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Design of a Low-Cost Solar simulator for Cubesats

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Abstract

CubeSats have become a popular satellite-standard choice for space missions due to their versatility and affordability. Despite their widespread use, extensive testing is still necessary to minimize in-orbit failures. In this paper, the design of a solar simulator, primarily for evaluating the energy management of CubeSats, is presented. The simulator consists of a box with LEDs on its internal walls, where a CubeSat is placed inside. By controlling the LEDs, it is possible to emulate the in-orbit conditions in which the CubeSat operates, allowing its power generation capacity to be assessed. Though the tests are conducted under non-space conditions, the controlled environment makes it possible to identify problems in CubeSat's power management, as well as to analyse the operation of its Electric Power System (EPS). The solar simulator can evaluate transient energy generation as well as battery performance by simulating varied orbits. It can also expose the CubeSat to critical scenarios to test its behavior under these conditions. Then, this paper outlines the design of the solar simulator and its components, such as the selection of LEDs and heatsinks. It also presents a preliminary methodology for

controlling LEDs aiming to replicate in-orbit conditions. The solar simulator is currently under development, but it is expected to aid in the design and testing of CubeSats. This includes evaluating individual components like photovoltaic panels and batteries, as well as subsystems such as the EPS, ultimately benefiting the overall design of the space segment.

1 Introduction

CubeSats, which are a category of small satellites commonly referred to as nanosatellites, are distinguished by their compact and modular design. Each CubeSat is based on a standard structure measuring $10 \times 10 \times 10$ cm, known as a "U." This standardized unit allows for flexibility in satellite design, as multiple units can be combined to create larger CubeSats, making them a versatile option for a wide range of space missions and applications, as can be seen in Figure 1.

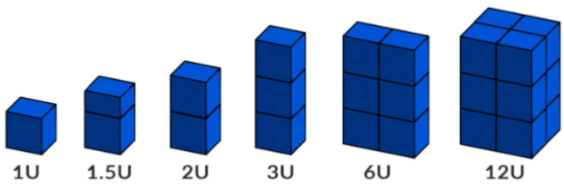

Figure 1: CubeSat standard sizes [1]

The development of small satellites, in contrast to the larger and more complex ones, has significantly increased space accessibility to a broader audience. One of the main areas impacted is academia and universities, which, even with less investment, now have the opportunity to conduct research in space.

Many technical difficulties still need to be resolved in developing these missions (e.g., communication, attitude control, and energy management). Therefore, previous studies of the structures are carried out to predict these errors, but one of the main difficulties is still estimating the energy generation in a satellite in orbit. As it is extremely complicated to capture data directly from the battery after the satellite is launched, this makes it difficult to simulate this information without prior testing.

Many institutions have developed sun simulators to analyze power generation from solar panels. One example is the indoor simulator, designed with LEDs to mimic solar irradiation, as described in [2].

This paper focuses on a similar application, placing the CubeSat inside a sun simulator platform to primarily test the functionalities of the Electrical Power System (EPS), simulating a scenario that closely resembles the conditions found in orbit. The idea for creating the box was inspired by [3], where other institutions simulated sunlight in a controlled environment to test photovoltaic cells. This concept was then adapted for use in the space sector. Therefore, the primary goal is to develop a test bench that accommodates a full 2U CubeSat with all its subsystems operational. This setup will allow for testing the functionality of the EPS by powering solar panels with an artificial solar source and evaluating the distribution of the energy throughout the nanosatellite system.

To achieve this goal, it will be necessary to ensure that all subsystems of the CubeSat are integrated and operational during testing. This includes not only the functionality of the power supply system but also the communication between subsystems, thermal management, and the structural stability of the satellite while it operates on the test bench. The test bench must be designed to simulate realistic operating conditions, using artificial solar light sources that emulate the space environment, thereby allowing for an accurate assessment of the CubeSat's performance in future missions.

This work will be organized as follows: the methodology applied by other authors will be adapted and detailed in the Methodology section section 2, where details of each main part will be presented. Further discussions on the project development will be explained in the section Discussion: Trends and Directions section 5, followed by a Conclusion section section 6.

