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Development of a payload for monitoring biological samples in microgravity and hypergravity conditions

Elber E. Canto-Vivanco[1], Sebastian Ramos-Cosi[1], Victor N. Romero-Alva[1], Natalia I. Vargas-Cuentas[1], Avid Roman-Gonzalez[2,3]
[1]Image Processing Research Laboratory (INTI-Lab), Universidad de Ciencias y Humanidades, Lima, Peru
[2]Aerospace Sciences and Health Research Laboratory (INCAS-Lab), Universidad Nacional Tecnologica de Lima Sur, Lima, Peru
[3]Business on Engineering and Technology S.A.C., Lima, Peru

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ABSTRACT

This research aims to address the need for monitoring the behavior of organic and inorganic materials in hypergravity conditions. To fulfill this objective, a container with specific features was designed. The container has a box with a lid, measuring 10×10×10 cm, conforming to the 1U volume of the CubeSat standard. It includes four cylindrical spaces to accommodate the sample wells. The container was 3D printed using polylactic acid (PLA) wire. For the electronic components, four ESP32-CAM modules were utilized, with two programmed to capture and upload photos to the cloud, and the other two programmed to capture and store photos on a micro SD memory card. Additionally, four light emitting diodes (LEDs) were incorporated to illuminate the well spaces. The total weight of the container is 450 grams, and it has a maximum wireless upload distance of 10 meters to the cloud. The storage capacity of the SD memory card determines the number of images that can be saved.

Corresponding Author:

Avid Roman-Gonzalez
Aerospace Sciences and Health Research Laboratory (INCAS-Lab)
Universidad Nacional Tecnológica de Lima Sur
Lima, Peru
Email: avid.roman-gonzalez@ieee.org

1. INTRODUCTION

In scientific research, obtaining visual data on both organic and inorganic materials under microgravity and hypergravity conditions holds significant importance. Numerous studies have delved into the behavior of diverse biological specimens in such environments, utilizing varied experimental configurations and approaches. This paper seeks to enhance this field of inquiry through the creation of a specialized container designed to facilitate real-time monitoring of samples and the capture of high-resolution images depicting their internal dynamics. By offering an innovative solution, this contribution aims to further our understanding of material responses in extreme gravitational settings, thus paving the way for advancements in various scientific disciplines, including space exploration, materials science, and biotechnology.

Kume *et-al.* [1] focused on studying plant growth in both microgravity and hypergravity conditions using a cubic-shaped container. Additionally, they utilized a microscope for image acquisition. Similarly, Du *et-al.* [2] investigated plant germination in microgravity. They employed a plate with cylindrical spaces and a sliding camera for image capture.

Salvetti *et-al.* [3] conducted experiments to study the effects of artificially altered gravities on cells and microorganisms. For this purpose, they utilized a random positioning machine to simulate microgravity and a large-diameter centrifuge to simulate hypergravity. These devices accommodated a box containing petri dishes with samples.

In the study by Kopp *et-al.* [4], the focus was on analyzing the gravity-induced changes in cancer cell samples. To achieve this, stacked containers were placed inside a rocket. This setup simulated hypergravity during launch and transitioned to microgravity afterward.

Azevedo *et-al.* [5] investigated the impact of hypergravity on the absorption of pills in intestinal cells. To expose cell cultures to increased gravity, they used a centrifuge machine. Meanwhile, Thiel *et-al.* [6] examined the metabolic changes in macrophages under microgravity conditions. They aimed to explore potential influences on the immune system. The payloads from those investigations are shown in Figure 1. Previous studies have explored the impact of machine learning, Figure 1(a) shows how NASA evokes its efforts to take advantage of gravity in different conditions and the promotion of plant cultivation as shown in Figure 1(b). On the other hand, in Figure 1(c) we can see a suitable infrastructure as in Figure 1(d). The use of cell cultures for their growth and analyze their records Figures 1(e) and (f).

Understanding the effects of gravity, including hypergravity (gravity values greater than Earth's), is crucial. This is because it influences the development of living organisms [7], [8]. Furthermore, the findings from these studies can contribute to addressing disturbances that may arise during spaceflights involving organisms [9]. Thus, it is essential to analyze the behavior of different species and cells under hypergravity conditions and evaluate any resultant changes to identify potential beneficial applications [10], [11]. To accomplish this, the changes can be monitored within a container equipped with an array of cameras, enabling subsequent image processing and analysis [12].

