Designing an F450-based Quadrotor UAV for Educational and Scientific Research Purposes

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Abstract: This paper outlines the construction of a functional Unmanned Aerial Vehicle (UAV), utilizing the F450 frame, carried out by one student in the context of a scientific research project. The student focused on selecting and integrating electronic components, such as motors, sensors, and communication modules, and configuring the Flight Control Unit (FCU). The research project subjected the UAV to comprehensive practical tests, both physical and simulated, using Software In The Loop (SITL) techniques to validate drone functionalities and to showcase its ability to respond to flight commands accurately. This paper concludes with an emphasis on the educational impact, highlighting the transformative potential of integrating UAV technology into the curriculum and preparing students for the evolving challenges in Electronics Engineering.

Keywords: UAV; Scientific Research Project; Prototype; ROS

1. INTRODUCTION

Unmanned Autonomous Vehicles (UAVs) are increasingly present in many applications Castro et al. (2023). In recent years, there is a growing interest in autonomous systems and the development of machines that are capable of interacting with people or robots. These systems usually perceive their environment through vision systems and sensors. In this sense, it is necessary to guarantee the correct functioning of these sensors and the robotic system to ensure a safe, stabilized, and efficient operation Ramos et al. (2022b). In a robotic system, it is essential to design and choose the hardware components appropriately. The control system must also be well-adjusted. The flight controller is the primary device to be configured for this. The control design of UAVs has two main challenges. The first challenge concerns the quadcopter, which is a nonlinear Multiple Input and Multiple Output (MIMO) system featuring four actuators and six Degrees of Freedom (DoFs). The second challenge is that this type of robot faces different difficulties, such as external and internal disturbances, uncertainty in the model, and parametric disturbances Carvalho et al. (2021).

UAVs play an essential role in solving problems that may involve risks to humans. Villa et al. (2020) presented a survey showing a deep analysis of a UAV to transport cargo, emphasizing the versatility of these aircraft. Santos et al. (2015) addressed the critical safety issue, recognizing that UAVs may face adversities, such as engine loss or component failure, and must be prepared for these situations. Medeiros et al. (2017) proposed integrating embedded systems to allow flight in controlled and monitored environments, highlighting the importance of compatibility with the prototype. It is interesting to note that all these works share the same fundamental methodology: the need for solid theoretical modeling as a basis for the construction and operation of the UAV.

There are many applications of Low-Cost Robots in the academic environment, and many of them contribute to graduate student lessons. For instance, Murcia et al. (2018) emphasizes the construction of a line-tracking robot for competition purposes, describing all the Cartesian math of the robot's movement. Serrano Pérez and Juárez López (2019) created a Low-Cost Line Follower Robot for programming and circuit classes, describing the platform and all the components used to teach computer lessons to students. This illustrates how such methodology improves some skills in the areas of robotics and embedded systems. Voštinár et al. (2018) developed modular and programmable drones to encourage children in Science, Technology, Engineering and Mathematics (STEM) classes, allowing them to program and assemble their drones. Krajník et al. (2011) developed a drone for Augmented Reality (AR) applications, and investigated how this type of drone can be used for scientific research in the academic environment. Metzler et al. (2018) describe the development of a low-cost drone to collect elevation data, and compare this application to the traditional methods.

This work aims to construct a functional quadcopter-type UAV capable of carrying out tests. These tests range from simple maneuvers, such as take-off, flight to a destination, and landing, to more complex ones, such as loading a load, for example. To prepare the prototype, the electronic components of this robot need to be chosen correctly for the prototype to perform well. This process involves selecting the equipment to be used, such as engines, propellers, the basic structure of the UAV body, and sensors, such as Global Positioning System (GPS), Inertial Measurement Unit (IMU), Electronic Speed Control (ESC), etc. Subsequently, the components are assembled and calibrated, and

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the control verification is carried out. The main objectives of this paper are as follows.

- Implementing an open control hardware platform to allow a more flexible adaptation of the UAV to different applications.
- Integrating additional resources, such as cameras and onboard computers, into the UAV to give it new functionalities.
- Analysis and validation of the system through simulations via Robot Operating System (ROS), before practical implementation.

