Development Of The Payload System And OBC Microcontroller Coding For A Cubic Satellite Performing An Additive Self-Repair Experiment In Space

Eduardo Macias-Zugasti
University of Texas at El Paso

DEVELOPMENT OF THE PAYLOAD SYSTEM AND OBC MICROCONTROLLER

CODING FOR A CUBIC SATELLITE PERFORMING AN ADDITIVE

SELF-REPAIR EXPERIMENT IN SPACE

EDUARDO MACIAS ZUGASTI

Master's Program in Computer Engineering

APPROVED:

Rodrigo Romero, Ph.D., Chair

Joel Quintana, Ph.D., Co-Chair

Virgilio Gonzalez, Ph.D.

Stephen L. Crites Jr., Ph.D.
Dean of the Graduate School

Dedication

To my parents, Rosi Isela Zugasti Vargas and Eduardo Macias Sustaita.

You are the greatest motivation that I have in my life. Thank you for the support and love that you give me every day. I could have not been done this without your advice. This is not only my work; it is also yours. You raised me and taught me that I can do anything I wish, so I can say we did it. Thank you and I love you.

DEVELOPMENT OF THE PAYLOAD SYSTEM AND OBC MICROCONTROLLER CODING FOR A CUBIC SATELLITE PERFORMING AN ADDITIVE SELF-REPAIR EXPERIMENT IN SPACE

by

EDUARDO MACIAS ZUGASTI, B.S.E.E.

THESIS

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Finally, I want to thank all cSETR members for always being nice and helping me in everything I needed. You are the best.

Abstract

Additive manufacturing, which is also known as three-dimensional printing, in space is one of the most promising technologies advancing current capabilities for in-orbit space manufacturing and assembly. Additive manufacturing contributes to the reduction of cost per kilogram and number of launches, thus facilitating extraterrestrial colonization and deep-space exploration. The state of the art includes advancing efforts inside the International Space Station (ISS). However, the ISS is a controlled environment and, to the best of our knowledge, no spacecraft or satellite has performed additive manufacturing tasks in the extreme environment of outer space. In this work a 1U CubeSat named Orbital Factory II (OF2) was developed to perform a technological capability demonstration featuring a 1-D printing mechanism that will deposit conductive ink and simulate repairing of an electric circuit. OF2 was launched on a Northrop Grumman Antares space rocket on November 2, 2019 and it was deployed from the CRS2 NG-12 (Cygnus) on January 31, 2020. This document presents the payload developed and the libraries coded for the on-board computer (OBC) for this OF2 CubeSat. This is the first satellite ever launched by the University of Texas at El Paso (UTEP).

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Chapter 1: Introduction

Satellites have become an important tool in modern life. They are used in a lot of different applications. When someone is making a long-distance phone call, there are satellites working in space to enable communication. Meteorologists use satellites to predict the weather and observe environmental phenomena. The Global Positioning System (GPS) uses satellites to provide users data to calculate their exact position. Television companies use satellites to broadcast their programs. All of the data that cell phones use is processed using satellites to transmit and receive.

Moreover, satellites are used also for space exploration. On September 1977, the National Aeronautics and Space Administration (NASA) launched a space probe named Voyager 1. Sixteen days later, they launched their second space probe, named Voyager 2. On November 5, 2018, Voyager 2 entered interstellar space. After 43 years, Voyager 2 has traveled more than 11 billion miles from earth [1].

Even though this is the space device farthest from Earth, it is not the only one in space. At present, there are more than 2000 satellites orbiting the Earth while performing various tasks. Some of these satellites are a little bit bigger than a Rubik’s cube, 1U units measuring 10 cm x 10 cm x 10 cm, and they are called CubeSats. In 1999, Jordi Puig-Suari, a professor at California Polytechnic State University (Cal Poly), and Bob Twiggs, a professor at Stanford University developed the first CubeSat. Their intent was to provide affordable access to space for their university science committee. Later on, many other universities around the world started to get involved in space programs. CubeSat dimensions are based on the standard CubeSat “unit” which is a 10cm cube with a mass approximately from 1 to 1.3 kg [2], as shown in Figure 1.1. The most popular sizes are 1.5U, 2U, 3U, and 6U.

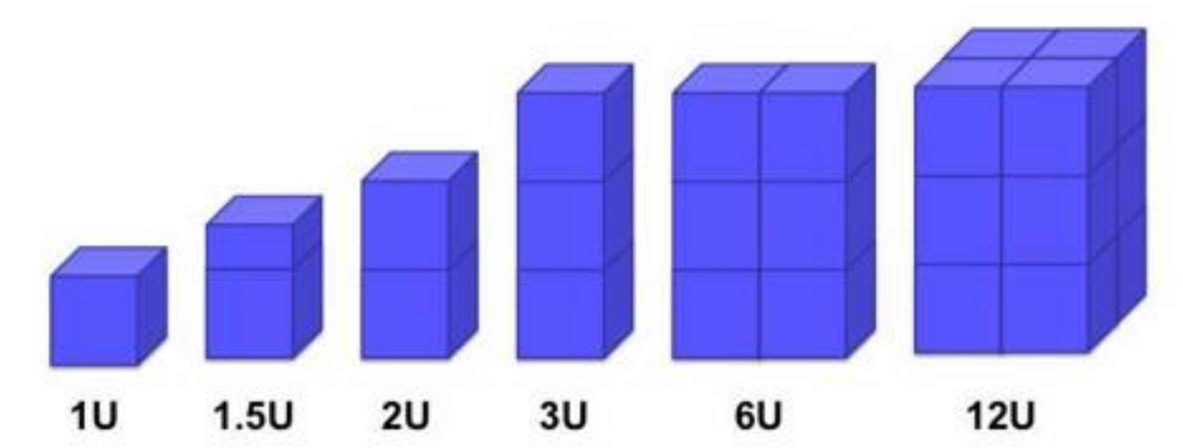
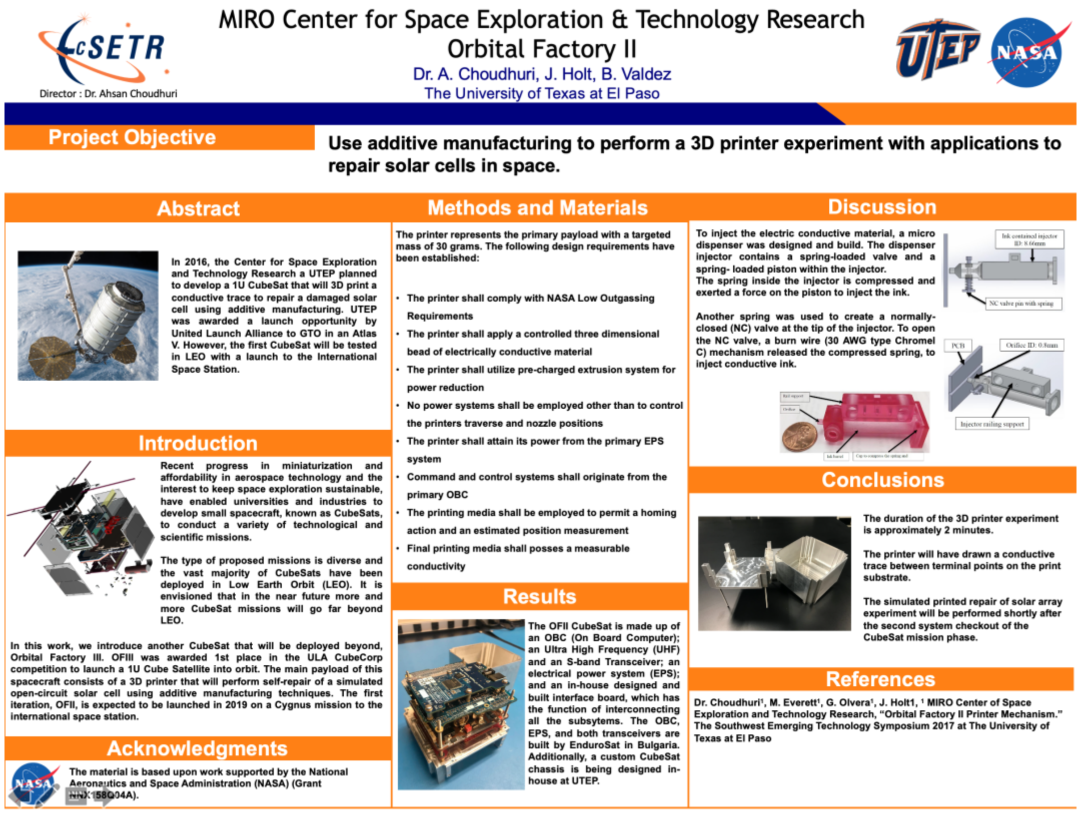


Figure 1.1: Examples of different CubeSat units, courtesy of NASA

Usually, CubeSats developed by universities are used for space research and experiments. A significant problem found in space is that sometimes solar cells get broken or electronic components get disconnected. This type of problems can be critical to some devices in space. A solution for this problem could be to have an electronic self-repair system that could reconnect electronic devices. In 2017, student members of the Center for Space Exploration and Technology Research (cSETR) at UTEP won the United Launch Alliance (ULA) CubeSat Competition, also called the CubeCorps competition. The prize from this competition was a spot for a CubeSat launch mission to geostationary transfer orbit (GTO) in the future. With the goal of gaining experience, cSETR decided to start CubeSat programs. The first satellite planned to be launched is Orbital Factory II (OF2), which is a 1U CubeSat that will perform an experiment consisting in 3D printing a conductive ink in space.


Ink contained injector ID: 8.66mm
NC valve pin with spring
PCB
Orifice ID: 0.8mm
Injector railing support
Rail support
Orifice
Ink barrel

Director : Dr. Ahsan Choudhuri

MIRO Center for Space Exploration & Technology Research

Orbital Factory II

Dr. A. Choudhuri, J. Holt, B. Valdez

The University of Texas at El Paso

Project Objective

Use additive manufacturing to perform a 3D printer experiment with applications to repair solar cells in space.

Abstract

In 2016, the Center for Space Exploration and Technology Research a UTEP planned to develop a 1U CubeSat that will 3D print a conductive trace to repair a damaged solar cell using additive manufacturing. UTEP was awarded a launch opportunity by United Launch Alliance to GTO in an Atlas V. However, the first CubeSat will be tested in LEO with a launch to the International Space Station.

Introduction

Recent progress in miniaturization and affordability in aerospace technology and the interest to keep space exploration sustainable, have enabled universities and industries to develop small spacecraft, known as CubeSats, to conduct a variety of technological and scientific missions.

The type of proposed missions is diverse and the vast majority of CubeSats have been deployed in Low Earth Orbit (LEO). It is envisioned that in the near future more and more CubeSat missions will go far beyond LEO.

In this work, we introduce another CubeSat that will be deployed beyond, Orbital Factory III. OFIII was awarded 1st place in the ULA CubeCorp competition to launch a 1U Cube Satellite into orbit. The main payload of this spacecraft consists of a 3D printer that will perform self-repair of a simulated open-circuit solar cell using additive manufacturing techniques. The first iteration, OFII, is expected to be launched in 2019 on a Cygnus mission to the international space station.

Acknowledgments

The material is based upon work supported by the National Aeronautics and Space Administration (NASA) (Grant NNX158Q04A).

Methods and Materials

The printer represents the primary payload with a targeted mass of 30 grams. The following design requirements have been established:

- The printer shall comply with NASA Low Outgassing Requirements
- The printer shall apply a controlled three dimensional bead of electrically conductive material
- The printer shall utilize pre-charged extrusion system for power reduction
- No power systems shall be employed other than to control the printers traverse and nozzle positions
- The printer shall attain its power from the primary EPS system
- Command and control systems shall originate from the primary OBC
- The printing media shall be employed to permit a homing action and an estimated position measurement
- Final printing media shall posses a measurable conductivity

Results

The OFII CubeSat is made up of an OBC (On Board Computer); an Ultra High Frequency (UHF) and an S-band Transceiver; an electrical power system (EPS); and an in-house designed and built interface board, which has the function of interconnecting all the subsytems. The OBC, EPS, and both transceivers are built by EnduroSat in Bulgaria. Additionally, a custom CubeSat chassis is being designed in-house at UTEP.

Discussion

To inject the electric conductive material, a micro dispenser was designed and build. The dispenser injector contains a spring-loaded valve and a spring- loaded piston within the injector.
The spring inside the injector is compressed and exerted a force on the piston to inject the ink.

Another spring was used to create a normally-closed (NC) valve at the tip of the injector. To open the NC valve, a burn wire (30 AWG type Chromel C) mechanism released the compressed spring, to inject conductive ink.

Conclusions

The duration of the 3D printer experiment is approximately 2 minutes.

The printer will have drawn a conductive trace between terminal points on the print substrate.

The simulated printed repair of solar array experiment will be performed shortly after the second system checkout of the CubeSat mission phase.

References

Dr. Choudhuri[1], M. Everett[1], G. Olvera[1], J. Holt1, [1] MIRO Center of Space Exploration and Technology Research, "Orbital Factory II Printer Mechanism." The Southwest Emerging Technology Symposium 2017 at The University of Texas at El Paso

Figure 1.2: Fist poster used to introduce OF2 in different presentations in 2018.

The purpose of this is to propose a solution for those devices in space that get disconnected or broken. Also, secondary missions that will be performed in this CubeSat include taking pictures of the earth and testing an SBAND module designed by Lockheed Martin. After two years of work, OF2 construction was completed. OF2 was launched on a Northrop Grumman Antares rocket on November 2, 2019, and deployed from the CRS2 NG-12 (Cygnus) on January 31, 2020. This document presents the payload developed and the software libraries developed for the on-board computer (OBC) of this small satellite.

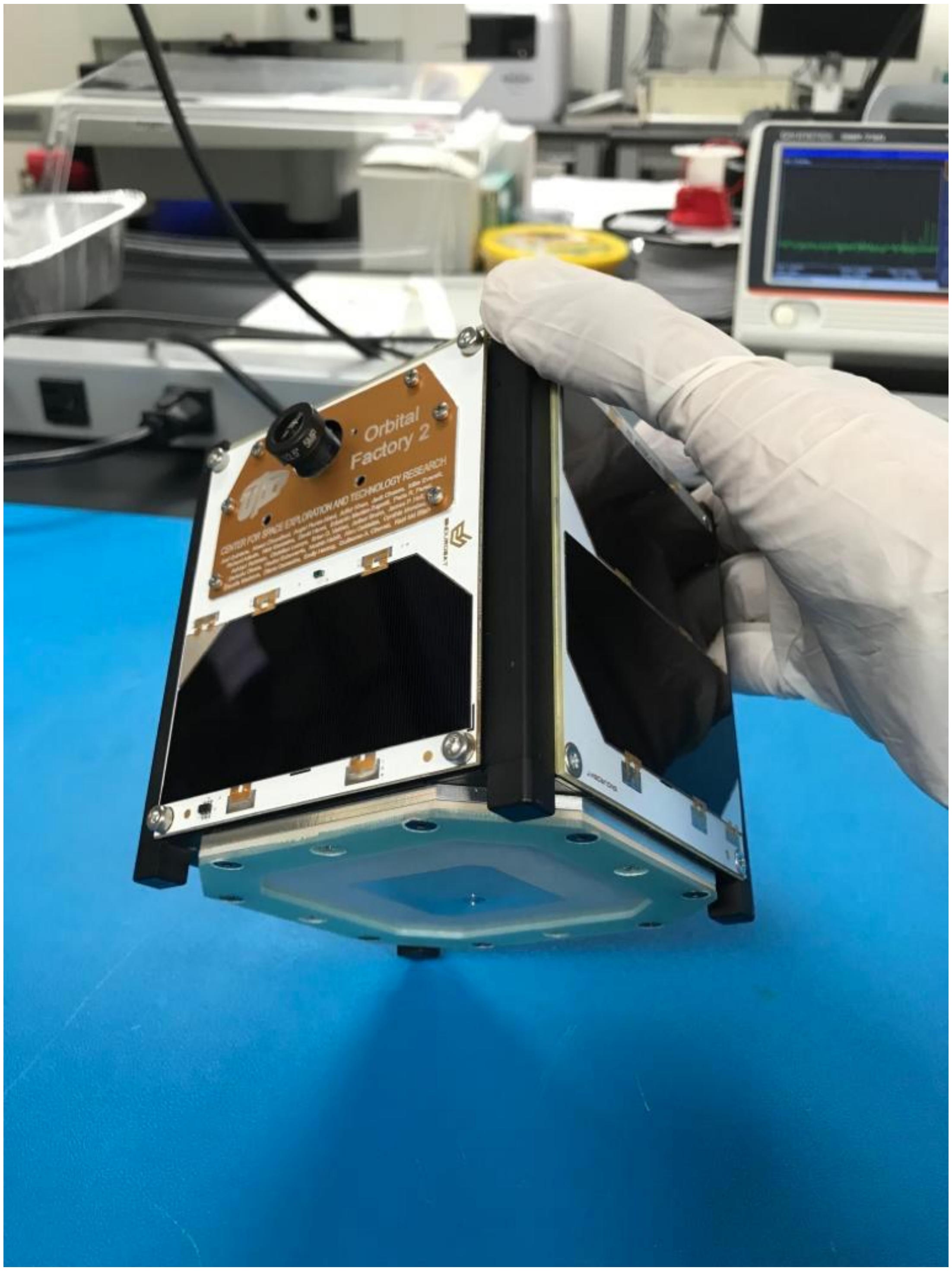


Figure 1.3: OF2 CubeSat fully assembled.