Given this context, the aim of this study is to devise a specialized container tailored for housing wells, enabling the capture of interior images of the samples. The specific goals encompass comprehending the operational principles and materials involved in the container's construction, crafting and utilizing 3D printing technology to fabricate the well container, devising the necessary electronic circuitry, programming the microcontroller to facilitate image acquisition, meticulously assembling the container alongside the circuitry, and conducting comprehensive tests and demonstrations to validate its functionality. This multifaceted approach ensures not only the development of a functional container but also its seamless integration and effective operation within the housing well environment.

This manuscript is structured as follows: section 2 presents the step-by-step development process of the payload. In section 3 we present the results and discuss the findings obtained during the equipment development. Finally, section 4 provides an analysis of the results and presents the conclusions drawn from this investigation.

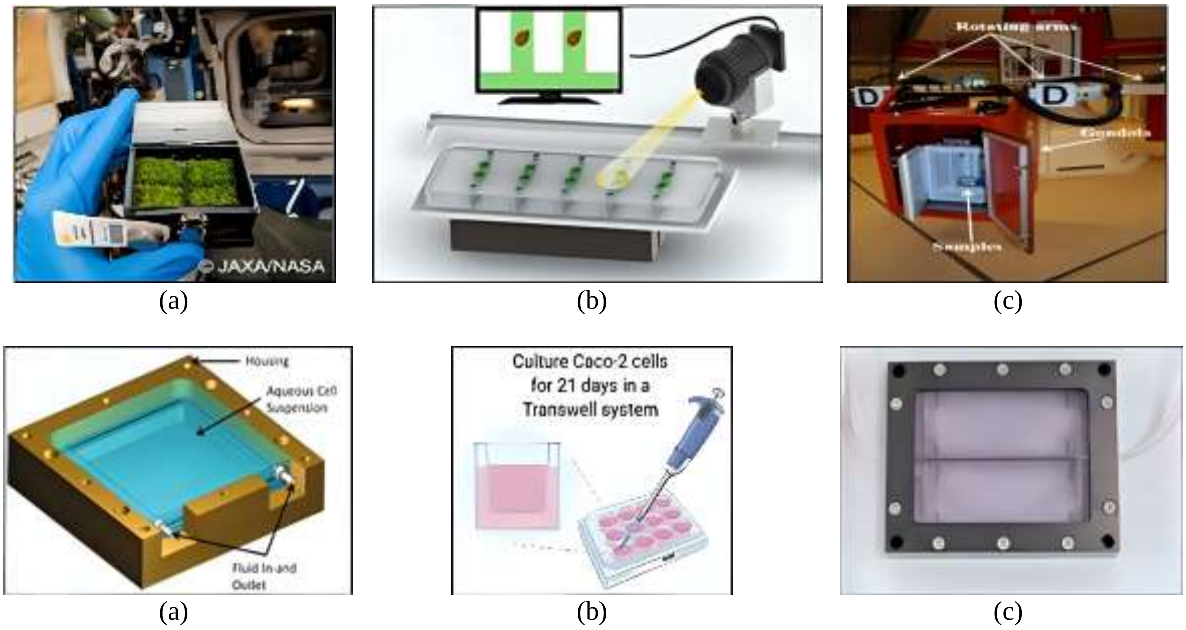


Figure 1. Sample container designs in: (a) Kume *et al.* [1], (b) Du *et al.* [2], (c) Salvetti *et al.* [3], (d) Kopp *et al.* [4], (e) Azevedo *et al.* [5], and (f) Thiel *et al.* [6]

2. METHOD

The methodology employed in this research entailed a series of pivotal steps aimed at the development of the payload container and its accompanying electronic circuitry, as depicted in Figure 2, illustrating the container's required operation. The subsequent sections delineate each step comprehensively. These sequential procedures encompassed the entire development process of both the payload container and its associated electronic circuitry. Activities such as container design, 3D printing, electronic circuit design, and microcontroller programming were meticulously undertaken to effectively accomplish the research objectives. Additionally, rigorous testing and validation procedures were implemented to ensure the functionality and reliability of the developed system.