2 Methodology

This section summarizes the articles that served as the foundation for the design of the Sun simulator. The research primarily focused on solar simulators utilizing LEDs as the light source to replicate sunlight, ensuring a more precise and efficient simulation of solar conditions.

The work of [4] developed a large-area solar simulator to study the optical melting and light absorption behavior of molten salts; therefore, it is not dedicated to satellite applications. Seven 1500 W metal halide outdoor stadium lights are used as the light source to simulate concentrating solar power (CSP) heliostat output. The authors suggest that these are far less costly per watt than typical xenon arc lamp solar simulator light sources, while they still match natural sunlight satisfactorily. By using off-the-shelf structural, lighting, and electrical components, the authors kept the fabrication cost below $10,000.

The study of [5] designed an LED-based solar simulator for use in the Cal Poly Space Environments Laboratory. The simulator, developed under ASTM (American Society for Testing and Materials) standards, is dedicated to enhance the capability of undergraduate students to evaluate solar cell and thermal coating performance, including for spacecraft thermal vacuum environmental testing. The authors had a target for a cost lower than $1000, achieved by utilizing spare equipment and identifying low-cost components. In particular, advantage has been taken of improvements in LED technology, which are cheap and reliable in comparison to costly arc lamps.

A key factor for the simulator was the appropriate LED's choice. For this task, the relevant wavelength range and spectral bins were determined as 250-2500 nm. The authors determined that choosing one LED per bin was the most straightforward way to ensure that the solar spectral match could be tuned appropriately, resulting in a simulator with 7 different LED and an incandescent bulb. Control of the LED duty cycle was implemented with a PID block in LabView.

The combination of LEDs for each interval of radiation spectrum with a halogen lamp is a common technique also found in the work of [6] where 8 LEDs were used; the work of [7] and [8] have 6 LEDS. Usually, the authors implement a hexagonal arrangement to achieve a uniform radiation source during the tests.

Focused on space applications, the work of [9] is based on a solar simulator for a 3U CubeSat geometry. Another solar simulator for satellite applications was developed by [10]. In this case, the authors also used LEDs to simulate the solar radiation, which were electronically controlled through a PC using an Arduino microcontroller. The whole structure is 3-D printed in black PLA plastic. The electrical current through the LEDs, and thus the spectral irradiance of the simulator, is controlled through LabVIEW interface.

The following sections will outline the key aspects considered in the development of the project, including the structure of the satellite that will be tested in the solar simulator. The methodology was based on a thorough review of previous work and was adapted to this case, incorporating a complete nanosatellite within the structure along with its critical systems.

Figure 2: Structure of GOLDS-UFSC CubeSat

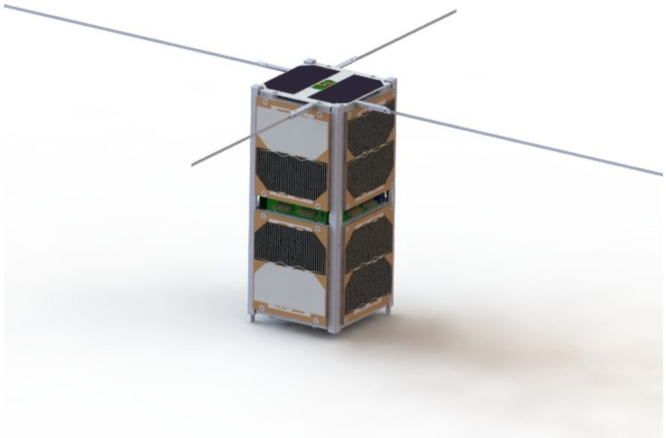

Figure 3: Isometric view of GOLDS-UFSC CubeSat

2.1 Main system of GOLDS-UFSC

In this subsection, the subsystems of the GOLDS-UFSC, platform FloripaSat-2 [11] that are important for the Sun simulator design are presented, highlighting the structure, the EPS, and Telemetry, Tracking & Command (TT&C). This way, the entire project will be based on the Cubesat developed at the Federal University of Santa Catarina by the Space Systems Laboratory (Spacelab).

