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MODES OF OPERATION FOR A 3U CUBESAT WITH HYPERSPECTRAL IMAGING PAYLOAD

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Abstract

The paper discusses the design of modes of operation of a 3U CubeSat that features a hyperspectral camera as its primary payload and a field programmable gate array as its secondary payload. A hyperspectral camera poses a unique challenge for nanosatellites as it has high power requirements, stringent pointing requirements for imaging and generates a large amount of data. Nanosatellites are also constrained by limited downlinking rates which restrict the amount of data that can be sent back to the Earth. This is tackled by employing a hyperspectral image compression algorithm (CCSDS-123.0-B-1) on the FPGA that is shown to achieve compression ratios of up to four. The satellite, over its time in space, must autonomously switch between various states, each state being determined by the tasks that the satellite is performing and the external and internal stimuli it is exposed to. These states, called modes of the satellite are divided into normal modes and emergency modes of operation. System state variables such as satellite location in the orbit, current power generation, state of charge of the battery and required power for the next mode, determine whether the mode will be able to sustain for a period of time in which it is able to complete the required action. Since the power consumed by electronic components largely depends on temperature, the power consumption for the next mode is calculated using lookup tables and power estimation equations with temperature as an input. The contingency modes of operation are defined to achieve mission success in case of a component failure. The paper also presents the choice of components, sustainable modes of operation and redundancy added to the system to counteract the harsh space environment.

Keywords: (maximum 6 keywords)

Acronyms/Abbreviations
OBC: On-Board Computer
EPS: Electrical Power System
FPGA: Field Programmable Gate Array
CCSDS: Consultative Committee for Space Data Systems
TTC: Telemetry, Tracking and Command System
TLE: Two Line Element format
ADCS: Attitude Determination and Control System
MPPT: Maximum Power Point Tracking
GS: Ground Station
IR: Infrared band.
PL: Programmable Logic
PS: Processing System.
MCU: Microcontroller Unit

1. Introduction

Modern satellites' functioning and building can be broadly classified into 6 subsystems, namely, OBC, EPS, TTC, ADCS, Payload and Structural & Thermal subsystem.

Our nanosatellite has a hyperspectral camera as the primary payload, with the mission objective to take images which allow us to measure the chlorophyll content of large water bodies in order to measure their health.

Hyperspectral cameras pose two challenges, the first being large image cube size and the second being the power consumed by it. The former is a big concern because of the limited downlinking capabilities possessed by a nanosatellite, and to counter this, we implement a compression algorithm on board. To speed up the compression process and minimize the energy spent (higher power but smaller duration), computationally intensive compression algorithm are implemented using FPGAs.

The satellite, over its time in space, must autonomously switch between various states, each state being determined by the tasks that the satellite is performing and the external and internal stimuli it is exposed to. We call these states modes of the satellite. Switching between different modes is an important part of mission planning and can alter how reliable a satellite's operation is. In our paper, we present a model of task division and the criteria used for switching between modes. The next section describes in more detail the various subsystems, the numerous tasks they may perform over the lifetime of the satellite and the major components they use to do so. The section after that describes each mode in terms of the tasks it does, the components that are being used to perform them and what are the state variables (measurements) which are used to switch between them. Finally, we give a brief insight into the emergency modes. the last section talks about the scope of future work that we are doing.

2. System Description

The satellite follows an amalgamation of centralised and distributed architecture with the OBC responsible for determining the data flow and control while the EPS and TTC microcontrollers responsible for executing the predetermined tasks for the particular mode, as decided by the Flightplan executing on OBC processing system.

The three microcontrollers work in a synergistic manner to ensure coherence in operation and hence result in a contention-free execution of satellite operation. The proposed architecture offloads the OBC microcontroller of the tasks of EPS and TTC which reduces the latency of execution of the main Flightplan and also introduces several redundancies to tackle emergency situations.

The following briefly describes the tasks and components associated with the six subsystems of the satellite.

2.1 OBC

2.1.1 Components

- ARM Cortex A9 based dual-core SoC with in-built FPGA fabric. System without FPGA is called PS (Common) and FPGA part is called PL.
- NOR Flash memory shared between OBC and TTC. (Common)
- NOR Flash memory shared between OBC and Payload.
- DDR based DRAM memory (512MB). (Common)

2.1.1 Tasks

Core 0

- Housekeeping - Collection of data from numerous sensors onboard, which are part of the different subsystems. This helps us determine the state that the satellite is currently in. (Common)
- Execution of ADCS algorithms - B-dot for detumbling, fine-pointing and tracking for high accuracy control.
- Implementation of orbit propagator iterations based on the TLE obtained, which is also useful in predicting the occurrence of the ground station and image taking location. (Common)
- Communication with EPS for collecting housekeeping of sensors and devices that the EPS is connected to. (Common)
- Responding to watchdog timer interrupt from EPS. The watchdog timer interrupt is a signal sent by the EPS processor to the OBC processor, this is mechanism by which the EPS keeps a track on the status of the OBC. If the OBC is stuck in a non-responsive state, it will be re-booted by the EPS. (Common)
- Storing housekeeping and compressed data on NOR flash shared between OBC and TTC from the DRAM where it is initially stored after collection. (Common)
- Switching between modes of operation based on internal and external stimuli, which forms the flightplan. For this, housekeeping parameters and orbit propagator parameters are constantly checked to decide if the current mode should be continued or another mode should be switched into and which that mode should be. (Common)
- Turn on payload heater when payload temperature goes below critical level.

Core 1

- Uplink of data in the Uplink/Downlink Mode in order to ensure full-duplex operation.
- Control of payload for duration of payload execution.

FPGA

- Implementation of CCSDS-123.0-B-1 Compression algorithm on FPGA for compressing the hyperspectral image

2.2 ADCS

2.2.1 Components

Sensors

- Magnetometers for sensing the magnetic field in the satellite's frame in order to determine the satellite's attitude. (Common)
- Inertial Measurement Unit for measuring angular acceleration and velocity. (Common)
- Sun-sensors to help determine the sun vector, as seen from the satellite in order to determine the satellite's attitude. (Common)

Actuators

- Magnetorquers for coarse control of the satellite, used during detumbling. (Common)
- Reaction wheels for fine control of the satellite, used during pointing and tracking.

2.2.2 Tasks

Note that all attitude control and determination algorithms of ADCS are implemented on the OBC's processor. Based on the output of the algorithm, a PWM wave is generated which determines the amount of current which goes as input to the reaction wheel and magnetorquers. The algorithms are based on the values given by the ADCS sensors, which are also interfaced to the OBC processor on an I2C bus.

