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A Base Model Architecture System for CubeSat Development

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Abstract

The article discusses the evolution of CubeSats from educational tools to versatile platforms for real missions. It emphasizes the importance of developing a robust general embedded system model to facilitate adaptable satellite designs for various applications. Thus, this work aims to present a system architecture structure to achieve this goal through the implementation of seven main systems - the Energy Power System, On-Board Data Handling, Attitude and Orbit Control System, Telemetry, Tracking, and Command, Thermal Control System, Structural Design, and Payload System -, as a partial result of the development of the Tupã CubeSat, a 2U academic satellite designed to collect lightning data using computational vision. Furthermore, this work intends to contribute to the discussion about CubeSats as educational tools, providing resources to students implementing high-level projects ready for real-world application.

1 Introduction

Although real world mission using CubeSats have been popularized [1] [2], the cubic satellites still play a significant role as educational tools, the goal they were initially introduced to achieve [3]. The limited size of CubeSats encourages the optimization and evolution of the equipment used, which promotes advances in various areas of the electronics, materials and energy efficiency industries [4].

Academic competitions, where students are encourage to work on solutions for certain aerospace problems, contributing to their professional formation, can act as an introduction to specific technology and first contact to the a development of solutions up to real-world problems.

For academic satellites, development is often focused directly on the overall project and not on system development, which is restricted to a single functionality. Even though a multi-mission platform have been recently presented for CubeSats that can receive a wide variety of payloads [5], this working methodology is more discussed in industry [6].

Aiming to meet all the survival requirements of a space system in a single platform, regardless of the type of orbit, pointing, power generation, thermal control, data management and telecommunication services, but also meet the competition criteria and mission requirements of CubeDesign, a student competition organized by the National Institute for Space Research (INPE) [7], Supernova, academic rocket and satellite team of Federal University of Juiz de Fora, developed Tupã, a student 2C CubeSat for lightning assessment

Considering that a CubeSat could have both educational and real-world application, and that in an academic competition team scenario a periodic renewals of members could affect project development overtime, it is useful to establish an adaptable satellite design for different missions. In this sense, the multi-mission platform was idealized.

Then, article aims to propose a methodology, based on a novel multi-mission platform, for the development of CubeSat satellites in academia, developing a robust general embedded system model. The paper is divided as follows: Section 2 shows how the project was organized and designed to be developed in a modular way to meet the project requirements. Section 3 reports the results of Tupã. Section 4 presents the experience acquired with the project and the proposed improvements that have been identified for the next version.

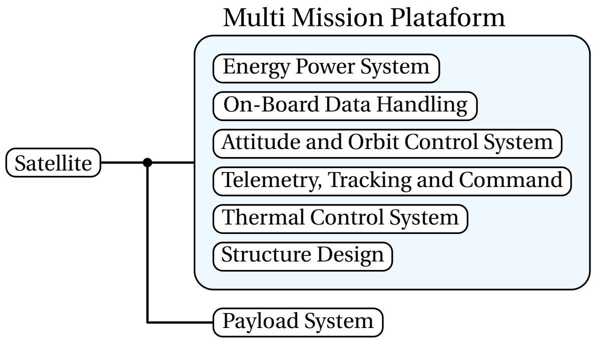

Figure 1: Architecture of Satellite with Multi-Mission Platform.

2 Architecture System Base Model

Due to this objective, some systems are requirable to achieve this goal, as: On-Board Data Handling (OBDH), Telemetry, Tracking, and Command (TTC), Energy Power System (EPS), Thermal Control System (TCS), Attitude and Orbit Control System (AOCS) and Structural Design (SD). Some requirements are necessary to be extremely refined due the type of the CubeSat's orbit, as an example, there is the Attitude and Orbit Control System (AOCS) system that is capable of control the attitude of the satellite.

The Fig. 1 illustrates the proposal for a satellite using a multi-mission platform, in which the combination of the subsystems Energy Power System (EPS), On-Board Data Handling (OBDH), AOCS, Telemetry, Tracking, and Command (TTC), Thermal Control System (TCS) and Structural Design (SD) represent the multi-mission platform and the Payload represents the system responsible for the satellite's functionality and purpose.

