Applying Cube Satellite System Development as a Vehicle for Systems Engineering Training

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Abstract A group of graduate engineers at Denel Dynamics have designed and built a 1U Cube Satellite (CubeSat) as a training initiative. A CubeSat is a small cubic nanosatellite with a weight restriction of 1.33 kg. Each side of the cube has a dimension of 100 mm. The CubeSat is a secondary payload on a satellite launch vehicle and enables low-cost space research. This paper provides an overview of the CubeSat system design and shows how the systems engineering processes were applied to realise a system that satisfies the mission requirements. The system utilised a combination of Commercial Off–The–Shelf and in-house designed system elements which were integrated and tested. The payloads include a camera, radiation sensors and temperature sensors. The paper describes the challenges encountered and addressed during the Exploratory Research, Concept and Development phases of the life cycle.

Introduction and Background

South Africa should become a key contributor to global space science and technology based on innovation towards a knowledge-based economy published by the Department of Science and Technology (DST) in its ten-year plan for South Africa (2008 – 2018). To achieve this goal, South Africa requires a growing satellite industry, a range of innovations in space sciences, earth observation initiatives, enhanced communication protocols, and focus on navigation and engineering.

The shortage of skilled engineers in science and engineering in South Africa is well documented and the technical nature of the work conducted within the aerospace industry combined with the high average age of engineers further compounds this problem. The Engineering Academy of Learning (EAL) was established within Denel Dynamics to develop and grow graduate engineers to enable them to be productive in a short time. The EAL uses a multifaceted approach to develop graduates by combining formal courses, on the job training, and a development project into a one year internship programme for graduate engineers. The intern project of 2012 was the design and construction of a one-rack (1U) CubeSat [1]. The project was divided into three parts: Ground Station and communications; structure and backbone (consisting of on-board computer (OBC), power and solar cells); and payload and launch. The interns worked on this project as three groups, each addressing a part of the design with an integration effort that involves members of all the groups. The interns were exposed to the systems life cycle, from design through to development, construction, utilisation and ultimately disposal.

Graduate engineers were exposed to system design through the development of a Cube Satellite. This paper describes the design of the Cube Satellite structure and its payload. Specific attention is paid to architecture design and synthesis. The architecture design was largely prescribed through the Cube Satellite specifications, and therefore the process of analysing requirements and deriving the system requirements from the science mission is not described in any detail in this paper. The design and integration with the Ground Station is also excluded from this paper.

Science Mission

The decision for initiating the primary science mission was based on the needs within the South African science and space community. A prospective collaboration with the South African National Space Agency (SANSA) led to the decision to utilise the satellite to accumulate data on the South Atlantic Anomaly (SAA) of the geomagnetic field using a combination of payloads. The SAA occurs in an area where the *Van Allen* radiation belt is closest to Earth and is caused by the non-concentricity of its magnetic dipole [2]. At this region, there is evidence of an increased flux of energised particles exposing satellites to escalated levels of particle radiation. The SAA is of great significance to satellites and other spacecraft that orbit the earth at several hundred kilometres altitude; these orbits take satellites through the anomaly periodically, exposing them to several minutes of strong radiation, caused by the trapped protons in the inner *Van Allen* belt [3], [4]. It is therefore a subject of great importance for future satellite development [5].

The main objectives of the satellite mission are to investigate the extent of the current borders of the SAA, the factors facilitating the change in its borders, the rate of growth of the anomaly relative to the magnetic field strength of the earth and the drift rate of the anomaly. It is also of interest to monitor the diurnal change in shape and density of the anomaly and any relation it may have to atmospheric weather within its 800 km orbit. If a launch is procured by 2013, it will be interesting to also study the behaviour of the anomaly around the time of Solar Maxim.

Also intended for this mission is the monitoring of the electronic commercial-off-the-shelf (COTS) components populating the satellite while it passes through the anomaly and the effectiveness of the shielding designed to protect the satellite against radiation damage [6].