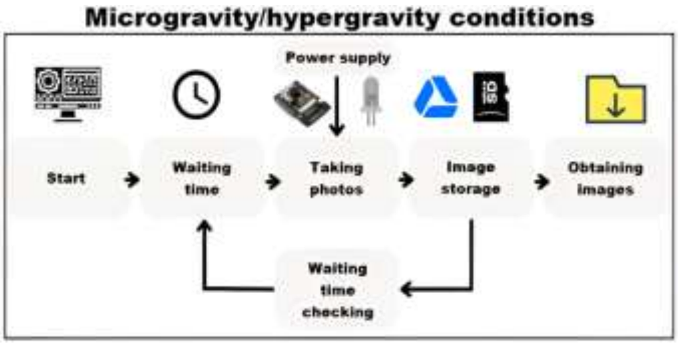


Figure 2. Container operation flow chart

2.1. Identification of the operation and materials of the container

At the inception of the project, the primary objectives for the container were established. These encompassed the parameterization of microcontroller variables, the configuration of camera optical sensors, and the assurance of the container's compatibility with standard power supply inputs, facilitating seamless integration into a payload or launch vehicle. Moreover, it was imperative for the container to securely house both organic and inorganic materials, ensuring their stability and inertness during image capture processes [13], [14]. To meet these stringent criteria, careful consideration was given to the selection of materials, which included:

- ESP32-CAM: this module, based on the ESP32 microcontroller, was chosen for its 32-bit architecture, Wi-Fi and Bluetooth connectivity, and integrated camera capabilities that could allow the samples monitoring at low cost [15]. It is shown in Figure 3, and some of its features are shown in Table 1.
- DC-DC step-down converter: the LM2596 module, capable of delivering a constant output voltage lower than the input voltage, was utilized because it is useful to regulate the power supply for the system and the illumination set [16], [17]. It is shown in Figure 4, and its features are shown in Table 2.
- LED: a high brightness LED with a 10mm diameter was selected for illuminating the well spaces; a good illumination is better to monitoring samples and, in some cases, it affects to the sample behavior, for example, helps plants to growth [18]. This LED is shown in Figure 5.

Figure 3. ESP32-CAM module

Table 1. Features of the assembled container

Feature	Description
Supply voltage	5 VDC
Input/output voltage (GPIO)	3.3 VDC
SoC	ESP32 (ESP32-D0WDQ6)
Wireless networks	Wi-Fi 802.11b/g/n, Bluetooth 4.2
Memory	520KB internal SRAM, 4MB external SRAM
Medium	Includes a socket for TF card micro-SD
Camera	OV2640
Photo resolution	1,600×1,200 pixels
Video resolution	1080p30, 720p60 y 640×480p90
Dimensions	27×40.5×6 mm
Weight	20 grams

Figure 4. DC-DC step-down module 3A LM2596

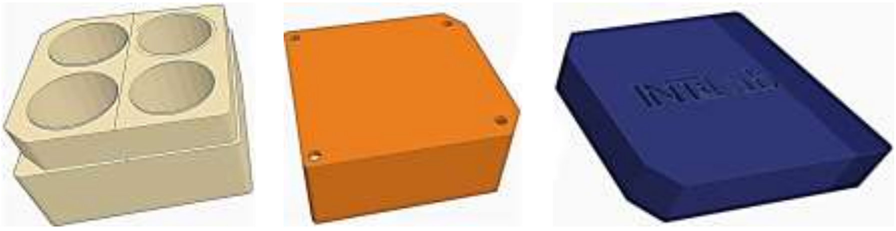
Table 2. LM2596 step-down DC-DC module features

Feature	Description
DC-DC buck converter	LM 2596
Input voltage	4.5 V to 40 V DC
Output voltage	1.23 V to 37 V DC (input voltage must be at least 1.5 V higher than output)
Output current	Maximum 3 A, 2.5 A recommended (use heatsink for currents greater than 2 A)
Output power	25 W

Figure 5. A high brightness LED

2.2. Design and printing of the well container

The well container was designed using the Tinkercad software, a web-based 3D modeling program. The 3D printing represents a great help when carrying out personalized projects [19], [20]. The design process involved creating three distinct parts: the well container, the electronics container, and an external cover to waterproof the circuitry, these designs are shown in Figure 6. The design of the containment model for the cells is divided into three key components, optimizing their functionality. Initially, Figure 6(a) details a module composed of four cells specifically designed for the cultivation of selected organisms, providing a controlled environment for their development. Next, Figure 6(b) presents a lid that ensures the tightness of the system, regulating critical variables such as humidity and lighting to maintain constant and optimal conditions. Finally, Figure 6(c) incorporates the electronic circuits necessary for image processing and transmission, as described in the methodology, ensuring efficient and accurate monitoring of the cultured organisms. This comprehensive approach not only improves the viability of the culture but also enhances the capacity for real-time analysis and monitoring.



