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Guatemala's Remote Sensing CubeSat - Tools and Approaches to Increase the Probability of Mission Success

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ABSTRACT

Universidad del Valle de Guatemala (UVG) is undertaking an undergraduate academic project with a mission to design, develop, and operate a CubeSat-class satellite to test a multispectral sensor prototype, opening the field of space science & technology in Guatemala, developing the country's human capital, and enabling the independent acquisition of remote sensing data for natural resource management. Throughout the four-year span of this project's design phase, more than 200 requirements, 70 risks, 220 controlled documents, 150 parts, 330 tasks, and 60 engineering drawings were monitored. Increasing the project complexity, it has to date included over 100 students and volunteers working at different points in time. To increase the odds of mission success, multiple tools and approaches were taken to manage the project's multiple physical and document components, and are here described. These tools include a Requirement Compliance Matrix, Requirement Verification and Validation Matrix, Risk Matrix, Failure Mode and Effects Analyses, Document Control, Capacitor Control, Parts Control, Material Off-Gassing, Engineering Drawings Architecture and Control, N-Squared Diagram, Structural and Thermal Finite Element Analyses, and Assembly Procedure, to name a few. This manuscript describes what each of these tools entail, how they are used, and their results with respect to Quetzal 1, UVG's student project.

INTRODUCTION

As part of the process to introduce Aerospace Engineering in Guatemala, Universidad del Valle de Guatemala (UVG) started in 2014 the development of the first Guatemalan Satellite, Quetzal 1, a 1U CubeSat. This is an academic project worked by undergraduate students of mechatronics, mechanical, electronics, and computer science programs, with the support of UVG faculty, the university's Research Institute, and international advisors. Its scientific mission is to acquire images of Earth at different wavelengths via an in-house developed payload. In addition to this scientific mission, the project has two main objectives: develop the human capital in Guatemala to design, build, and operate this type of satellites, and motivate more children and young people to study science and technology. In September 2017, this project was selected as the winner of the KiboCUBE program of the United Nations Office of Special Affairs (UNOOSA) and the Japan Aerospace Exploration Agency (JAXA), providing UVG with a free-of-cost launch to and deployment from the International Space Station (ISS).

QUETZAL 1 – THE GUATEMALAN CUBESAT

A CubeSat is a satellite based on "units" or "U's" each of 10x10x10 cm with a mass of 1 kg, or less (Cal Poly, 2015). This type of satellite is used by universities around the globe to provide students with hands-on aerospace experience, by institutions to develop in-house capabilities or test new technologies, and by the private sector to provide space-based services or data. The technical objectives of Quetzal 1 include the acquisition of multispectral images of Earth at specific wavelengths as part of the testing of an in-house-developed payload. This mission was selected following the methodology described by Zea et al. (2016). The wavelengths were selected to enable the characterization of chlorophyll-a (Chl-a) concentrations on bodies of water as a proxy to monitor algal contamination. Quetzal 1 is composed of multiple subsystems, including payload, structure and thermal, power, on-board computer, on-board communications, antenna deployment mechanism, ground control station, and attitude determination and control. The development of Quetzal 1 abided by JAXA and UVG-internal requirements.

Payload

To acquire water quality data through the monitoring of Chl-a concentration, Quetzal 1's Payload (shown in Figure 1) is an in-house developed multispectral sensor prototype. This subsystem consists of a monochromatic sensor (Crystalspace, Cat. No. CAM1U, Estonia) and a carrousel rotated by a rotary piezoelectric motor (Tekceleo, Cat. No. WLG-30, France). The rotary piezoelectric motor is controlled by a driver, which originally was designed with one free-electrolyte capacitor and, due to requirements it was changed to a tantalum capacitor. The carrousel houses four optical filters centered at 450, 550, 680, and 700 nm wavelengths (Edmund Optics, Cat. Nos. 86-653, 86-655,88-571,86-658, USA), similar to the wavelengths used by previous space-borne sensors for water quality monitoring.

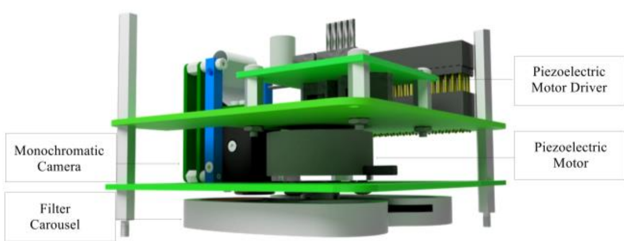

Figure 1: Payload components arrangement.

Structure and Thermal Protection

The CubeSat structure is composed of two lateral, one top, and one bottom pieces held together by M2 screws and nuts (see Figure 2). This design was based on 1U CubeSat interface requirements per the JEM Payload Accommodation Handbook (JAXA, 2015). The structural pieces are machined from Aluminum 7075 T651 blocks, and were subsequently anodized.