System Design

System Overview

The CubeSat (designated DynaCube) comprises of the satellite and Ground Station located at Denel Dynamics. For the purpose of this paper, the system will be confined to the satellite only (excluding the Ground Station). The fundamental sub-systems of the satellite are computing, communications, power management, mechanical structure, attitude determination and payloads to execute the science mission. These sub-systems are a combination of in-house developed and bought-out hardware and software, thus creating a challenging integration process. Figure 1 shows and overview of the sub-systems located on DynaCube.

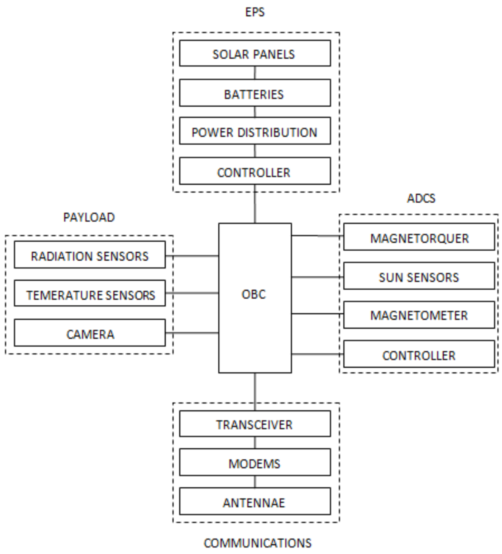

Figure 1: Sub-system overview

The critical high level computing was executed by the OBC. The communication sub-system of the satellite was designed completely in-house, using ultra-high frequency (UHF) and very high frequency (VHF) bands for the command uplink and data downlink respectively. The communication system is made up of antennas, transceiver and modems allowing the satellite to communicate with the Ground Station. An antenna deployment system was also designed to house the antennas within the spatial constraints of the satellite. The power management of the satellite system is executed by the Electrical Power System (EPS) which is made up of solar panels developed in-house as well as a power controller and batteries. To control the orientation of the satellite, an Attitude Determination and
Control System (ADCS) was developed. The system uses sun sensors and magnetometers to determine the attitude of the satellite and a combination of air core and steel core magnetorquers to control the rate of spin of the satellite. A series of temperature and radiation sensors have been incorporated to achieve the science mission. A modified COTS camera is also implemented as an additional payload, which transmits images to earth. Once all the electronic sub-systems were integrated, the mechanical structure was developed in-house. The structure was designed to contain the hardware of the satellite within the constraints of cube satellite standards. The structure also provides shielding to the components within the satellite against particle radiation.

Sub-system analysis

Processing. The CubeSat community has expanded to include several online stores that sell components for CubeSats. Several options exist for purchasing an OBC. An alternative is to design a new OBC. The budget and time constraints placed on the project these alternatives infeasible. OBC prices range from R40 000 to R350 000. These prices made the online options infeasible for our project. Ultimately we found an OBC designed by the Electronic System Laboratory (ESL). ESL is a Computer and Control Systems Group laboratory in the Electronic and Electrical Engineering department at the University of Stellenbosch.

This purchase was beneficial because of ESL being in South Africa, this reduced the delivery delays of the product. The OBC that was purchased is the CubeComputer. It is based on a high performance, low power 32-bit ARM Cortex-M3 microcontroller unit (MCU). It has electrically erasable programmable read-only memory (EEPROM), flash memory, and external static random access memory (SRAM). It interfaces through the CubeSat standard header to the various other sub-systems using universal asynchronous receiver/transmitter (UART) and inter-inter communication (I^2C).

The software for the OBC was implemented in-house. This software was designed to operate in several modes as a function of the power budget. The OBC has to determine whether the battery voltage on the EPS is sufficient to switch to the designated mode. Table 1 shows the different modes with a description of all the modes.

