Dynamic Active Thermal Control of a LEO Nanosatellite Based on its Mode of Operation

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ABSTRACT

The paper explains the design of an active thermal control system which would work as per the needs of the current operational mode of the satellite. The modes of the satellite have been classified into two major groups: the normal modes and the emergency modes. The modes of interest to the thermal control system are three of the emergency modes and the image capture mode, which is one of the normal modes. The electrical loop of the system will be dynamically controlled by the TI MSP430 microcontroller of the Electrical Power System (EPS) as per the present mode of operation set by the On-Board Computer (OBC). The dynamic control loop ensures that the imager is heated to its optimal working range from its storage range during the image capture mode. A separate dynamic control loop is also used to maintain the optimal temperature for the satellite's batteries as per the mode of operation. Redundancy has been established using a mechanical thermostat-based control loop in addition to the already planned dynamic control loop. This ensures the protection of the components during the emergency modes.

ABBREVIATIONS

EPS	Electrical Power System
OBC	On Board Computer
FPGA	Field Programmable Gate Array
MCU	Micro-Controller Unit
CMBR	Cosmic Microwave Background Radiation

INTRODUCTION

Team Anant is the student satellite team of BITS Pilani. The team was established with the aim of developing a 3U CubeSat with hyperspectral imager as the primary payload and a FPGA based System on Chip as the secondary payload to be used for onboard compression of the image. The satellite will be used to image ocean surfaces for the estimation of Carbon Dioxide levels. A polar sun synchronous orbit of 607km has been chosen for the mission. This paper details the design of the planned control system for dynamic active thermal control of the components of the satellite. The system aims to reduce the power consumption and enhance the reliability of the control system by use of intelligent onboard control and redundancy respectively. Due to absence of a dedicated onboard microcontroller for the thermal system, the microcontroller of the Electrical Power Subsystem (EPS) will be used. The dynamic control would be dependent on the operating mode of the satellite. This dependency ensures the usage of power by the heaters will be moderated as per the overall status of the systems in the satellite and its position and orientation in space. A control loop that uses thermostats will also be included in the system to add redundancy. This control loop will ensure the functioning of the system in the scenario of an electronic failure. Further applications of the system have also been discussed.

THERMAL ENVIRONMENT IN SPACE

The harsh thermal environment of space makes the thermal control system very important for the desired operation of the systems. Due to the absence of a material medium to transfer heat via conduction and convection, most heat loads in space are radiative in nature.

The major heat sources in the space environment are:

- Solar radiative flux: these are the sun's rays directly incident on the satellite accounting for most of the incident energy,
- Earth's Albedo: the sun's rays reflected from the earth's surface and incident on the satellite
- Earth's IR: the infrared radiation emitted by the earth
- Internal Heat Dissipation: the heat generated and radiated by the components of the satellite.

Apart from these major contributors, other sources of radiation include CMBR, radiation from distant stars, etc. The effect of these components on the satellite is very negligible, however, they tend to increase the ambient temperature of space and hence also need to be studied.

The space environment is very complicated and unpredictable; hence, the simulations are done for the worst possible cases for the satellite's orbit. Thermal simulation is carried out for two extreme cases namely the worst hot case and the worst cold case. As the name suggests the worst hot case considers the maximum heat load on the satellite. The assumptions for the worst hot case include maximum solar flux (1414 W/m^2 at the winter solstice), maximum illumination (β angle = 90°)

and maximum internal heat dissipation (100% heat dissipation at maximum power load, 10W, according to the power budget of the EPS). Similarly, the assumptions for the worst cold case include minimum solar irradiation (1322W/m^2 at the summer solstice), minimum illumination (i.e. maximum eclipse period) and least internal heat dissipation (all components non-operational, i.e. 0 W). As the orbit of the satellite is a sun-synchronous orbit the beta angle remains almost constant throughout the orbit. However, to make the design more reliable and robust, different beta angles have been considered for the absolute worst cases when the planned imaging area is changed.

Table 1: Variables for Worst Cases

Parameters	Worst Cold Case	Worst Hot Case
Incident Solar Flux	1322 W/m^2 (Summer Solstice)	1414 W/m^2 (Winter Solstice)
Time Illuminated	Minimum β angle (Maximum eclipse duration)	β angle =90° (Permanent illumination)
Internal heat dissipation	Minimum (No components operational)	Maximum (All components operational)