In this scenario, the multi-mission platform there are to be presented is related to development of all the systems of Tupã, in the next subsections all of the subsystems and project requirements will be separately discussed. The payload subsection is amply discussed as a result of this work, as it is the core of the platform introduced.

2.1 Energy Power System

The Electrical Power System is responsible for the generation, storage, regulation and distribution of electrical power to all of the Cubesat subsystems. The EPS block diagram describes the functionalities of the EPS, exposed at Fig.2. The functions are delimited by the requirements established in Concept Operations System (CONOPS), such as the satellites dimensions, orbit and adequacy for launch vehicles. With this information it is possible to define the Mission and Design Requirements, which define the operational requirements for the system.

Energy generation is limited by the size of the satellite, as it imposes a limit on the number of photovoltaic cells the project can use. The pointing of the satellite is also an important point to consider in generation calculations, as is the orbit to define the times of sunlight, when the satellite receives sunlight, and eclipse, when the satellite does not receive sunlight.

Storage is crucial for times when the satellite is in eclipse, as it is responsible for powering the subsystems during this period. It is usually done using batteries, which can be Li-ion, for example. The battery cells can be grouped in series or parallel, depending on the voltage and current required to power the system.

Power Regulation consists of supplying the correct voltage level to the equipments. To do this, DC-DC converters are used and buses

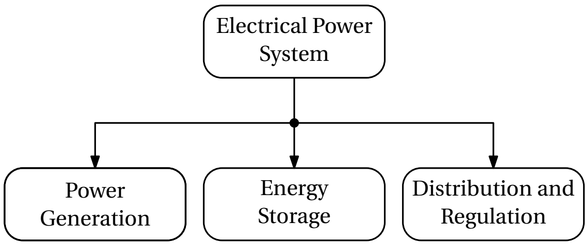

Figure 2: Power Subsystem Architecture.

are established to supply the voltage levels set by each subsystem. A direct-energy-transfer (DET) is used if the power provided by the solar panels does not need to be controlled. A peak-power-traker (PPT) can be used to control the power supplied by the solar panels. The system adopted in this project uses PPT. Finally, distribution takes the energy to the subsystem equipment[8].

EPS requirements are defined in the base model:

- Bus supply voltage of 3.3V , 5V and 12V.
- Maximum DoD of 20%.
- Battery life of at least 5 hours, operating in communication mode.
- Removed before flight required.
- Solar panels required

"Depth-of-Discharge (DoD) is simply the percent of total battery capacity removed during a discharge period" [8]. Keeping the DoD low is essential to preserve the health of the batteries and the life of the satellite [9].

The first version of the project uses a body mounted array, cells that are affixed to the body of the satellite and not deployed panel. The panels have an effective area of 0.3 m^2 and generate an average of 6.5W. The battery

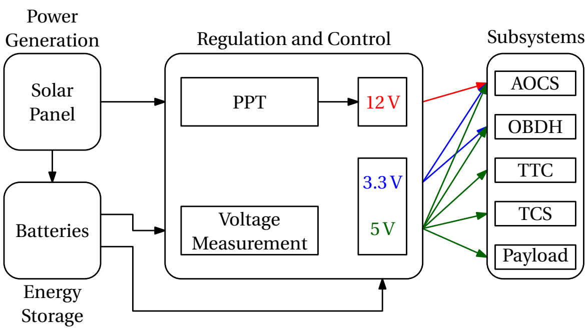

Figure 3: EPS General Diagram.

pack consists of three cells connected in series and provides an average voltage of 12V and 2450 mAh.

Distribution is achieved using PC104 connectors to supply power to the subsystems. Two regulated buses are used, with 3.3V and 5V, and an unregulated 12V bus. The system is grounded to the satellite structure at a single point [10]. The 3 shows the general diagram of the EPS, with the flow of energy and equipment at each stage.