Chapter 2: Related Work

As Valvano said:

“The true engineering experience occurs not with your eyes and ears, but rather with your fingers and elbows. In other words, engineering education does not happen by listening in class or reading a book; rather it happens by designing under the watchful eyes of a patient mentor. So, go build something today, then show it to someone you respect.” – J. Valvano [3].

This project was possible thanks to related work from people who spent time researching and experimenting. For instance, the material selection for the ink was made based on Billah’s research [4]. In 2017 Billah presented the results of his experimentation using two types of electrically conductive ink. The first type was E1660 (Ecron) ink, which is made on a flake-based silver particle. The second ink type was CB102 (Dupont), which is made of nano silver particles. These two inks were chosen specifically because they passed NASA’s requirements for low outgassing. Billah tested both inks under a thermal ambient analyzing the conductivity results from these two types of ink under temperature ranging from -150 ºC to 350 ºC. Then Billah used a thermal vacuum chamber to simulate outer space pressure and temperature and analyzed the behavior of these two inks under these conditions. According to his results, both inks could work, but the best option for this project was to use Ecron ink.

Also, at a certain point of the OF2 project, the need for using a slave microcontroller in the payload became urgent. The OBC did not have enough general-purpose input-output (GPIO) ports for peripherals to run the conductivity test, which is the primary mission of the CubeSat. Actually, the OBC did not have any GPIO peripheral. It only had GPO pins, so it was not able to do a conductivity test. After some research it was found that Felker used an MSP430FR4133 microcontroller [5]. In 2018 Felker presented a project about the development of the first CubeSat from Rowan University. The mission of this satellite was to compare resistive memory against non-resistive memory such as dynamic random-access memory (DRAM) and electrically erasable programmable read only memory (EEPROM) under the effects of solar radiation including single event upsets. The payload microcontroller chosen for this mission was an MSP430FR4133, which is responsible for accumulating sensor and single event upset (SEU) data. The MSP430FR4133 will then search two types of memory, conductive-bridging random access memory and Flash, for SEU-induced bit flips. Felker used and MSP430FR4133 because this microcontroller family includes an architecture that is radiation-tolerant. After checking the specification sheet of this microcontroller, a 64-pin version was available for the OF2 PCB. This microcontroller resulted compatible to this project needs, not only because of its radiation tolerance, but because of the number of pins that it has. This microcontroller also solved the GPIO problem in the OBC.

In addition, to checking how ink spreads over the experimental printed circuit board (PCB), a small camera was considered for inclusion in the payload. However, it could not have been a high-power consumption camera, it just needed to have enough resolution to analyze the results of conductive ink deposition. Finally, when it was needed to decide which type of cameras were going to be used in the project, Khurshid's survey resulted helpful [6]. In 2013, the CubeSat Program of Pakistan’s Institute of Space Technology (IST) was going to launch their first CubeSat ICUBE-1. The objective of this project was to familiarize IST students with a satellite imaging system with image capture, analysis, compression, storage and retrieval. Khurshid, a member of ICUBE-1 project, presented that year a survey comparing CMOS vs. charged-coupled device (CCD) cameras. Based on his survey, CCD cameras consume more power and are likely to have more errors than CMOS cameras. However, CMOS-camera data fetching is slower than CCD’s. Based on Khurshid's survey of nine different cameras, the MicroCAM TTL camera was the best fit for OF2 needs. MicroCAM TTL features include low power consumption, JPEG compression, a UART serial interface, adjustable resolution, and a small size. The OF2 final decision was to use this serial CMOS camera mainly because of its good resolution and low power consumption.

In 2019, Perla Perez presented her thesis based on her work in the OF2 project [7], which focused on mechanical design of the payload.

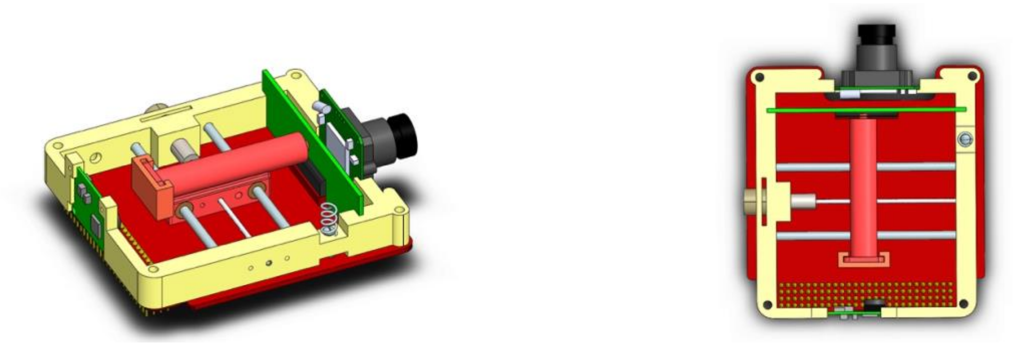


Figure 2.1: OF2 Payload CAD design, courtesy of Perla Perez.

Following this philosophy, this project is a little contribution to the vast world of engineering – hoping that the reader can get guidance from the experiments and conclusions that this thesis presents.

Chapter 3: Fundamental Theory and Principles

The fundamental theory and principles for this project are based on microcontroller applications. Microcontrollers are nowadays used for many different applications that include some form of computation. They can be used to solve a variety of real-life problems. For instance, microcontrollers are at the core of applications in the Internet of things (IoT) [8]. In this project, the purpose of the use of microcontrollers is to solve a real-life problem that is crucial for space exploration. As an illustration, when an ISS electronic device gets broken, an astronaut needs to fix it or replace it. A good example of such devices are solar cells, sometimes they get damaged in space and they cannot generate enough power to drive their electric system load. Thus, the idea of implementing a microcontroller to run an experiment that potentially could fix a solar cell in space could save a lot of time spent on repair. Moreover, this could open the doors for space exploring satellites to survive more time in space.

3.1 Embedded Systems

A microcontroller is a control unit (CU) that can be reprogrammed. Because of this, and using different data processing methods, a microcontroller can do different tasks without the need for fixed-hardware digital design. This enables the user to spend more time on developing the software and testing the system. When a microcontroller is programmed and implemented in a system, this system is referred to as an embedded system. There are different data processing techniques that can be applied in most microcontrollers. Basic techniques used in this project are presented in the next sections of this chapter.

3.2 General Purpose Input and Output

In embedded systems, general purpose input and output (GPIO) is the simplest data processing technique. It consists of reading a logical zero (0) for voltages between 0 volts (V), or ground, and 0.7 volts. To read a logical one (1), the voltage range is between 2.5V and 3.3V. This leaves a gap of 1.8 volts between logical 0 and logical 1.

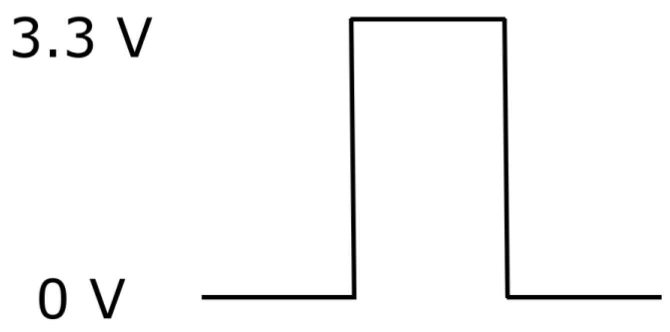


Figure 3.1: Example of a logic 1.

Depending on the 0s and 1s that are read, the microcontroller can execute different tasks from acting like a logic gate to more complex systems such as manipulating data sent from a satellite in space to a specific ground station on earth.

Figure 3.2: Example of a logic 0.

3.3 Pulse Width Modulation

Pulse width modulation (PWM) is a technique to manipulate DC power transmission with a microcontroller. Basically, PWM consists of an alternation of logical 0s and 1s in a certain amount of time. For instance, let’s assume a microcontroller uses GPIO to transmit a signal every millisecond. During this millisecond, for five hundred microseconds the GPIO signal is a 1, while the other 500 microseconds the GPIO signal is a zero. If this signal keeps repeating this process every millisecond the frequency of the signal results in 1KHz and the percentage of the modulation is 50 percent because half of the period the signal is one, and the other half of the period the signal is zero. If a DC voltmeter is connected to the signal, it will be observed that the output is half of the voltage supplied by a 1. In this case, assuming that 1 is 3.3V the voltage read would be 1.65V. In the same way, if the percentage is changed to ten percent, which is one hundred microseconds as a 1 and nine hundred microseconds as a zero, the voltmeter would read 330 millivolts. This technique is good for controlling the power of any output device that works using DC and is not adversely affected by the PWM signal frequency.

3.4 Analog to Digital Conversion

Most of the sensors in the electronics field work in an analog way. This means producing different continuous voltage levels that correlate with a physical measurement that is being read. For instance, the TMP36 integrated circuit is a common temperature sensor. This sensor can measure temperatures from negative 25ºC up to 125ºC. This sensor outputs a voltage that changes 10 millivolts for every 1ºC of temperature change. These changes in voltage could not be read using GPIO because of the digital voltage levels that GPIO uses. The solution for this problem is to use analog to digital conversion (ADC), where the microcontroller represents the voltage or current in a specific continuous range with an integer number. The accuracy of the number read depends on the resolution of the conversion and the voltage range. As an example, if a microcontroller has a range from 0 volts to 3.3 volts and a precision of conversion of 2_{14} bits, this means that the integer number will be represented with the numbers from 0 to 16,383 (2_{14}-1) for 0 to 3.3 volts respectively. In this case 1.5 volts or 1,500 millivolts would be represented with the integer number 7,446.

3.5 Universal Asynchronous Receiver Transmitter

Universal Asynchronous Receiver Transmitter (UART) is a serial communication mode that does not need clock synchronization. Instead of a synchronization clock, devices have the same baud rate, which is the number of bits that are transmitted per second. The most common baud rate is 9600 bits per second. Nevertheless, some devices can go up to three million (3000000) bits per second.

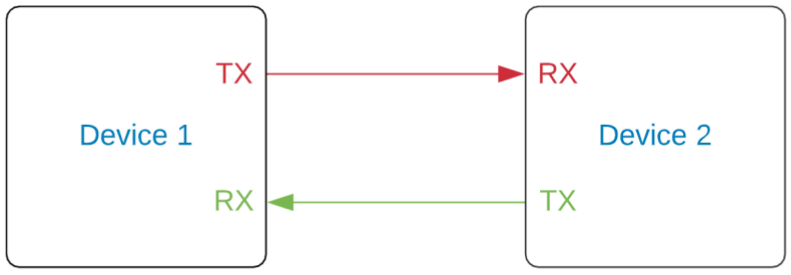


Figure 3.3: UART Connection.

When the communication is half-duplex, data can be sent bidirectionally but not simultaneously. When there is no data transmission, the transmitter sends a 1 constantly, which means the channel is idle. The standard protocol consists in the transmitter starting the transmission by sending a start bit, which is a zero. After the start bit, a data package is sent which consists of a byte (eight bits). To finish the transmission a stop bit is sent, which is a logical 1, thereafter the receiver goes back to idle mode. Also, an extra bit can be sent between the last data bit and the stop bit. This is called a parity bit and is used to ensure robust communication by detecting wrong packages received with a single bit error.

3.6 Inter-Integrated Circuit

Inter-integrated circuit (I2C) is a serial bus for communication where a master can communicate with different slaves. The bus consists of two lines, one for source clock synchronization (SCL), and one for data transmission (SDA). When the clock line starts to oscillate, the data line sends a one-byte packet. Every time that a byte has been sent in the data line, the clock stops oscillating for a small amount of time and this separates every packet that is being sent from other packets. Every slave has its own address, which is a seven-bit address where the least significant bit is a signal for the slave to know if it will receive or transmit data. If this last bit is a 0 from the master, this means transmit to the slave. On the other hand, if the last bit received from the master is a 1, this means receive from the slave.

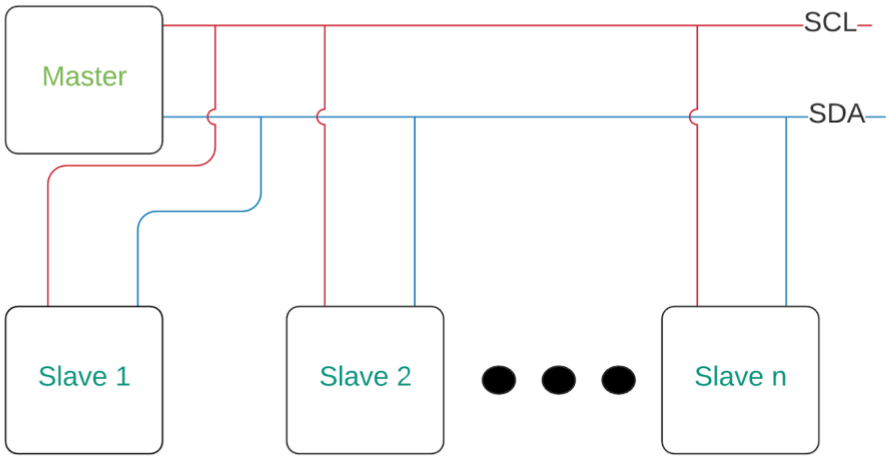


Figure 3.4: I2C Connection.

For instance, assuming that the address of a slave is 1011 110x in binary and the master starts to transmit data to this slave and writes 1011 1100, this means that after an acknowledge signal from the slave, the master is going to transmit one byte to the slave. On the other hand, if the master writes 1011 1101, this means that the master is expecting to receive a byte from the slave after the acknowledge signal.

3.7 Serial Peripheral Interface

Serial Peripheral Interface (SPI) is a synchronous communication approach that can communicate a master with different slaves. The difference between I2C and SPI is that SPI does not use addresses to communicate, but it uses a GPIO signal that enables the slaves that the master needs to communicate with. There are two signals to send data, namely, Master Out Slave In (MOSI) and Master In Slave Out (MISO). When the master wants to communicate with a slave it sends a 0 using GPIO to select the slave. After this, the clock starts to oscillate and MOSI starts to send data from master to slave. If the slave needs to send data to the master, MISO starts to send data. A disadvantage when SPI is used is the number of connections that are needed. If there are seven different slaves, seven different GPIO lines are needed for slave selection. A decoder would be a good option to reduce the number of output pins from the master. However, it is needed to connect every output of the decoder to the slave selection inputs.

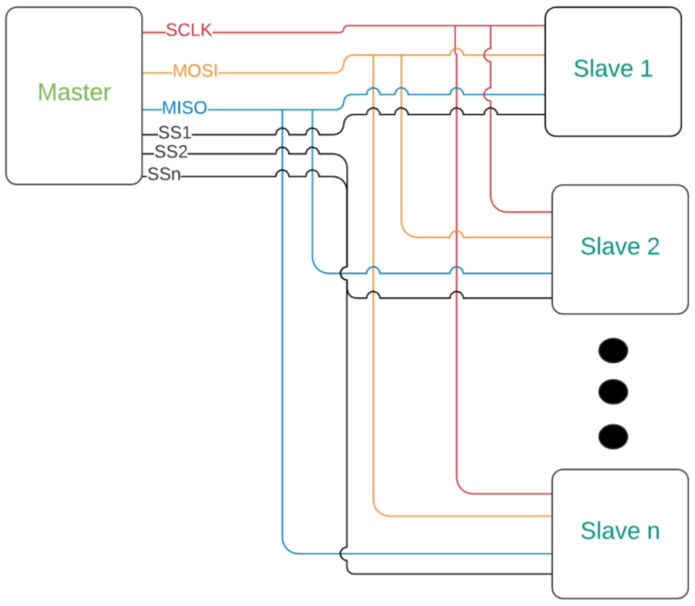


Figure 3.5: SPI Connection.