2. MATERIALS AND METHODS

Figure 1 presents a detailed view of the components that make up the drone, offering a comprehensive understanding of its architecture and functionalities.

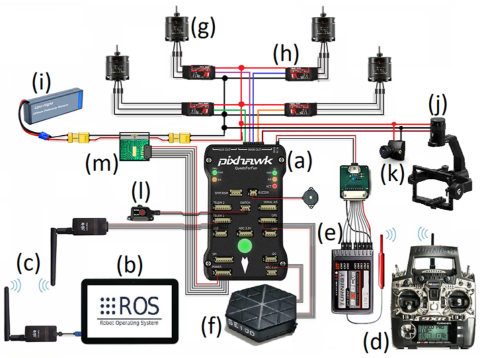

Figure 1. Diagram of the drone built, as in Ramos et al. (2022a). (a) PixHawk Px4 FCU; (b) Base station running the ROS; (c) MavLink telemetry radio; (d) Turnigy 9XR radio; (e) RC receiver; (f) SE100 GPS module; (g) [4x] Sunnysky 720 kV brushless motor; (h) [4x] Hobbywing 40 A Electronic Speed Controller; (i) Tattu 4-cell 5200 mAh LiPo battery; (j) Camera gimbal; (k) Eachine TX03 NTSC FPV Camera; (l) Safety switch; (m) Current sensor.

Below is an analysis of the data presented in the figure:

(a) PixHawk Px4 Flight Control Unit (FCU): this is the drone's brain, being responsible for the control and stabilization of the flight. It is a fundamental component that ensures safety and stability during aerial operations.

(b) Base station running the ROS: the base station provides a robust platform for controlling and monitoring the drone. ROS is a flexible framework widely used in robotics Cheng et al. (2020), supporting various operations and interactions.

(c) MavLink Telemetry Radio: this radio establishes a two-way communication between the drone and the base station, and enables the transmission of essential data, such as flight status, positioning, and other information.

(d) Turnigy 9XR Radio: the remote control device that is used to operate the drone. It allows the operator to send precise commands to the drone, including direction, altitude, and speed.

(e) RC Receiver: this component receives signals from the remote control, and transmits them to the PixHawk Px4 FCU, ensuring an immediate response to operator commands.

(f) SE100 GPS Module: this module provides geographic position data, which allows the drone to locate itself accurately. This is essential for autonomous navigation, route planning, and other location-related applications.

(g) [4x] Sunnysky brushless motor: these four motors provide the power needed for the drone to fly. These engines are energy efficient, and provide reliable performance for various aerial activities.

(h) [4x] Electronic Speed Controller: speed controllers regulate the motors' speed, ensuring a smooth response to command changes while maintaining the drone's stability during flight.

(i) LiPo Battery: this provides the energy necessary to power the drone's motors and other electronic systems, which is important to scale the flight time for each application.

(j) Camera gimbal: this component is a stabilization device that allows the camera to hold its level and stability during flight. This is essential for capturing high-quality images and videos, especially when the drone moves. It was not included in this project once we are only assembling the drone without camera.

(k) Eachine TX03 NTSC FPV Camera: this camera transmits real-time video to the operator, allowing a first-person view of what the drone is capturing. This is useful for in-flight guidance, and for capturing images more accurately. It was not included in this project.

(l) Safety switch: the safety switch is a crucial device that allows the operator to activate or deactivate the drone's systems quickly, ensuring immediate control in emergencies or preventing unauthorized operations.

(m) Current sensor: the current sensor monitors the drone's power consumption, providing accurate data on battery usage. This is essential for flight planning, ensuring the drone returns safely before the battery runs out completely.