Table 1. Different modes of operation within the OBC

Mode	**Description**
Launch Idle Mode	During this mode DynaCube will be in its idle state where none of the sub-systems are on except the OBC. The OBC has a timer on for 15 minutes before booting up and initialising.
Boot Mode	DynaCube will boot up and initialise all systems. A system's check should be done.
Detumbling Mode	The ADCS will execute the algorithm to detumble the satellite from its uncontrolled tumble.
Orbital Idle Mode	DynaCube will be in a waiting state between successive modes or mission plans. Only critical systems enabled. Charging is done in this mode.
Image Acquisition Mode	Images will be captured by the camera. The images will be sent to the OBC for storage on the SD card.
Measurement Mode	The secondary payloads are cycled during this mode as to limit power of the satellite. The measurements are taken and stored for transmission. The values and a timestamp should be saved.
Data Acquisition Mode	The satellite communicates with the Ground Station. The satellite can either send or receive data from the Ground Station.
Silent Mode	In the time that the satellite fails to establish communication with the Ground Station for a period exceeding the orbit time, the CubeSat will be put in silent mode. In silent mode the satellite cannot transmit any data until communication is re-established.

Each of these modes satisfied requirements at the systems level. In addition to the modes all the interfaces had to be implemented between the OBC and the other sub-systems. I^2C is a computer bus used to communicate, at relative low speed, between peripherals. It only uses two buses (data and clock) for communication. However multiple devices can be connected to the buses for communications. This is in contrast to UART that requires two buses per two devices communicating

Communications. The communication link between the combinations of transmitters and the receivers consists of a radio (as opposed to optical) baseband-modulated carrier signal [7]. The modulation schemes are audio frequency shift keying (AFSK) and G3RUH, also a variant of FSK modulation. G3RUH modulation enables amateur satellite communications of 9600 baud transmission, whereas FSK modulation with its 25 kHz channel spacing provides transmissions only up to 1200 baud. The lower bandwidth transmissions are modulated through AFSK, which adds simplicity to the design and has the advantage of demodulation through any device that can carry music or speech (such as a personal computer (PC) sound card). A simplified diagram of the communications on the satellite and the dependencies with the OBC is presented in Figure 2.

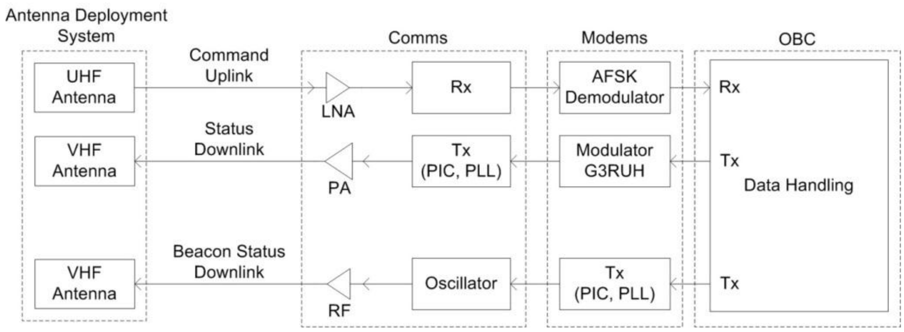

Figure 2: Communication dependencies on the satellite

Telecommunications in space differs from earthbound communications is two major respects; very long range transmissions and potentially large velocities between the transmitter and receiver (resulting in significant *Doppler* shift considerations). Another difficulty (for LEO satellites) is the limited (short) communication coverage during each orbit. Mass, power, and volume limitations also limit the hardware and the performance of the on-board communication systems. Component choices for the command sub-systems are similar in space-based applications, including complementary metal-oxide semiconductors (CMOS) and bipolar transistors; however, radiation hardening of these components are crucial to ensure limited degradation of electronic equipment. This degradation occurs from a variety of mechanisms, depending on the type of radiation and the orbit of the satellite. Energetic charged particles passing through the junctions of electronic components can cause temporary errors (*flipping* of bits and *latchup* conditions) and can cause components to completely fail over long periods of exposure. Radiation hardening is a limited and time-consuming practise, and results in components that can become extremely expensive. To decrease to overall cost of the device, COTS components were implemented; however temperature and air-pressure tests were performed to ensure compatibility and reliability of these components in the harsh space environment.