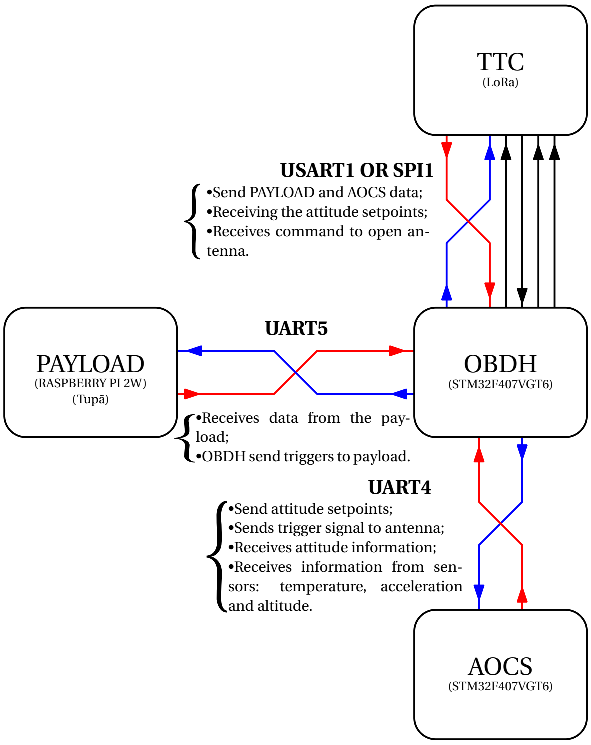

Figure 4: On-Board Data Handling's communications and connections diagram.

2.2 On-Board Data Handling

The OBDH is the subsystem responsible for handling all the data generated and received by the satellite, and its tasks are to process, encode, verify, store and make the data available for transmission to the ground station or for internal communicate with other subsystems in spacecraft. In general, the OBDH can be characterized as the brain of the multi-mission platform [8].

In this project, the OBDH was designed to be not only the brain, but also the bridge between all the systems. Through the OBDH, information from all systems is centralized and available as needed.

The Fig. 4 illustrates the connections and communications of the OBDH. The OBDH communicates with the AOCS subsystem via a Universal Asynchronous Receiver/Transmitter (UART) interface, where the pointing setpoints and the trigger to generate the antenna deploy signal, and the attitude information and data from all the sensors are received.

For the Tupã project, the OBDH receives the data from the payload and sends a trigger to start the operation via UART protocol. In addition, this subsystem communicates with the TTC via UART or SPI communication, depending on the frequency at which you want to send the data to a ground station.

2.3 Attitude and Orbit Control System

On larger satellites, the AOCS is the system responsible for pointing and controlling the satellite's trajectory. This requires various sensors, such as a star tracker - a sensor to determine the satellite's orientation - a sun sensor - a sensor to detect the direction of the sun - an Inertial Measurement Unit (IMU) to measure the satellite's pointing and angular velocity, among others. In addition, actuators are also needed, such as reaction wheels or control moment gyros to rotate the satellite and point it at the desired point, at many others.[11].

For the design of the multi-mission platform, due to size and power limitations in CubeSats, some components present in conventional satellites were suppressed - a common occurrence in smallsats. As such, the AOCS was designed to contain a temperature sensor (BMP-280 barometer), which will be used to take temperature measurements inside the satellite, communicating with the AOCS via a UART interface. An IMU is connected to the AOCS via an SPI interface, and its data and measurements will be used to point the satellite.

A servo motor will be used to deploy the antenna, which will be interfaced with the AOCS via a Pulse Width Modulation (PWM) output. In addition, analog outputs and PWM signals will be needed to act on the power electronics responsible for driving the reaction wheels. The AOCS board is designed to be able to control up to three reaction wheels.

Furthermore, as this is an academic project with a focus on learning, the platform has an Global Positioning System (GPS), to help locate the satellite in the event of a suborbital rocket launch.

In terms of communication, the AOCS is designed to communicate with the OBDH subsystem via the UART communication protocol. In this communication channel, the AOCS sends all the attitude and location data, and receives the respective setpoints and trigger to deploy the antenna.