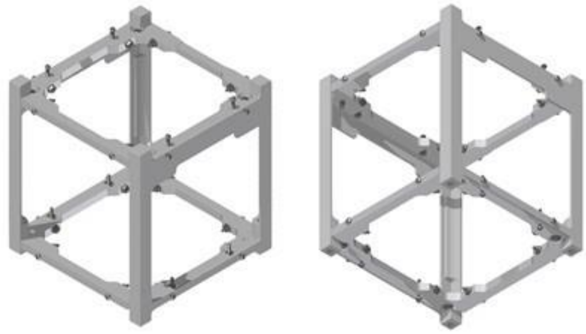

Figure 2: Quetzal 1's structure. The left side of the image shows a view of the top part of the structure while the right side shows the bottom part of the structure.

The internal printed circuit boards (PCB) are stacked with aluminum standoffs which are secured with the structure by M3 screws (see Figure 3). External PCBs are secured to the main frame of the structure with M2 screws. Those external PCBs also act as the thermal control system, ensuring that the internal temperature will always be within the components operational temperature ranges, including during the worst-case scenarios. The only exception are the heaters added to the batteries, as they have the highest low-operational-temperature (0ºC for charging state). The thermal subsystem also included temperature sensors close to the geometric center and the batteries.

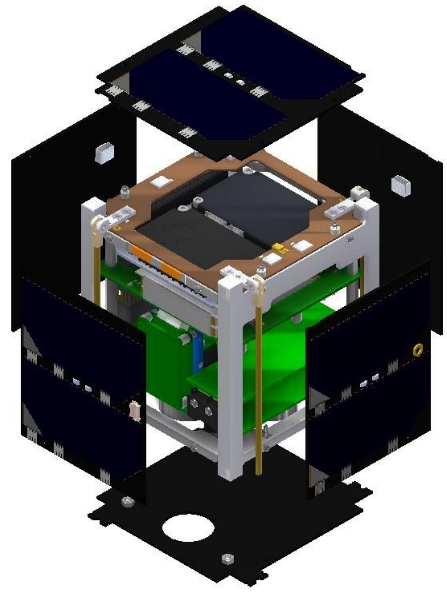

Figure 3: Arrangement of the components to the structure.

Power

Power in Quetzal 1 will be handled with a combination of flight-proven solar cells, lithium polymer (LiPo) batteries, and an in-house designed Electrical Power Subsystem (EPS). The EPS delivers power to all of Quetzal 1's subsystems and also protects them from transient electrical behavior. Quetzal 1 draws power from 11 photovoltaic cells distributed among its 6 faces. The selected cells were Azur Space´s triple junction solar cell assembly (Azur Space Solar Power GmbH, Cat. No. TJ Solar Cell Assembly 3G30A, Germany) with a minimum rated beginning of life (BOL) efficiency of 29.3%. Solar cells are connected in parallel to provide 4.6V to the EPS.

The PCB includes a commercial off-the-shelf (COTS) current and voltage monitor (Texas Instruments, Cat. No. INA3221, United States) that permits the accurate measurement of up to 3 different channels. Each channel can monitor shunt voltage drops and bus supply voltages. The device also offers alerts to detect out-of-range conditions for the direct or the average measurement in the channels. A COTS Battery Fuel Gauge (Texas Instruments, Cat. No. BQ28Z610, United States) was implemented to protect and regulate battery charging. This circuit protects from the overcurrent during discharge and short circuits during charge and discharge. In addition, power Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET) were used as redundant protection. Finally, an independent on-board microcontroller was considered in charge of enabling voltage regulators, battery heaters and the antenna deployment so that the main On-Board Computer (OBC) could focus in the data handling.

On-Board Computer and Command & Data Handling

The On-Board Computer consists of a NanoMind A3200 (GOMSpace, Cat. No. NanoMind A3200, Denmark). Software for the OBC microcontroller (Microchip Technology, Cat. No. AT32UC3C0512C, United States) was developed with FreeRTOS in combination with the GOMSpace SDK (customized and extended version of the Atmel Software Framework Library) (GOMSpace, Cat. No. NanoMind A3200 SDK, Denmark). Different communication protocols were used to establish the data transfer, the OBC communication architecture is described in Figure 4. Every single subsystem component was tested first with an ATmega328P and the Arduino IDE for a relatively fast hardware verification considering the capabilities of the microcontroller. Finally, as additional protections for the NanoMind A3200, an independent voltage supply regulator was implemented.