Performance of the transmitting equipment is measured by its effective isotropic radiated power (EIRP). The EIRP consists of the maximum power fed to the transmitting antenna and multiplied by the (directional) gain of the antenna (*G*). The figure of merit (*FOM*) of the receiving equipment is determined by the gain of the antenna and the noise temperature (*T*) within the receiver. The types of links used are low-bandwidth (a function of the information data rate, the channel coding rate, and the type of modulation) uplink signals from the Ground Station to the satellite to control and interrogate the satellite. Low-bandwidth telemetry and housekeeping downlinks from the satellite to the Ground Station, high-bandwidth downlink signals to send photos to the Ground Station, and a Beacon downlink to provide constant (but controlled) identification of the satellite to the control station. The operation frequencies and power budget for the individual links are determined through investigation of the required link performance and data throughput and the noise-contribution on each link to maximize the quality of service (QoS) conditions. The bit error rate (BER) is dependent on the ratio of the energy per information bit to the power spectral density of the noise (E_b/N_0) and also impacts the QoS. Additional losses such as the attenuation of waves as it propagates through the atmosphere, losses in the transmitting and receiving equipment, depointing losses (assuming line-of-sight (LOS) communication), and polarisation mismatch losses (resulting from the Earth's troposphere and ionosphere) also contribute to the QoS. The choices of components and performance were determined by considering the equation of the signal-to-noise ratio (*SNR*) of each transmission (links). From a system-engineering perspective, this equation is not discussed in detail, and the resulting parameters for the DynaCube communication protocols are presented in Table 2.

Table 2. Different modes of operation within the OBC

Parameter	Command uplink	Status / telemetry downlink	High-*B* downlink	Beacon
Frequency (MHz)	435.050	145.980	145.980	145.840
Transmit power (dBm)	47	27	27	16
Modulation	AFSK	G3RUH	G3RUH	CW-OOK
Data rate (bps)	1200	9600	9600	1200

From Table 2, the frequency (in MHz), transmit power (dBm), modulation scheme, energy per information bit (dB), receiver sensitivity (dBm), and the maximum achievable data rate (bps) for the transmitters and receivers are given. The Ground Station transmitter is classified as the command uplink, whereas the status / telemetry downlink, high-*B* downlink, and beacon is situated on the satellite. The frequencies are allocated by the International Amateur Radio Union (IARU) and only the preferred band was specified within the project requirements. The command uplink was chosen within the UHF band since a higher transmit power was available from the Ground Station (47 dBm) to account for the higher wavelength-dependent atmospheric losses, and less interference from adjacent channels were expected (also as a result of the higher atmospheric losses at higher frequencies). VHF transmission from the satellite was preferred due to lower losses, and increased achievable sensitivity of the Ground Station receiver. The modulation schemes (AFSK and G3RUH) are the preferred methods of modulation in amateur satellite communication as it presents less complex hardware implementation (a function of weight and size restrictions). The beacon is a continuous-wave on-off keying (CW-OOK) *Morse Code* implementation and is used to track the satellite. The beacon is implemented through first principle hardware design, and contains a logical unit, a VHF oscillator, and an RF amplifier (to achieve 16 dBm power). The beacon is switched off if the satellite is 'seen' by the Ground Station to conserve energy. Only the callsign is transmitted by the beacon as it is not permitted to transmit any meaningful data if the satellite is not within LOS. The 145.980 MHz high-*B* downlink transmission at 9600 bps is used to transmit images taken by the on-board camera if the satellite is within LOS.

Power. The power system provides continuous source of electrical power to the load. Photovoltaic cells are used to generate electrical power which is stored in batteries; this electrical power is then monitored, regulated and distributed to the sub-systems. The photovoltaic cells used for the solar panels were Triangular Advanced Solar Cells (TASC). TASC are triple junction gallium arsenide (GaAs) cells with a nominal efficiency of 27 %. Two cells in series provide ideal voltage for charging a standard 3.6 V li-ion battery and with four times the voltage and twice the efficiency per unit area compared to typical silicon based photovoltaic cells [12]. The TASC cells have a mass of 0.234 g and area of 2.277 cm^2 which makes them ideal for CubeSat solar panels. The cells are mounted on a PCB to form a solar panel; the space to mount cells is reduced by the temperature and sun sensors to be mounted on the same PCB and also the camera hole.