(a) (b) (c)

Figure 6. Designs for: (a) wells container, (b) electronic circuit container, and (c) outer cap

The overall dimensions of the box were set at 10x10x10 cm, with a lid divided into two sections to accommodate the circuitry. The base of the container featured four cylindrical hollow spaces for housing the samples. The container design was printed using PLA filament, with a total printing time of approximately 11 hours. Figures 7 and 8 show the process and the result of the 3D printing, respectively.

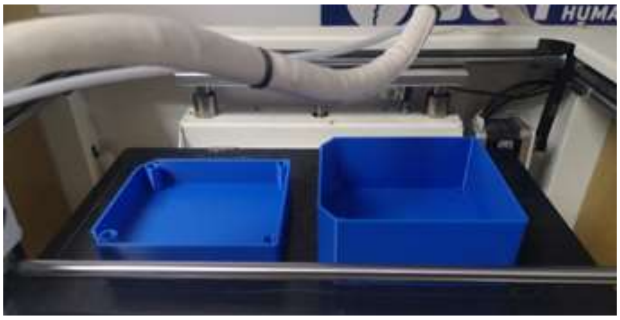


Figure 7. Container printing process

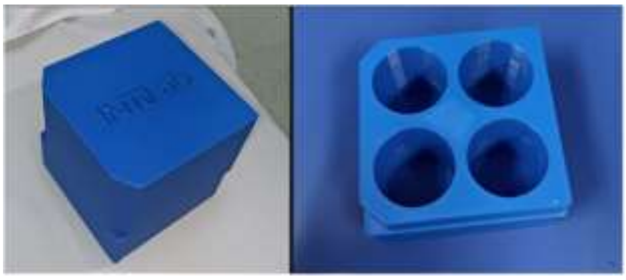


Figure 8. Container for the wells

2.3. Design and development of the electronic circuit

The electronic circuitry, as illustrated in Figure 9, underwent a meticulous design and simulation process employing Proteus software, a highly regarded tool renowned for its effectiveness in validating electronic circuits prior to physical implementation [21]. This simulation phase proved invaluable, enabling a comprehensive analysis of the output ports and configurations of the ESP32-CAM modules. By utilizing Proteus software, potential design discrepancies were identified and rectified early on, ensuring the seamless integration and optimal performance of the electronic circuitry. Considering the dimensions of the container and the ESP32-CAM microcontroller, the components were strategically arranged to guarantee precise alignment of the OV2640 camera sensor with the wells. The arrangement is visually depicted in Figure 10.