On-Board Communications

Communications of Quetzal 1 with the ground segment will be established using a COTS radio transceiver (GOMSpace, Cat. No. AX100, Denmark) and a COTS deployable antenna system (GOMSpace, Cat. No. ANT430, Denmark), both with successful spaceflight heritage. The NanoCom AX100 is a UHF half-duplex software configurable radio transceiver. Parameters of the radio transceiver such as frequency, bitrates and data encapsulation formats can be configured on orbit. The NanoCom ANT430 is a canted turnstile UHF system that uses 4 individual antennae - each mounted on a torsion spring - to provide, after deployment, an omnidirectional gain pattern. During launch, the antennae elements will be stowed and restrained with fishing line to a deployment mechanism, which was developed in-house.

Antennae Deployment Mechanism

When the antennae are released from their stowed position, they will automatically rotate to an angle on 45° abode the PCB were the mechanism is mounted (Quetzal 1’s bottom surface, see Figure 5). An Antenna Deployment Mechanism (ADM) was developed in-house to securely hold them in their stowed position and deploy them at the required time. The ADM consist of a fishing line that holds down the antennae passing through an eight Ohms resistor. This way, 30 minutes after the satellite is ejected into space, a current will pass through the resistors, heating them and melting the fishing lines. The antennae will be then deployed, releasing also a micro switch which confirms the correct deployment of each antenna.

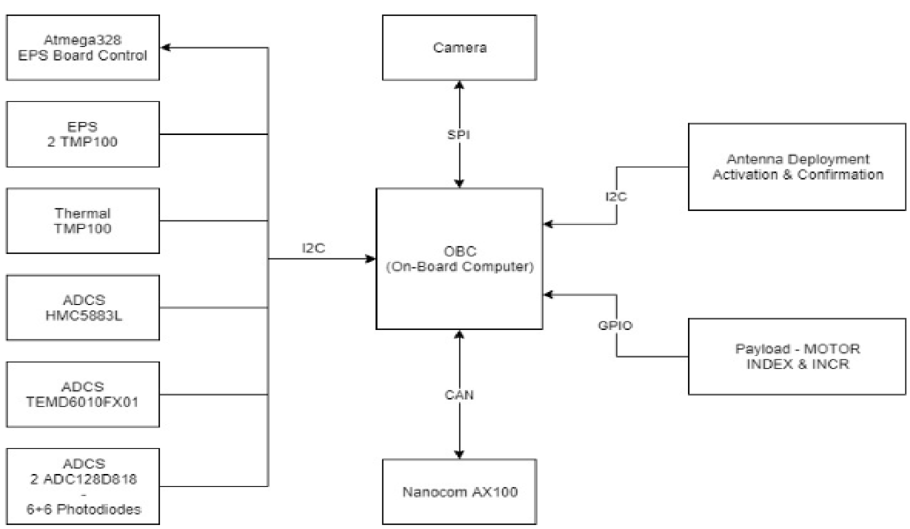

Figure 4: OBC communication architecture illustrating the type of connection with the different types of sensors and actuators use in Quetzal 1.

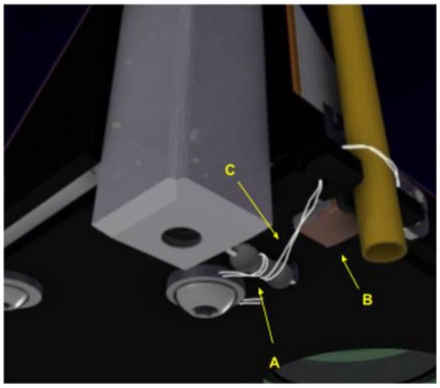

Figure 5: Antenna deployment mechanism. A - resistor. B – microswitch. C - fishing line.

Ground Control System

The ground control system consists of a 70 cm crossed Yagi type antenna (M2 Antenna Systems, Inc, Cat. No. 436CP16, United States) mounted on a software control Az/El rotor (WiMo Antennen &. Elektronik GmbH, Cat. No. 25082, Germany) The antenna is connected to a HackRF One SDR dongle (WiMo Antennen & Elektronik GmbH, Cat. No. HACK-RF, Germany) which is later connected to the ground control station main computer. The SDR software is based in GNUradio environment. For reception, the antenna is connected to a SP-70 UHF mast pre- amplifier (WiMo Antennen & Elektronik GmbH, Cat. No. 26105, Germany) to increase the strength of the incoming signal. The SP-70 UHF mast preamplifier is connected to 13.8 V power supply (QJE, Cat. No. QJ-PS5OSW III, China). For transmission, the outgoing signal will pass through a Mitsubishi RA30H4047M preamplifier (Mitsubishi Electric, Cat No. RA30H4047M, Japan), afterwards, the outgoing signal will pass through a Microset RU 432-95 switching power amplifier (WiMo Antennen & Elektronic GmbH, Cat. No. RU 432-95, Germany) and into a voltage standing wave ratio meter (SWR) (WiMo Antennen & Elektronik GmbH, Cat. No. 24004.N, Germany). Finally, the outgoing signal will be sent to Quetzal 1.