One of the main technical challenges of UAV performance is how to manage the energy provided by the batteries, which is a relevant aspect of the construction of UAVs. Batteries are the main power source, and the most used type of battery is lithium-ion. Lithium batteries have high energy density, and enough stored energy to allow UAVs to fly for a useful period. There are different types of lithium-based batteries. However, the lithium polymer cell is the most commonly used due to its lightweight construction and performance. To achieve longer flight times, it is important to ensure that the battery will provide the capacity needed, while maintaining the UAV's maximum take-off weight. The most crucial factor is the battery's C discharge rate. This determines the maximum output of direct current. The discharge rate is a measure of how quickly the battery can release its stored energy to power the motors. For example, if a low C discharge rate is chosen, the UAV will not be able to release current quickly enough to power the motors, and the battery might be damaged. The maximum output of the battery's direct

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current is calculated by

$$A = A_h \cdot C, \tag{1}$$

where A is the maximum direct amperage, A_h is the battery capacity, and C is the discharge rate. For example, a battery with a capacity of 5100 mAh and a 10 C rate has a total continuous output of 51 A. Hence, if the amperage of the motors is at the maximum thrust of 10 A, the total amperage consumed by a quadcopter (i.e., its four motors) is about 40 A. Other equipment, such as the flight controller, will consume only a few milliamps in total. In this sense, we assume the addition of 1 A as a safety margin to our project. The battery performs well in this configuration, and there is still the possibility of an even lower discharge rate parameter if a lighter battery is desired.

Another factor is the voltage of the UAV. For example, high-voltage batteries cause motors to produce more speed, and then more energy for the engine. On the other hand, these batteries are heavier as they contain more cells. This implies a trade-off, as it is important to ensure that the ESC and other electronic components can withstand the battery voltage. The battery used here is the 4S LiPo 10400 mAh 45 C. This notation is described as follows, 4S means that there are four cells in series and none in parallel; Each cell has a capacity of 10400 mAh; 45 C means that the battery can be discharged at a rate of 45 times its 3.3 Amp Hour capacity.

Before choosing specific components, many questions arise. The main task before selecting the elements that will be part of the UAV assembly is to carry out a project based on the choice of battery capacity, flight time, and engine capacity. Thus, it is possible to know whether the robot will achieve flight. In this way, a research is carried out on the methodology for choosing components, and an online calculator[1] is used. Figure 2 presents additional data obtained through battery selection, engine energy efficiency, maximum engine use, hover scenario, and general multi-rotor information. This data complements the information shown in the previous figure, offering a more comprehensive view of the drone's characteristics. Figure 2 also includes further details about the battery used, engine performance during hovering, maximum power usage, and total multi-rotor data.

It is worth to mention that an extra weight of 100 g is taken into account for the calculations. As the UAV is intended to be expandable, this additional weight represents future components that could be assembled in it. Additionally, it is crucial to be aware that the calculator can have a margin of error of approximately 15%. Therefore, when carrying out practical tests, it is possible that the data obtained may not correspond exactly to the calculated values, highlighting the importance of carrying out realistic checks to ensure adequate UAV performance.

In addition to providing quantitative data, the online calculator also delivers two graphics: (i) one that estimates the drone's range, and (ii) other that shows characteristics of the engine. Figure 3 estimates how far the prototype can reach, while considering two situations: with drag, which is realistic, and without drag, which simplifies the model by

(a) Battery		**(b) Motor @ Optimal Efficiency**		**(c) Motor @ Maximum**	
Charge	6.29 C	Current	11.05 A	Current	15.98 A
Voltage	7.63 V	Voltage	7.64 V	Voltage	7.54 V
Nominal Voltage	7.40 V	Revolutions	8870 rpm	Revolutions	8447 rpm
Energy	76.96 Wh	Electrical Power	84.4 W	Electrical Power	120.5 W
Total Capacity	10400 mAh	Mechanical Power	72.8 W	Mechanical Power	102.8 W
Used Capacity	8840 mAh	Efficiency	86.3 %	Power-Weight Ratio	116.3 W/kg
Minimum Flight Time	8.1 min			Efficiency	85.3 %
Varied Flight Time	12.1 min			Estimated Temperature	32 °C
Hover Flight Time	13.7 min			**Wattmeter Readings**	
Weight	440 g			Current	63.92 A
(d) Motor @ Hover		**(e) Totals**		Voltage	7.63 V
Current	9.29 A	Component Weight	928 g	Power	487.7 W
Voltage	7.65 V	Thrust-Weight Ratio	1.4:1		
Revolutions	6293 rpm	Hover Current	37.15 A		
Acceleration (log)	66 %	Hover Power (input)	291.4 W		
Acceleration (linear)	74 %	Hover Power (output)	239.8 W		
Electrical Power	71.2 W	Hover Efficiency	82.3 %		
Mechanical Power	59.9 W	Max Current	63.92 A		
Power-Weight Ratio	155.0 W/kg	Max Power (input)	501.5 W		
Efficiency	84.2 %	Max Power (output)	411.2 W		
Estimated Temperature	29 °C	Max Efficiency	82.0 %		
Thrust	6.60 g/W				

