 Control Station Requirements

The control station requirements are as follows:

- The control station must be able to receive telemetry data from the UAV in real-time, with the ability to send commands to the UAV to update its flight plan.
- The control station must be able to be used remotely, with the ability to communicate with the UAV via a 4G or 3G connection.
- The control station must be able to create a geofence around the area of operation, with the ability to monitor the UAV's position and altitude in real-time.
- The control station must have the capability be able to track multiple UAVs simultaneously, with the ability to coordinate their flight plans and tasks.
- The control station must log all telemetry data and flight information, with the ability to analyze the data and generate reports.

11.4 Software Platform Requirements

The software platform requirements are as follows:

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

12. DESIGN

13. IMPLEMENTATION

14. TESTING

Part IV

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Part V

Conclusions

15. CONCLUSIONS

16. FUTURE WORKS

17. SOCIO-ECONOMIC ENVIRONMENT

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