3.8 Software Development in C

C is a programming language developed as a tool for programmers working in Bell Labs in 1972 by Dennis Ritchie and Ken Thompson [9]. Nowadays C is one of the most common programming languages used both by the hobbyist and the professional programmer. C language results very useful for microcontrollers when programming at the register lever because it enables the programmer to interact directly with memory and registers. Also, C language is directly related to assembly language, which is the lowest abstraction layer between hardware and software. This helps the programmer to understand what is going on inside of the microcontroller as the instructions in C are being written. Microcontrollers used in this project have been programmed employing C language using different integrated development environments (IDE), which resulted helpful for debugging and behavior analysis.

3.9 FreeRTOS

FreeRTOS is a real-time operating system with a set of libraries for microcontrollers that simplify the development of a real time embedded system. A disadvantage of programming using this tool is that access to the microcontroller registers is partially limited. However, both the kernel and the threads are easy to manipulate and the use of libraries for all the functions result in a more convenient experience for the software engineer. The OBC was provided by EnduroSat and it included a code base with a FreeRTOS library. Due to this situation, the software for the OBC was written in C using FreeRTOS.

Chapter 4: System Design

To have a working embedded system, two things are necessary: hardware and software. Hardware relates to the physical part of the system while software refers to the instructions implementing algorithms to be executed inside the central processing unit (CPU). This chapter begins with section 4.1 introducing the hardware provided by EnduroSat, the CubeSat hardware vendor, because they provided the OBC and the software that controls it. The rest of the chapter covers all of the software and hardware designed for the OF2 payload, which are the basis of this thesis. In addition to meeting functional requirements, the design of payload subsystems aimed at reducing the probability of failures. The main hardware and software subsystems that comprise the OF2 payload are shown in Figure 4.10 as part of the system data flow and call graph.

4.1 Hardware

Some modules in this project were provided by Eurostat while some others were designed in-house specifically for OF2. In the next sections, hardware modules are presented.

4.1.1 On-Board Computer (OBC)

Due to lack of time before the launch, an OBC was bought from EnduroSat, which is a company specialized in CubeSat products. The OBC contains a detumbling controller, an attitude determination controlling system, a diagnostic module, and power management. These control units are manipulated using complex drivers. Peripheral devices provided in the embedded system are two three-axis gyroscopes, two three-axis accelerometers, three magnetometers, five sun sensors connected to solar panels, and an SD card. The microcontroller uses different data transmission techniques to communicate with the drivers like GPIO, UART, I2C, and SPI. The microcontroller provided is an STM32F42IIT6 and the IDE used to program this microcontroller is System Workbench, containing a FreeRTOS C library. This made coding easier for the mission. Even though some libraries were provided for basic communication, new libraries had to be built since the payload was designed, tested and assembled using different commercial off-the-shelf (COTS) products.

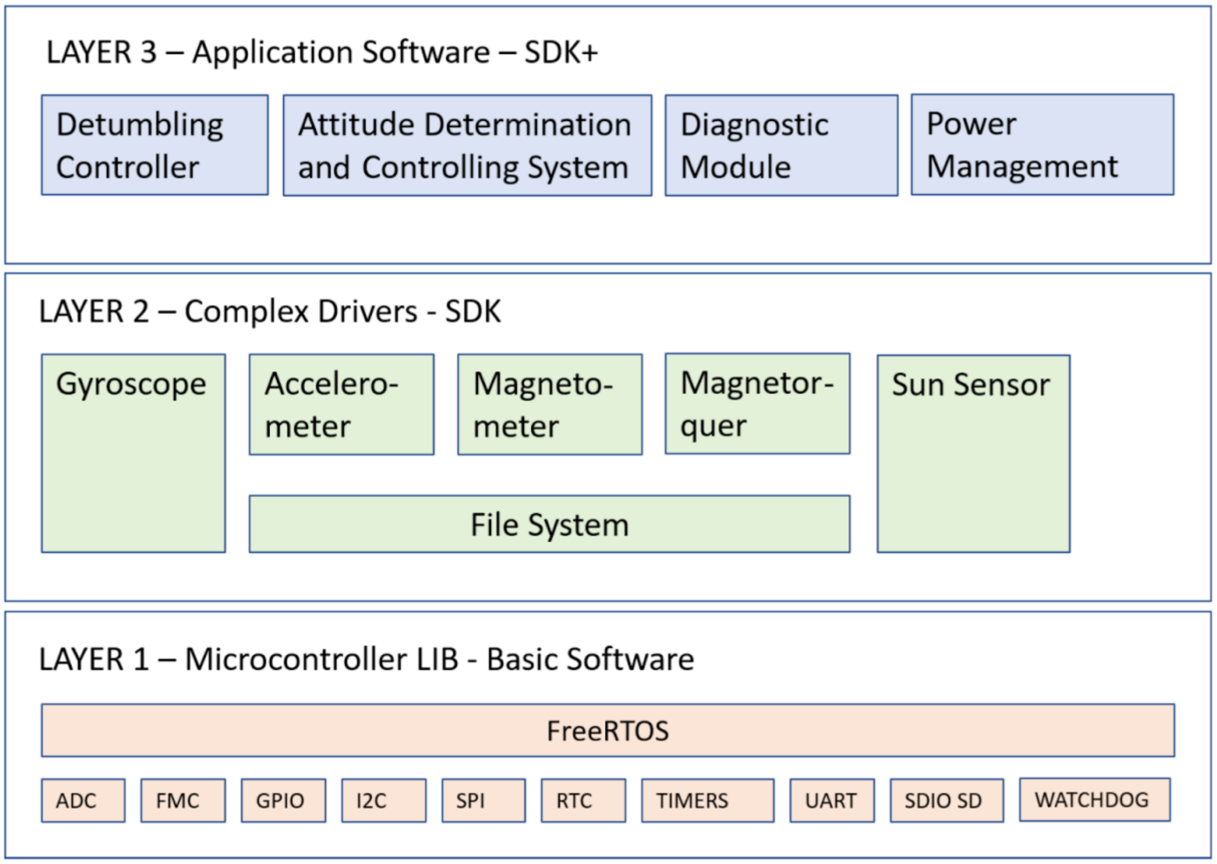


Figure 4.1: Layers for the OBC's components, courtesy of EnduroSat.

4.1.2 Accelerometers

Two three-axis linear accelerometers are included in the OBC unit. These two accelerometers are facing opposite sides of the printed circuit board (PCB). Accelerometers can be used to measure the non-gravitational forces acting on the CubeSat. However, this could not be implemented due to the lack of time with respect to the launch. Both accelerometers were tested and they operate fine. Accelerometer communicate with the OBC via I2C.

4.1.3 Magnetometers

Two magnetometers are included in the OBC unit. In the same way as the accelerometers, these two magnetometers are placed facing opposite sides of the PCB. The function of the magnetometers is to read the magnetic field that is being exerted on the small satellite in space and activate magnetorquers using PWM to make a detumbling system. This helps to avoid the Doppler effect that would be generated if the satellite is spinning while it is orbiting around the earth. These accelerometers communicate to the OBC via I2C and they are integrated in the system. Nevertheless, a detumbling algorithm was not implemented due to lack of time before the launch.

4.1.4 Diagnostic Module

The diagnostic module collects data and manages data and an SD card connected to the OBC via SPI. This diagnostic module keeps different text files for the most important modules, namely, the modules for the Electric Power System (EPS), OBC, Payload, Solar Panels, and UHF.

Diagnostic values of the EPS have a one- or two-byte number for every register status that can be decoded using Eurostat's reference sheet. As an example, register one has a 12-bit ADC conversion that refers to the battery voltage status. A number read from that register needs to be multiplied times 0.0023394775 and the result is the actual voltage stored in the batteries from the EPS in volts.

Diagnostic values of the OBC give an update of the actual time that is being read by the real-time clock (RTC) and an update of status for the magnetometer sensors.

The diagnostic values of the solar panels give an update of the temperature of every solar panel and the status of five photodiodes, each one connected to one axis of the CubeSat except for the one that does not have a solar panel.

Diagnostics of the UHF module give a two-byte status register that can be decoded using the user manual. This register can be used to determine if the antennas were deployed correctly, the frequency of receiving and transmitting, the time period for beacon signals, and the number of resets that the UHF module has performed.

Text files can be accessed and read sending a specific instruction ping (+2%) from the ground station. This instruction is discussed in detail in table 4.5.

4.1.5 Power Management

All of the power management is controlled using an electric power system (EPS) designed by EnduroSat. This system has two Li-Po battery packs encapsulated inside an aluminum box. The capacity of these battery packs can go up to 20.98 Wh. The EPS has a system protection against overvoltage, overcurrent, and overtemperature. Moreover, the system has a low power mode algorithm that shuts down the battery bus when the raw voltage in the batteries goes below 3.05 volts. Once the batteries reach a voltage of 4.65 volts or above, the algorithm turns on the battery bus again. Also, the EPS has two latch-up voltage switches that turn off the power supply for 5 volts and 3.3 volts. When the current exceeds 2 amperes, these latch up switches can be turned off sending an instruction via I2C from the OBC. Also, the EPS system has 52 registers that can be read to check the status of different modules. The system also has six connections for the solar panels, so that it can get charged once the satellite is in space. Finally, the system has six general purpose output (GPO) pins that can be accessed using the OBC. Some of these GPO pins have a pre-assigned function, like turning on the OBC, UHF module, or SBAND module. Every GPO pin has a diode connected to avoid reverse current flow, this is for safety purposes of the whole CubeSat.

4.1.6 File System

The OBC has an SD card system to store data to be transmitted to earth. This storage uses a FATS file system. The library implemented to send commands to the SD card using C is called FATS FS. This is a multi-microcontroller file system that resulted useful.

4.2 Payload

Even though the payload can be considered hardware, it was decided to cover it in an independent section. The purpose of this is to describe in more detail how the payload was designed, tested, improved, retested, assembled, and included in the OF2 CubeSat. Every part of the payload was designed and tested in UTEP by different team members of the OF2 project. In the next sections a description of the printer is presented focusing in its electronics and sensors.

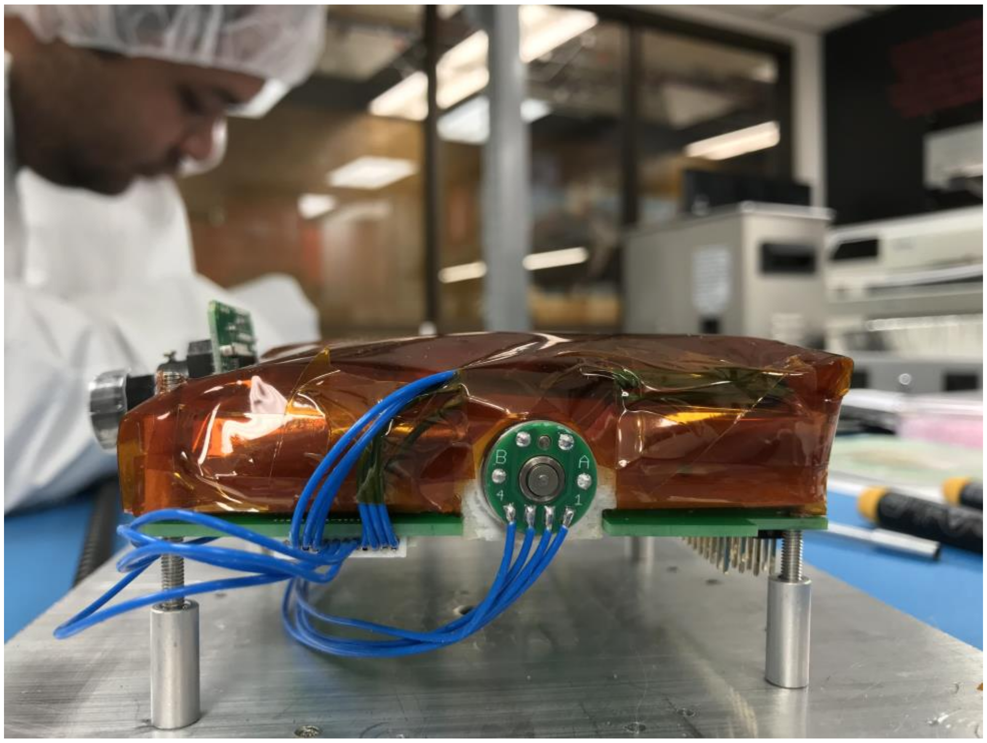


Figure 4.2: Payload module before being placed in the CubeSat.

4.2.1 Early Design

The primary mission for this CubeSat is to deposit a special ink that cures in space and becomes conductive. At the beginning of the project, the ink was being released from a nozzle using a nylon wire that was burned using electricity. The heat generated by the burned wire melted wax on the tip of the nozzle. Using a motor driver and a stepper motor connected to a one-axis rail, the ink could be spread over a PCB. The ink was tested in a vacuum chamber. After three minutes the ink cured. Then it was taken out of the vacuum chamber and conductivity was tested using a voltmeter to prove that indeed the cured ink was conductive.

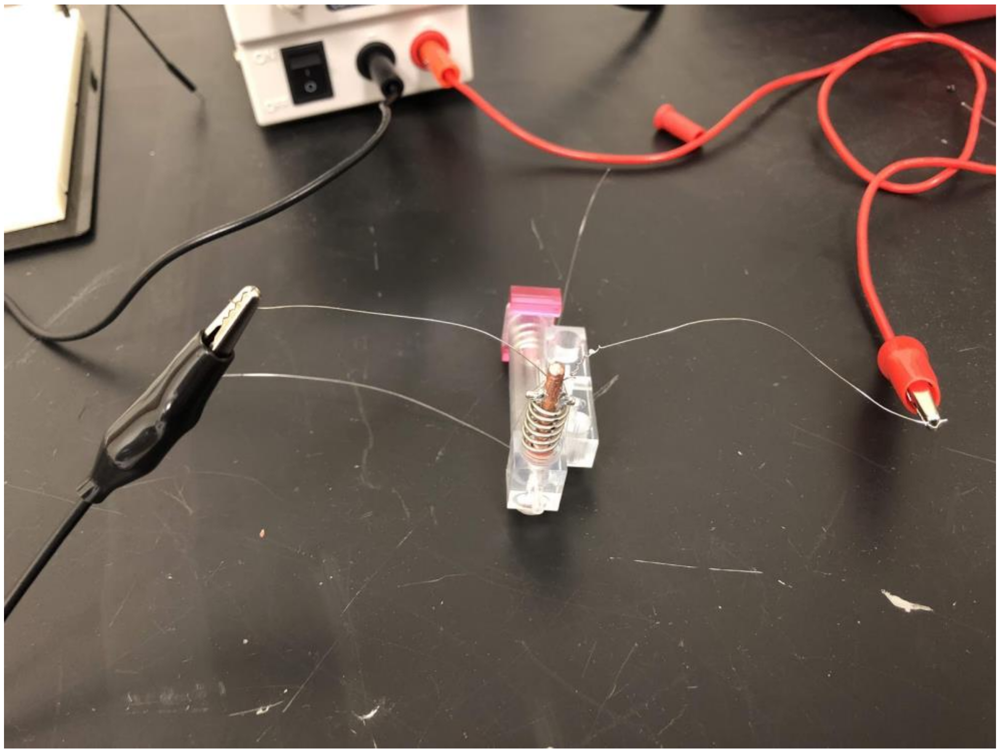
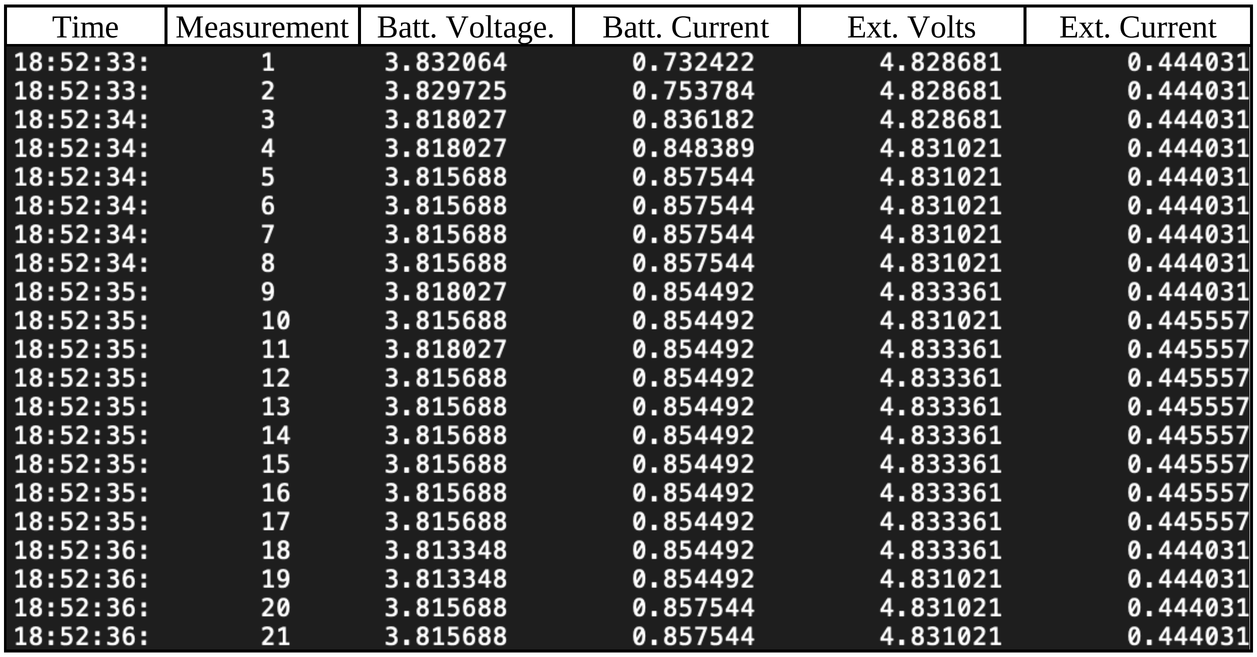


Figure 4.3: Early design of the nozzle using nylon wire.