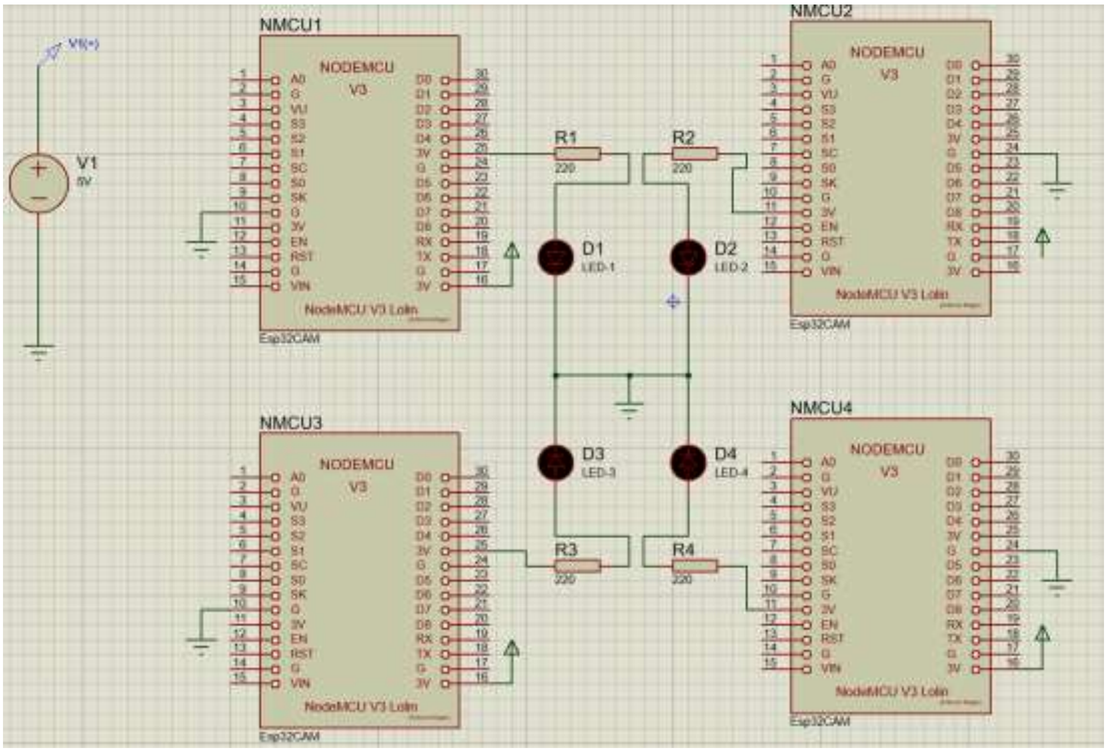


Figure 9. Schematic of the electronic circuit

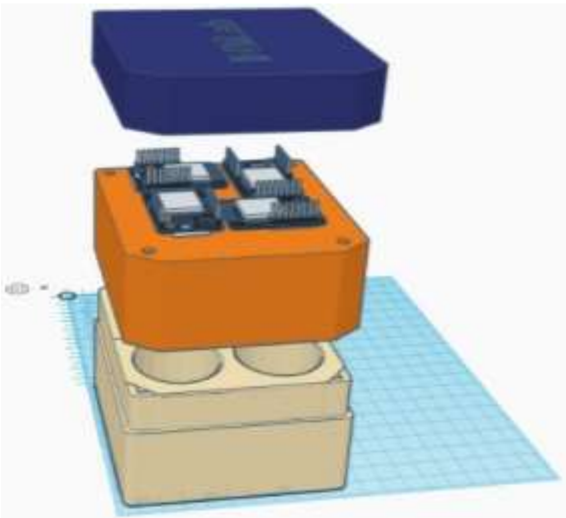


Figure 10. Complete design of the container with the electronic part

2.4. Programming the microcontroller for image acquisition

Two ESP32-CAM modules were programmed to capture photos and manage image uploads to the cloud. This process involved utilizing Apps Script, which facilitates communication between Google Drive and various electronic devices [22], [23], and subsequently programming the ESP32-CAM microcontroller accordingly. Meanwhile, for the remaining two modules, programming was executed to capture photos and store them on a micro SD card inserted into the module slot. The flowcharts detailing these codes are presented in Figure 11. In Figure 11(a) for the algorithm that stores information in the Google Drive Cloud, and in Figure 11(b) that which stores the images in the memory of the micro SD card.