Attitude Determination & Control

The attitude determination and control system (ADCS) was based in the design in the Colorado Student Space Weather Experiment (CSSWE) (Gerhardt, 2014). The passive magnetic control stabilizes through a damping action and aligns the satellite with the Earth's magnetic field. To integrate the design, one magnet and two hysteresis rods were selected. A 0.25 x 0.25 x 0.25 inch neodymium cubic magnet (K&J Magnetics, Cat. No. B444, United States), secured to the ADCS circuit board through a polycarbonate flange controls the attitude on the *z* axis, see Figure 6.

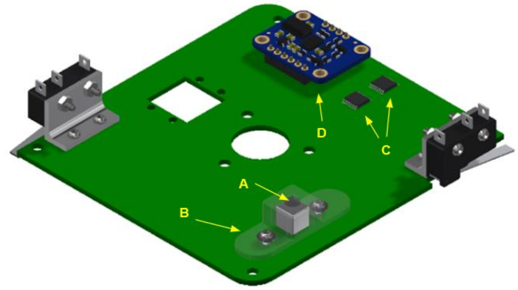

Figure 6: The ADCS circuit board. A – neodymium magnet. B – magnet's flange. C – analog to digital convertors. D – IMU.

Hysteresis rods made of HyMu80, secured with Kapton tape and epoxy (3M, Cat. No. Scotch-Weld 2216, United States) to the satellite's structure (see Figure 7) control the attitude in the *x* and *y* axes.

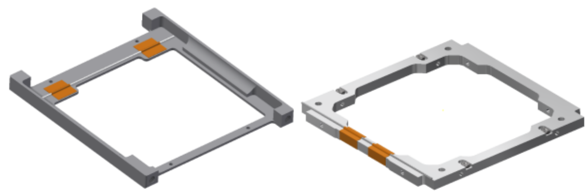

Figure 7: Positioning of the two hysteresis rods in the structure's pieces.

The second part of the design involves two different subsystems that will determine when the camera is facing nadir and if the passive magnetic control worked correctly. To achieve this, twelve photodiodes (Vishay, Cat. No. TEMD6010FX0 sun sensors, United States) (two in each of the six faces of the satellite, see Figure 8), two analog-to-digital converters (ADC) (Texas Instruments, Cat. No. ADC128D818, United States) and one absolute orientation inertial measurement unit (IMU) (Bosch, Cat. No. BNO055, Germany) are assembled on the ADC's circuit board (see Figure 8). This design enables the implementation of an Extended Karman Filter (EKF) and to construct an algorithm to detect Nadir and the Sun vector.

Figure 8: Location of the two photodiodes in every CubeSat's face.

TECHNICAL AND PROGRAMMATIC TOOLS TO INCREASE PROBABILITY OF SUCCESS

The development of a satellite comes with inherent risks and complexities that require the design and implementation of tools to keep them under control. In the case of the Quetzal1 satellite project, this included tools that were dynamic in nature, i.e. once they were produced they were revised on a monthly fashion as the design matured. This section describes some of the approaches implemented in this project to increase the probability of success, as more than 200 requirements, 70 risks, 220 controlled documents and reports, 150 parts, 330 tasks, and 60 engineering drawings were monitored (to name a few items) throughout the over-four years span of this project's design phase, which has to date included over 100 students and volunteers working at different points in time.

Requirement Compliance Matrix

A Matrix was developed and maintained to keep an efficient control of all the requirements that the satellite has to meet. In this matrix, the requirements were divided into three groups following JAXA's specifications (JAXA, 2015): (*i*) mission requirements, defined by Quetzal 1 Team geared towards meeting the project's objectives; (*ii*) design requirements, provided by JAXA and related to the satellite's physical characteristics such as dimensions and mass; and (*iii*) operational requirements, which are all of those the satellite had to meet once it is in orbit. Each requirement was given a unique code that depended on the type of requirement they were. A monthly revision of the Requirements Compliance Matrix was done in order to keep a control over the possible changes that might have occurred on the matrix during the development of the project. At the moment of transitioning from the design to the test phase of the project, 201 requirements were being monitored.

Requirement Verification and Validation

The Requirement Verification and Validation (V&V) Matrix enables to systematically control that each requirement is verified and/or validated. Following JAXA (2015), it was decided that each requirement was going to be verified by at minimum one of the following methods: analysis, inspection, review of design, or test. Analysis is the verification through mathematical models, inspection is the verification of physical properties through common tools and methods, review of design is used when verification is done through reviewing documentation or drawings, and test are used when none of the previous methods can be used. In this matrix, information regarding the methods that were implemented to verify each requirement, and a reference to the internal document that proved that such verification was done, was included. A requirement was considered verified or validated only after an internal document specifying how the verification was performed, was reviewed and released as a controlled document.