2.3 EPS

2.3.1 Components

- Battery and associated charging circuit. (Common)
- Solar panels on 5 faces of the satellite. (Common)
- MPPT converters which help optimise power collection from the sun. (Common)
- Buck and boost converters which help provide required voltage busses for components of different voltages. (Common)
- MSP430 used as the MCU which controls the tasks that the EPS performs and monitors the status of the components. (Common)
- Over Current Protection Circuit which helps protects important components from high current flow. (Common)
- Current and Voltage sensors to keep track of their consumption. (Common)
- Temperature sensors to measure battery temperature, based on which battery heater is used. (Common).
- Battery heater circuit.

2.3.2 Tasks

- Collect housekeeping for various components associated with it, like the various current & voltage sensors and the battery's state of charge. (Common)
- Handle housekeeping requests and other commands from the OBC (entertaining on/off requests of any subsystem by OBC). (Common)
- Implement MPPT to optimise power generation. (Common)
- Control the Simple Beacon (which contains only the call sign of satellite) before the TTC gets switched on.
- Implement a watchdog timer to keep a check on the operation of the OBC. (Common)
- Take action on the basis of OCPC triggers. (Common)
- Deployment of antenna at the time of satellite initialisation.
- Generate PWM for operation of various converters. (Common)
- Turn on battery heater when temperature goes below critical level.

2.4 TTC

2.4.1 Components

- Turnstile antenna for Downlink of data and beacon (simple and advanced). (Common)
- Monopole antenna for Uplink. (Common)
- Power amplifier for amplification at the source side. (Common)
- GMSK Transceiver for sending and receiving data using GMSK based modulation technique.
- OOK/ASK modulator for sending advanced and simple beacon. (Common)
- RF switch for choosing between the OOK modulator and GMSK transceiver. (Common)
- MSP430 microcontroller for controlling the functioning of the above components and packaging data appropriately. (Common)

2.4.2 Tasks

- Control of configuration settings of the transceiver and flow of data to the transceiver. (Common)
- Conversion of data on the memory shared between the OBC and TTC subsystem into AX.25 packets, ready to be sent down. (Common)
- Sending of beacon data to the OOK/ASK modulator and hence, sending the advanced beacon through the OOK modulator. (Common)
- Implementation of connection oriented data transmission protocol in synergy with the OBC core 1 CPU, which controls the uplink circuitry in full-duplex mode, and sends the ARQ information to the telemetry to the MCU.

2.5 Payload

2.5.1 Components

- Hyperspectral camera which is controlled by the OBC core 1, the collected data is put on a memory shared between the OBC and the payload subsystem.
- Payload heater circuit.

2.5.2 Tasks

Payload is controlled by the OBC processor so the tasks of the payload subsystem already fall under the responsibilities of the OBC subsystem.

2.6 Structural & Thermal

The operations and constraints of the structural and thermal subsystem are not real-time in nature. Though the requirements of this subsystem have a deep impact on various design parameters of the system, they have not been discussed here because changes based on these effects are made during the design stage itself and don't affect the flight plan execution.

In the above section, those components which have been marked as common are used in all the modes in which those subsystems are on. In the next section we describe the various non-emergency operational modes of our satellite design, what tasks each subsystem is performing in those modes, which components are being used in each mode and on what basis the switching between any two modes will be performed. Note that, the mode of the satellite is based on various state variables like power available, location of satellite, angular velocity of satellite, momentum collected by the onboard reaction wheels etc. These are all measured during the housekeeping process by the OBC. Hence, in every mode, there is one task of the OBC of checking the various state variables if the criteria for switching to any other mode from the current mode is feasible or not.

3. Modes of Operation

There are a few main activities that the satellite can be doing at any point of time. The first subsystem of the satellite to start its operations is the EPS, this is because it is responsible for managing the power requirements for all other subsystems. This boot up process happens mechanically using a kill switch and this forms the init mode. After the satellite's expulsion from the deployer it is expected that the satellite will be moving at a high angular velocity, in such a situation the satellite is said to be tumbling. A satellite which is tumbling is moved into a detumbling state where the main focus of all subsystems is to decrease its angular velocity. A detumbled satellite is able to generate more power for other operations and is more prepared to undertake operations which require pointing and tracking like downlinking, payload execution and sun tracking. Downlinking is the process of sending data from the satellite to the ground station, payload execution is the process of operating the camera to take images of the desired location. Sun tracking refers to the process in which the satellite tracks the sun such that the area over which the sun's rays are falling is maximised. The image obtained from payload operation is very big and needs to be compressed before it can be downlinked. These processes are the power intensive and location dependent tasks that the satellite has to perform. Based on the critical and power intensive nature of these operations, separate states of the satellite need to be specified in which performing them is the main focus of the satellite. Sun-tracking, downlinking and payload execution all require us to point the satellite in the right direction as well. Based on all this discussion, our satellite can be found in the following modes:

1) Init mode - The mode in which the EPS gets turned on and starts its basic functionality.
2) EPS-OBC boot up sequence - In this mode an intricate process involving the boot of the OBC by the EPS is carried out.
3) Basic mode - The mode in which the EPS and OBC are turned on and operates its basic functionalities.
4) Detumbling mode - The mode in which the main task is to detumble the satellite.
5) Idle mode - The mode in which the TTC begins its basic functionalities. This is the mode in which all subsystems of the satellite are functioning at a basic level.
6) Image compression - The mode in which the primary focus of the satellite to perform compression of the image which has been collected so far.
7) Sun-tracking - The mode in which the satellite tracks the sun in a way that the maximal area of the satellite continues facing the sun.
8) Sun-tracking with image compression - In sun-tracking mode the power is expected to increase, so it is possible that enough power is collected in the sun-tracking mode to perform image compression. Hence, these two tasks may happen simultaneously.
9) Pointing - The mode in which the satellite is made to point to the right direction.
10) Payload execution - The mode in which the satellite is operating the payload.
11) Downlink - The mode in which the satellite's primary focus is sending data to the ground station.
12) Momentum Dumping - Reaction wheels are actuators used for the pointing mode which is a prerequisite for a lot of other modes. These reaction wheels collect momentum over time. Occasionally this momentum needs to be dumped after a critical level is reached.

Note that downlinking and payload execution will never be combined together as the ground station location and location for taking an image should be far apart in the orbit. It will not be considered as good mission plan if both occur close to each other as both operations are power intensive.

Another main part of the design is the process of switching between these modes. The switching is done by checking certain parameters occasionally and a more elaborate description of the modes and the switching criteria is given in the sections below. While switching we might find that multiple modes may be possible, and to deal with that situation we provide the priorities as below:

1) Detumbling mode
2) Momentum dumping mode
3) Ground station/payload execution (equal because they never occur simultaneously)
4) Sun-tracking with Image compression
5) Sun-tracking/Image Compression
6) Idle mode

Note the rest of the modes aren't optional and become a part of the boot up sequence. It is important to observe that the pointing mode is prerequisite for sun-tracking, image execution and payload-execution. So, though the decision is made to switch to one of these modes (and never explicitly pointing mode), we have to go into the pointing mode before entering those. Hence, the decision making process for entering those modes always takes that into account the power required for pointing as well. Sun-tracking and image compression are of equal priority and the decision between them is made based on an additional condition described later.