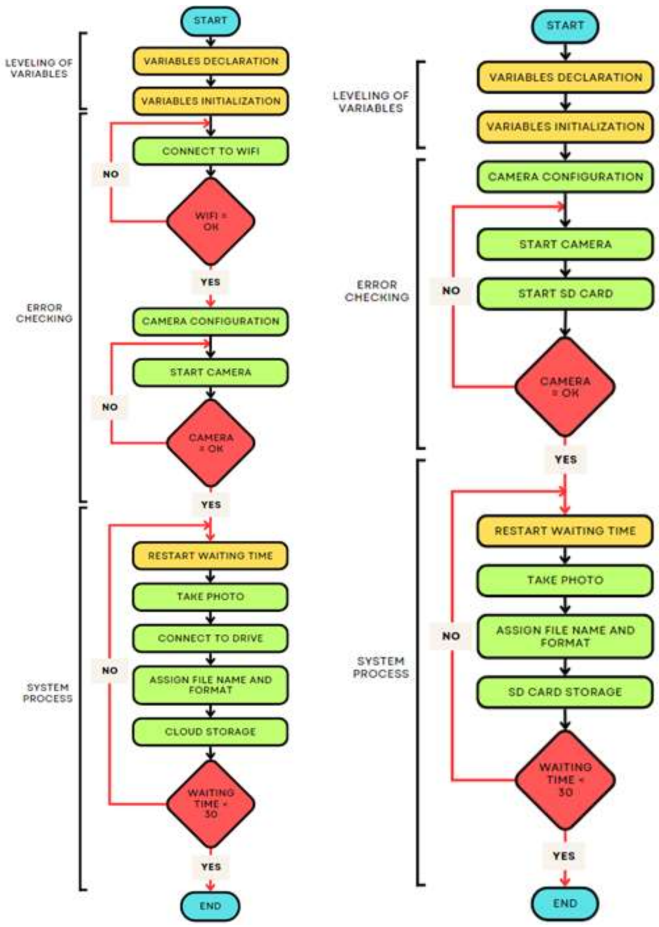


Figure 11. Flowcharts for programming that saves photos to (a) Google Drive and (b) SD card

2.5. Assembly of the container with the circuitry

Once the camera positions have been established, the subsequent step involves powering the four modules and integrating LEDs to illuminate the interior of the wells, thus ensuring uniform lighting conditions for optimal image capture. To accomplish this task, a perforated plate was employed to organize the modules, LEDs, and power terminal block effectively. Visual representations of both the container and the circuitry are provided in Figures 12 to 14, offering insightful glimpses into the structural layout and electronic configuration of the system.

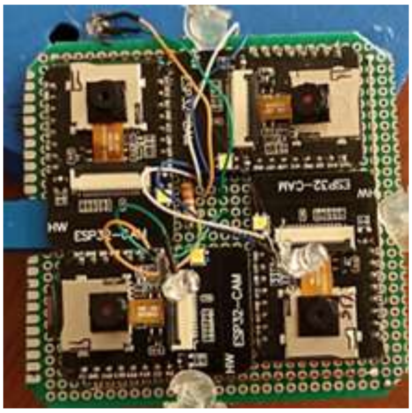


Figure 12. Configuration of the circuitry for image capture

Figure 13. Assembly of the circuitry in the middle section of the container

Figure 14. Bottom view of the middle cover revealing the cameras and LEDs

3. RESULTS AND DISCUSSION

Thorough testing was conducted to meticulously validate both the container's functionality and its effectiveness in image acquisition and storage. The comprehensive results of these tests are meticulously depicted in Figure 15, providing a detailed insight into the container's performance under diverse conditions and across various parameters. This rigorous testing process ensures the reliability and robustness of the container's operations, confirming its suitability for real-world applications.

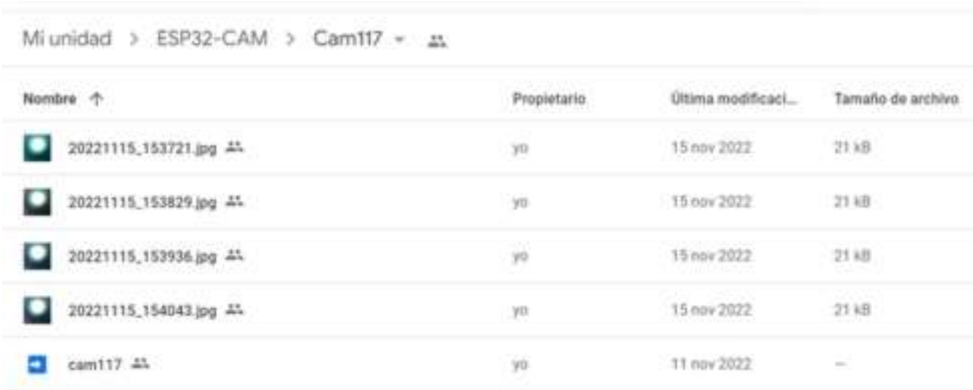


Figure 15. Images successfully uploaded to the cloud

The modules designated for storing images in the micro SD memory effectively captured and saved images as per the intended functionality. Notably, exemplary images extracted from the wells are vividly portrayed in both Figures 16 and 17, providing tangible evidence of the container's capability to capture and retain images with precision. The implemented container successfully meets the specified requirements, boasting dimensions not exceeding 10×10×10 cm, a weight of 450 grams, and a power consumption of 2.4 W. It efficiently utilizes a terminal block for a 5 V power supply. Incorporating four DEVKIT v1 MCU ESP32-Cam development boards, the container facilitates image capture with a maximum resolution of 1,600×1,200 pixels. These high-resolution images can be seamlessly transmitted to the cloud via Wi-Fi communication or alternatively stored on a micro-SD card for future retrieval.