Figure 2. UAV design data. (a) the battery. (b) Engine – efficiency. (c) Engine – Maximum. (d) Engine – Hover. (e) Totals.

removing real variables, such as air resistance, wind gusts. The latter shows the best range that can be achieved. For example, the UAV can reach around 7000 meters in 14 minutes, while increasing its speed by about 40 km/h. The graphic in Figure 4 refers to the engine characteristics. It includes, for example, its efficiency, maximum revolutions given a particular drop, evolution of the temperature of the engine shell. These consider that the engine has around 80% efficiency.

3. RESULTS AND DISCUSSION

3.1 *Construction and associated costs*

Figure 5 shows the quadrotor UAV developed in this research project. These images show the quadcopter completely assembled with the previously mentioned parts and equipment. The calibration phase was conducted with precision, including precise configuration of sensors, tuning of controllers, and other fundamental adjustments to optimize aircraft performance. These calibrations confirmed the drone's ability to respond to flight commands in a controlled and precise manner. Additionally, flight tests were carried out. The components selected for this project and their respective price during March 2023 are indicated in Table 1. This table does not consider engineering work or the finishing of equipment assembly.

Table 2 compares the drone built in this project with the same class of commercial drones. This comparison considered the operation and characteristics of the flights. The models were chosen on the manufacturer's website, and delivery costs are not included.

It is possible to observe that the prices of commercial drones vary greatly depending on the features available in each piece of equipment. For comparison with the prototype developed in this work, we chose two DJI Phantoms that are easily found on the market and widely used in robotic applications.

[1] http://ecalc.ch

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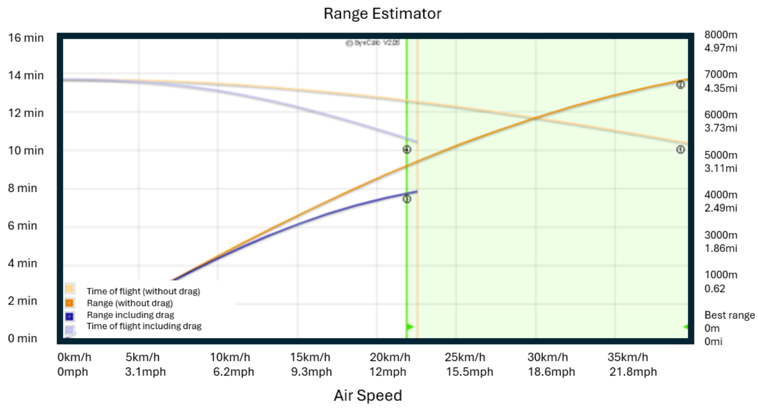

Figure 3. Range graphic.