In Fig. 5, the connections between the AOCS and the aforementioned sensors and the other subsystem are shown, as well as the communication protocols and components used.

2.4 Telemetry, Tracking, and Command

The TTC subsystem is responsible for the communication interface between the satellite and the base station. Its main operations are command reception and detection, telemetry modulation and transmission, as well as subsystem operation and control. In order to project the TTC subsystem, three parts of the satellite design must be considered [8]:

- **requirements**: capacity (channels and bandwidth), coverage area, signal strength, connectivity (direct links, crosslinks etc), avaiability (link times per period) and mission lifetime.
- **constraints**: limits of the subsystem such as power, size and mass available budget, both dependent on mission design and the launch vehicle.
- **regulations**: international law and regulations regulate specially frequencies, power flux density on surface etc. The main regulatory agency is the International Telecommunications Union (ITU).

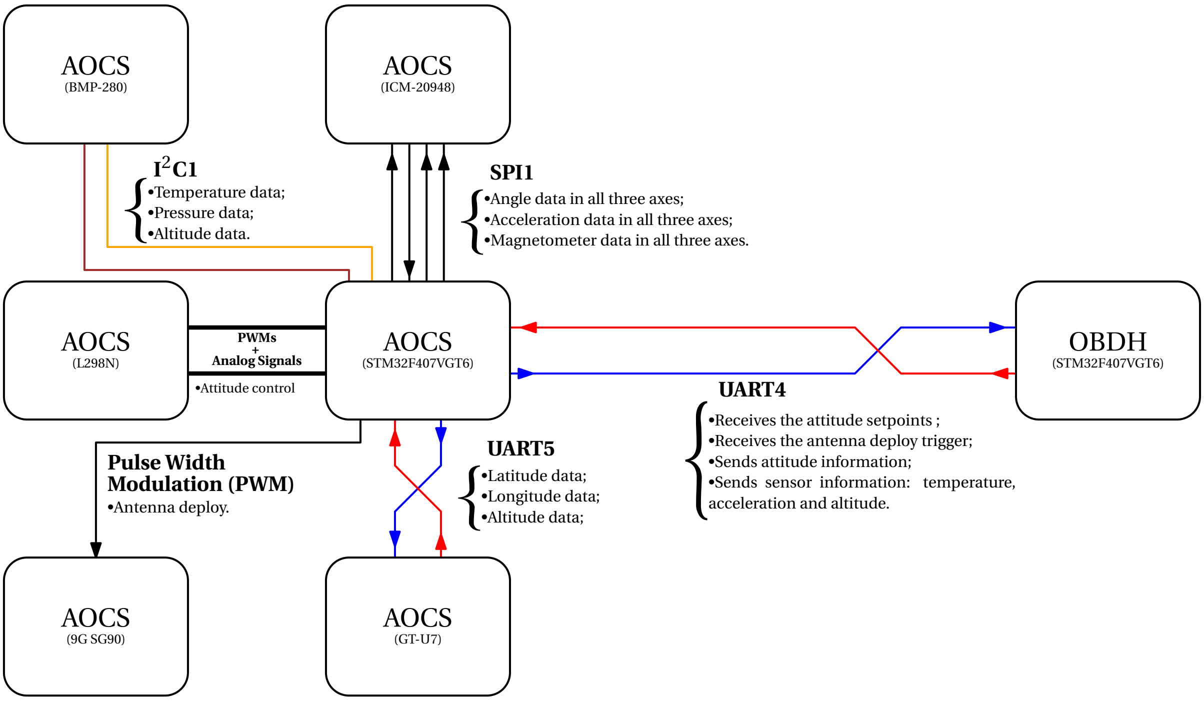

Figure 5: Attitude and Orbit Control System's communications and connections diagram.