3.1 Init Mode

3.1.1 Requirement

After the ejection of the satellite from the deployer, the kill switch is removed and the EPS microcontroller switches on. This mode is the first that the satellite will enter into, with only the EPS being functional. The EPS microcontroller draws power directly from the batteries, which are charged prior to launch. This is to ensure that the microcontroller can switch on even if the satellite is in eclipse upon power up.

The EPS microcontroller will start implementing MPPT (Maximum Power Point Tracking) to optimize the power generation from solar panels and will start a timer for antenna deployment. After receiving an interrupt from the aforementioned timer, antennas will be deployed and feedback will be collected by the EPS MCU regarding the antenna deployment process. The deployment circuit is designed to have four deployment switches for each door, deploying a total of five antenna elements, specifically four arms of a crossed dipole (turnstile) and a monopole antenna (as shown in figure 1). The deployment status is necessary for determining the working configuration of the Telemetry Tracking and Command System (TTC). Based on the feedback collected, the EPS Microcontroller will send the configuration status to the OBC, once it is switched on.

3.1.2 Detection

After ejection of the satellite from the deployer and the removal of kill switch.

3.1.3 Action

EPS

- EPS microcontroller is switched on which draws power directly from the batteries, this is to ensure that the microcontroller can be switched on even when the satellite is in eclipse.
- A timer is started by the EPS microcontroller for antenna deployment. Upon receiving an interrupt from this timer, antennas will be deployed and feedback will be taken by the EPS which is communicated to the OBC later when the OBC is turned on.
- EPS MCU will transmit a simple beacon signal, containing the satellite call sign. (Since the TTC subsystem is off)
- EPS will begin performing all common tasks other than those involving the OBC since it hasn't been switched on yet.

3.1.4 Components

EPS

- Common components are turned on.

TTC

- Antennas are deployed by EPS MCU and common components of TTC other than TTC MCU and uplink circuit are turned on.

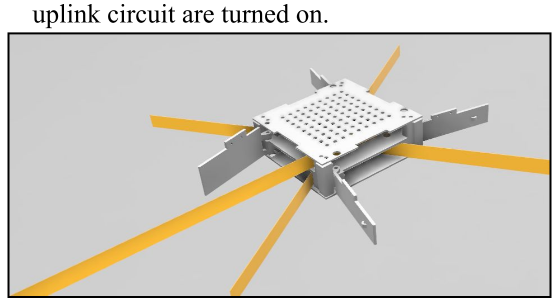

Fig. 1. Antenna deployment module (on Autodesk Fusion 360)

3.2 EPS-OBC Bootup Sequence

3.2.1 Requirement

The On-Board Computer (OBC) needs to be turned on as soon as sufficient power is available. On the basis of the current state of charge and power generated from the solar panels, EPS microcontroller enters EPS-OBC bootup sequence. To ensure redundancy for the boot image of the OBC, two memories viz. two NOR flash memories have been incorporated. One flash memory stores the golden image which is used in case the updated image carrying flash memory fails to boot the OBC. EPS microcontroller is responsible for selecting the memory using GPIO pins on the OBC microcontroller and generating necessary signals to boot OBC. When the OBC boots up, it is required to send an interrupt to the EPS microcontroller to communicate successful boot from the image. If the OBC fails to send such an interrupt after a predetermined time, EPS microcontroller reboots OBC and changes the memory port. The EPS MCU continues its operations as before, namely transmission of simple beacon signal and collection of housekeeping data from sensors interfaced to it.

3.2.2 Detection

Table 1: Conditions for entry to EPS-OBC Bootup Sequence

Previous Mode (Entry From)	Conditions to enter EPS-OBC Bootup Sequence
Init Mode	● Enough power is available to turn on OBC. ● At least one antenna element has been deployed in the Init Mode or deployment has failed despite the number of attempts exceeding a predefined threshold.

3.2.3 Action

EPS

- All common operations other than handling housekeeping requests from OBC.
- EPS MCU will transmit a simple beacon signal, containing the satellite call sign. (Since the TTC subsystem is off).
- EPS MCU is responsible for selecting the memory using GPIO pins on the OBC microcontroller and generating necessary signals to boot OBC.

OBC

- OBC microcontroller will be carrying out the internal bootup sequence. It should be noted that only the processing system of the Zynq-7000 will be turned on in this mode.
- Upon successfully booting up, the OBC is required to generate an interrupt to the EPS microcontroller indicating successful boot. This is also an exit condition from this mode. This interrupt mechanism continues as a watchdog mechanism for checking the boot condition of OBC.

3.2.4 Components

EPS

- Common components are turned on.

OBC

- Common components are turned on and PL is off.

TTC

- Common components of TTC other than TTC MCU and uplink circuit are turned on.

3.3 Basic Mode

3.3.1 Requirement

This mode follows the successful bootup of the OBC. This is called the Basic Mode because the flightplan will arrive at this mode from any later modes if power or energy requirements are not met for running operations of TTC and ADCS. This mode supports minimal operations, those of EPS and OBC. TTC and ADCS operations are not running in this mode.

In this mode, EPS continues collecting housekeeping data and execute MPPT to generate power from solar panels. It will also communicate with OBC at regular intervals using SPI to receive housekeeping data from EPS. It continues to monitor the watchdog timer. The OBC microcontroller will run the Flight Plan, that in turn will collect housekeeping data from sensors interfaced to the OBC.

In order to ensure full-duplex communication with the ground station, the uplink circuit is interfaced to the second core of OBC. The uplink circuit is enabled to obtain the first TLE (Two Line Element), a data format that encodes the orbital elements of the satellite for a given epoch. This TLE is needed by the Orbit Propagator running on the OBC, to predict the subsequent arrival of the ground station location (for downlinking data) or the image location (for image capture).

3.3.2 Detection

Table 2: Conditions for entry to Basic Mode

Previous mode (Entry From)	Conditions to enter Basic Mode
EPS-OBC Boot sequence	● OBC boot is successful ● State of Charge of battery and power requirements are met for running basic EPS, OBC operations.

3.3.3 Action

EPS

- Transmit a simple beacon signal, containing the satellite call sign. (Since the TTC subsystem is off)
- Performs all common tasks.

OBC

- Perform all common operations.
- Switch on and control the uplink circuitry to obtain the TLE (which gets used in the orbit propagator).

3.3.4 Components

EPS

- Common components are turned on.

OBC

- Common components are turned on and PL is off.

TTC

- Common components of TTC other than TTC MCU are turned on.

ADCS

- Sensors like the magnetometers and inertial measurement unit will be providing the measurements of the various parameters which are required.