During this early experimentation, an Arduino processor was used. The OBC could not be used for the experiments because it needed to control at least four GPIO peripherals. Due to the lack of GPIO peripherals in the OBC, the Arduino processor became an early solution. However, it was not a good idea to use an Arduino because it was not for sure at all that this device could survive being exposed to space radiation. Another solution that was tested was to use a field programmable gate array (FPGA). However, during the SETS Symposium in 2019, a presentation about OF2 was given [10] and there was a recommendation to use a radiation-tolerant microcontroller. Following these exchanges, the option of using an FPGA was discarded.

After looking for different options for the payload microcontroller and reviewing Felker document [5] as mentioned in chapter 2, a Texas Instruments MSP430FR4133 microcontroller was chosen as the OBC slave for payload control. This microcontroller was chosen specifically because its architecture is proven to work under radiation. This microcontroller has an IC version with 64 pins. This model fitted completely the specification needed for running the experiment. For testing conductivity, twenty-six GPIO pins were used, ten pins would deliver signals, while sixteen pins would read voltage in different areas of a PCB. If the ink cured properly, all of the input pins in the PCB would be set resulting in a successful conductivity proof. The number of the pins reading voltage and their result would be stored in the OBC's SD card with a two-byte number representing the number of pins that resulted positive after the conductivity test.



Time	Measurement	Batt. Voltage.	Batt. Current	Ext. Volts	Ext. Current
18:52:33:	1	3.832064	0.732422	4.828681	0.444031
18:52:33:	2	3.829725	0.753784	4.828681	0.444031
18:52:34:	3	3.818027	0.836182	4.828681	0.444031
18:52:34:	4	3.818027	0.848389	4.831021	0.444031
18:52:34:	5	3.815688	0.857544	4.831021	0.444031
18:52:34:	6	3.815688	0.857544	4.831021	0.444031
18:52:34:	7	3.815688	0.857544	4.831021	0.444031
18:52:34:	8	3.815688	0.857544	4.831021	0.444031
18:52:35:	9	3.818027	0.854492	4.833361	0.444031
18:52:35:	10	3.815688	0.854492	4.831021	0.445557
18:52:35:	11	3.818027	0.854492	4.833361	0.445557
18:52:35:	12	3.815688	0.854492	4.833361	0.445557
18:52:35:	13	3.815688	0.854492	4.833361	0.445557
18:52:35:	14	3.815688	0.854492	4.833361	0.445557
18:52:35:	15	3.815688	0.854492	4.833361	0.445557
18:52:35:	16	3.815688	0.854492	4.833361	0.445557
18:52:35:	17	3.815688	0.854492	4.833361	0.445557
18:52:36:	18	3.813348	0.854492	4.833361	0.444031
18:52:36:	19	3.813348	0.854492	4.831021	0.444031
18:52:36:	20	3.815688	0.857544	4.831021	0.444031
18:52:36:	21	3.815688	0.857544	4.831021	0.444031

Figure 4.4: Power analysis while the motor was running.

4.2.2 Power Analysis

After power analysis while the experiment was running, some modifications were needed because the payload was consuming too much power. The current supplied to burn the wire was between two and three amperes. Also, the stepper motor was consuming about 0.8 amperes for ninety seconds when it was moving the nozzle around the rail. As can be seen in Figure 4.4, the first column shows the timestamp, the second column shows the number of them measurement, the third column shows voltage supplied in the battery bus in volts, the fourth column shows the current consumed from the battery bus in milliamperes, the fifth column shows the external battery voltage, and the last column shows the external battery current in milliamperes.

4.2.3 Improvements in Design

The results of this analysis showed that a shutdown of the CubeSat could happen while the experiment was running. To avoid a possible shutdown, the whole payload was moved from the regular voltage bus to the LUP bus and to avoid the two-ampere consumption generated by burning the wire, an electric valve was implemented to open and close the nozzle. The specification sheet of this valve recommends to use it at a temperature above 10 ºC degrees, otherwise the valve could neither open nor close. Thus, a temperature sensor was connected to the valve. The first sensor tested was a DS18B20, a digital sensor that uses a one-wire protocol. Since this protocol was not included in the MSP430, this temperature sensor was exchanged for a TMP36, a temperature sensor that works using ADC. A spring was placed inside the valve to release the ink and a pressure sensor was tested to detect if the ink was being deployed. Nevertheless, this could not succeed because the spring was not strong enough to create a considerable change in the pressure sensor. Even with an amplifier, not too much change in the pressure sensor reading was detected. Thus, the pressure sensor had to be discarded from the payload.

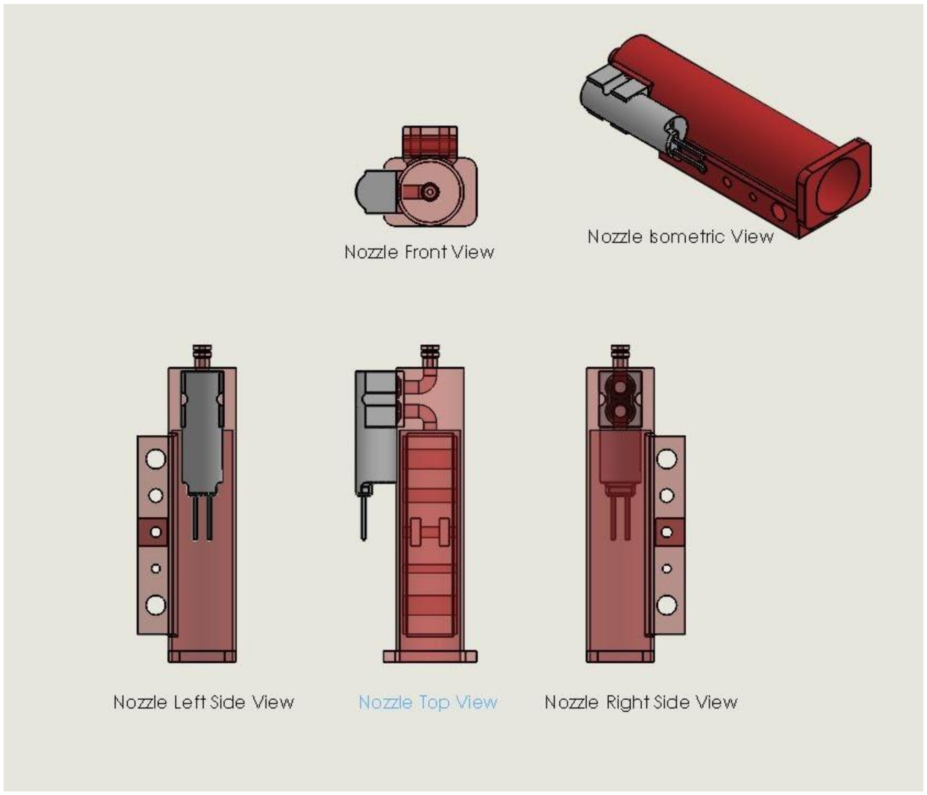


Figure 4.5: Design of the nozzle using the valve.

4.2.4 Commercial Off-The-Shelf Cameras

To see how the ink spread around the payload, a small camera was going to be connected inside of the payload. For a secondary mission, another camera was going to be taking pictures of the earth. Some inexpensive cameras were found at Spinel Electronics. The camera chosen for earth pictures is a SC50MPA model. This is 5.0-megapixel camera. For internal pictures, not too much resolution was needed. Thus, an SC03MPA model was chosen. This is a 0.3-megapixel camera. Both cameras are built in the same fashion, the only difference is their resolution. They are one fourth CMOS color image sensors with JPEG compression. They have a UART serial interface at a baud rate of 115,200 bits per second. The communication protocol that these cameras use is VC0706, which consists in sending and receiving data for instructions. Cameras turn on and off using LUP buses and they were routed to the OBC bus using two pico-Molex connectors in the payload. The algorithm implemented to take pictures from the OBC is shown in Figure 4.6.

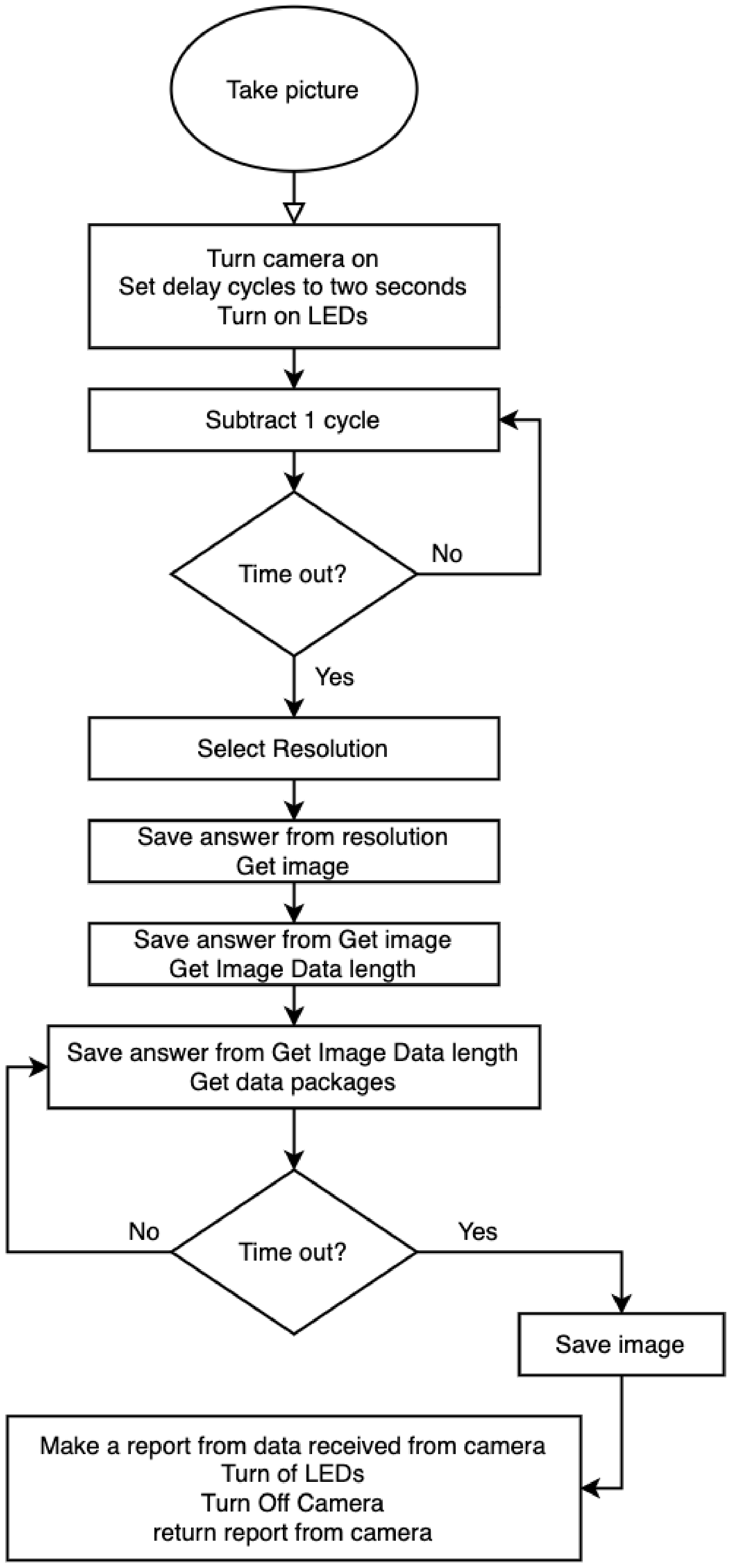

Take picture
Turn camera on
Set delay cycles to two seconds
Turn on LEDs
Subtract 1 cycle
Time out?
No
Yes
Select Resolution
Save answer from resolution
Get image
Save answer from Get image
Get Image Data length
Save answer from Get Image Data length
Get data packages
No
Time out?
Yes
Save image
Make a report from data received from camera
Turn of LEDs
Turn Off Camera
return report from camera

Figure 4.6: Algorithm implemented to take pictures.

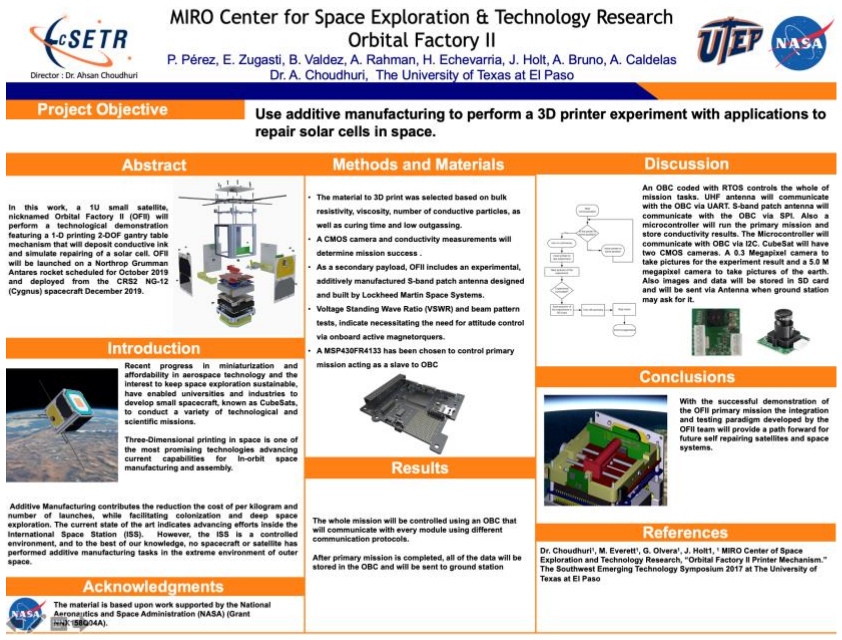
First, when the camera is turned on, an initial set of bytes is sent. After these bytes are sent, an instruction is sent to set the resolution selected. The next step is to send an instruction to the camera to get an image. If the camera answers back with and image taken, the next step is to ask about data length of the image. Once the camera answers with the data length, this specific amount of data is asked to be sent from the camera. At this point, the beginning of the picture will start with 0xFFD8 because this is how the jpeg format starts. In the same way, the picture must finish with 0xFFD9. If this ending is not received, the picture may be corrupted. Data is received and stored in ASCII representing hex format, so once downloaded it needs to be converted from hex to jpeg to see the actual picture. All of the answers from the camera are revised by the OBC. At the end, the OBC creates an array with a report for any wrong answer from the camera during the execution of the algorithm. If any step is wrong, the picture taken will not be stored in the SD card.

For internal pictures, two white LEDs were placed inside the payload board pointing to the conductivity test PCB. LEDs turn on using the MSP430 slave. It was expected that in every pass in space, the ground station would have between seven to nine minutes to download data from the CubeSat. A picture would need about thirty minutes to be downloaded completely. Also, some earth pictures may be completely black if the camera was pointing to space at the moment they were taken. The solution to this data problem was to make every camera to take two pictures. One with the lowest resolution possible and the second one with the full resolution. The lowest resolution pictures need about 10 minutes for transmission and could be downloaded in 2 passes. Cameras needed to be turned on only when they were taking pictures, so they are connected also to the LUP voltages to save power. When everything was tested in a FlatSat. A PCB for connecting everything in the payload was designed and tested. The MSP430FR4133 was debugged and coded using a spy-bi-wire connection. Instead of buying an MSP430 debugger, an MSP430FR4133 Launchpad was bought and connected to the spy-by-wire pins of the IC in the PCB. After a few corrected versions of the PCB, the first picture taken by the payload and controlled by the OBC was taken, thus running a successful experiment.