2.1.1 Structure

The structure developed for the GOLDS-UFSC project measures $10 \times 10 \times 20$ cm (CubeSat 2U), and it aims to organize and stabilize all of the other subsystems safely during all the mission phases (from fabrication to end of life). Furthermore, it was designed to be efficient when integrating PCB and cables. As can be seen in Figure 2, the sides are hollow for the possibility of internal handling after assembly. Then, when the assembly is complete, over each side solar panels are mounted, as observed in Figure 3.

2.1.2 EPS

It is a critical subsystem of a CubeSat's service module, interfacing between the solar panels, batteries, and the satellite's loads (including other subsystems of the service module). Essentially, the EPS manages energy collection, storage, and conditioning for the entire system.

As detailed in [12], this subsystem is typically divided into three units: the Energy Harvesting Unit (EHU), the Energy Storage Unit (ESU), and the Power Distribution Unit (PDU). The EPS2 of GOLDS-UFSC follows this same structure.

The EHU of the EPS2 (Figure 4) includes three boost converters, one for each pair of parallel solar panels (Figure 5). To optimize the power transfer from the panels to the loads and batteries (Figure 6), it employs a Maximum Power Point Tracking (MPPT) algorithm, specifically the perturb and observe method. The control signals for this process are generated by the MCU (MSP430).

Regarding the ESU, the EPS2 uses an integrated circuit to monitor the batteries, which also provides protection mechanisms and manages the charging and discharging processes. Finally, the PDU in the EPS2 contains multiple Buck converters to supply $3.3V$, $5V$, and $6V$ buses to the satellite's loads.

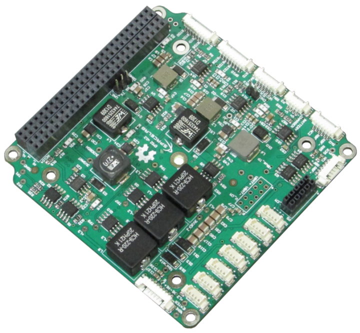

Figure 4: EPS2

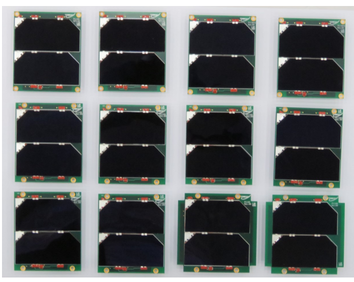

Figure 5: Photovoltaic panels

Figure 6: Battery board

2.1.3 TT&C

It is responsible for establishing communication and decoding data between Earth and the nanosatellite. The main component of this subsystem valid to mention here is the antenna, which is responsible for capturing data from Earth (ground stations) and transmitting it to the $TT\&C$. The antenna model (Figure 7) is from the ISIS model and it has 1314 mm opened in orbit.

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Figure 7: Antenna

2.2 Dimensions of the Sun Simulator

The construction of a Sun simulator should guarantee a spectrum similar to the Sun to emulate the sunlight that the satellite would encounter in orbit. In this subsection its main components will be described: the box, LEDs, coolers, and the support for the satellite.

2.2.1 The Box

It is basically a wodden box with sides of $44x34x34$ cm, as can be seen in Figure 8.

The function of the box is to accommodate all the parts of the simulator, fit a 2U CubeSat

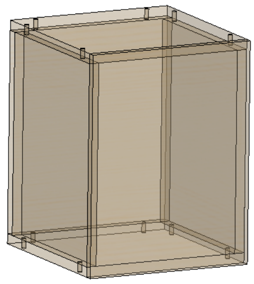

Figure 8: Solar simulator: the box

in its interior and isolate it from the external environment. An schematic view of the box and further components of the simulator are in Figure 9.