3.4 Detumbling Mode

3.4.1 Requirement

In all modes, the OBC is collecting data regarding the state of the satellite. One of the parameters collected as part of this housekeeping is the angular velocity. Everytime the angular velocity is collected, it is also compared with a critical angular velocity, $\omega_{c,entry}$. If the angular velocity is found to be above that threshold then the satellite is considered to be tumbling. It is important that the satellite should not continue to tumble because a tumbling satellite generates much lesser power and takes a long time to go into more productive modes like downlinking and image taking.

Note that this mode has higher priority than all other non-emergency modes and is immediately entered into if the angular velocity goes above $\omega_{c,entry}$. In the detumbling mode iterations of the B-dot control algorithm is implemented as frequently as possible, constrained only by the available power. The frequency at which iterations of B-dot occur hence depends on the power available to the system. Therefore, even if power is relatively low, it will still go into the detumbling mode and perform the B-dot at low frequency. This will be the case until the power is so low that the ADCS subsystem components need to be switched off.

Since the amount of power generated while the satellite is tumbling is diminished, we should also try to decrease the amount of power consumed in this mode. To that end, the TTC MCU is switched off in this mode and only simple beacon is being transmitted.

Finally, the satellite continues to be in this mode till the the angular velocity goes below another threshold angular velocity, $\omega_{c,exit}$. The $\omega_{c,exit}$ is smaller than $\omega_{c,entry}$, allowing for a more stringent leaving criteria. This is done to avoid oscillation between tumbling and detumbling modes.

3.4.2 Detection

Table 3: Conditions for entry to Detumbling Mode

Previous mode (Entry From)	Conditions to enter Detumbling Mode
Any non-emergency mode	Satellite is tumbling, that is, angular velocity is greater than $\omega_{c,entry}$

3.4.3 Action

EPS

- Performs all common tasks.
- EPS MCU will transmit a simple beacon signal, containing the satellite call sign. (Since TTC is off).

OBC

- Implementing iterations of the B-dot algorithm as fast as possible based on the power available and state of charge of the battery. The frequency is decided based on simulations done on the ground which take into account the power consumed at a particular frequency and the time taken for it to detumble if operating at a particular frequency.
- All common tasks are performed.
- The uplink circuitry is kept on and controlled by the OBC in anticipation of TLE information which can be sent by any ground station.

3.4.4 Components

EPS

- Common components are turned on

OBC

- Common components are turned on and PL is off.

TTC

- Common components of TTC other than TTC MCU are turned on.

ADCS

- Since detumbling control is happening, the magnetorquers will be on. Their operation will be based on the current flowing through. That in turn is based on the width of the PWM wave generated by the OBC. This width is determined by the B-dot algorithm running on the OBC.
- Magnetorquers are the only actuators used in this mode. Magnetometers, sun-sensors and IMU are the sensors used to measure the state of a satellite.

3.5 Idle Mode

3.5.1 Requirement

This is the mode of the satellite in which it operates in the absence of external and internal stimuli. That is, no external factors force it into any other state, for example, the satellite is not tumbling or over the ground station or at the right place to be taking images. At the same time, the satellite does not have enough power to perform power intensive tasks like image compression for the image which is stored on board or fine pointing and tracking required to do sun tracking. So this mode has to be designed in a way that it doesn't consume too much power and the bare minimum operations required for the satellite to be considered fully operational should be occurring. It is also expected that continued operation in this mode should result in an increase in available power so that we can eventually switch to the mode for image compression if an image exists or move into sun-tracking mode to increase our power collecting capabilities. Another reason for designing this state to be such that it results in an increase in available power is so that we are in a position to perform downlinking or have enough power to take an image if the satellite arrives over the right position.

3.5.2 Detection

Common Conditions for entry into Idle mode :

- Satellite is not tumbling (angular velocity is less than $\omega_{c,entry}$) **&**
- State of charge is sufficient to run all the operations required in this mode as per the actions given below.

Table 4: Conditions for entry to Idle Mode

Previous mode(s) (Entry From)	**Conditions to enter Idle Mode**
Basic Mode	● Common Conditions
Detumbling mode	● Satellite is not tumbling, that is, angular velocity is less than $\omega_{c,exit}$ **&** ● Common conditions (first one is valid by definition)
Image Compression mode	● Common Conditions **&** ● Stored momentum in reaction wheels is less than critical momentum (if it was then handling it would have higher priority) **&** ● Continuation of image compression is not feasible (because there isn't enough power) **&** ● It is not feasible to go into sun-tracking and pre-requisite pointing (because there isn't enough power) **&** ● It is not feasible to go into payload execution and pre-requisite pointing (Either because of power or location is not approaching) **&** ● It is not feasible to go into downlinking and pre-requisite pointing (Either because of power or location is not approaching)
Sun-tracking mode	● Common Conditions **&** ● Stored momentum in reaction wheels is less than critical momentum (if it was then handling it would have higher priority) **&** ● Image compression is not feasible (because there isn't enough power for it) **&** ● It is not possible to continue sun-tracking (because there isn't enough power) **&** ● It is not feasible to go into payload execution and pre-requisite pointing (Either because of power or location is not approaching) **&** ● It is not feasible to go into downlinking and pre-requisite pointing (Either because of power or location is not approaching)

Sun tracking + Image Compression mode	● Common Conditions **&** ● Stored momentum in reaction wheels is less than critical momentum (if it was then handling it would have higher priority) **&** ● Continuation of image compression is not feasible (because there isn't enough power for it) **&** ● It is not possible to continue sun-tracking (because there isn't enough power) **&** ● It is not feasible to go into payload execution and pre-requisite pointing(Either because of power or location is not approaching) **&** ● It is not feasible to go into downlinking and pre-requisite pointing (Either because of power or location is not approaching)
Momentum dumping mode	● Common Conditions **&** ● Stored momentum in reaction wheels has been made less than critical momentum.
Pointing	● Common Conditions **&** ● Stored momentum in reaction wheels is less than critical momentum (if it was then handling it would have higher priority) **&** ● Image compression is not feasible (because there isn't enough power for it) **&** ● If the pointing is for X and it is not feasible to go into X* **&** ● It is not feasible to go into Y and pre-requisite pointing..
Payload Execution	● Common Conditions **&** ● Stored momentum in reaction wheels is less than critical momentum (if it was then handling it would have higher priority) **&** ● Image compression is not feasible (because there isn't enough power for it) **&** ● It is not feasible to go into sun-tracking and pre-requisite pointing (because there isn't enough power) **&** ● It is not feasible to go into downlinking and pre-requisite pointing (Either because of power constraint or location is not approaching) **&** ● Image taking has succeeded or payload execution time has exceeded or payload execution can no longer be continued (due to a lack of power)
Downlinking	● Common Conditions **&** ● Stored momentum in reaction wheels is less than critical momentum (if it was then handling it would have higher priority) **&** ● Image compression is not feasible (because there isn't enough power for it) **&** ● It is not feasible to go into sun-tracking and and pre-requisite pointing (because there isn't enough power) **&** ● It is not feasible to go into payload execution and pre-requisite pointing (due to a lack of power or the location for taking image isn't approaching) **&** ● Uplink is not received from GS even after waiting for 2 minutes that is, pass is over or downlinking is no longer feasible because of power constraints.