Risk Matrix

The Risk Matrix is a tool that helps identify and categorize the mission's risks. In this tool, each of the mission's risks are given a value for likelihood and consequence between 1 and 5. For likelihood, 1 means low and 5 high probability of the risk occurring. For consequence, 1 means low and 5 high impact on the mission should the risk actually happen. These values become the coordinates of the risk in the Risk Matrix (see Figure 9). The level of criticality (low, medium or high) of a risk is subsequently determined by the location of the risk. If the risk position falls in the green, yellow, or red region, it is determined to be of low, medium, or high criticality, respectively.

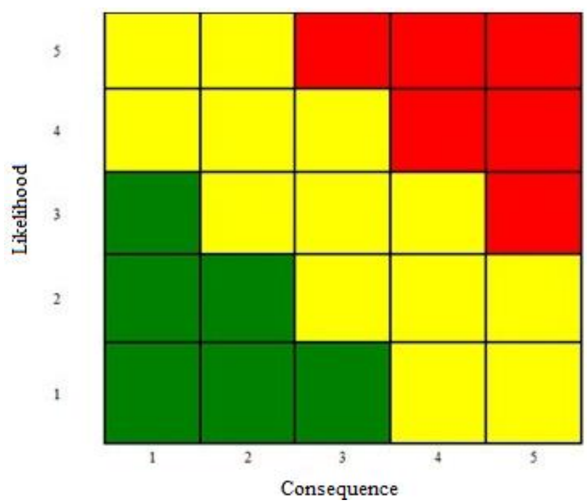

Figure 9: Risk Matrix. The combination of consequence and likelihood determine the criticality of a risk, described as green, yellow, or red for low, medium, and high, respectively.

This tool helps controlling and categorizing the mission's risks since it gives an overview of each of them and how critical they are to the mission. A Risk Matrix is dynamic, meaning that as the design matures, or further testing is accomplished, new risks are found and old ones may be demoted in terms of criticality or even removed. This tool also helps indicating what technique to follow in order to mitigate the risk. Over 70 risks were monitored during the design phase of this project. The actions taken to mitigate each risk are controlled under the Failure Mode and Effects Analysis.

Table 1: FMEA matrix organization utilized to quantify, rank, resolve and mitigate risks that affect Quetzal 1. In this case, the table sets the example of an error in communication protocols in the module of command and data handling. An action has not been taken hence the 'No' in the 'Action Taken' field. Due to the length of the table, it is broken in two for formatting purposes.

Module	Risk Code	Failure Mode	Potential Cause(s) of Failure	Severity	Potential Effects of Failure	Occurrence	Current Controls	Mitigation
C&DH	CDH-04	Error in communications protocol	False activation, clock asynchronized	64	Interruption in communications between OBC and GCS	8	Functionality test of AX100	8

			Action Results				
Risk Priority Number (RPN)	Severity Category	Recommended Action	Action Taken	Severity	Occurrence	Mitigation	RPN
4096	Critical	Generate AX100 functionality test report verifying clock synchronization	No	-	-	-	-

Failure Mode and Effects Analyses (FMEA)

A Failure Mode and Effects Analysis (FMEA) allows to better characterize each risk, identifies how the risks will be mitigated, and quantifies to what level the risks were taken care of. The FMEA also allows ranking all the mission's risks from most to least critical. The organization of Quetzal 1's FMEA matrix was based on NASA's Standard for Performing a Failure Mode and Effects Analysis (FMEA) and Establishing a Critical Items List (CIL) (NASA, 2010) (see Table 1).

Each failure mode a risk represents is added into the FMEA matrix and is given a number for (*i*) severity, which describes how much of the mission's capabilities are lost if the failure mode happens, (*ii*) occurrence, which is the probability of the failure mode to take place, and (*iii*) mitigation, which describes how much the current design mitigates the failure mode. Each of these values are described in NASA (2010). The must be taken and subsequently, the new values of severity, occurrence, and mitigation are determined and then multiplied to obtain a revised RPN (which is recorded under the Action Results column). Hence, the objective of the FMEA matrix is to identify all the mission's failure modes, record the action taken in order to reduce the risk's RPN, and then obtain a revised RPN. This serves to monitor and record all the actions taken to mitigate each risk, increasing the mission's probability of success.

N-Squared Diagram

In the design phase of the project an N-Squared Diagram (see Table 2) was created; this type of diagram has the form of a matrix and is used to represent functionality or physical connection between system elements. The diagram enabled team members to define and analyze the interfaces the satellite needed. The diagram presented the four types of interfaces that were

Table 2: N-Squared diagram. The matrix shows the relationship between the different types of interfaces that the modules share. These interfaces were categorized as: M – mechanic. E – electrical. S – software. SS – service supplier.