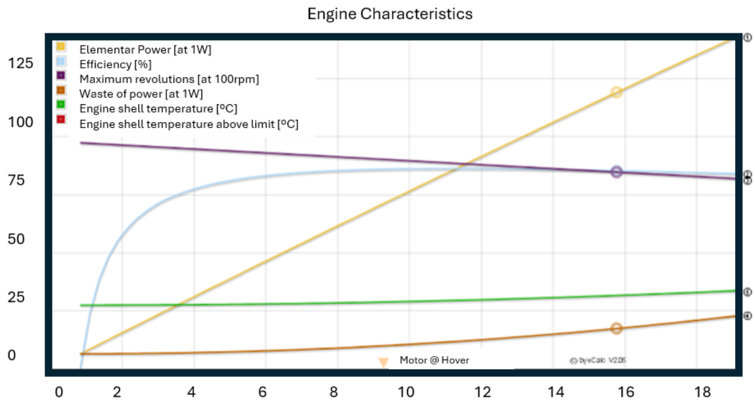

Figure 4. Engine characteristics.

Figure 5. Assembled Drone (Front Perspective).

Table 1. Component Price

Component	Quantity	Unity Price (R$)	Total Price (R$)
Base	1	175.00	175.00
UFC	1	304.81	304.81
Battery	1	648.95	648.95
ESC	4	105.03	420.12
Motor	4	249.00	996.00
GPS	1	435.00	435.00
Microcontroller FCU PX4 2.4.8	1	304.81	304.81
Radio	1	1,203.94	1,203.94
Propeller	4	24.23	96.90
Cost (total)			4,585.53

Table 2. Comparison between the assembled drone and commercial drones

UAV	FCU	Battery (mAh)	Weight (grams)	Price (R$)
Project	Pixhawk	10400	2023	4,585.53
Dji Phantom 4 Advanced	DJi Naza	6000	1368	15,500.00
Dji Phantom 3 Standard	DJi Naza	4480	1300	5,745.00

3.2 Software in the Loop

This section presents the project's results in the software-in-the-loop (SITL) environment. SITL is a technique that involves testing a system's control software in a computer simulation environment. This offers advantages like saving time and resources, security, ease of repetition, iterative development, evaluating edge cases, and supporting education and training in safe and controlled environments Ramos et al. (2022a) After designing the theoretical prototype, the subsequent stage is assembling the drone by incorporating all the previously mentioned components. Then, all the components are calibrated and integrated using the QGROUNDCONTROL software Meier (2010), preparing it for practical and virtual tests.

The first practical test took place at the CEFET/RJ Campus Maracanã facilities to verify the drone's ability to take off. Then, the SITL technique was used. This method involved using GAZEBO software, an advanced robotics simulator capable of faithfully representing real-world conditions. We can conduct highly accurate and detailed simulations through SITL, allowing complete analysis of the drone's behavior in different scenarios and under other operating conditions. Furthermore, SITL enabled the evaluation of new control algorithms in a virtual environment before practical implementation.

In this way, the tests on the loop software played a fundamental role in obtaining relevant results, validating the drone's functionalities, and providing valuable insights for future project improvements. With all parameters loaded, the simulation is carried out in QGROUNDCONTROL. The same was done by sending coordinates for the drone to follow a certain path. However, taking a route manually using a USB controller is also possible. Figure 6 shows the graphical representation of a route defined and delimited in this software.

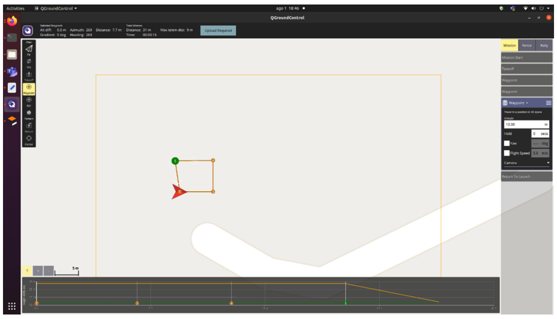

Figure 6. Delimited route in QGROUNDCONTROL software.

Along the route, flight data is recorded on the drone's PIXHAWK flight controller, whether during simulations or operations in the physical world. These records are stored in .ulg format. To view the corresponding graphics, access the website https://logs.px4.io/ and upload the file to extract the graphic information. The virtual test site is CEFET-RJ shown in Figure 7.

Figure 7. Test location.