Batteries provide power during eclipse and when the power from the photovoltaic cells is limited. Rechargeable battery technology alternatives are Lead-acid, Nickel Cadmium (NiCd), Nickel-Metal Hydride (NiMH), Lithium ion (Li-ion) and Lithium ion Polymer (Li-Ion Poly). Li-ion poly batteries were used on DynaCube because of its high number of discharge and charge cycles (> 1000), low self-discharge (0.16 %), high discharging and charging thermal range (-20 to +60°C and 0 to +45°C respectively) and high battery capacitor. The protection circuitry maximizes the battery life.

The power system architect is based on Maximum Power Point Tracking (MPPT). The MPPT optimizes the point of operation of the photovoltaic cells in order to maximize power delivered from photovoltaic cells, this enable the photovoltaic cells to operate at its maximum power point. The electrical power from the photovoltaic cells is regulated using switch-mode regulators. Loads are protected by voltage and current limited switches and surplus power is stored in the batteries. Due to limited power available a power budget was constructed to prevent the CubeSat from operating with a negative power budget. At maximum power delivery, the power consumed is larger than the power generated, resulting in a negative power budget. This was solved by recycling the loads turning on only the critical loads that are needed at that particular time.

Mechanical structure. The requirements for the mechanical design of DynaCube structure were derived from a combination of user defined requirements as well as industry standard and launch provider specific requirements. The satellite structure was designed to the mass and spatial parameters as specified in the Stanford/Calpoly CubeSat design specification [3]. One of the greatest mechanical design challenges was material selection for the structure. Due to out-gassing of materials in space, only low out-gassing materials were permissible to be utilized in the design. Any material selected was required to have a Total Mass Loss (TML) of less than or equal to 1.0 % and the Collected Volatile Condensable Material (CVCM) was required to be less than or equal to 0.1 %. The satellite was also required to be compatible with the launch mechanism used, the most common of which is the Poly Picosatellite Orbital Deployer (P-POD). To integrate the satellite with the P-POD system, the structure required four launch rails along the edges of the cube to ensure ease of ejection. It was required to ensure that at least 85.1 mm of the rail was in contact with the P-POD rail at all times.

Aluminium 7075 or 6061 was specified for the main satellite structure. However, aluminium 6082-T6 was utilised as it is readily available in South Africa and has a similar chemical composition and mechanical properties to aluminium 6061. All aluminium components that come into contact with the P-POD system were required to be hard anodized to ensure electrical isolation and prevent cold welding. The aluminium also acts as a radiation shield and is therefore an enclosed structure as shown in Figure 3. The COTS components within the structure can operate with radiation exposure from a range of 3 krads to 35 krads. An aluminium shield thickness of 1.2 mm is sufficient to limit the radiation exposure to the components to 3 krads [8]. Confirming this will be one of the objectives of the satellite mission. Although using the structure as a radiation shield is advantageous, it is not desirable for heat dissipation within the satellite. Thermal analyses were conducted to simulate the temperature exposure within the satellite when it will be in orbit and it was found that the exposure was within the operational temperature range of the components. The cube satellite structure is given in Figure 3.

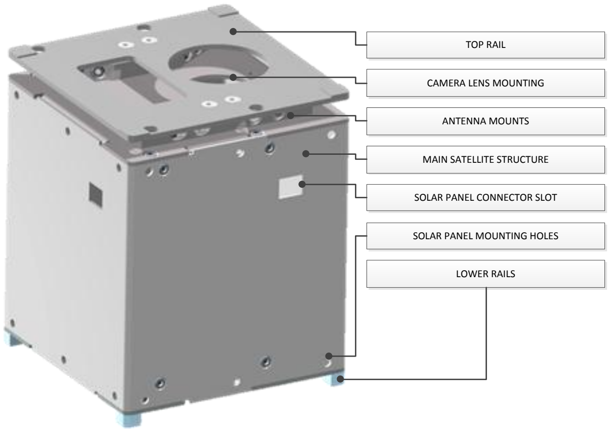

Figure 3: Cube satellite structure

The design in Figure 3 included a structural core with an outer aluminium skin. The structural core was made up by the PCB unit shown in Figure 4. The PCBs were held together using custom designed aluminium spacer mounts and mounting blocks. This way, the mass constraint can be adhered to as the outside satellite structure is not required to provide all the rigidity to the structure, allowing for an enclosed structure with very thin wall thickness. The mounting blocks and spacer mounts included ventilation to ensure no air was trapped.