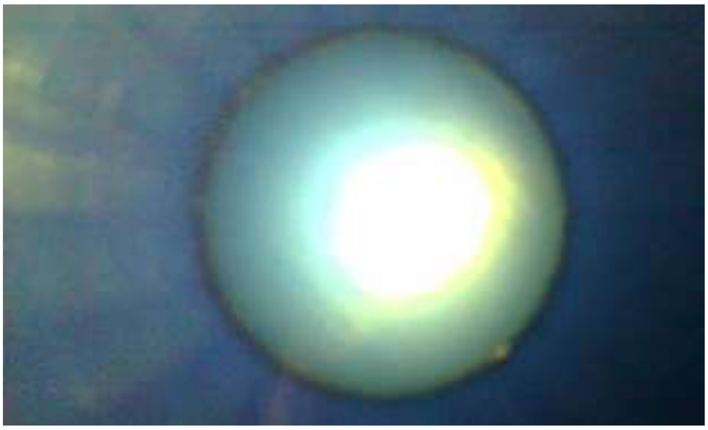


Figure 16. Image successfully saved in a micro SD memory

The Wi-Fi communication feature ensures a stable connection within a maximum range of 10 meters in the absence of obstacles, or up to 7 meters when obstacles are present. The storage capacity of the micro-SD card depends on its size, with each image averaging a size of 21 kilobytes. For instance, with a 16 GB micro-SD card, approximately 761,904 images can be stored, providing ample storage capacity for prolonged data collection and analysis.

Figure 17. Example image captured inside a well, showing germinating seeds

The successful development of this payload container for monitoring biological samples in microgravity and hypergravity conditions marks a significant achievement. Featuring a compact design measuring 10×10×10 cm, the container is ideally suited for integration into CubeSat missions or other space exploration platforms [24], [25]. Its versatile capabilities allow for the seamless capture and storage of images of both organic and inorganic materials, facilitating comprehensive studies of their behavior in diverse gravitational environments.

In contrast to prior investigations by Kume *et-al.* [1], Du *et-al.* [2], Salvetti *et-al.* [3], Kopp *et-al.* [4], Azevedo *et-al.* [5], and Thiel *et-al.* [6]. This study introduces an innovative methodology employing a container equipped with multiple ESP32-CAM modules. These cutting-edge modules enable the acquisition of high-resolution images (1,600×1,200 pixels) and provide versatile options for storing captured images.

The outcomes of the conducted tests and demonstrations unequivocally affirm the successful performance of the container. Images were efficiently uploaded to the cloud and stored in the micro SD memory, underscoring the system's reliability and functionality. The container's design, featuring a perforated plate for precise module positioning, integrated LEDs for illumination, and a convenient power terminal block, ensures seamless operation and user-friendliness. This pioneering approach not only advances the field of scientific research but also sets a new standard for the acquisition and storage of crucial data in various gravitational environments.

4. CONCLUSION

In conclusion, the developed payload container offers a practical solution for monitoring biological samples in both microgravity and hypergravity conditions. By harnessing the capabilities of ESP32-CAM modules, the container facilitates the capture and storage of high-resolution images, thereby enabling comprehensive studies of the behavior of organic and inorganic materials across diverse gravitational environments. The container's compact size, lightweight design, and efficient power consumption render it ideal for deployment in space missions. Its successful implementation, boasting dimensions not exceeding 10×10×10 cm, a weight of 450 grams, and a power consumption of 2.4 W, underscores its feasibility for integration into small satellite platforms. The obtained results affirm the container's effectiveness in fulfilling its objectives, facilitating seamless image acquisition and storage. With Wi-Fi communication for image transmission to the cloud and a micro-SD card option for reliable local storage, the container offers versatile data management solutions. Practical considerations, such as the maximum distances for Wi-Fi communication and the storage capacity of the micro-SD card, further enhance its utility in real-world scenarios. Overall, the developed payload container represents a significant advancement in the field of monitoring biological samples across varying gravitational conditions. It paves the way for further research and experimentation, with potential applications spanning space exploration, biotechnology, and life sciences. Future studies may explore enhancements to the container design, including the integration of additional sensors for capturing supplementary data and the implementation of advanced image processing techniques to extract valuable insights from the acquired images. In summary, this research contributes significantly to the realm of microgravity and hypergravity studies by providing a reliable and versatile container for monitoring biological samples. It heralds new possibilities for scientific investigations, furthering our understanding of the effects of gravitational forces on living organisms and materials.