The purple square in Figure 7 represents the drone's route, previously delimited in the QGROUNDCONTROL software. It is important to highlight that, after completing the test, the results obtained were satisfactory and aligned with the project objectives. The drone managed to follow the route precisely. This result indicates the success of the strategies adopted during the development and validation of the drone, contributing significantly to the proof of its viability and functionality. The resulting graphics can be seen in Figure 8. As mentioned, the test was conducted at the CEFET Campus Maracanã facilities.

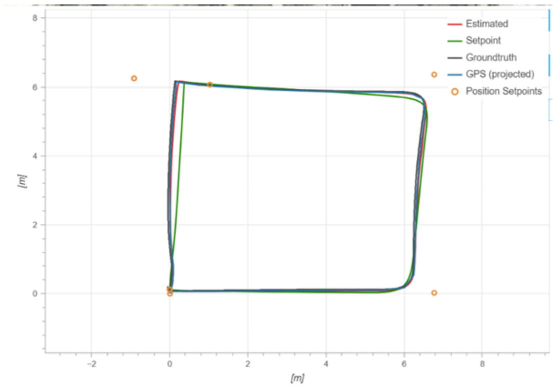

Figure 8. The route taken by the UAV at SITL.

4. INTEGRATION OF THE QUADRIROTOR IN ELECTRONICS ENGINEERING EDUCATION

The successful construction of the quadcopter-type UAV in this project opens up exciting opportunities for its integration into the Electronics Engineering curriculum at CEFET-RJ. This section explores the potential utilization of the drone as a practical teaching tool in various subjects, fostering hands-on learning experiences for students.

- Control Systems: In control systems, the drone can be a tangible platform for students to implement and test theoretical concepts. PID controllers, stability analysis, and real-time systems can be practically demonstrated. Students can experiment with different control algorithms and observe their impact on the drone's flight behavior, providing valuable insights into the complexities of real-world control systems.
- Electronics: The drone's modular design allows students to delve into hardware integration and design aspects. They can explore the selection and integration of electronic components, understanding how each element contributes to the overall functionality of the UAV. Practical exercises involving the selection of sensors, motors, and communication modules provide students with hands-on experience in designing and assembling complex electronic systems.
- Embedded Systems and Programming: With its PixHawk Px4 Flight Control Unit, the drone becomes an excellent platform for studying embedded systems and programming. Students can delve into the programming of microcontrollers, communication protocols, and the integration of various sensors. The drone's open control hardware platform enables flexibility in adapting to different applications, allowing students to explore the versatility of embedded systems in real-world scenarios.

Table 3 is an example that serves as a guide to the disciplines, corresponding drone practices, and the knowledge acquired through these interactive learning experiences. It showcases the transformative potential of integrating UAV technology into the educational curriculum.

Table 3. Integration of Drone into Engineering Curriculum.

Disciplines	**Practices**	**Knowledge Acquired**
Control Systems	Implement and test theoretical concepts of PID controllers, stability, and real-time systems using drones as a tangible platform.	Practical observation of the impact of different control algorithms on the drone's flight behavior. Understanding the complexities of real-world control systems.
Electronics	Explore the selection and integration of electronic components, including sensors, motors, and communication modules. Perform practical exercises in hardware selection.	Hands-on experience in designing and assembling complex electronic systems. Understanding the role of each component in the overall functionality of the UAV.
Embedded Systems and Programming	Study embedded systems and programming using the drone's PixHawk Px4 Flight Control Unit. Program microcontrollers, communication protocols, and sensor integration.	Explore the versatility of embedded systems in real-world scenarios. Acquire practical skills in embedded systems programming.

5. CONCLUSIONS AND FUTURE WORK

This work presented the entire construction process of a quadcopter-type UAV developed during scientific initiation research. One of the main challenges in designing a UAV was balancing various components, such as the number of engines, frame configuration, propellers, motors, and battery, to achieve optimal performance. The importance of selecting the appropriate number of engines based on the expected payload was emphasized, considering the balance between efficiency, cost, and system complexity. A critical path to be considered for future work involves optimizing control algorithms to improve flight stability and efficiency. This requires research into advanced control techniques and precise adjustments.

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