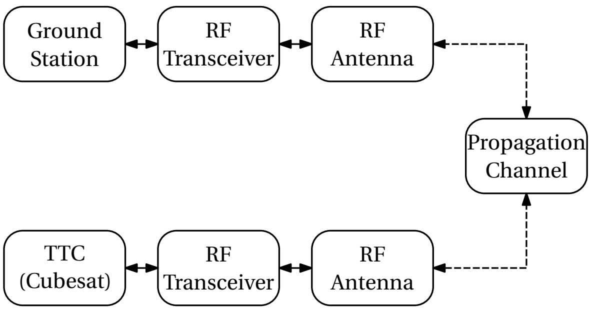

Figure 6: Simplified diagram of the communication interface.

In terms of the ground-satellite communication, all operations go through the TTC subsystem communication interface, which can be summarized in Ground Station, Ground Transceiver, Propagation Channel, Cubesat Transceiver and Cubesat TTC subsystem.

As shown in the Fig. 6, the Ground Station should perform the needed operations over tracking, telemetry, command, control and data processing [12]. The Ground Station is connected to the transceiver, which is determined by requirements including power, frequency, bandwidth and data rate. Typically, a low noise amplifier is used between Tranceiver and Antenna to amplify and also filter the signal. Amplifiers should have high efficiency as well as the antennas, which must also have high gains. Initially, the propagation channel can be modeled by the attenuation in free space. It is given by the following equation

$$A_{FS}(dB) = 92.44 + 20\log_{10}(f_{GHz}) + 20\log_{10}(d_{km}) \quad (1)$$

where f_{GHz} is the frequency in gigahertz and d_{km} the distance in kilometers. The relationship (1) is plotted in Fig. 7 for the frequency

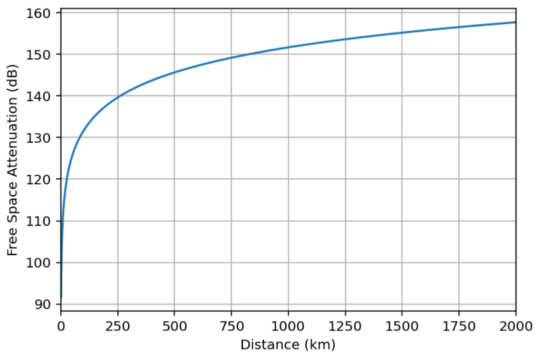

Figure 7: Attenuation in free space with distance

of 915 MHz and a distance of up to 2000 km.

However, total losses should include losses in the atmosphere, cables, equipment, thermal noise, polarization and pointing. As for the TTC subsystem in Cubesat, it consists of a properly designed antenna, a radio frequency transceiver, capable of receiving and sending telemetry and telecommands, connected to the OBDH subsystem as shown in Fig. 4. For the Tupã project, the TTC receives data from the OBDH Microcontroller Unit (MCU). The data packet, on the main transceiver, is transmitted by UART to the LoRa transceiver, chosen at 915 MHz, since attenuation will be lower the lower the transmission frequency. This was the lowest unlicensed frequency that meets the bandwidth and data rate requirements is desired. The power received on one side of the link can be calculated from the (2) below, derived from the Friis formula [13]

$$P_R = P_T + G_T - A_{Total} + G_R, \qquad (2)$$

where P_R is the received power, P_T the transmitted power, G_T the transmission gain, G_R the reception gain and A_{Total} is the total attenuation which includes attenuation in free space given by (1), plus other attenuations mentioned above.

2.5 Thermal Control System

The thermal control subsystem in CubeSats ensures components remain within safe operational temperatures throughout the mission, protecting against extreme space temperature variations. Key heat sources include direct solar radiation, infrared radiation from Earth, and heat generated by onboard electronics.

Effective thermal control requires understanding the space environment, selecting appropriate materials and integrating the system efficiently into the satellite's structure. Proper satellite orientation can also reduce direct solar exposure to sensitive components. Thermal control can be passive or active, depending on the project requirements and specifics [14].

The integration of resistors in Tupã power supply must respect the voltage and current parameters to avoid overloads. In addition, to maximize the efficiency of thermal dissipation and ensure that the system operates within safe thermal limits, a mini-cooler is added. It actively removes heat from the resistors and the metal surface, improving heat transfer and contributing to the overall thermal control of the CubeSat.