Figure 4.7: Experiment picture taken by the payload.

4.2.5 Assembly

Finally, to have control of the position of the nozzle when the experiment is meant to start, a home-position switch was implemented using two screwdrivers that close a circuit when they are touching each other. A GPIO pin is connected to this circuit with a pull-down resistor to avoid static voltages. If the nozzle is not in home position at the beginning of the experiment, the nozzle will be moved towards home position.



MIRO Center for Space Exploration & Technology Research

Orbital Factory II

P. Pérez, E. Zugasti, B. Valdez, A. Rahman, H. Echevarria, J. Holt, A. Bruno, A. Caldelas

Dr. A. Choudhuri, The University of Texas at El Paso

Director : Dr. Ahsan Choudhuri

Project Objective

Use additive manufacturing to perform a 3D printer experiment with applications to repair solar cells in space.

Abstract

In this work, a 1U small satellite, nicknamed Orbital Factory II (OFII) will perform a technological demonstration featuring a 1-D printing 2-DOF gantry table mechanism that will deposit conductive ink and simulate repairing of a solar cell. OFII will be launched on a Northrop Grumman Antares rocket scheduled for October 2019 and deployed from the CRS2 NG-12 (Cygnus) spacecraft December 2019.

Introduction

Recent progress in miniaturization and affordability in aerospace technology and the interest to keep space exploration sustainable, have enabled universities and industries to develop small spacecraft, known as CubeSats, to conduct a variety of technological and scientific missions.

Three-Dimensional printing in space is one of the most promising technologies advancing current capabilities for In-orbit space manufacturing and assembly.

Additive Manufacturing contributes the reduction the cost of per kilogram and number of launches, while facilitating colonization and deep space exploration. The current state of the art indicates advancing efforts inside the International Space Station (ISS). However, the ISS is a controlled environment, and to the best of our knowledge, no spacecraft or satellite has performed additive manufacturing tasks in the extreme environment of outer space.

Acknowledgments

The material is based upon work supported by the National Aeronautics and Space Administration (NASA) (Grant NNX158Q04A).

Methods and Materials

- The material to 3D print was selected based on bulk resistivity, viscosity, number of conductive particles, as well as curing time and low outgassing.
- A CMOS camera and conductivity measurements will determine mission success .
- As a secondary payload, OFII includes an experimental, additively manufactured S-band patch antenna designed and built by Lockheed Martin Space Systems.
- Voltage Standing Wave Ratio (VSWR) and beam pattern tests, indicate necessitating the need for attitude control via onboard active magnetorquers.
- A MSP430FR4133 has been chosen to control primary mission acting as a slave to OBC

Results

The whole mission will be controlled using an OBC that will communicate with every module using different communication protocols.

After primary mission is completed, all of the data will be stored in the OBC and will be sent to ground station

Discussion

An OBC coded with RTOS controls the whole of mission tasks. UHF antenna will communicate with the OBC via UART. S-band patch antenna will communicate with the OBC via SPI. Also a microcontroller will run the primary mission and store conductivity results. The Microcontroller will communicate with OBC via I2C. CubeSat will have two CMOS cameras. A 0.3 Megapixel camera to take pictures for the experiment result and a 5.0 M megapixel camera to take pictures of the earth. Also images and data will be stored in SD card and will be sent via Antenna when ground station may ask for it.

Conclusions

With the successful demonstration of the OFII primary mission the integration and testing paradigm developed by the OFII team will provide a path forward for future self repairing satellites and space systems.

References

Dr. Choudhuri¹, M. Everett¹, G. Olvera¹, J. Holt1, ¹ MIRO Center of Space Exploration and Technology Research, "Orbital Factory II Printer Mechanism." The Southwest Emerging Technology Symposium 2017 at The University of Texas at El Paso

Figure 4.8: Poster used for presentation to NASA visitors in 2019 introducing a new payload design.

When the experiment was run, sometimes the ink started to leak outside of the objective PCB board. If this could happen in space, there is a possibility for the ink to spread around critical components of the CubeSat creating a short circuit. To avoid this possibility the payload was wrapped in Kapton tape.

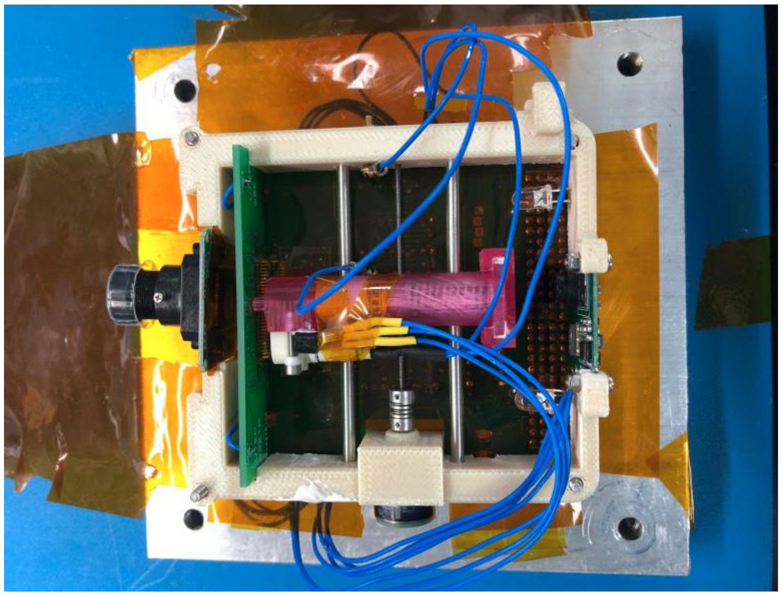


Figure 4.9: Assembled Payload.

4.3 Software

All the software for this project was written in C. The OBC has an STM32F42IIT6 microcontroller, which is based on the ARM Cortex M4 processor. The main clock frequency of this microcontroller can go up to 180 MHz and consumes typically 104 mA. It has 2MB for program memory and 256kB of RAM. EnduroSat provided basic code using FreeRTOS and libraries for the devices included in the OBC. The software development kit (SDK) used is System Workbench, which is an Eclipse-based platform. Even though basic libraries were provided by the OBC vendor, others had to be written to meet the needs of this mission. For the payload an MSP430FR4133 was used. This is a Texas Instruments mixed signal microcontroller with a 16-bit RISC architecture that can operate at 16 MHz. However, it was used at a frequency of 1MHz for this project. This microcontroller consumes 139 microamperes because it was programmed to be in low power mode when not in use. It has 15KB of program flash memory and 2KB of RAM. The software development kit used for programming this microcontroller is Code Composer Studio provided by TI and it is also an Eclipse-based platform. The microcontroller was programmed at the register level using only the msp430.h header file.

4.3.1 SCMPA Library

The OBC has three UART channels available. One is used to communicate with the UHF antenna module, another one is used for ground-station communications, and the last one is intended to be used for payload. At the beginning, it was planned to use one camera to communicate using UART and the other one with SPI. However, after a few weeks this task resulted harder than expected. Then the option of using both cameras with UART was put on the table. The problem with this alternative was that the OBC only had one UART bus and both cameras used the same communication protocol. The baud rate could be changed in one of the cameras but this could cause a problem if the cameras get reset, because by default both have a baud rate of 115,200 bits per second. A decoder was another option, but in the end the communication UART bus was tested and worked without any interruption in other tasks of the OBC. Every picture that is taken successfully is stored in the SD card in a text file with a unique identification number in the name of the file. In Table 4.1, the functions developed are presented with a brief description.

Table 4.1: SCMPA library instructions.

Function	void take_picture(char cam);
Brief	Depending on the character received, the OBC will take an internal picture or an external picture.
Param in	char cam
Return	void

Function	void SC03MPA_TAKE_PICTURE(char s);
Brief	Depending on the character received, the internal camera will take a low-resolution picture or a high-resolution picture.
Param in	char s
Return	void

Function	void SC50MPA_TAKE_PICTURE(char s);
Brief	Depending on the character received, the external camera will take a low-resolution picture or a high-resolution picture.
Param in	char s
Return	void

Function	void SC50MPA_ON (void);
Brief	Send a specific set of bytes that turn on external camera.
Param in	void
Return	void

Function	int SC50MPA_GET_IMAGE (void);
Brief	Send the instruction to external camera to get an image.
Param in	void
Return	Answer from the camera following VC0706 communication protocol.

Function	int SC50MPA_READ_IMAGE_DATA_LENGTH (void);
Brief	Send the instruction to external camera to get the number of bytes of the image taken.
Param in	void
Return	Answer from the camera following VC0706 communication protocol.

Function	int SC50MPA_READ_IMAGE_DATA (char s);
Brief	Send the instruction to send the bytes of the picture and then save them in the SD card in a txt file.
Param in	void
Return	Answer from the camera following VC0706 communication protocol.

Function	int SC50MPA_RESOLUTION_SELECT (int Res);
Brief	Select the resolution for the picture to be taken
Param in	void
Return	Answer from the camera following VC0706 communication protocol.

Function	int SC50MPA_STOP (void);
Brief	Stop taking pictures from external camera
Param in	void
Return	Answer from the camera following VC0706 communication protocol.

Function	int SC03MPA_RESET (void);
Brief	Send a specific set of bytes that turn on internal camera.
Param in	void
Return	void

Instruction	int SC03MPA_GET_IMAGE (void);
Brief	Send the instruction to internal camera to get an image.
Param in	void
Return	Answer from the camera following VC0706 communication protocol.

Function	int SC03MPA_READ_IMAGE_DATA_LENGTH (void);
Brief	Send the instruction to internal camera to get the number of bytes of the image taken.
Param in	void
Return	Answer from the camera following VC0706 communication protocol.

Function	int SC03MPA_READ_IMAGE_DATA (char s);
Brief	Send the instruction to send the bytes of the picture and then save them in the SD card in a txt file.
Param in	void
Return	Answer from the camera following VC0706 communication protocol.

Function	int SC03MPA_BAUD_RATE_SELECT (int Baud03);
Brief	Change the baud rate of the internal camera.
Param in	void
Return	Answer from the camera following VC0706 communication protocol.

Function	int SC03MPA_COMPRESS (int comp);
Brief	Change the compression ratio of the internal camera.
Param in	void
Return	Answer from the camera following VC0706 communication protocol.

Function	int SC03MPA_RESOLUTION_SELECT (int Res);
Brief	Change the resolution of the internal camera.
Param in	void
Return	Answer from the camera following VC0706 communication protocol.

Function	int SC03MPA_STOP (void);
Brief	Stop taking pictures from internal camera.
Param in	void
Return	Answer from the camera following VC0706 communication protocol.

4.3.2 Payload Library

The payload is controlled by a TI MSP430F4133 microcontroller. However, this microcontroller only acts as a slave receiving instructions from the OBC master. Both microcontrollers interact using I2C. A custom application protocol was designed for communication of these two devices. This protocol is explained in detail in chapter 4 section 4.3.6. The OBC has three I2C buses, the one selected to communicate with the MSP430 is the payload bus. The address of the MSP430 is 0xD0. The MSP430 is in low power mode and as soon as it gets an instruction from the OBC, it executes the instruction and goes back to low power mode. When the experiment was being tested, sometimes the EPS was shutting down the whole CubeSat because the batteries did not have enough power. To avoid this problem, a threshold voltage of 3.9 volts was set at the beginning of the experiment. If there were a need to force the experiment avoiding the threshold voltage, a "force" variable is set to run the experiment. Once the experiment is done, the conductivity test results are stored in a file called "test.txt." All of the functions needed to run the experiment by the OBC are in a file called "payload.c" and "payload.h". Also, some functions were created to have an updated status of the most important modules which are EPS, UHF, OBC, Payload, and Panels. All of these files contain a timestamp based on the real-time clock inside the OBC. These functions are discussed in Table 4.2.

Table 4.2: Payload library functions.

Function	uint8_t check_home(void);
Brief	Check if the nozzle is in home position.
Param in	void
Return	uint8_t 1 (true) or 0 (false) for home position.

Function	void move_nozzle(char position, int steps);
Brief	Move the nozzle towards ('+') home position or against ('-') home position the desired number of steps for the stepper motor.
Param in	char position, int steps
Return	void

Function	void deploy_ink(int force);
Brief	Open valve to deploy ink.
Param in	int force
Return	void

Function	int check_temperature (void);

Brief	Check if temperature is above 10°C to open the valve. This function returns the temperature in an integer representing °C.
Param in	void
Return	int

Function	void LEDS_ON (void);
Brief	Turn on white LEDs from payload to take a picture of the experiment with the internal camera.
Param in	void
Return	1 (true) or 0 (false) for home position.

Function	void LEDS_OFF (void);
Brief	Turn off LEDs from payload.
Param in	void
Return	1 (true) or 0 (false) for home position.

Function	void enable_mux_read_demux (uint8_t test);
Brief	Run conductivity test and check conductivity in specific pin.
Param in	uint8_t test
Return	void

Function	void log_test(uint8_t I,uint8_t da);
Brief	Create log file to store the experiment result of specific pin.
Param in	uint8_t I, uint8_t da
Return	void

Function	void stop_ink(void);
Brief	Close the valve to not deploy ink anymore.
Param in	void
Return	void

Function	void I2C1_Reset(void);
Brief	Reset payload I2C to default settings.
Param in	uint8_t test
Return	void

Function	void logger (char data[], char path[]);
Brief	General function that creates a file in a specific folder with the data requested.
Param in	char data, char path
Return	void

Function	void loggerEPS (void);
Brief	Create a file called "EPS.txt" storing all of the status register numbered from 0 to 52. This file can be also opened in excel.
Param in	void
Return	void

Function	void loggerUHF(void);
Brief	Create a file called "UHF.txt" which present the actual status of the UHF. This file can also be opened in excel
Param in	void
Return	void

Function	void loggerOBC(void);
Brief	Create a file called "OBC.txt" which present the last reads of the magnetometers and the accelerometers in the OBC. This file can also be open in excel.
Param in	void
Return	void

Function	void loggerPayload(void);
Brief	Create a file called "PAY.txt" which present the status of the Payload.
Param in	void
Return	void

Function	void loggerPanels(void);
Brief	Create a file called "PAN.txt" which present the last reads of the from the photovoltaic sensors and the temperature sensors in every solar panel. This file can also be open in excel.
Param in	void
Return	void

4.3.3 EPS Library

The EPS has its own microcontroller and some instructions can be sent to it to manipulate the GPIO of the OBC and check the voltage and current of different buses and batteries in the EPS module. The interface is via I2C and the address of the EPS module is 0x18, but it is a 7-bit address, so this address needs to be shifted one bit to the left in the OBC code. Some functions had to be developed for power analysis and debugging. Functions are in the files named "EPS.h" and "EPS.c". The functions written in this file are presented in Table 4.3.

Table 4.3: EPS library functions.

Function	void Read_EPS_Reg (uint8_t regNumber);
Brief	Reads a specific register of the EPS module and stores it in a global array.
Param in	uint8_t regNumber
Return	void

Function	float EPS_Battery_Voltage (void);
Brief	For debugging purposes. Reads register 1 which stores the voltage of the battery bus in ADC format. Then multiplies it by a constant and prints it out in the terminal. This function returns a float variable for the voltage in volts units with 2 decimals precision.
Param in	void
Return	float

Function	float EPS_Battery_Current (void);
Brief	For debugging purposes. Reads register 2 which stores the voltage of the battery bus in ADC format. Then multiplies it by a constant and prints it out in the terminal. This function returns a float variable for the current in milliampere units.
Param in	void
Return	float

Function	float EPS_Extern_Battery_Voltage (void);
Brief	For debugging purposes. Reads register 3 which stores the voltage of the raw battery in ADC format. Then multiplies it by a constant and prints it out in the terminal. This function returns a float variable for the voltage in volts units with 2 decimals precision.
Param in	void
Return	float

Function	float EPS_Extern_Battery_Current (void);
Brief	For debugging purposes. Reads register 4 which stores the current of the raw battery in ADC format. Then multiplies it by a constant and prints it out in the terminal. This function returns a float variable for the current in milliampere units.
Param in	void
Return	float

Function	void Power_Analysis (void);
Brief	For debugging purposes. Creates a file called “POW.txt”. This file has 6 columns containing a timestamp, number of row, battery bus voltage read, battery bus current read, raw battery voltage read and raw battery current read.
Param in	void
Return	void

Function	void Enable_LUP (uint8_t v);
Brief	Enables LUP bus voltage for 5 volts (int 5) or 3.3 volts (int 3).
Param in	uint8_t v
Return	void

Function	void Disable_LUP (uint8_t v);
Brief	Disables LUP bus voltage for 5 volts (int 5) or 3.3 volts (int 3).
Param in	uint8_t v
Return	void

4.3.4 UHF Library

This CubeSat has two antennas for communication: a UHF antenna and an experimental SBAND antenna provided by Lockheed Martin Space. The primary antenna is a UHF antenna provided by EnduroSat. This antenna is set to communicate at a frequency of 435.04 MHz. By default, it uses a two-frequency shift key (2GFSK) modulation with a data rate of 9600 bits per second, and a frequency deviation of 2.4 KHz. The parameters and other options in the antenna can be configured using the UART. By default, the antenna is neither in beacon mode or pipe mode. Also, an instruction is necessary to be sent to the UHF module to deploy the antennas once it is in space. A library was written to interact with the UHF antenna module. The files are named "UHF.h" and "UHF.c." The functions inside this library are presented in Table 4.4.