1. X can be downlinking, payload execution or sun-tracking.
2. Y!=X and can be downlinking, payload execution or sun-tracking.
3. If X/Y is downlinking then its infeasibility is in terms of power or if first uplink from the GS is not received even after waiting for 5 minutes, that is some failure in anticipating the GS pass.
4. If X/Y is payload execution then its infeasibility is in terms of power or payload failure.

5. If X/Y is sun-tracking then its infeasibility is in terms of power or k-condition being in favour of image compression.

3.5.3 Action

EPS
- Perform all common tasks.

OBC
- Implementing iterations of the B-dot algorithm at a fixed low-frequency to keep the angular velocity controlled.
- Perform all common tasks.
- The uplink circuitry is kept on and controlled by the OBC in anticipation of TLE information which can be sent by any ground station

TTC
- All common tasks are performed

3.5.4 Components

EPS
- Common components are turned on

OBC
- Common components are turned on and PL is off.

ADCS
- Since low frequency B-dot is happening the magnetorquers will be on, and will be operating based on the current flowing through them which is based on the width of the PWM wave generated by the OBC. This width is determined by the B-dot algorithm running on the OBC.The detumbling control can be stopped if the power is required for a higher priority task within the mode.
- Magnetorquers are the only actuators used in this subsystem. Magnetometers, sun-sensors and IMU are the sensors used to measure the state of a satellite.

TTC
- Common components are turned on.

3.6 Image Compression Mode

3.6.1 Requirement

If there is an uncompressed image present in the memory shared between the OBC and the payload, and the power available and state of charge of the battery is such that the PL based operation of compressing the image is possible, then the satellite enters this mode. This mode has higher power consumption because of the power consumed by the PL fabric but the overall energy consumed is lower than if performed on a MCU. This is because compression happens faster if implemented using a hardware accelerator.

Note that, in the situation that both image compression and sun tracking is possible then the choice between them will be based on how far away the downlinking opportunity is. Downlinking opportunity comes once every ‘k’ orbits, before this opportunity if there is an uncompressed image present at least some of it should be available for sending below, hence, if the number of orbits left to downlinking is k/2 then we should give priority to compressing the image else sun-tracking should be given a higher priority. From now on this is called the “k-condition” and if the k-condition results in us going to image compression mode then the k-condition is said to be in favour of image compression. For k condition to be useful, either of sun-tracking or image compression are power feasible but doing both simultaneously is not possible. In addition to this, other parameters (like the amount of compressed image data already present) can also be used to make the decision regarding switching between these modes.

3.6.2 Detection

The brackets in the detection table signify precedence of logical operation i.e. A **or** (B**&**C) = A|(B&C).

Common Conditions :
- Satellite is not tumbling (angular velocity is less than $\omega_{c,entry}$)
- State of charge is sufficient to run all the operations required in this mode as per the actions given below.
- Power is sufficient for image compression and image is present in shared memory.
- Stored momentum in reaction wheels is less than critical momentum (if it was then handling it would have higher priority)

Table 5: Conditions for entry to Image Compression Mode

Previous modes (Entry From)	**Conditions to enter Image Compression Mode**
Idle mode (or) Momentum dumping mode	● Common Conditions **&** ● It is not feasible to go into payload execution and pre-requisite pointing **&** ● It is not feasible to go into downlinking and pre-requisite pointing **&** ● Sun tracking and pre-requisite pointing is not feasible either due to power constraint **or** (because k-condition is in favour of image compression

	& both image compression and sun-tracking are not possible).
Sun-tracking mode	● Common Conditions **&** ● It is not feasible to go into payload execution and pre-requisite pointing **&** ● It is not feasible to go into downlinking and pre-requisite pointing **&** ● Sun-tracking is no longer feasible either due to power constraint **or** (because k-condition is in favour of image compression **&** both image compression and sun-tracking are not possible).
Sun tracking + Image Compression mode	● Common Conditions **&** ● It is not feasible to go into payload execution and pre-requisite pointing **&** ● It is not feasible to go into downlinking and pre-requisite pointing **&** ● Doing sun-tracking and image compression simultaneously is no longer feasible due to power constraint **&** ● k-condition is in favour of image compression **or** k-condition is in favour of sun tracking but sun-tracking is not feasible due to power constraints.
Pointing	● Common Conditions **&** ● If Pointing is for operation X and operation X is not possible **&** ● It is not feasible to go into Y and pre-requisite pointing **&** ● Sun-tracking and pre-requisite pointing is not feasible either due to power constraint **or** (because k-condition is in favour of image compression **&** both image compression and sun-tracking are not possible).
Payload Execution	● Common Conditions **&** ● Sun-tracking and pre-requisite pointing is not feasible either due to power constraint **or** (because k-condition is in favour of image compression **&** both image compression and sun tracking are not possible) **&** ● It is not feasible to go into downlinking and pre-requisite pointing **&** ● Image taking has succeeded or payload execution time has exceeded **or** payload execution can no longer be continued (due to a lack of power)
Downlinking	● Common Conditions **&** ● It is not feasible to go into payload execution and pre-requisite pointing (due to a lack of power or the location for taking image isn't approaching) **&** ● Uplink is not received from GS even after waiting for 2 minutes, i.e. pass is over **&** ● Sun-tracking and pre-requisite pointing is not feasible either due to power constraint **or** (because k-condition is in favour of image compression **&** both image compression and sun-tracking are not possible).

1. X, Y is downlinking and payload execution and X != Y
2. If X/Y is downlinking then its infeasibility in the context of 1) is based on power constraint or no response from GS for 5 mins.
3. If X/Y is payload then its infeasibility in the context of 1) is based on power constraint.

3.6.3 Action

EPS

- EPS will perform all common tasks.

OBC

- Implementing iterations of the B-dot algorithm at a fixed low-frequency to keep the angular velocity controlled.
- OBC will perform all common tasks.

- The uplink circuitry is kept on and controlled by the OBC in anticipation of TLE information which can be sent by any ground station
- The NOR memory shared between the payload and the OBC is accessed for the image and the compression algorithm is executed in the hardware on the PL fabric.

TTC

- Performs all common tasks.

3.6.4 Components

EPS

- Common components are turned on

OBC

- Common components are turned on
- PL is switched on for implementing compression algorithm.

ADCS

- Magnetorquers are the only actuators used in this subsystem. Magnetometers, sun-sensors and IMU are the sensors used to measure the state of a satellite.

TTC

- Common components are turned on.