This approach not only helps manage heat generated by electronic components but in the future can also be combined with passive systems, like heat sinks, to create a hybrid solution. This balances thermal efficiency, energy consumption, and cost considerations.

CubeSats face unique challenges due to their size, requiring careful planning and optimization of heat distribution. In long-duration missions, material degradation and space radiation can impact thermal control, underscoring the

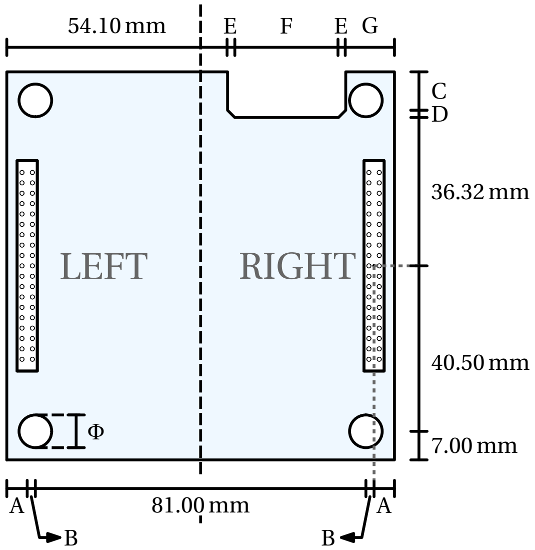

Figure 8: Circuit board with dimensions.

Table 1: Structure board dimensions.

Label	Dimension	Label	Dimension	Label	Dimension
A	5.00 mm	D	1.78 mm	G	11.94 mm
B	2.00 mm	E	1.78 mm	Φ	5.00 mm
C	9.40 mm	F	25.40 mm		

importance of durable and reliable solutions for future projects.

2.6 Structural Design

As one may imply, CubeSats have a cubic format. More the one cube can be used in a CubeSat project, and, in fact, those cubes can be rearranged in order to fit better the application planned. Fixed combinations have been imposed, which leads to fixed volumes and size limits for CubeSat projects [15].

Unlike the volume, depending on the mission conducted, some structure adaptation may have to take place. As for Tupã, one of the mission requirements was the deployment of an antenna, which had to be taken into account for the the design. Moreover, the choice for components of the other subsystems also consider the internal arrangement of the components, such as the boards, which dimensions are shown in Fig. 8. The sizes referenced in the figure are shown in the Table 1.

2.7 Payload System

The Payload subsystem is defined as the equipment inserted into the spacecraft that acts directly on the mission objective. In short, the payload is the main reason why the mission was developed, and directs the entire development of the project in terms of size, costs and risks [8]. CubeSats can be applied to accomplished a series of different missions.

The payload acts as a simple mission executor, without the need to supply information or act in such a way as to maintain the spacecraft's survival. Furthermore, this platform also makes it easier and quicker to modify existing satellites as well as makes it maintenance and changes. The Independence of the payload system is shown on the architecture system diagram, shown in Figure 4.

Payload can be developed separately from the other systems or even completely changed, as long as the systems compatibility includes the communication protocol, discussed at Subsection 2.2, but the others relations between the systems. As for the structure, for example, as previously stated CubeSats have fixed dimensions, so the payload system have to able to properly assemble in this volume, as well as be supplied with enough energy to successfully achieve the mission.

3 Results

Tupã is a satellite developed by members of the Supernova competition team, from the Universidade Federal de Juiz de Fora, for the Cube Design competition, hosted by Instituto Nacional de Pesquisas Espaciais (INPE). The development of this satellite achieved interesting results that will have a strong impact on the team's future projects.

For hardware development, a methodology achive the use of reusable schematic sheets, so that each page corresponds to a micro-functionality, such as a sensor, a signal conditioning circuit, a dc-dc converter and other similar things. These schematic sheets have inputs and outputs and follow a hierarchy of systems, to be used later on. After that, each subsystem represents a part of a printed circuit board or even a entire printed circuit board.