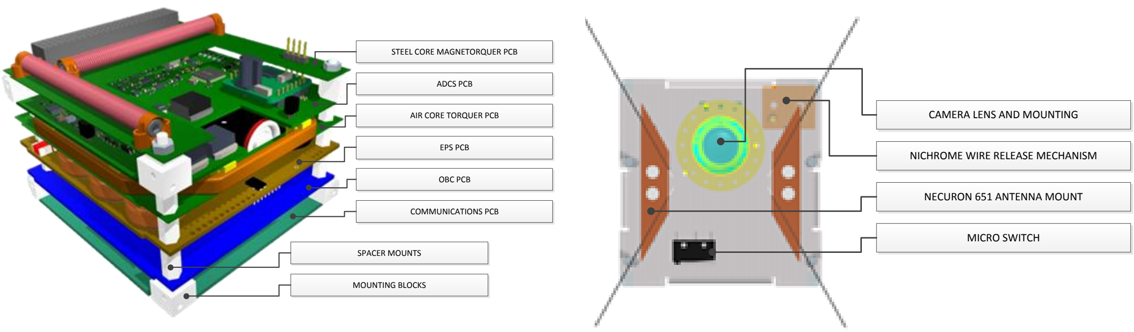

Figure 4: Satellite PCB (left) and antenna deployment system / camera mount (right)

The mechanical design of the structure had to also incorporate the antenna deployment system on the satellite as well as a modified camera as a secondary payload. The antenna deployment system comprised of two antenna mounts, a nichrome wire release mechanism and a micro switch as shown in Figure 4. An important consideration that had to be taken into account was the manufacturability of the components. The main satellite structure was wire Electrical Discharge Machined (EDM) while the ends of the structure were milled.

Temperature Sensors. The temperature in low-earth orbit (LEO) can vary between -100°C and +100°C. The variations in temperature can be attributed to the exposure to the sun (high rise in temperature) and the temperature minimums are observed during solar eclipse [9]. Temperature sensors are used to monitor the temperature of the system. Manufacturers specify the operating range of the COTS used on DynaCube. Temperature sensors used on the satellite were selected based on power consumption, size, weight, interface, operating temperature range and cost. The chosen sensor uses one wire interface to communicate with the microcontroller. The sensor is connected to the global +5 V power line. There is a total of seven temperature sensors placed in the satellite and data is transmitted to the OBC for further processing.

Radiation Sensors. The *Van Allen* belt in LEO prevent some of the radiation from reaching the earth. The trapped particles in the earth's magnetic field travel at high speed causing radiation damage to satellites orbiting within the *Van Allen* belt. Sensors considered for radiation measurement were electromagnetic radiation sensors, integrated dosimeter sensors, and bandwidth sensitive photodiodes. Sensors used in the satellite were Radiation FETs (RADFET), there are p-type Metal-Oxide Semiconductor (PMOS) transistors whose gate voltage is proportional to the amount of radiation dose the sensor is exposed to, and the RADFET are dosimeter. The advantage of these sensors is their wide operating range. The RADFET sensors were used on DynaCube, supporting circuits for the sensors were designed which consist of a biasing circuit, current source, voltage source and Analogue-to-Digital Converter (ADC). The radiation sensor data collected is sent to the OBC for post-processing.

Camera. All constraints were considered when choosing the camera that was used on DynaCube. The main components of a camera are the image sensor, lens and communication interface. The image sensor determines the resolution of the camera, the shutter speed and aperture that is necessary to take well-lit images.

There are two types of image sensors that are used the most on CubeSat; namely CMOS and Charge Coupled Device (CCD) image sensors. These sensors differ in the way it converts the light to a voltage as well as the amount of on-chip circuitry the sensor contains. After researching in detail the CMOS and CCD image sensors and analysing advantages and disadvantages of using each, it was decided to use the CMOS sensor rather than a CCD sensor. This was mainly due to lower power consumption and ease of implementation. The photos that will be taken by the camera will cover a horizontal area of 550 km on the earth surface. The camera block diagram is depicted in Figure 5.