3.7 Sun Tracking Mode

3.7.1 Requirement

To increase the satellite's ability to generate power for onboard usage we might want to point the satellite a in way to maximize the area over which the sun's rays fall. To this end the satellite will have to keep pointing towards the sun, which will require tracking algorithms to be implemented on the OBC and reaction wheels to be used as actuators for the same. Though more power might be generated in this mode, it also takes more power to do it. Therefore, if the power generated is expected to be greater than the power consumed then it is advisable to go into the mode. Note that the net power generated depends on the amount of power that will get consumed in pointing to the sun and tracking it, which in turn depends on the initial angle that the satellite needs to be turned. To aid the decision on board, pre launch simulations will be performed for different starting angles along with the power required and generated in each case. Based on the state on board and this stored information, a decision will finally be made. Further, the satellite must not be in eclipse. OBC and EPS continue to collect housekeeping data and periodically update the binary flag array. TTC also continues its basic operation.

3.7.2 Detection

Table 6: Conditions for entry to Sun Tracking Mode

Previous mode (Entry From)	**Conditions to enter Sun Tracking Mode**
Pointing	• Satellite is not tumbling (angular velocity is less than $\omega_{c,entry}$) **&** • State of charge is sufficient to run all the operations required in this mode as per the actions given below including operation reaction wheels for tracking **&** • Power generated from sun-tracking is greater than power consumed in doing sun-tracking **&** • Stored momentum in reaction wheels is less than critical momentum (if it was then handling it would have higher priority) **&** • If Pointing is for operation X and operation X is not possible **&** • It is not feasible to go into Y and pre-requisite pointing **&** • Power is not sufficient for image compression **or** (k-condition is in favour of sun-tracking **&** both image compression and sun-tracking are not possible).

1. X, Y is downlinking and payload execution and X != Y
2. If X/Y is downlinking then its infeasibility in the context of 1) is based on power constraint or no response from GS for 5 mins.
3. If X/Y is payload then its infeasibility in the context of 1) is based on power constraint.

3.7.3 Action

EPS

- Performs all common tasks.

OBC

- Implementing sun tracking algorithms to maximize the area of the solar panels exposed to the sun, thereby optimizing power generation.
- Performs all common tasks.
- The uplink circuitry is kept on and controlled by the OBC in anticipation of TLE information which can be sent by any ground station

TTC
- Performs all common tasks.

3.7.4 Components
EPS
- Common components are turned on.

OBC
- Common components are turned on.

ADCS
- Magnetometers, sun-sensors and IMU are the sensors used to measure the state of a satellite.
- Reaction wheels are the only actuators used for sun tracking.

TTC
- Common components are turned on.

3.8 Sun tracking *with Image Compression*
3.8.1 Requirement
One of the largest power consuming modes, this mode can occur only if the previous mode is sun tracking mode or pointing mode. This is because pointing is required before sun tracking can occur, so any other mode would have to go into pointing for sun-tracking before arriving at sun tracking. The reason for combining these two modes is that sun tracking is a mode which is expected to result in increased power generation, allowing us to perform a power intensive task. These cannot be downlinking and payload execution as those require pointing the satellite in a different direction.

3.8.2 Detection

Table 7: Conditions for entry to Sun Tracking with Image Compression Mode

Previous mode (Entry From)	**Conditions to enter Sun tracking with Image Compression Mode**
Sun tracking (or) Pointing for sun-tracking	• Satellite is not tumbling (angular velocity is less than $\omega_{c,entry}$) **&** • State of charge is sufficient to run all the standard operations required in this mode as per the actions given below **&** • Power is sufficient for image compression and sun-tracking operations **&** image is present in shared memory **&** power generated from sun tracking is greater than power consumed in doing sun-tracking **&** • Power is sufficient for operation of reaction wheels for tracking **&** • Stored momentum in reaction wheels is less than critical momentum (if it was then handling it would have higher priority) **&** • It is not feasible to go into downlinking and pre-requisite pointing (because there isn't enough power or GS is not approaching) **&** • It is not feasible to go into payload execution and pre-requisite pointing (due to a lack of power or the location for taking image isn't approaching).

3.8.3 Tasks
EPS
- EPS performs all common tasks.

OBC
- Implementing sun tracking algorithms to maximize the area of the solar panels exposed to the sun, thereby optimizing power generation.
- Performs all common tasks.
- The uplink circuitry is kept on and controlled by the OBC in anticipation of TLE information which can be sent by any ground station.
- The NOR memory shared between the payload and the OBC is accessed for the image and the compression algorithm is executed in the hardware on the PL fabric.

TTC
- Performs common tasks.

3.8.4 Components
EPS
- Common components are turned on

OBC
- Common components are turned on and PL is switched on for compression algorithm.

ADCS
- Magnetometers, sun-sensors and IMU are the sensors used to measure the state of a satellite.
- Reaction wheels are the only actuators used for sun tracking.

TTC
- Common components are turned on.

3.9 Pointing
3.9.1 Requirement

The OBC needs to implement different tracking algorithms for three purposes, Image-taking, Downlinking and Sun-tracking. Thus when either of the modes become feasible and their occurence possible, the satellite enters pointing mode. In other words, when the onboard ADCS orbit propagator running on OBC predicts that the GS Location or Image location is approaching, or it is determined that sufficient power is available to do sun tracking, then this mode will be initiated. The aim of this mode is to point the satellite appropriately and ensure almost zero tumbling. The pointing algorithm implemented is dependent on what it is meant for. Note that whenever the feasibility of one of the modes requiring pointing is checked, it is also checked if pre-requisite pointing is feasible. Note that feasibility of just pointing mode is never checked. It should not happen that we spend a lot of energy trying to perform pointing for our satellite in order to perform a certain task but then it can no longer be done due to a power constraint. This is because the pointing would have wasted power anyway.

3.9.2 Detection

Common Conditions for entry to Pointing mode:

- Satellite not tumbling (Angular Velocity is less than $\omega_{c,entry}$)
- Power is sufficient to run all operations in Pointing mode
- Power is sufficient to perform all operations required in the mode for which we are performing pointing.
- Momentum stored in reaction wheel is less than maximum momentum limit.

Table 8: Conditions for entry to Pointing Mode

Previous mode (Entry From)	Conditions to enter Pointing Mode
Idle Mode (or) Momentum Dumping (or) Image Compression	• Common Conditions **&** • (Image-taking Location is approaching **&** payload operation is feasible) **or** (Ground Station location approaching **&** downlinking is feasible) **or** (sun tracking and image compression are feasible) **or** (only sun tracking and not image compression is power-feasible) **or** (either sun-tracking or image-compression but not both are power feasible **&** k-condition is in favour of sun-tracking)
Sun tracking (or) Sun tracking with Image Compression	• Common Conditions **&** • Image Location **or** Ground Station location is approaching
Payload Execution	• Common Conditions **&** • Image taking has succeeded or payload execution time has exceeded or payload execution can no longer be continued (due to a lack of power) **&** • (either sun-tracking or image-compression but not both are power feasible **&** k-condition is in favour of sun-tracking) **or** (sun tracking and image compression are feasible) **or** (Ground station location is approaching **&** downlinking is feasible).
Downlink	• Common Conditions **&** • Uplink is not received from GS even after waiting for 2 minutes that is, pass is over or power is insufficient to continue downlinking **&** • (either sun-tracking or image-compression but not both are power feasible **&** k-condition is in favour of sun-tracking) **or** (sun tracking and image compression are feasible) **or** (image-taking location is approaching **&** image-taking is feasible)
Pointing	• Common Conditions **&** • If Pointing is for operation X and operation X is no longer feasible **&** • It is feasible to go into Y and prerequisite pointing

	or Z and pre-requisite pointing.