As for firmware development, the whole multi-mission platform was programmed in C language, the standard for developing embedded systems, it does not have native support for classes. Thus, the concept of object orientation was implemented using structs and functions to simulate behavior similar to a class. In this way, structs and functions were made separeted for a micro-funcionality in such a way that it can be reused in various codes and projects. An example of that is a PID controller, where we have a struct to store the parameters of controller and function to perform the mathematical calculation.

The Fig. 9 shows the hardware result obtained. From top to bottom, the first board is the payload board, which will be presented in the next subsection. The second board contains the EPS regulation and distribution part. The third contains the entire OBDH and TTC system, and the fourth contains all the AOCS components.

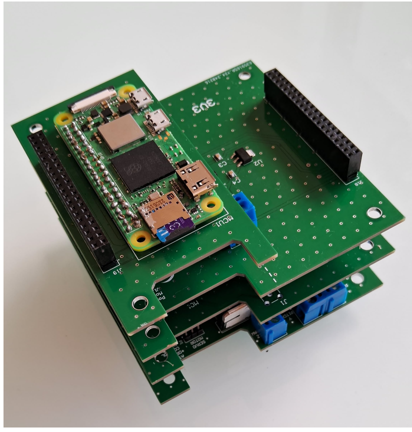

Figure 9: Printed Circuit Boards to subsystems.

This methodology makes it easier to update and create new projects, as it modularizes the entire development. In addition, this modularization facilitates testing, since it makes it possible to manufacture electronic circuits for bench testing of each module, so that each part of the circuit can be tested separately.

Another benefit of using this methodology is the ease of maintaining knowledge, since modularization separates the entire project into smaller portions, making it easily understandable to personnel who were not present at the initial scope of the project, a fact that is very relevant to the competition team scenario, which suffers from the constant renewal of members.

3.1 Tupã - initial results

The main mission of Tupã is lightning detection through imaging, processing two distinct scenarios, and transmitting telemetry as instructed via telecommand. The first inte-

Figure 10: Tupã first integration test.

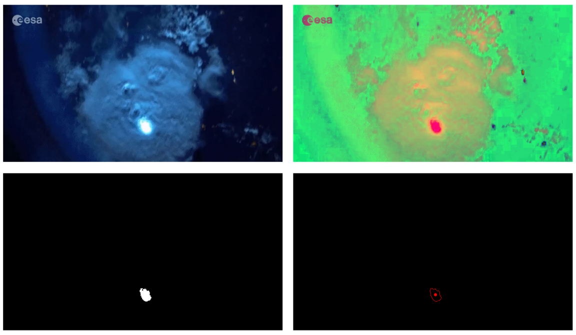

Figure 11: Output images.

gration test of Tupã is being shown in Figure 10.

The payload architecture described applies a Raspberry Pi Zero 2W Single-Board Computer (SBC) and a 5MP camera for lightning detection via computer vision, using a Python developed code using OpenCV. The Figure 11 shows a sequence of images that are outputs of each process carried-out by the code, responsible to provide information regarding the are affected by a lightning, such as its centroid.

The embedded Wi-Fi and Bluetooth connectivity of the Raspberry Pi Zero 2W, although not used in this project, offers opportunities for future missions requiring satellite-to-satellite communication or more efficient data transfer to ground stations. Additionally, the use of the OpenCV library for image processing makes the solution highly scalable, enabling the implementation of more complex algorithms, such as those based on machine learning. The camera can be used for environmental monitoring, Earth imaging, or astronomical studies. The Raspberry Pi Zero 2W, in turn, can be configured to process different types of collected data, such as vegetation analysis, atmospheric pollution monitoring, or climatic phenomena. The combination of accessible, lightweight, and low-power consumption components is highly versatile and adaptable to different mission contexts.

4 Conclusion

The modularity and adaptability of the multi-mission platform presented in this work, a robust hardware design foundation for future CubeSat missions that require visual data capture and processing originated from the development of Tupã, saves time and resources in developing new solutions, while also enhance the efficiency of future missions.