Structure	M	M	M	M	M	M	M	M	M	M	SS	M
	ADCS Module					E	E, S					
		COMM Module				E	E, S					
			Antenna									
				Monochromatic Sensor		E	E, S					M
					Batteries	E, M		M				
						EPS	E, S	E	E	E	SS	
							OBC	E, S		E, S		
								Thermal			SS	
									Sollar Array			
										Motor		M
											Deployer	
												Carrousel

considered: mechanical (M), electrical (E), software (S) and service supplier (SS). From this tool, it was observed that all subsystems share a mechanical interface with the structure, even the deployer that will be used to release the satellite into space. It also showed that EPS is completely connected by electrical connections to other interfaces. While in the case of the OBC, it is a mix between electrical and software interfaces. This enabled to establish what level of voltage was needed or what communication protocol to use between sub-systems. This mitigated the possibility of not having a proper planning and selecting an OBC that wouldn't be able to control the whole system.

Document Control

During the development of this project, every design decision and every result given during the requirements verification phase was recorded in internal documents, each with a unique code. All of these documents were stored on a cloud service so every member of the team could have access to them. The documents were grouped depending on the sub-system to which they belonged. This was done in order to ensure that every key decision on the project was justified in an objective fashion and recorded so that current and future members could have access to previous decision-making processes. Before being released as a controlled document, each new document had to be reviewed by an engineer who did not participate on its development and subsequently approved by a project director. If modifications were done to a document that had already been released, a new revision of the document was published and the old revision was sent to a folder for obsolete documents. Obsolete documents were never erased so a paper trail could always be maintained. At the moment of transitioning from the design to the test phase of the project, 226 documents had been created for the development of the satellite.

Parts Control

Just like with the internal documents, a strict control over the components in the satellite was kept at all times. A unique code was given to each component so they could be easily recognized. A list of all the components was created and maintained from the beginning of the project, and it included component's properties that affected the overall design of the satellite, e.g. mass, voltage required, power consumed, material composition, and outgassing properties. Similarly, this control would allow the team to backtrack and find the source vendor, catalogue number, and lot number of each item, from the OBC to every single screw. Hence, over 150 different components were controlled on Quetzal 1 Flight Article.

Capacitor Control

The aluminum electrolytic capacitor is one of the most common passive electronic components used. However, it is also one of the most unreliable due to its susceptibility to physical and thermal overstress. Physical stresses – such as vibrations, breakdowns of the oxide layer, shocks, radiation and electrical discharges and charges – and thermal stress – such as cooling and heating cycles – create changes in pressure in the capacitor. The pressure change is mostly due to the evaporation of the electrolyte, that produces the degradation over time of the capacitor, even an explosion of the component (Kulkarni, 2012). To mitigate this problem, it was ensured from the design phase that no electronic parts of Quetzal 1 would include electrolyte capacitors. In the cases of COTS components where an electrolyte capacitor was used, the manufacturer was contacted to request a custom part that used tantalum capacitors. This is because tantalum capacitors have stable electrical parameters making them more reliable. The tantalum capacitors also have better resistance to elevated temperatures, which make them ideal for aerospace electronic applications (Vishay, 2003).

Material Off-Gassing

In order to prevent contamination in the optical equipment and other electronics, the outgassing properties of the components in the satellite had to be determined. The off-gassing value of the materials that composed each component needed to be under a value established by as 1% for the Total Mass Lost (TML) and 0.1% for the Collected Volatile Condensable Material (CVCM) (JAXA, 2010). NASA's Material and Processes Technical Information System (MAPTIS) (NASA, 2018) was used to obtain the TML and the CVCM of the main materials of each component.

Structural Finite Element Analysis

Performing Finite Element Analysis (FEA) is a common practice to determine if a CubeSat will withstand the rough launch environment, including vibrations and accelerations as described in JAXA (2015). For this purpose, ANSYS® Academic Research Mechanical, Release 19.0 was used to analyze static, quasi-static, modal, and random vibrations. The static analysis was based on the compression load that the structure rails will be subjected to on the JSSOD; the quasi-static analysis is based on the highest possible acceleration of the launch vehicle; modal analysis determines the natural frequencies of the CubeSat; and the random vibration is based on the frequency and Power Spectral Density (PSD) values of the launch vehicles described in the JAXA (2015).