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BIOGRAPHIES OF AUTHORS

Elber E. Canto-Vivanco is a B.Sc. student of Electronic Engineering with a major in Telecommunications at Universidad de Ciencias y Humanidades. Currently, he works as a research assistant of the Image Processing Research Laboratory (INTI-Lab). He can be contacted at email: ecantov@uch.edu.pe.

Sebastian Ramos-Cosi received his B.Sc. degree in Electronic Engineering with a major in Telecommunications at Universidad de Ciencias y Humanidades, also graduated as a Professional Technician in Industrial Electronics. His research interests are in the area of agricultural technology, aerospace engineering, virtual reality and augmented reality. Currently, he works in the Image Processing Research Laboratory (INTI-Lab). He can be contacted at email: sramos@uch.edu.pe.

Victor N. Romero-Alva Master of Science in Space and Cosmonautics Technology from the Samara Space University (Russia) and a Bachelor in Electronic Engineering with a mention in telecommunications from the University of Sciences and Humanities (Peru). Work experience in the areas of electronics and aerospace technology. He has worked in the space research Department of the University of Samara developing nanosatellite projects and in the Peruvian Space Agency (CONIDA) developing probe balloons for studying the atmosphere and at the University of Sciences and Humanities as a research assistant. On the other hand, he is writing scientific articles on electronics, aerospace and biomedical. He can be contacted at email: vromero@uch.edu.pe.

Natalia I. Vargas-Cuentas is a Ph.D. Candidate for the Doctorate in Geomatics and Space Systems from the Mario Gulich Institute of Advanced Space Studies of CONAE (National Commission for Space Activities) and the Universidad Nacional de Córdoba (UNC), Argentina. Besides, she holds a master's degree in Space Technology Applications, with a major in Remote Sensing and Geographic Information Systems from Beihang University (BUAA), China. She is an Electronic Engineer at the Military School of Engineering (Escuela Militar de Ingeniería - EMI) in La Paz, Bolivia. Currently, she is the Coordinator of the Image Processing Research Laboratory (INTI-Lab) of the Universidad de Ciencias y Humanidades in Peru. Also, she is a Senior Member of IEEE and Chief Operating Officer (COO) of the research incubator BE Tech (Business on Engineering and Technology). She can be contacted at email: nvargas@uch.edu.pe.

Avid Roman-Gonzalez is CEO and Founder at Business on Engineering and Technology S.A.C. (BE Tech). Full Professor at Universidad Nacional Tecnologica de Lima Sur (UNTELS). Distinguished Lecturer IEEE AESS, IEEE Senior Member. Electronic engineer from the Universidad Nacional San Antonio Abad del Cusco. Systems engineer from the Universidad Andina del Cusco. Received his M.Sc. Degree in industrial and human automatic, from the Université Paul Verlaine de Metz - France, and he received his Ph.D. Degree in image and signal processing from TELECOM ParisTech. He was a postdoctoral fellow at Universidad Peruana Cayetano Heredia. His work experience includes research at the French Space Agency (CNES) and German Aerospace Center (DLR), University Teaching (UNSAAC, UAC, UNI, UPCH, UCH and UNTELS), consulting engineer at CONIDA, SPECTRUM, and EGEMSA. He participates as keynote speaker and jury of projects in various academic events. He has many international published papers. His areas of interest are Signal and image processing, biometrics, artificial intelligence, human automation, bioengineering, industrial automatic, control, and aerospace technology. He can be contacted at email: avid.roman-gonzalez@ieee.org.