The integration and communication between the subsystems has already been tested and validated. The next step is to carry out environmental tests, studying electromagnetic compatibility, structural stability and simulating the space environment (Thermovacuum Test). With these advances, the team is validating a system for operation in low orbit.

Furthermore, this work intends to contribute to the discussion about CubeSats as educational tools, providing resources to students implementing high-level projects ready for real-world application. In an academic competition team scenario, where there are periodic renewals of members, the platform can be used a way to facilitate knowledge maintenance management. The authors hope that this work can be helpful in this context, committing to improve where the CubeSats first started.

References

[1] K. Sano, T. Nakagawa, S. Matsuura, K. Takimoto, A. Takahashi, T. Fuse, R. Cordova, V. Schulz, P. Lepcha, N. Örger, and Others, "Astronomical 6u cubesat mission vertecs: Scientific objective and project status," in *Space Telescopes And Instrumentation 2024: Optical, Infrared, And Millimeter Wave*, vol. 13092, 2024, pp. 214–224.

[2] J. Colosimo, D. Fox, A. Falcone, D. Palmer, F. Hancock, M. Betts, W. Bevidas, J. Buffington, D. Burrows, Z. Catlin, and Others, "Expected gamma-ray burst detection rates and redshift distributions for the blackcat cubesat mission," *The Astrophysical Journal*, vol. 969, p. 138, 2024.

[3] M. Rycroft and N. Crosby, *Smaller Satellites: Bigger Business?: Concepts, Applications and Markets for Micro/-Nanosatellites in a New Information World*. Springer Science & Business Media, 2013.

[4] Nasa, "State-of-the-art of small spacecraft technology," https://www.nasa.gov/wp-content/uploads/2024/03/soa-2023.pdf?emrc=8ad1a1, accessed on: September 1, 2024.

[5] J. M. L. Degrave, "Plataforma multi-missão para nanossatélites cubesat," Undergraduate Thesis, Universidade Federal do Rio de Janeiro, 2021, bachelor of Electronics and Computer Engineering.

[6] I. N. de Pesquisas Espaciais (INPE), "Plataforma multi-missão (pmm)," https://www.lit.inpe.br/pt-br/pmm_plataforma_multi_missao, accessed on: September 1, 2024.

[7] I. N. de Pesquisas Espaciais (INPE), "Cubedesign presencial 2024," https://www.gov.br/inpe/pt-br/eventos/cubedesign/2024/, accessed on: September 1, 2024.

[8] W. J. Larson and J. R. Wertz, *Space Mission Analysis and Design*. USDOE, 1992.

[9] R. N. M. Macambira, "Otimização do consumo de energia em uma rede de satélites de baixa órbita em cenários de alta vazão," Ph.D. dissertation, Universidade Federal do Amazonas/Programa de Pós Graduação em Engenharia Elétrica, 2021.

[10] M. R. Patel, *Spacecraft Power Systems*. CRC Press, 2004.

[11] Y. Kumar, "Satellite attitude and orbit control system or aocs in a nutshell," www.spacenavigators.com/post/satellite-attitude-and-orbit-control-system-or-aocs-in-a-nutshell, 2023, accessed: 11-Sep-2024.

[12] P. Fortescue, G. Swinerd, and J. Stark, *Spacecraft Systems Engineering*. Wiley, 2011.

[13] C. M. Ho, C. Wang, K. Gritton, and K. S. Angkasa, "Microwave propagation attenuation due to earth's atmosphere and weather at shf band," https://api.semanticscholar.org/CorpusID:128319322, 2004, accessed on: September 1, 2024.

[14] J. Meseguer, I. Pérez-Grande, and A. Sanz-Andrés, *Spacecraft thermal control*. Elsevier, 2012.

[15] T. C. P. C. P. S. University, "Cubesat design specification," https://api.semanticscholar.org/CorpusID:128319322, 2021, accessed on: September 1, 2024.