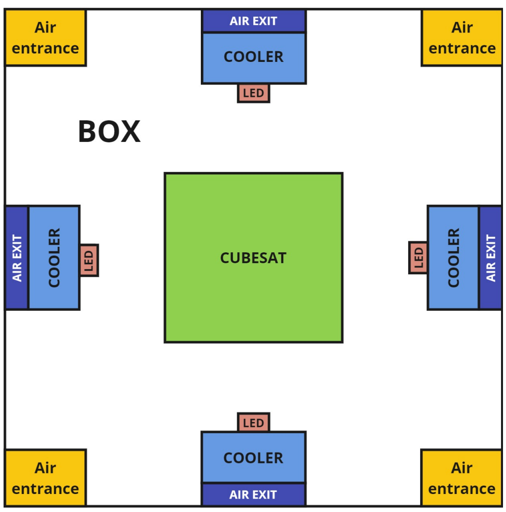

Figure 9: Schematic of the solar simulator

2.3 Material's selection

For the selection of the material for the enclosure, materials with good heat transfer properties and availability in the Brazilian market were considered. The options included: Medium Density Fiberboard (MDF) and PLA. Throughout the proposed design, careful attention was given to the necessary air outlets to prevent the system from overheating due to the high temperatures of the LED. The main features of these material are:

2.3.1 MDF

it has good thermal dispersion, and it was already previously used in solar simulator projects [3];

2.3.2 PLA

it is a biodegradable thermoplastic derived from renewable resources like corn starch or sugarcane. It is less heat-resistant compared to other plastics and can become brittle over time, but it was already used in a similar project [10].

2.3.3 The LEDs

the system is compound with 10 LEDs placed two on the bigger plates and one at the smallest ones. The LEDs are $40 \times 40 \times 6$ mm as shown in Figure 10. The number of LEDs was determined based on the flux radiation and spectrum requirement.

2.3.4 Coolers

following the same number of LEDs with 10 sets, each one is placed behind an LED to promote its thermal management, as presented in Figure 11.

2.3.5 Support for the Satellite

is a structure designed to uphold the Cubesat and prevent its contact with the LED at

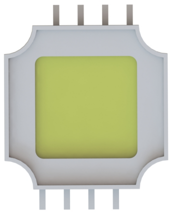

Figure 10: LED

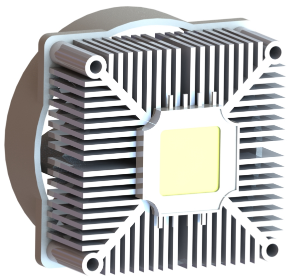

Figure 11: LED and cooler

the bottom. It is made made of Polylactic Acid (PLA) and its dimension are $108 \times 108 \times 100$ mm (Figure 12).

Figure 12: Support for the satellite

3 Design

The design of the Sun simulator plays a critical role in the development of systems that test the thermal behavior of the satellite in orbit. This process involves the careful selection of materials and the study of the optimal configuration of LEDs to accurately represent solar irradiance, as well as the system's thermal management. The precise implementation of these elements is essential to ensure that the simulator faithfully reproduces environmental conditions, thus creating a controlled volume that closely approximates the satellite's orbital environment without requiring the use of a vacuum chamber.

For the project development, the use of 10 white light LEDs was stipulated, providing 100 W of power, and 36 V of load, in order to simulate the irradiance of 1000 watts per square meter, thereby approximating the simulation as closely as possible to real solar radiation.

These LEDs will be controlled by a specific power source to simulate the solar radiation in the satellite's orbit. Thus, the satellite remains stable, but the radiation in each LED varies to mimic all the phases the satellite will go through, from total solar eclipse to constant radiation.

According to [13], the incoming solar radiation over a satellite is influenced by its altitude and orbit, highlighting that the duration a satellite spends in Earth's shadow varies with its altitude. CubeSats can achieve orbits of up to 2000 km, classified as Low Earth Orbit (LEO) as noted at [14]. The profile used in this study was simulated for the FloripaSat-1 nanosatellite, which is designed to travel in circular orbits at an altitude of 400 km and an inclination of 51.5º. The satellite completes a full orbit around Earth in approximately 5125 seconds, with 3053 seconds in sunlight and 2072 seconds in Earth's shadow. For the GOLDS-UFSC, a 2U CubeSat, the same orbital parameters as FloripaSat-1 were used to simulate its orbit with the LEDs in the Sun simulator.

Figure 13: CubeSat Orbit obtained by STK [13]

To implement a similar scenario, the following parameters of the LEDs will be monitored: voltage and current at each instant.