1) X, Y and Z is downlinking, payload execution and sun-tracking. X != Y != Z
2) If X is downlinking then its infeasibility in the context of 1) is based on power constraint or no response from GS for 5 mins.
3) If Y/Z is downlinking then its feasibility in the context of 1) is based on the vicinity of GS location and power feasibility.
4) If X is payload execution then its infeasibility in the context of 1) is based on power constraint.
5) If Y/Z is payload execution then its feasibility in the context of 1) is based on the vicinity of image taking location and power feasibility.
6) If X is sun-tracking then its infeasibility in the context of 1) is based on power constraint and k-condition.
7) If Y/Z is sun-tracking then its feasibility in the context of 1) is evaluated based on (either sun-tracking or image-compression but not both are power feasible **&** k-condition is in favour of sun-tracking) **or** (sun tracking and image compression are feasible)

3.9.3 Tasks

EPS
- Performs common tasks.

OBC
- Implementing pointing control algorithm to decrease the angular velocity and angular error as much as possible before the tracking can be performed.
- Performs common tasks.
- The uplink circuitry is kept on and controlled by the OBC in anticipation of TLE information which can be sent by any ground station.

TTC
- Performs common tasks.

3.9.4 Components

EPS
- Common components are turned on.

OBC
- Common components are turned on.

ADCS
- Magnetometers, sun-sensors and IMU are the sensors used to measure the state of a satellite.
- Both, magnetorquers and reaction wheels are the actuators used for pointing.

TTC
- Common components are turned on.

3.10 Image Taking (Payload Execution)

3.10.1 Requirement

After required accuracy in fine-pointing is achieved, if the power requirements for payload capture are met and imaging location arrives as per predictions from the ADCS orbit propagator, the satellite starts taking the image through its hyperspectral imaging camera. The mode carries on for the time the satellite is over the imaging area based on approximations made by the ADCS onboard orbit propagator.

3.10.2 Detection

Table 9: Conditions for entry to Image Taking Mode

Previous mode (Entry From)	Conditions to enter Image Taking Mode
Pointing	• Required accuracy in fine pointing is achieved. • Power sufficient for running all operations in Image Taking mode. • Imaging location reached. • Momentum stored in reaction wheel is less than the maximum momentum limit.

3.10.3 Tasks

EPS
- Performs common tasks.

OBC
- Implementing tracking algorithm to continue following the target.
- Performs common tasks.
- The uplink circuitry is kept on and controlled by the OBC in anticipation of TLE information which can be sent by any ground station
- Performing control of hyperspectral camera at appropriate frequency to take images at the right time.

TTC
- All common tasks are performed.

3.10.4 Components

EPS
- Common components are turned on.

OBC
- Common components are turned on.

ADCS

- Magnetometers, sun-sensors and IMU are the sensors used to measure the state of a satellite.
- Only reaction wheels are used in this mode to continue the tracking process.

TTC

- Common components are turned on.

3.11 Downlink Mode

3.11.1 Requirement

After ADCS predicts that the GS is approaching, the satellite goes into Pointing mode. After this it waits for the uplink from the GS. As soon as the first uplink signal is received from the GS, the satellite enters the downlink mode. This first uplink initiates handshake operations. Core 1 of OBC, which controls uplink operations, will receive the handshake packet being continuously transmitted by the ground station. This packet will also contain TLE information that the OBC will process. The telemetry downlink MCU shall receive information from the OBC as soon as the handshake packet is received, and it will send acknowledgement to establish connection. Once link has been established, the satellite downlinks image data to the ground station. We have decided to use connection oriented mode of AX.25 protocol which supports ARQ (Automatic Repeat Request) for packet retransmission. When any acknowledge packets from GS cease to arrive, the pass is concluded to be finished and downlink mode is terminated.

3.11.2 Detection

Table 10: Conditions for entry to Downlink Mode

Previous mode (Entry From)	Conditions to enter Downlink Mode
Pointing	• Required accuracy in fine pointing is achieved. • Power sufficient for running all operations in Downlink mode. • Uplink from GS received within 5 minutes of GS approach, as predicted by the on-board propagator.

3.11.3 Tasks

EPS

- Common EPS tasks are performed.

OBC

- Implementing tracking control algorithm to continue following the target.
- Common OBC tasks are performed.
- The uplink circuitry is kept on and controlled by the OBC. In this mode the uplink circuitry and the core 1 receives more signals as there are ack signals for the packets received sent up. This information is processed by core 1 and sent to the Telemetry subsystem.

TTC

- In this mode the GMSK modulator is on and the AX.25 packets which were being prepared in all other modes are downlinked using the modulator. (no other operations are performed, not even the common one because the TTC MCU is expected to be extremely busy with the data downlink process)

3.11.4 Components

EPS

- Common components are turned on.

OBC

- Common components are turned on.

ADCS

- Magnetometers, sun-sensors and IMU are the sensors used to measure the state of a satellite.
- Only reaction wheels are used in this mode to continue the tracking process.

TTC

- Common components other than the OOK/ASK modulator will be turned on.
- GMSK Transceiver for sending and receiving data using GMSK based modulation technique.

3.12 Momentum Dumping

3.12.1 Requirement

This mode is required to dump the excessive momentum which is stored in the reaction wheels. Hence the satellite enters this mode when the stored momentum exceeds a critical value. This mode is assigned a high priority and if momentum stored in reaction wheel is greater than or equal to maximum momentum limit, then this mode is initiated, provided power requirements are met.

Table 11: Conditions for entry to Momentum Dumping Mode

Previous mode (Entry From)	Conditions to enter Momentum Dumping Mode
Idle Mode (or) Idle Mode with Image Compression	• Satellite is not tumbling (Angular velocity is less than critical angular velocity) • Momentum stored in reaction wheel is greater than or equal

(or) Sun tracking (or) Sun tracking with image Compression (or) Downlink (or) Payload Execution (or) Pointing	to the maximum momentum limit. ● Power is sufficient to run all operations in momentum dumping mode.

3.12.3 Tasks

EPS

- Common tasks are performed.

OBC

- Generating the required signals for controlling the magnetorquers and the reaction wheels to dump the momentum of the former.
- Common tasks are performed.
- The uplink circuitry is kept on and controlled by the OBC in anticipation of TLE information which can be sent by any ground station

TTC

- Common tasks are performed.