Thermal Finite Element Analysis

Similarly, FEA can help determine the temperatures profiles that a satellite will experience while in orbit. For this analysis, the heat fluxes were determined for each of the faces of the CubeSat, considering: solar radiation, albedo radiation, infrared radiation, reflected radiation, heat dissipation, and position with respect to the Earth and Sun. Results of transient thermal FEA indicated that most of the satellite will withstand the worst-case scenario temperatures, this occurs when only one face of the satellite is facing towards the sun. The results showed that the batteries will be exposed to a lower temperature than its lower functional temperature. The analysis enabled to make design changes to maintain all components within their functional range of temperatures.

Engineering Drawings Architecture and Control

To help with the organization of what would eventually become over 60 engineering drawings produced by the Quetzal 1 team, an Engineering Drawing Architecture was designed and implemented, where each drawing's identifier quickly conveyed its position within a hierarchical structure. This scheme was based on four categories: the complete CubeSat drawing, the assemblies of all the CubeSat modules (COMM assembly, ADCS assembly, etc.), the subassemblies of a module and, finally, all the parts that make up a subassembly (see Figure 10).

CST-ASY identifies the drawing as the complete CubeSat assembly drawing, while drawings starting with ASY indicate that the drawing corresponds to a module assembly. Similarly, drawings starting with SAS and with PT indicate the drawing is a subassembly of a module, or that is a part that makes up a subassembly, respectively. The revision letter is placed at the end of every name. All drawings were added to a master list of drawings for their control.

Assembly Procedure

The assembly procedure is a detailed document that describes, step by step, the process that must be performed to assemble the CubeSat correctly. This document was created to proactively mitigate any errors and to avoid potential surprises while assembling the CubeSat. Each step is aided by an image of the step to make, a detailed description of the step and a section to write the initials and comments of the person accounted for performing it. Besides the description of each step, the procedure has a list of materials, each part's part number, and tools to be used to avoid any confusion in the assembly. Another feature of this document is that it provides the adequate torque value in each step that involves a threaded part, avoiding the risk of a part to become loose, overtightened, or even damage. This torque was calculated considering the materials of the parts involved and later compared to existent values to verify the result.

DISCUSSION

The small size of a CubeSat can be deceiving, as it is a highly complex system that requires meticulous controls for the appropriate managing and monitoring of its multiple subsystems and components as they evolve during the design phase. Quetzal 1, UVG's CubeSat developed mostly by undergraduate students, produced hundreds of controlled documents,

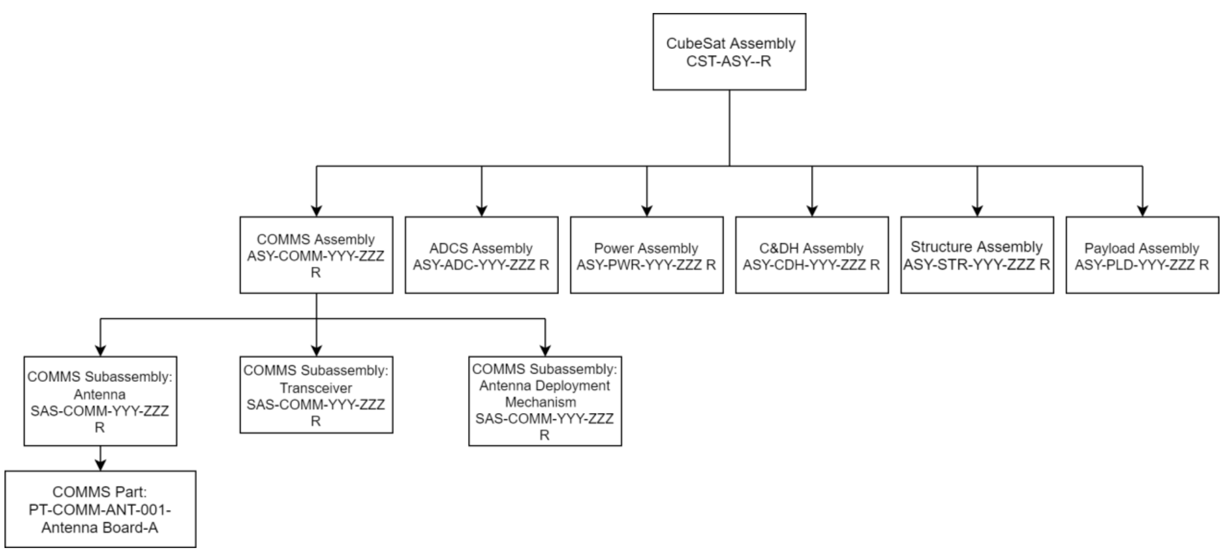

Figure 10: Engineering drawing organization tree, designed to convey the hierarchical structure of each drawing in the engineer drawing package. Starting from the main assembly, the submodules, the subassemblies and specific parts.