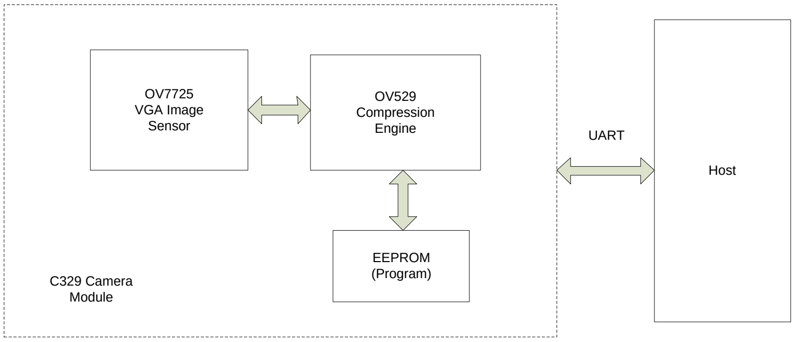

Figure 5: Camera block diagram

The camera compresses the image using the serial bridge that contains an embedded JPEC codec and outputs it via a UART interface for easy interfacing with the OBC. The camera uses a 3.6 mm CMOS image sensor from. The exposure time for the camera under low light conditions is 10 ms with a resolution of 640 × 480 pixels and the aspect ratio of 4:3.

Integration and Verification

The *Vee Model* [10] was used as to manage the design and integration of the system. This describes the levels in a system's architecture, with focus on the design development, verification and validation. System integration was performed as a bottom up process with verification performed at each step of the integration according to test plans that were produced during the design phases. Environmental and functionality tests were conducted at various levels of the architecture. Various analysis techniques were used to support the verification at each level of the hierarchy. An example of such analysis is Finite Element Analysis (FEA). The contribution of FEA to the verification of the system at each level is discussed in this section as an example.

Integration management. Integration and Information Management are two systems engineering roles that have been used during the integration. The connections and interfaces (at a high level) between the different parts as well as subsystems had to be defined. These mainly consisted of mechanical and electrical interfaces, and a naming convention was defined to differentiate between the various interfaces.

Initially a schematic layout of the subsystems was developed during the design phase with COTS items treated as black boxes and verified against their specification. Volume and mass budgets were allocated during the design phase. The subsystems were integrated according to these budgets during the integration phase. As the design and integration were not necessarily conducted by the same person or according to strict baselines, information management was a crucial process. Spread sheets were used as an informal method to capture information and managed on a shared drive. Each person responsible for a subsystem had created a spread sheet conforming to a defined template during the design phase. These sheets were used during the integration phase to ensure that all the functional and interface requirements had been met as integration proceeded towards the system level. The information in the spread sheets became more detailed as integration progressed. Changes were tracked and managed by the project team. Integration and verification delays were found to have to have a domino effect. Some sub-assemblies had to be tested in a sequence, and unforeseen problems caused delays in the overall schedule. Planning and communication through spread sheets as well as verbal feedback was used to mitigate the delays. The information was then captured within the formal configuration management system.

The hardware and software testing plans included the requirements for availability of facilities and expected test dates. The design of specific test equipment and the acquisition of specialised tooling were also considered.

Analysis contribution. Various cross cutting analysis techniques were used during throughout the project. FEA is one such technique used for the structural and thermal analyses. The thermal analysis is discussed in this section as an example. A prediction of the thermal interaction of the satellite with the space environment was required in order to aid in identifying areas for concentration during testing for qualification. This would consist of modal analysis of DynaCube. The same model was used for both analyses. The modal modelling and analysis was still in progress at the time submission of this paper. These would then. The structural design could also be modified as necessary.

The detailed assembly in Figure 4 was simplified for the purposes of analysis. This involved selecting parts which contribute most significantly to the heat transfer, and removing small geometry such as pin holes, cut-outs, fillets and chamfers. All fasteners and threads at holes were removed. Clearances and interferences in the detailed assembly were also removed. Simple shapes such as cylinders, cuboids and spheres were used to model some of the significant parts with vastly detailed geometry. In the analysis, the simplified CAD model is an input for FEA.