Table 4.4: UHF library functions.

Function	void UHF_On (void);
Brief	Turn on the GPO from the OBC to turn on the UHF.
Param in	void
Return	void

Function	void UHF_Pipe_Mode (void);
Brief	Make the UFH to work in pipe mode, so that data can be transmitted and received.
Param in	void
Return	void

Function	void UHF_Transmit(char *msg);
Brief	Once the UHF is in pipe mode, this function transmits the data contained in the variable "msg" in ASCII format.
Param in	char *msg
Return	void

Function	void UHF_Receive (uint32_t t);
Brief	Once the UHF is in pipe mode, this function runs a timer and keeps the OBC waiting for that amount of time to receive data using a DMA interrupt.
Param in	uint32_t t
Return	void

Function	void UHF_Beacon_Mode(void);
Brief	Changes the UHF from pipe mode to beacon mode.
Param in	void
Return	void

Function	void UHF_Automatic_Deploy_Enable(void);
Brief	Give the instruction to the UHF to deploy the antennas.
Param in	void

Return	void

Function	void UHF_Check_Antenna(void);
Brief	Check if the antennas have been deployed. The answer is stored in a global variable called UHF_Ans.
Param in	void
Return	void

Function	void UHF_Stop_Transmission(void);
Brief	Disable UHF pipe mode.
Param in	void
Return	void

Function	char Check_Pipe_Mode (void);
Brief	Check if UHF is in pipe mode.
Param in	void
Return	char

4.3.5 SBAND Library

A secondary mission of this CubeSat is to test a patch antenna designed by Lockheed Martin Space. The antenna is connected to an S-Band module designed by EnduroSat and they made a library with all the functions needed to test it. Since this library was not developed in this project, it will not be documented here.

4.3.6 Payload Software

Since the MSP430FR4133 microcontroller is a Texas Instruments (TI) device, it was decided to develop software for it using TI's integrated development environment (IDE). The MSP430FR4133 is an extension of the OBC used for different tasks. One task using GPIO is to detect if the printer is in its home position. Another GPIO task is to communicate with a motor driver that controls the printer's valve and the stepper motor. GPIO is also used to check conductivity test results and turn on LEDs to photograph ink deposition results. ADC is used for a temperature sensor, as below 10 ºC the printer valve would not be able to open.

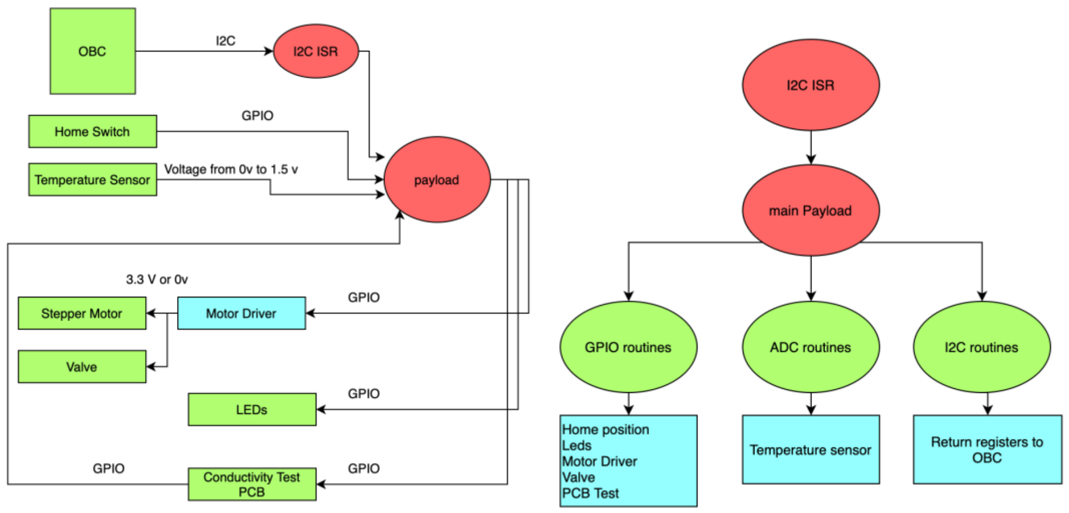
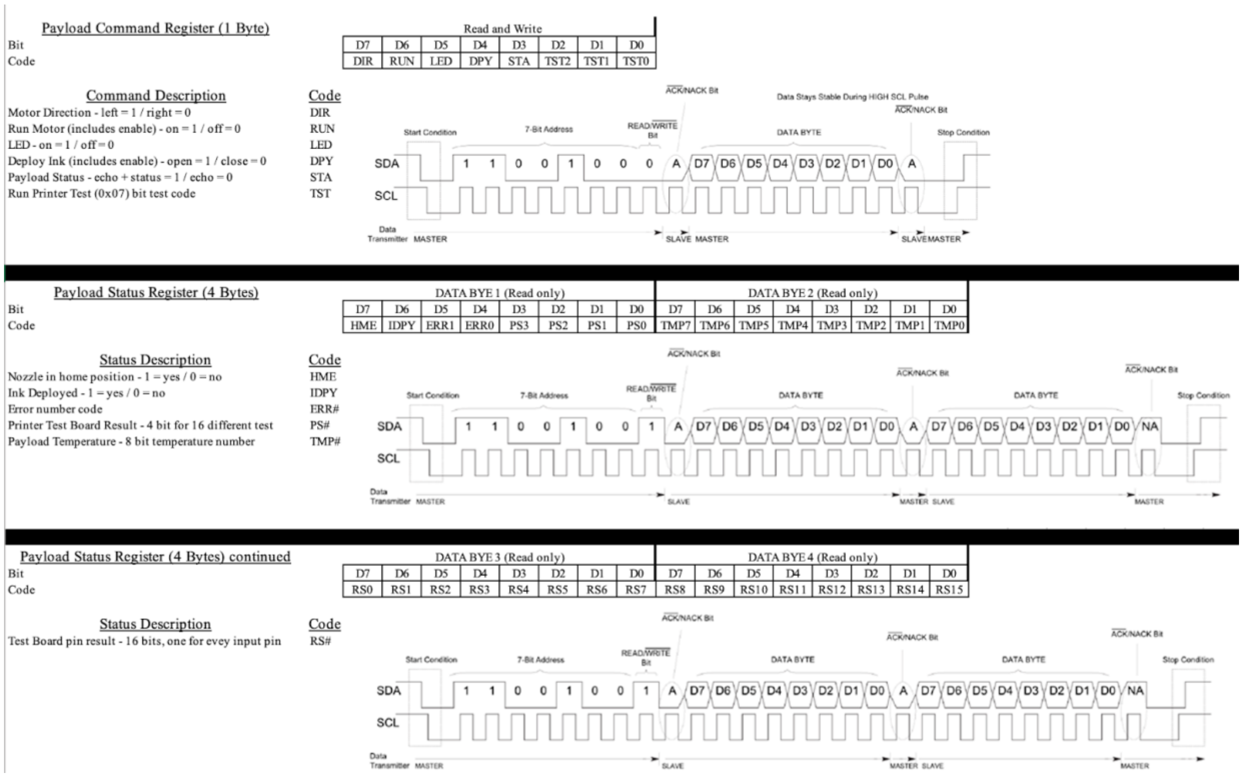


Figure 4.10: Payload data flow and call graph.

When it is not performing a task, the microcontroller is in low power mode waiting on an interrupt to receive I2C data. Once the slave receives data representing an instruction, the task associated with the instruction will be executed and then the slave will return to low power mode. A protocol was designed to ensure communication between the OBC and the MSP430 slave. As can be seen in Figure 4.11, two registers designed for the protocol were implemented in the MSP430. To access these registers, the OBC first sends an update of the Payload Command Register (PCR) to the payload. Then the payload echoes back the command received from the OBC and, depending on the command received, the payload will do different tasks and modify its Status Register (SR).

The PCR is a read and write, one-byte register with 6 different bit entries. The DIR entry defines the direction of the nozzle. If DIR is 0, the stepper motor will move the nozzle towards the home position one hundred steps; if DIR is 1, the stepper motor will move the nozzle away from the home position one hundred steps. The next entry is RUN and it controls the motor. When RUN is set, the stepper motor will run. On the other hand, if this entry is reset, the stepper motor will not run. Next, the LED entry is used to turn on or off payload LEDs when it is 1 or 0, respectively. The DPY entry opens and closes the valve to deposit ink. When DPY is enabled, the valve will open; when it is disabled, the valve is closed. The STA entry indicates payload status. When the OBC sends an instruction and STA is set, the payload slave will reply with an update of the register submitted and an update of the status register. When STA is cleared, the OBC will just receive an echo of the instruction sent. The last entry is TST, which is a code to run the printer conductivity test. This code needs to be 0x07 to run the test.

The Status Register (SR) is a 4-byte register that can only be accessed enabling the STA bit in the PCR. The SR has seven-bit entries or bit fields. The HME is set if the nozzle has reached the home position. In case the nozzle is not in its home position, HME is cleared. IPDY is set once the ink has been deployed. If IPDY is cleared, this means that the ink has not been deployed, yet. ERR is a set of bits. Two types of errors can be detected. If ERR is 00, no error has been detected. If ERR is 01, it specifies that the home switch is not working; 10 means that ink has been deployed before the experiment is run. Next, PS is a set of bits that specifies which output pins are working during the conductivity test. Every one of the four pins is directly related to one of the four PS bits. Next, TMP is a byte that stores the temperature inside of the payload, the values are in Celsius degrees and in integer format. Finally, RS is a set of sixteen bits that are directly related to the pins that are connected to the experiment PCB. In case any of these sixteen input pins detects a voltage, the bit referred to that voltage gets set.



Payload Command Register (1 Byte)

	Read and Write							
Bit	D7	D6	D5	D4	D3	D2	D1	D0
Code	DIR	RUN	LED	DPY	STA	TST2	TST1	TST0

Command Description	Code
Motor Direction - left = 1 / right = 0	DIR
Run Motor (includes enable) - on = 1 / off = 0	RUN
LED - on = 1 / off = 0	LED
Deploy Ink (includes enable) - open = 1 / close = 0	DPY
Payload Status - echo + status = 1 / echo = 0	STA
Run Printer Test (0x07) bit test code	TST

ACK/NACK Bit
Data Stays Stable During HIGH SCL Pulse
ACK/NACK Bit
Start Condition
7-Bit Address
READ/WRITE Bit
DATA BYTE
Stop Condition
SDA 1 1 0 0 1 0 0 0 A D7 D6 D5 D4 D3 D2 D1 D0 A
SCL
Data Transmitter MASTER SLAVE MASTER SLAVE MASTER

Payload Status Register (4 Bytes)

	DATA BYE 1 (Read only)								DATA BYE 2 (Read only)							
Bit	D7	D6	D5	D4	D3	D2	D1	D0	D7	D6	D5	D4	D3	D2	D1	D0
Code	HME	IDPY	ERR1	ERR0	PS3	PS2	PS1	PS0	TMP7	TMP6	TMP5	TMP4	TMP3	TMP2	TMP1	TMP0

Status Description	Code
Nozzle in home position - 1 = yes / 0 = no	HME
Ink Deployed - 1 = yes / 0 = no	IDPY
Error number code	ERR#
Printer Test Board Result - 4 bit for 16 different test	PS#
Payload Temperature - 8 bit temperature number	TMP#

ACK/NACK Bit
ACK/NACK Bit
ACK/NACK Bit
Start Condition
7-Bit Address
READ/WRITE Bit
DATA BYTE
DATA BYTE
Stop Condition
SDA 1 1 0 0 1 0 0 1 A D7 D6 D5 D4 D3 D2 D1 D0 A D7 D6 D5 D4 D3 D2 D1 D0 NA
SCL
Data Transmitter MASTER SLAVE MASTER SLAVE MASTER

Payload Status Register (4 Bytes) continued

	DATA BYE 3 (Read only)								DATA BYE 4 (Read only)							
Bit	D7	D6	D5	D4	D3	D2	D1	D0	D7	D6	D5	D4	D3	D2	D1	D0
Code	RS0	RS1	RS2	RS3	RS4	RS5	RS6	RS7	RS8	RS9	RS10	RS11	RS12	RS13	RS14	RS15

Status Description	Code
Test Board pin result - 16 bits, one for evey input pin	RS#

ACK/NACK Bit
ACK/NACK Bit
ACK/NACK Bit
Start Condition
7-Bit Address
READ/WRITE Bit
DATA BYTE
DATA BYTE
Stop Condition
SDA 1 1 0 0 1 0 0 1 A D7 D6 D5 D4 D3 D2 D1 D0 A D7 D6 D5 D4 D3 D2 D1 D0 NA
SCL
Data Transmitter MASTER SLAVE MASTER SLAVE MASTER

Figure 4.11: Design of payload’s communication protocol and registers.

Chapter 5: Testing

OF2 system testing, as opposed to unit and integration testing performed while modules were developed and integrated, was designed to be performed by testing the payload functions. For the tests, the OBC invoked all of the functions to be executed by the payload slave processor. A protocol was designed to ensure communication between processors and to have instructions from OBC performed by the MSP430 slave. These instructions, which were encoded in the data field 2 of the protocol, were tested in a laboratory environment to simulate how OF2 would behave in space.

When the CubeSat was completely assembled, some critical bugs were found. To simulate the ground station a LimeSDR device was bought and EnduroSat provided a radio application that was able to send and receive data from the small satellite. The application uses GNU radio, which is a good tool to create your own radio applications with an inexpensive software-defined radio (SDR). Before using a radio, a terminal connected to the satellite simulated the radio. Also, the software was always running in debugging mode. When no critical errors were found, the software was uploaded to the small satellite and some instructions were sent to the CubeSat. Unfortunately, the CubeSat started to act buggy and the watchdog was resetting the whole system. Moreover, after execution of a few threads was tried, the only thread that was not causing trouble was the apptask. It was decided to move all of the threads to this one and transform the other threads into functions of the apptask thread. Later on, some functions using dynamic memory were causing some unexpected problems. For instance, when the program counter (PC) was trying to return from the functions called, the link register was pointing to another place and this was resulting in a reset from the whole system. Other weird behavior that was found in functions using dynamic memory is that when a string was made and another function was called inside this function, the data that was supposed to be sent was being changed to some corrupted data. Imagine having this type of troubles in important functions like log files that save the status of the system in an SD card. After some debugging time, software defects were corrected and the OF2 started to communicate as expected with LimeSDR.

The packet structure for communication between modules consists of 5 fields. The first field consists of a five-byte preamble and the data sent is 0xAAAAAAAAAA. The second field is the synchronization word, which is 0x7E. The third field is a byte that specifies the number of bytes that will be sent in the next data field, which is the one that contains the actual data. The last field is a cyclic redundancy check for data field 1 and data field 2.

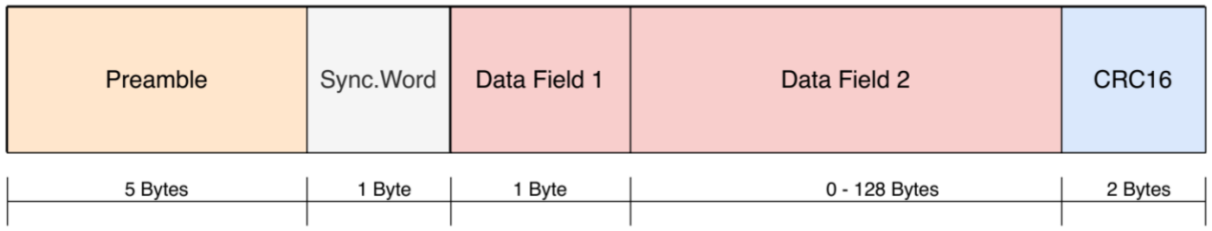


Figure 5.1: Packet structure for UHF courtesy of EnduroSat.

It was established for the data field 2 to contain instructions. These instructions were tested in a laboratory environment having OF2 about 10 meters away from the LimeSDR using 30 dB attenuators. The purpose of this experiment was to see how successful it would be to communicate with OF2 once it was in space. An example of a satellite instruction is presented in Table 4.5

Table 4.5: OF2 Instructions.