engineering drawings, reports, and hundreds of requirements and risks that needed monitoring to increase the odds of mission success. From the systems engineering and project management perspectives, one of the most essential controls was the Requirements Verification and Validation Matrix. This matrix informed team members of what the design needed to abide by, and system engineers, project managers, and directors to monitor that these were indeed being fulfilled, especially as the design evolved. The FMEA matrix served as a tool for the Systems Engineers to quantify each risk, which in turn enabled an informed decision – in an objective fashion – of their criticality. This comes from the principle that understanding how a subsystem can fail, a design that is capable of mitigating that failure's root cause can be produced. Additionally, the Risk Matrix, helps management easily monitor risks and their mitigation plans. A drawing naming architecture and revision scheme was helpful in ensuring every team member was working with the latest designs, hence mitigation human-error risks that can translate to re-work or even mission failure. The same is true for the project's reports and controlled documents, which serve to provide organized documentation of how and why each engineering decision was made (e.g. trade studies between several options) - this is especially important in a project that runs for several years and, in the case of academia, with a high personnel rotation characteristic of graduation (senior, capstone) projects. Similarly, a systematic part control helps track each component and their main characteristics (physical properties, power consumption, operational temperature ranges, off-gassing properties, etc.). A type of component, capacitors, require further controls: no aluminum electrolytic capacitors are to be used as these tend to fail in the vacuum of space - in lieu of these, tantalum capacitors need to be utilized.

Multiple tools were implemented during the design phase of Quetzal 1 to help increase the odds of mission success from the engineering perspective. These include the N-squared diagram, which we recommend be performed as early in the design phase as possible. This tool showed how every subsystem will interact with each other, thus enabling the design of mechanical, electrical, software, and service interfaces, and provided constraints and drivers not usually described by the Requirements. After this diagram was finished, other work such as the EPS electric diagrams and the OBC communication protocols diagrams could be created. Later on the design phase, structural finite element analysis (FEA) done with ANSYS software enabled the validation of the structure subsystem and the CubeSat assembly, corroborating that the satellite would withstand the vibration and acceleration environment of the launch. Similarly, thermal FEA computationally confirmed no further insulation was needed beyond the solar panels to withstand the temperature changes of the satellite's orbit, with the exception of a heater for the batteries. FEA is a cost-effective method to validate structural design and thermal protection of the CubeSat. Finally, developing an assembly procedure ensured that safety and cleanliness protocols are in place, tools and materials are ordered ahead of time, and each step will have a responsible party, further increasing the probability of successfully performing this final stage of development and minimizing the occurrence of negative surprises on a time-sensitive phase of the project.

To increase the odds of a CubeSat's mission success, multiple tools and approaches can be taken to manage the project's multiple physical and document components, risk, requirements, documents, drawings, and other items. In the case of Quetzal 1, this was further necessary due to its academic nature that has translated to over 100 students, volunteers, and faculty working in the project at different times during the four-year long design phase. While a 100% certainty can never be achieved, significant effort was invested in the design phase of this project - here conveyed by describing some of the tools in place - to get as close to the 100% as possible, and help ensure a successful flight of Guatemala's first satellite.

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References

1. Zea, L., Ayerdi, V., Argueta, S. and Muñoz, A. "A Methodology for CubeSat Mission

Selection”, Journal of Small Satellites, JoSS, Vol. 05, No. 03, pp. 483–511, 2016.

2. JAXA. “JEM Payload Accommodation Handbook -Vol.8- Small Satellite Deployment Interface Control Document”, Rev. B. JAXA. JX-ESPC-101133-B. 40 pages, 2015.
3. Gerhardt, D. T. “Small Satellite Passive Magnetic Attitude Control (Doctoral dissertation, University of Colorado at Boulder)”. Retrieved from: http://scholar.colorado.edu/asen_gradetds/78/ , 2014.
4. NASA. “Work Instruction - Failure Modes and Effects Analysis (FMEA), Critical Items List (CIL), and Fault Tree Analysis (FTA)”. NASA Doc. No. GLWI-QE-8720.2. Retrieved from: https://prod.nais.nasa.gov/eps/eps_data/161793-AMEND-002-002.pdf, 2010.
5. California Polytechnic State University (CalPoly). “CubeSat Design Specification”. California. The CubeSat Program. 13 pages. Retrieved from: http://www.cubesat.org/resources/, 2015.
6. Kulkarni, C. *et al.* “Physics Based Electrolytic Capacitor Degradation Models for Prognostic Studies under Thermal Overstress”. First European Conference of the Prognostics and Health; Dresden; Germany, 2012.
7. Vishay. “Wet Electrolyte Tantalum Capacitors”. Retrieved from: https://www.vishay.com/docs/40021/wtintro.pdf , 2003.
8. NASA. “Materials and Processes Technical Information System”. Retrieved from: https://maptis.nasa.gov/, 2018.