Thus, with the carefully selected number of LEDs and the estimated control strategy in place, the design can now be finalized, ensuring that all parameters meet the expected performance standards. Moreover, addressing the potential thermal challenges, such as overheating, contingency plans have been outlined, which include the strategic use of coolers and heat sinks to maintain optimal operating temperatures. With these precautions and design considerations taken into account, the project is well-positioned for the next phase, which is the practical implementation and testing of the system in real-world conditions.

4 Implementation

Building on the studies and design choices outlined before, the implementation phase of the project followed a structured approach to ensure accurate simulation and control of the heat transferred to the CubeSat. We began the implementation phase by configuring the hardware, focusing on the construction of the box and the setup of the LEDs, we then focused on the power source system to replicate the solar irradiance conditions. Following this, the software for controlling the LEDs' radiation phases was developed. Throughout the project, many adjustments were made both in the hardware selection/configuration and the software algorithms to optimize the system's performance, aiming for an accurate representation of our orbit's conditions, following [13].

Based on all the studies conducted previously, the number of LEDs was determined according to the total volume of the box, as shown in **??**. Following the parameters established in the methodology to achieve 1000 watts per square meter at the CubeSat surface, resulted in a total of 10 LEDs being required in the box. This number ensures that the lighting system meets the power density criteria while maximizing efficiency and uniformity of light distribution across the box surface. Thus, 10 LEDs were chosen as the optimal configuration to meet the specified energy and lighting requirements.

To further prevent overheating during the tests, additional coolers are integrated on the box to dissipate the heat generated. Thus, the final result of the project prototyping was a design featuring 10 LEDs coupled to 10 coolers, 10 extra coolers on the box, a support structure for the 2U satellite, and a central box with dimensions of $440 \times 340 \times 340$ mm, as can be seen in Figure 14. This configuration was carefully selected to ensure the optimal performance of the system, balancing thermal management, structural integrity, and space efficiency. The design reflects the culmination of detailed planning and precise engineering to meet the project's requirements while maintaining practicality and functionality throughout the process.

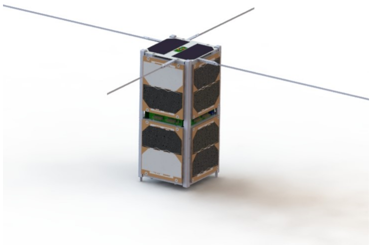

Figure 14: Isometric view of a complete Low-Cost Sun Simulator

5 Discussion: trends and directions

With the advancement of this project, it is evident that there is a need to develop a Sun simulator to model the energy distribution throughout the CubeSat system. The energy system is one of the most critical components of a satellite, as previously demonstrated.

It is crucial to conduct an in-depth study of the thermal dynamics within the CubeSat box to predict the behavior of heat generated by the 10 LEDs and the heat sinks. This study will help to understand how heat is distributed and dissipated within the CubeSat, which is essential for ensuring the efficiency and longevity of the electronic components.

Once the prototyping phase is completed, it is important to be aware of potential future issues that may arise during the assembly and execution of the box's functions. These issues should be thoroughly analyzed and discussed to ensure that all concerns are addressed effectively.

In conclusion, it is essential to recognize that as we advance in the prototyping and implementation of the CubeSat, ongoing monitoring of emerging trends and adaptation to new technologies will be crucial for the project's success. The development of solar simulators and detailed thermal studies are just the beginning. The ability to identify and address potential future issues during assembly and operation, along with integrating technological innovations, will allow for the optimization of the CubeSat's performance and reliability. Commitment to critical analysis and adaptation to new trends will ensure that the CubSat's energy system remains robust, efficient, and capable of meeting mission demands.

6 Conclusion

The design and development of the Sun simulator proposed in this study represent a significant advancement in the testing and validation of CubeSats, particularly regarding their *EPS*. By simulating in-orbit conditions using LEDs and an optimized control system, the simulator provides a controlled environment to assess the performance of photovoltaic panels, batteries, and overall energy distribution in nanosatellites. The implementation of the simulator is not only cost-effective but also essential for mitigating risks associated with energy management in space missions. The findings from this work contribute to the ongoing evolution of CubeSat technology, enabling more reliable testing protocols and enhancing the resilience of these small satellites in future space endeavors. Future work will focus on refining the thermal management aspects and addressing potential challenges identified during the prototyping phase.

Acknowledgements

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