Instruction	+2% or +2~arg%
Nickname	Ping
Task	Answers “OF2 OK!” + last status update, arg is optional. Eg. +2~Hello% will make OF2 to answer back “OF2 Received: Hello”.
Result	Instruction is working with no problem found.

An interesting problem was found two days before the shipment to Nanoracks. It was found that after a software update provided by EnduroSat, the whole system was shutting down. And when the CubeSat started to get charged, perhaps the whole instructions were erased because the OBC started to act like it was running its sample code. During those two days, a power analysis was done and different solutions were tried, like moving the whole PC instructions from the OBC to the SD card or uploading the instructions to the OBC via the UHF module. Nevertheless, the CubeSat was still not responding. One day before the shipment, it was found that the problem was that LUP buses were being turned off in the main file. This was shutting down the EPS and the OBC. After moving these instructions to the apptask file, the OBC started to work as expected. After testing every instruction twice and checking their results, OF2 batteries were charged during the last day before turning it in. OF2 was turned in to Nanoracks on September 19, 2019. It was encapsulated with other small satellites and launched on a Northrop Grumman Antares rocket on November 2, 2019.

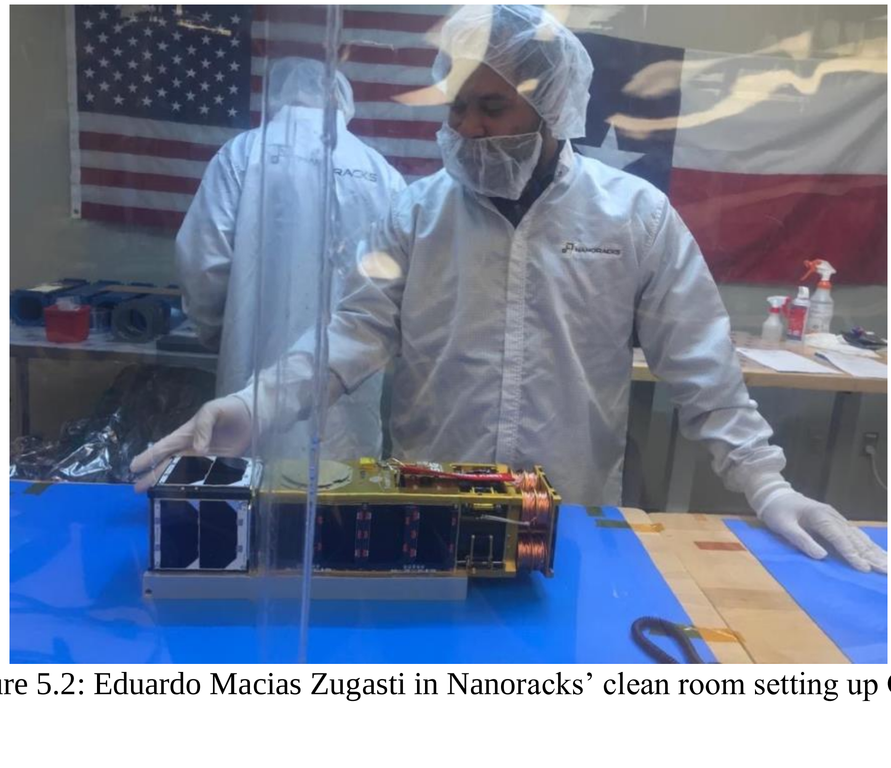
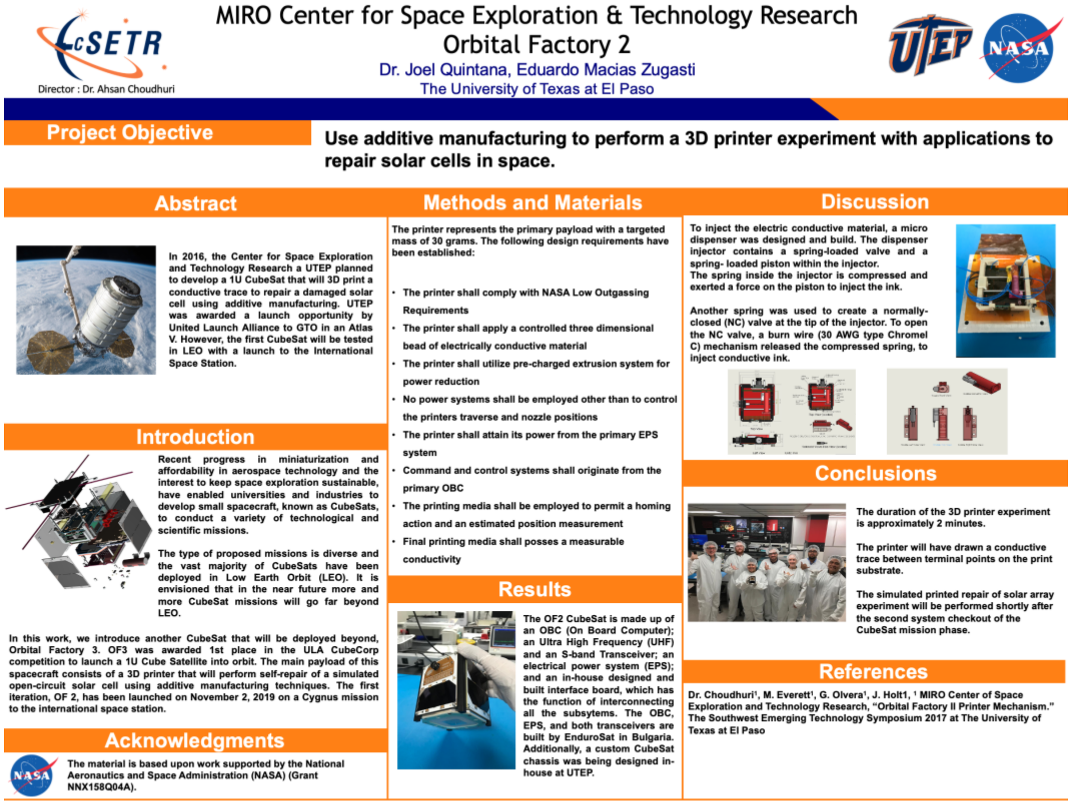


Figure 5.2: Eduardo Macias Zugasti in Nanoracks' clean room setting up OF2.

During this time, a presentation was given to ULA, giving an update about the status of OF2. In this presentation it was confirmed that OF2 has been successfully launched to space and it was waiting to be deployed to space. Also, preparations for future missions started, including the ULA-awarded deploy. Finally, OF2 was deployed from the CRS2 NG-12 (Cygnus) on January 31, 2020. After that, OF2 started orbiting around the world.



MIRO Center for Space Exploration & Technology Research
Orbital Factory 2
Dr. Joel Quintana, Eduardo Macias Zugasti
The University of Texas at El Paso

Director : Dr. Ahsan Choudhuri

Project Objective

Use additive manufacturing to perform a 3D printer experiment with applications to repair solar cells in space.

Abstract

In 2016, the Center for Space Exploration and Technology Research a UTEP planned to develop a 1U CubeSat that will 3D print a conductive trace to repair a damaged solar cell using additive manufacturing. UTEP was awarded a launch opportunity by United Launch Alliance to GTO in an Atlas V. However, the first CubeSat will be tested in LEO with a launch to the International Space Station.

Introduction

Recent progress in miniaturization and affordability in aerospace technology and the interest to keep space exploration sustainable, have enabled universities and industries to develop small spacecraft, known as CubeSats, to conduct a variety of technological and scientific missions.

The type of proposed missions is diverse and the vast majority of CubeSats have been deployed in Low Earth Orbit (LEO). It is envisioned that in the near future more and more CubeSat missions will go far beyond LEO.

In this work, we introduce another CubeSat that will be deployed beyond, Orbital Factory 3. OF3 was awarded 1st place in the ULA CubeCorp competition to launch a 1U Cube Satellite into orbit. The main payload of this spacecraft consists of a 3D printer that will perform self-repair of a simulated open-circuit solar cell using additive manufacturing techniques. The first iteration, OF 2, has been launched on November 2, 2019 on a Cygnus mission to the international space station.

Acknowledgments

The material is based upon work supported by the National Aeronautics and Space Administration (NASA) (Grant NNX158Q04A).

Methods and Materials

The printer represents the primary payload with a targeted mass of 30 grams. The following design requirements have been established:

- The printer shall comply with NASA Low Outgassing Requirements
- The printer shall apply a controlled three dimensional bead of electrically conductive material
- The printer shall utilize pre-charged extrusion system for power reduction
- No power systems shall be employed other than to control the printers traverse and nozzle positions
- The printer shall attain its power from the primary EPS system
- Command and control systems shall originate from the primary OBC
- The printing media shall be employed to permit a homing action and an estimated position measurement
- Final printing media shall posses a measurable conductivity

Results

The OF2 CubeSat is made up of an OBC (On Board Computer); an Ultra High Frequency (UHF) and an S-band Transceiver; an electrical power system (EPS); and an in-house designed and built interface board, which has the function of interconnecting all the subsytems. The OBC, EPS, and both transceivers are built by EnduroSat in Bulgaria. Additionally, a custom CubeSat chassis was being designed in-house at UTEP.

Discussion

To inject the electric conductive material, a micro dispenser was designed and build. The dispenser injector contains a spring-loaded valve and a spring- loaded piston within the injector.
The spring inside the injector is compressed and exerted a force on the piston to inject the ink.

Another spring was used to create a normally-closed (NC) valve at the tip of the injector. To open the NC valve, a burn wire (30 AWG type Chromel C) mechanism released the compressed spring, to inject conductive ink.

Conclusions

The duration of the 3D printer experiment is approximately 2 minutes.

The printer will have drawn a conductive trace between terminal points on the print substrate.

The simulated printed repair of solar array experiment will be performed shortly after the second system checkout of the CubeSat mission phase.

References

Dr. Choudhuri[1], M. Everett[1], G. Olvera[1], J. Holt1, [1] MIRO Center of Space Exploration and Technology Research, "Orbital Factory II Printer Mechanism." The Southwest Emerging Technology Symposium 2017 at The University of Texas at El Paso

Figure 5.3: Poster used to present the OF2 project during ULA visit.

Chapter 6: Analysis

This section focuses on the ground station that was built to analyze the behavior of OF2 in space. Also, the results from communication with this CubeSat are presented. Up to now, no answer from OF2 nor a beacon signal has been received by UTEP's ground station. However, it is known that the satellite is sending beacon signals because other ground stations around the world have received them.

6.1 Ground Station

While OF2 was in the International Space Station waiting to be deployed, UTEP started to build a ground station. Since this is the first satellite that was built by this University, it had no ground station. The facility for the ground station has been nicknamed cSPACE by the students and professors working on the project. The ground station was designed to establish communication with OF2. Moreover, the ground station was to track other satellites in the same range of frequency of OF2. The operation of the UHF antennas is in the range of frequencies between 420-450 MHz while the SBAND antenna operates in the frequency of 2.426 GHz.

During the first month of the ground station construction, satellites were tracked with a small antenna that is commonly used for amateur communications. Software used for tracking is SATPC32, which communicates with the antenna and changes the azimuth and degrees of position of the antenna. This results helpful when a satellite is being tracked and the antenna needs to be moved to point directly to the satellite. G-Predict is a software that calculates the position of a satellite and can predict the Doppler correction needed in Hertz to ensure communication with the satellite. Finally, GNURadio is a software that can be used with different software-defined radios (SDRs) to allow a ground station to receive data. It can be coded in python or in blocks. EnduroSat provided the GNURadio software that can communicate with their UHF. This software has been modified and used to communicate with OF2. G-Predict is updated every day with the newest TLE files that determine the movement in space of OF2. When OF2 is in range, G-Predict transmits to SATPC32 the position that the antennas need to be in and they are updated every 0.5 degrees. SATPC32 is directly connected to the control unit of the antenna rotors, so they are placed pointing as accurately as possible to OF2. At the same time, G-Predict is transmitting to GNURadio the Doppler correction that is needed and GNURadio takes the Doppler correction and implements it in LimeSDR. When GNURadio is running, a waterfall of data can be observed. Also, a spectrogram of the received data is shown. Data transmitted can be seen and demodulated; data received is stored in a file.

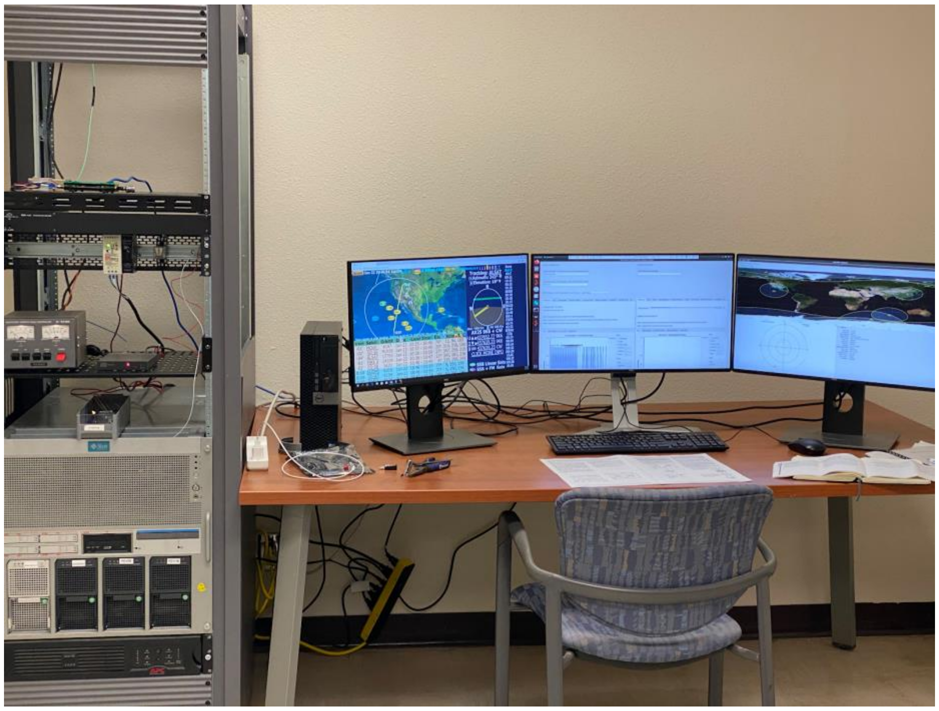


Figure 6.2: Operation room at cSPACE ground station.

Later on, better antennas were acquired. A new 6-feet diameter dish antenna was connected for SBAND. Also, two new Yagi antennas were mounted in the SBAND antenna. Testing proved that these antennas have more accuracy than previous ones. Also, the team started using SDR Angel software to demodulate different types of data. For instance, after UHF antennas were connected to LimeSDR using SDR Angel, some radio stations could be tracked. Moreover, a DVB-S2 video transmitter software was used for testing by simulating SBAND transmissions. After a few demodulation attempts, SDR Angel was able to demodulate a broadcasting transmission from a PC.

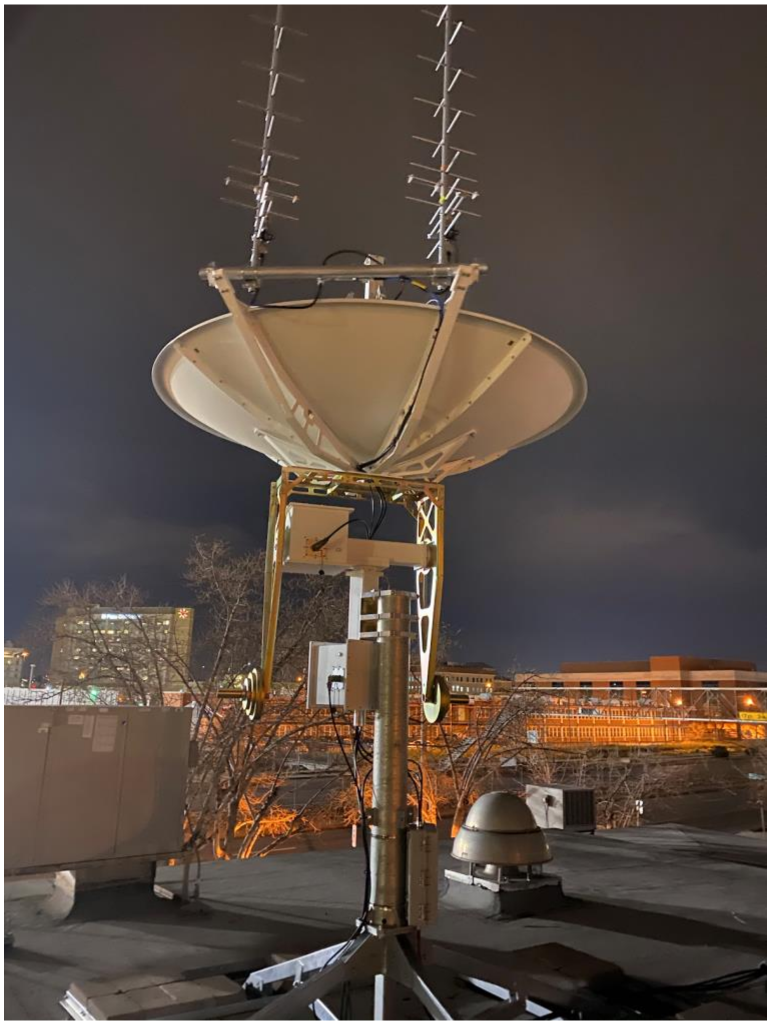


Figure 6.3: SBAND and UHF antennas.