3.12.4 Components

EPS

- Common components are turned on.

OBC

- Common components are turned on.

ADCS

- Magnetometers, sun-sensors and IMU are the sensors used to measure the state of a satellite.
- Reaction wheels and magnetorquers are used in this mode.

TTC

- Common components are turned on.

4. Implementation of Non-Emergency and Emergency Modes

In [8] the implementation of the process used for switching between modes and the process by which OBC gives instructions to other subsystems which changes the mode of the entire satellite is given in more detail. However, here we give a brief description, keeping in mind that the OBC has a software running on a Linux based OS. In the OBC software a constantly running process is the flightplan. In the flightplan, for each mode a separate linked list is maintained. Each node is a task which needs to be implemented in that mode, which are ordered by the next time of implementation. The next time of implementation is compared with the system time and to find out if the time to complete that task has come or not. The next time of implementation depends on the required frequency at which the task needs to be implemented. One of the nodes has a task called "check", this check function checks the recently obtained housekeeping parameters and orbit propagator values to determine what the next mode should be. The method by which it decides the next mode is based on the section above. Note that a linux based OS is a soft-real time one, so in most cases when we want to execute a task, a process corresponding to that is started. It is possible that processes which were started earlier are still executing, the OS's scheduler will perform the required time sharing between all processes running at a time.

Based on this it is possible that there is some amount of latency in terms of when the satellite actually begins tumbling and when the satellite enters detumbling mode. However, this latency has been accounted for in our calculations.

In some situations however, the situation needs to be dealt with on priority, that is the latency between detecting the problem and doing the necessary corrective action needs to be minimum. These modes are emergency modes, which are described in the next section. As soon as these conditions are detected, a software interrupt is triggered and its implementation is not like another scheduled task of a mode but rather is expected to be the very next set of instructions executed by the processor by calling the necessary ISR.

5. Emergencies

5.1 Emergency Modes

Emergency modes occur whenever a system component or application encounters an error in its normal operation, and requires an immediate corrective action in a separate state where the normal non-emergency operations cannot be sustained or should not be sustained because they take away bandwidth from the processor.

Some emergencies can occur regardless of the mode that the satellite is operating in and are categorized as state-independent emergencies. Some occur due to operations in particular modes or are dependent on inputs from sensors operational only in certain modes. These have been classified as state-dependent emergencies.

Table 13: State Independent Emergencies

Identified Causes	**Action in emergency mode**
Critically Low Battery State of Charge (SoC)	The following components are switched off in the order specified: 1. Uplink Monopole and TTC MCU 2. All ADCS sensors and magnetorquer 3. OBC 4. Beacon 5. Power System At any stage if it is felt that the power is sufficient to sustain continued operation in that mode then we continue in that mode.
Battery Low Temperature	Interrupt raised for Battery heater control
Payload Low Temperature	Camera heater control

Table 13: Identified State Dependent Emergency

Identified Emergency Causes	All antenna elements not deployed
Entry from mode(s)	INIT MODE
Entry condition(s)	Antenna deployment feedback to EPS shows all elements undeployed.
Possible action in emergency mode	Retry antenna deployment periodically if power is sufficient.
If resolved, exit to mode	EPS-OBC BOOTUP SEQUENCE

Note that with more development more emergency situations are expected to be identified, including those where certain critical components turn off.

5.2 Redundancy

To minimize the number of emergencies that occur in the satellite, various system components are provided with duplicates, which take the original components' place in case of failure.

Table 14 lists the redundancies introduced in the on-board architecture, with the implementation explained.

Table 13: Redundancies

Need for Redundancy	**Implementation**
Change of telemetry duplex configuration if antennas are partially deployed	Telemetry receives configuration of deployment from OBC in the form of a configuration file, the system can switch between full/half-duplex modes depending on: Case (i) Only monopole deployed Case (ii) Only turnstile deployed Case (iii) Only 1 dipole element pair of turnstile is deployed Case (iv) Any other deployment configuration implies a full-duplex normal operation
In case of system failure for booting On Board Computer (OBC)	Two memories viz. Two NOR flash memories have been incorporated. One flash memory stores the golden image which is used in case the updated image carrying flash memory fails to boot the OBC. EPS microcontroller is responsible for selecting the memory using GPIO pins on the OBC microcontroller and generating necessary signals to boot OBC.
To assure a more reliable power distribution structure (EPS)	Redundant Buck and Boost Converters for delivering bus voltages.

6. Future Work

Though a lot of work is yet to be done, the following tasks are already being worked on:

1) Using an orbit simulator and the arrangement of the satellite's solar panels, the amount of power generated can be simulated. Further, based on the components used in each subsystem the power consumed in each mode can be calculated. Based

on these and other parameters, we plan on finding accurate power estimates which will be used onboard for making decisions regarding switching between modes.

2) Once the power is incorporated and actual numerical values obtained, we try to incorporate these in the simulations to test the satellite's operations from the point of launch to observe its transition from one mode to the next over its operation. This will help us fine-tune the parameters and figure out changes that should be made in the design to allow the satellite to perform requisite operations.
3) Simultaneously, we are also building testbeds which will allows us to perform HIL simulations. For example, we have built a system in which the orbit simulations are being run on MATLAB on a PC but using an arduino, the changing magnetic field values are being sent to the actual Zynq based SoC used on board. The arduino is interfaced to the Zynq SoC using an I2C interface to simulate the actual interface of the magnetometers onboard. The B-dot algorithm running on the Zynq SoC generates a PWM signal which is then sensed by another arduino and given as input to the same MATLAB simulation, based on which the relevant actuation calculations are done and the new magnetic field values are determined.

7. References

[1] "Documentation of AAU-Cubesat On Board Computer Software", November 8, 2002, Available Online:http://www.space.aau.dk/cubesat/dokumenter/software.pdf [Active]

[2] "CubeSat Design Specification Rev. 13" The CubeSat Program, Cal Poly SLO Available online: CalPoly CubeSat Design Specifications Document [Active]

[3] Indian Space Research Organization, "Guidelines for Student Satellite Proposal", ISRO Satellite Centre, Bangalore, February 2012, Available online: http://nitrsat.nitrkl.ac.in/ISRO.pdf [Active]

[4] M. Noca, G. Roethlisberger et. al., "Project, Mission, Space and Ground System Overview", Delta-PDR, Phase B/C, SwissCube Project, , August 2007.

[5] "The AAU-CubeSat student satellite project: Architectural overview and lessons learned," Denmark, 2004.

[6] P. Shippert, "Why use hyperspectral imagery?," Photogrammetric engineering and remote sensing, pp. 377-380, 2004.

[7] CCSDS, "Lossless Multispectral & Hyperspectral Image Compression, Recommended Standard, " 2012.

[8] Mr. Sourabh Raje, Mr. Abhishek Goel et. al., "Development of On Board Computer for a Nanosatellite".