Of particular interest were the temperature profiles with time. This related directly to the performance effectiveness measures for the required mission. Fringe plots and videos were generated in order to identify heat sources and sinks, as well as localised heating and cooling of the subsystems. The result of the analysis showed that the temperature for the fully integrated system ranged between -9°C and +45°C. These temperatures were well within the tested range of the individual subsystems and provided justification for continued integration.

Testing and verification levels. Environmental tests had to be conducted at various levels on the *Vee Model* in accordance with the system requirements. However a full set of environmental tests at every level was not feasible due to cost and schedule constraints. Analysis was used to decide which tests needed to be conducted at which level.

Lower level system element tests comprise the subsystem tests, for the purposes of qualification. In addition to the functional tests defined in the element specifications, environmental testing was also performed. Temperature extremes were specified and all subsystems were subjected to the temperature tests. Functionality was tested at each temperature extreme. Only the solar cells were subjected to temperature cycling as they are most sensitive and experience the largest thermal gradients. This aided in risk-reduction for the next level of tests and integration.

All subsystems were put through the vacuum chamber. This was to ensure that each subsystem can withstand the prescribed vacuum conditions prior to integrating. Upper level system element tests focused of the testing and verification and verifying interfaces. The interaction between subsystems was tested. For example, the interaction between the OBC and EPS was tested to evaluate interfaces and functionality. System level tests subjected the system to the complete suite of environmental and functional tests as specified.

Conditions that vary with satellite communication within a LEO are extreme temperatures, temperature shocks, pressure vacuum, pressure gradients, vibration intensity, humidity variations, steady-state loads, dynamic loads, electromagnetic interference, acoustic noise, and solar radiation. These conditions are replicated as accurately as possible within a laboratory environment to identify possible failures of the system and sub-systems. These tests are not a perfect representation of the exact environment experienced during orbit; however considering the overall costs involved during testing, representing these conditions as closely as possible was of importance. For acceptance testing, a thermal uncertainty for DynaCube of ±11°C was added to the predicted temperature ranges with an additional ±5°C for non-tested models. Qualification thermal temperature margins of minimum and maximum of -56°C and +86°C was established through this model in accordance with COTS operating temperatures. The temperature gradient, as provided by the launch provider, was 90 minutes through the full spectrum of the possible extreme temperatures. Vibration testing of a sinusoidal correction margin with amplitude of ±10 % and frequency ±2 % and random correction margin of RMS level ±10 % and acceleration spectral density of ±3 dB was added.

Operation and Support. Testing and troubleshooting during the operating phase will be conducted by constructing two Cube Satellites. The first will be the flight model which will be launched into space and the second will be the engineering model which will be used to emulate events that may occur on the flight model. This could possibly negate a complete failure once the satellite is no longer accessible.

Conclusion

The team of engineers responsible for designing and building DynaCube had to overcome variable changes in environmental conditions and unknown parameters to ensure that all sub-systems of the satellite operate successfully during the mission. This paper focuses on design considerations and techniques specific to the communications between the satellite and the Ground Station, as well as communication protocols used on the satellite, and environmental considerations such as radiation and temperature impacts, including operation of electronic components in a vacuum. Mechanical, electronic, thermal, and environmental analysis was done on the satellite to prepare it for its primary mission; to gather information on solar radiation within the *Van Allen* belt, and transmit the data (and pictures taken with the on-board camera) effectively to the Ground Station. Redundancy and mechanical considerations increase the probability of achieving these tasks; however existing finance limitations incurred on such a project eliminate the possibility to test for all possible upsets that might occur during orbit. DynaCube was tested rigorously and components were modified to prepare COTS components for the harsh space environment and identify possible weaknesses within the system, prior to launching the satellite into its 800 km orbit. Frequency allocation for transmitting and receiving signals and a strict power budget outlined the specifications that could be achieved and tested, also described in this paper.

The Cubesat project has been used as a vehicle to expose the graduate engineer to the aches and pains of high tech development work to realise a system design.

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