6.1 Communication

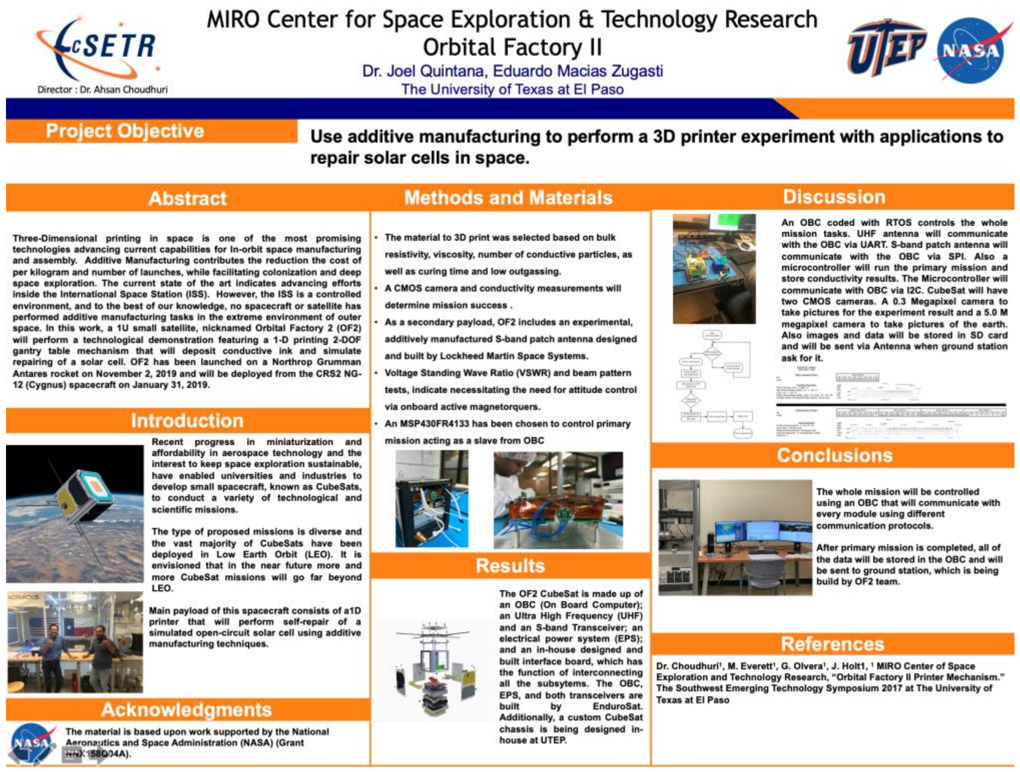
From the first day of OF2 orbiting, cSPACE has been trying to communicate with it. Nevertheless, no answer has been received, nor a beacon signal has been demodulated. Sometimes, when OF2 passes over the ground station with an altitude above 20 degrees, some signals can be seen in the waterfall, but no signal has been demodulated. Some changes in the ground station have been made, such as connecting the power amplifiers as close as possible to the antennas and implementing digital and analog filters for the exact frequencies needed for communications with the satellite. Unfortunately, none of this has resulted in a successful communication with the satellite. Also, the place of the ground station is not really favorable, because non-negligible noise has been detected in the exact frequency OF2 operates. Testing has started using a LimeSDR simulating OF2 transmissions from Scenic Drive, near the UTEP main campus, but no signal has been received. In Bulgaria, EnduroSat has tracked OF2 and received beacon signals with OF2's unique id code. Also, CalPoly has been able to demodulate signals from OF2 decoding successfully the "Hello World" beacon signal from it. Moreover, amateur people from the SatNOGS community have reported receiving beacon signals from OF2 from different parts of the world including England, Switzerland, Mexico, Greece, Indonesia, and Holland. Results of these observations report that the satellite usually transmits beacon signals every 5 seconds. Then it waits for a minute and continues with beacon signals. This means that the code in the satellite is working properly. Unfortunately, the only ground station with the license to communicate with OF2 is cSETR. Until today the cSPACE team is still working on how to communicate with OF2.

Chapter 7: Conclusions and Future Work

Development of the project is continuing. Due to the situation of the cSPACE ground station, the OF2 experiment has not been run. Also, no pictures have been taken of the experiment and the SBAND antenna has not been tested yet. However, updates will be done to the ground station until it is able to receive signals from OF2. As long as beacon signals are reported from OF2 around the world, there is still opportunity to communicate with it.

Also, OF2 has created opportunities for different new projects. There is already a project nicknamed OF3 that will run a robotic arm in space. Also, there is another project nicknamed OFX-CG that consists of a 1U CubeSat that will be propelled using cold-gas pressure. And a more ambitious project is under way for a small satellite orbiting in geostationary transfer orbit (GTO) thanks to ULA. The OF2 project also provided a lot of experience to the team. Thanks to presentations given, more investors got interested in CubeSat projects from UTEP. The last lesson learned from a presentation was during a visit from CalPoly members. During a tour of the cSPACE ground station, one of the visitors recommended to have power amplifiers as close as possible to the antennas to reduce noise as much as possible. This greatly improved data received during operation.

There is also plenty of lessons learned that will not be repeated in future projects. A good lesson learned is that it is necessary to have at least two CubeSats per project. An engineering unit, and a flight unit. The purpose of the engineering unit is to simulate and analyze the behavior of the flight unit on the ground to obtain better conclusions of the behavior of the satellite. Also, the ground station can be used to simulate transmissions from space adding attenuators to the small satellites. Another important lesson learned is that every part of the satellite needs to be tested in an environment that simulates as close as possible the actual environment that the satellite is going to confront. In 2016, NASA announced that almost every one of two small satellites failed [11]. Moreover, the probabilities of failure increase when it is the first satellite designed by a university.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Project Objective

Use additive manufacturing to perform a 3D printer experiment with applications to repair solar cells in space.

Abstract

Three-Dimensional printing in space is one of the most promising technologies advancing current capabilities for In-orbit space manufacturing and assembly. Additive Manufacturing contributes the reduction the cost of per kilogram and number of launches, while facilitating colonization and deep space exploration. The current state of the art indicates advancing efforts inside the International Space Station (ISS). However, the ISS is a controlled environment, and to the best of our knowledge, no spacecraft or satellite has performed additive manufacturing tasks in the extreme environment of outer space. In this work, a 1U small satellite, nicknamed Orbital Factory 2 (OF2) will perform a technological demonstration featuring a 1-D printing 2-DOF gantry table mechanism that will deposit conductive ink and simulate repairing of a solar cell. OF2 has been launched on a Northrop Grumman Antares rocket on November 2, 2019 and will be deployed from the CRS2 NG-12 (Cygnus) spacecraft on January 31, 2019.

Introduction

Recent progress in miniaturization and affordability in aerospace technology and the interest to keep space exploration sustainable, have enabled universities and industries to develop small spacecraft, known as CubeSats, to conduct a variety of technological and scientific missions.

The type of proposed missions is diverse and the vast majority of CubeSats have been deployed in Low Earth Orbit (LEO). It is envisioned that in the near future more and more CubeSat missions will go far beyond LEO.

Main payload of this spacecraft consists of a1D printer that will perform self-repair of a simulated open-circuit solar cell using additive manufacturing techniques.

Acknowledgments

The material is based upon work supported by the National Aeronautics and Space Administration (NASA) (Grant NNX15BQ04A).

Methods and Materials

- The material to 3D print was selected based on bulk resistivity, viscosity, number of conductive particles, as well as curing time and low outgassing.
- A CMOS camera and conductivity measurements will determine mission success .
- As a secondary payload, OF2 includes an experimental, additively manufactured S-band patch antenna designed and built by Lockheed Martin Space Systems.
- Voltage Standing Wave Ratio (VSWR) and beam pattern tests, indicate necessitating the need for attitude control via onboard active magnetorquers.
- An MSP430FR4133 has been chosen to control primary mission acting as a slave from OBC

Results

The OF2 CubeSat is made up of an OBC (On Board Computer); an Ultra High Frequency (UHF) and an S-band Transceiver; an electrical power system (EPS); and an in-house designed and built interface board, which has the function of interconnecting all the subsytems. The OBC, EPS, and both transceivers are built by EnduroSat. Additionally, a custom CubeSat chassis is being designed in-house at UTEP.

Discussion

An OBC coded with RTOS controls the whole mission tasks. UHF antenna will communicate with the OBC via UART. S-band patch antenna will communicate with the OBC via SPI. Also a microcontroller will run the primary mission and store conductivity results. The Microcontroller will communicate with OBC via I2C. CubeSat will have two CMOS cameras. A 0.3 Megapixel camera to take pictures for the experiment result and a 5.0 M megapixel camera to take pictures of the earth. Also images and data will be stored in SD card and will be sent via Antenna when ground station ask for it.

Conclusions

The whole mission will be controlled using an OBC that will communicate with every module using different communication protocols.

After primary mission is completed, all of the data will be stored in the OBC and will be sent to ground station, which is being build by OF2 team.

References

Dr. Choudhuri[1], M. Everett[1], G. Olvera[1], J. Holt1, [1] MIRO Center of Space Exploration and Technology Research, "Orbital Factory II Printer Mechanism." The Southwest Emerging Technology Symposium 2017 at The University of Texas at El Paso

Figure 7.1: Poster used for presenting the OF2 project during a visit from CalPoly members.

Once a presentation about OF2 was given to employees of Lockheed Martin. One of the guests said to the OF2 team that if its beacon signals were being received, the team can "pop up the champagne and celebrate," because the probabilities were against the project. OF2 should be considered at least a partial success because it was an accelerated training experience for the team and third parties all over the world have received proofs that the satellite is working. Later on, when cSPACE is able to communicate with OF2, experiments may be run and additional successful results will be presented.

Figure 7.2: Members of OF2 team in clean room.

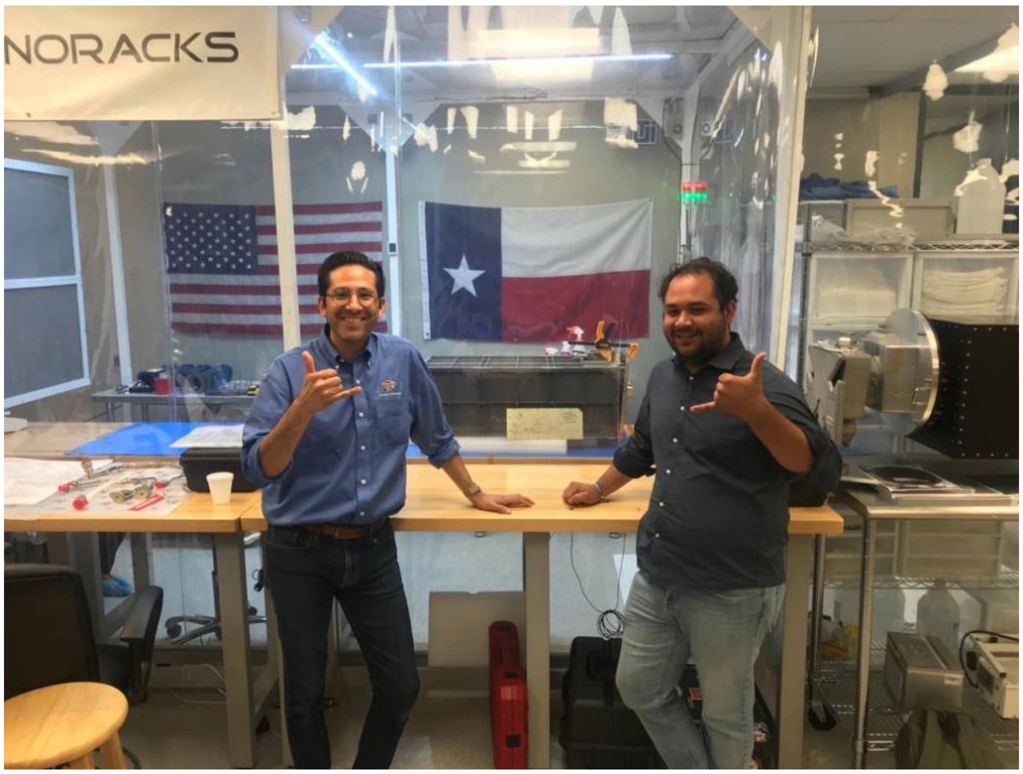

Figure 7.3: Dr. Joel Quintana and Eduardo Macias Zugasti,
two of the OF2 team members in Nanoracks.

References

[1]	NASA’s Voyager 2 Probe Enters Interstellar Space, Retrieved from https://voyager.jpl.nasa.gov/mission/timeline/#event-nasas-voyager-2-probe-enters-interstellar-sace.

[2]	CubeSat 101 Basic Concepts and Processes for First-Time CubeSat Developers, Retrieved from https://www.nasa.gov/directorates/heo/home/CubeSats_initiative.

[3]	Valvano, J. 2015. Embedded Systems: Introduction to the MSP432 Microcontroller.

[4]	Billah, Kazi Md Masum, "Characterization Of Electrically Conductive Inks In Simulated Space Environment" (2017). Open Access Theses & Dissertations. 413. Retrieved from https://digitalcommons.utep.edu/open_etd/413.

[5]	Felker, N. 2017. Building MemSat: A CubeSat for Testing Resistive Memory. IEEE Sensors Application Symposium.

[6]	Khurshid, K. 2013. A survey of camera modules for CubeSats – Design of Imaging payload of ICUBE-1. IEEE.

[7]	Perez, P. 2019. Development and Environmental Testing of a Single-axis Printer Inside a 1U CubeSat for On Orbit Servicing Repairs in Low Earth Orbit.

[8]	Ünsalan, C. 2015. Programmable Microcontrollers. McGraw Hill.

[9]	Prata, S. 2014. C Primer Plus. Pearson Education.

[10]	Macias-Zugasti, E., Caldelas, A., Quintana, J., “OF II Payload Control,” Proceedings of the Southwest Emerging Technology Symposium, El Paso, TX, 2019.

[11]	Small Satellite Mission Failure Rates. Retrieved from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190002705.pdf.

Glossary

CMOS	Complementary Metal Oxide Semiconductor
COTS	Commercial-Off-The-Shelf
CPU	Control Processing Unit
cSETR	Center for Space Exploration and Technology Research
DC	Direct Current
EPS	Electric Power System
FPGA	Field Programmable Gate Array
GPIO	General Purpose Input Output
GPO	General Purpose Output
GPS	Global Positioning System
IC	Integrated Circuit
IDE	Integrated Development Environment
ISS	International Space Station
I2C	Inter-integrated circuit
LUP	Latch Up
MOSI	Master Out Slave In
MISO	Master In Slave Out
OBC	On-Board Computer
OF2	Orbital Factory 2
PCB	Printed Circuit Board
RTC	Real Time Clock

RTOS	Real Time Operating System
SCL	Source Clock
SDA	Source Data
SPI	Serial Peripheral Interface
UART	Universal Asynchronous Receiver Transmitter
UHF	Ultra-High Frequency

Vita

Eduardo Macias Zugasti attended the University of Texas at El Paso, where he received a Bachelor of Science in Electrical Engineering in 2018. Deciding to learn more about embedded systems, he continued his studies with a Master Degree in Electrical Engineering. At the end of his first graduate semester, he was hired for a research opportunity at UTEP’s NASA MIRO Center for Space Exploration and Technology Research. From the beginning, he was placed in the CubeSats team focused on the payload design and the OBC coding for the first small satellite that UTEP was going to launch, the OF2. After OF2 was launched, Macias Zugasti started to work in another CubeSat project which works with cold gas by designing the control unit. Macias Zugasti also worked as a teaching assistant for the class “Introduction to Thermodynamic Fluids” in 2019. Also, Macias Zugasti has participated in different conferences and he has presented at the local Southwest Emerging Technology Symposium.

After graduation, Macias Zugasti plans to apply for a Ph.D. program and continue with his studies by focusing his research in embedded systems for space exploration devices.