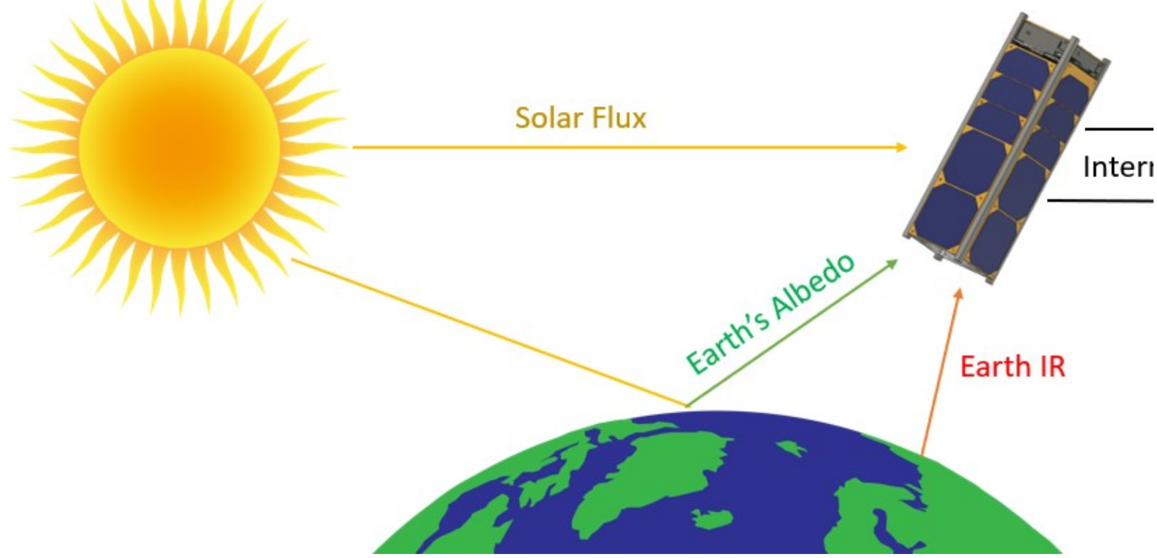

Figure 1: Heat loads in Space

The preliminary thermal model of the satellite has been simulated using the software Systema Thermica developed by Airbus. The results suggest a temperature range of a minimum of -7.4°C for the worst cold case and a maximum of 68.7°C for the worst hot case. The working temperature of most of the electronic components used lie between -20°C to +50°C. Hence the thermal requirements of the components can be handled by passive control methods. The batteries and Payload however need an active thermal control system due to their specific needs, which are discussed later.

MODES OF OPERATION OF THE SATELLITE

The operating modes of the satellite have already been studied by *Rutwik Jain et.al. (2018).* The modes of operation have been widely divided into two groups: Normal modes and emergency modes. The operating mode of the satellite would be decided by the OBC using measured and/or calculated variables at that point of time. Of the various modes that exist, Payload execution mode, which is one of the normal modes and three of the emergency modes are of importance for thermal control.

The emergency modes for the satellite under consideration are:

- Critically Low Battery State of Charge
- Battery Low Temperature
- Payload Low Temperature

Payload Execution

In this mode, the image is captured by the hyperspectral camera, i.e. payload is executed. When the payload is pointed with required accuracy and the satellite reaches the image capture position as per the calculation by ADCS, the payload execution starts. The execution will continue until the satellite passes the imaging region.

Critically Low Battery State of Charge

The satellite will switch to this mode when its state of charge becomes critically low. Components are switched off according to a pre-defined order. This would continue until the state of charge meets the requirements for one of the other modes.

Battery Low Temperature

The satellite will switch to this mode when its battery temperature falls close to the lower limit of its storage temperature. In this mode, preference would be given to battery heating over other operations for supplying power.

Payload Low Temperature

The satellite will switch to this mode when its payload temperature falls close to the lower limit of its storage temperature. In this mode, preference would be given to payload heating over other operations for supplying power. The Battery Low Temperature mode would take preference over this mode. In case of insufficient power for heating both battery and the payload, battery would be heated instead of the payload.

THERMAL CONTROL REQUIREMENTS OF THE COMPONENTS

Battery

Specification

The current system configuration of the satellite uses 4 ***Panasonic NCR 18650B*** lithium-ion batteries. These batteries have a capacity of 3350mAh each, a volumetric charge density of 676Wh/I, weigh 48.5g each, and have a nominal voltage of 3.6V. The battery was selected based on their tried and tested reliability in the space environment and high energy density.

Thermal control requirements

The safe storage temperature of the batteries ranges from -20°C to +50°C while the optimal charge temperature ranges from +10°C to +45°C. As the results from our thermal analysis show that the lowest temperature encountered by the satellite in its orbit is -7.4°C which is quite far away from the optimal charge temperature of the battery and the highest temperature crosses the safe storage limit by +18.7°C. Hence thermal control is required for both heating and cooling of the batteries to maintain operations. The devised thermal control system consists of using passive thermal control to prevent overheating of the batteries by using MLI and hermetically sealing the battery box. However, for heating of the battery in cold cases, the use of active thermal control is required.

Payload

Specification

The payload consists of two major components, a hyperspectral imager and an optical system. The hyperspectral imager is an MQ022RG-CM line sensor from Ximea. The imager weighs 31 grams. The optical arrangement to focus the imaging region on the imager is yet to be designed. The thermal control needs of the optical arrangement would be satisfied through passive systems.

Thermal Control Requirements

The optimum temperature for operation is +10°C to +25°C and the safe storage temperature is -25°C to +60°C. The imager is also capable of operating between +0°C and +50°C. The maximum temperature crosses the operating range by 18.7°C and the minimum temperature falls behind by 17.4°C. The payload will hence need cooling at certain points in the orbit, which will be achieved by the design of passive systems. Due to the small range of optimal operating temperature, very delicate control is required increasing the need for a dynamic control system. Thermostat based systems are usually less accurate than dynamic systems.

THE CONTROL SYSTEM

The control system would consist of two control loops. One would be a dynamically controlled loop. This loop would be controlled by the TI MSP430 MCU of the EPS. This loop would use LM75 temperature sensors to measure the temperature and will operate the heaters accordingly. Since the kapton heaters to be used is a simple resistor, the microcontroller would be able to control the power supplied as per need. The interrupt from the temperature sensors will be constantly monitored. When the temperature falls below a certain *threshold temperature*, the rate of fall of temperature would be measured using the interrupts. The microcontroller would then provide power to heat the component at 1.5 times the measured rate. This would be calculated using the pre-defined specific heat capacity of the component, which would be obtained experimentally. The heating would stop when the temperature crosses a pre-defined value, called the *safe temperature*.

The advantages of the dynamically controlled loop over a mechanically controlled thermostat-based loop are:

1. The threshold values can be changed according to the mode of operation of the satellite.
2. The amount of power to be supplied would be lower in certain situations.
3. Thermostats are susceptible to fail open and fail closed conditions while temperature sensors are not.
4. The uncertainty in measurement is much lower for temperature sensors.

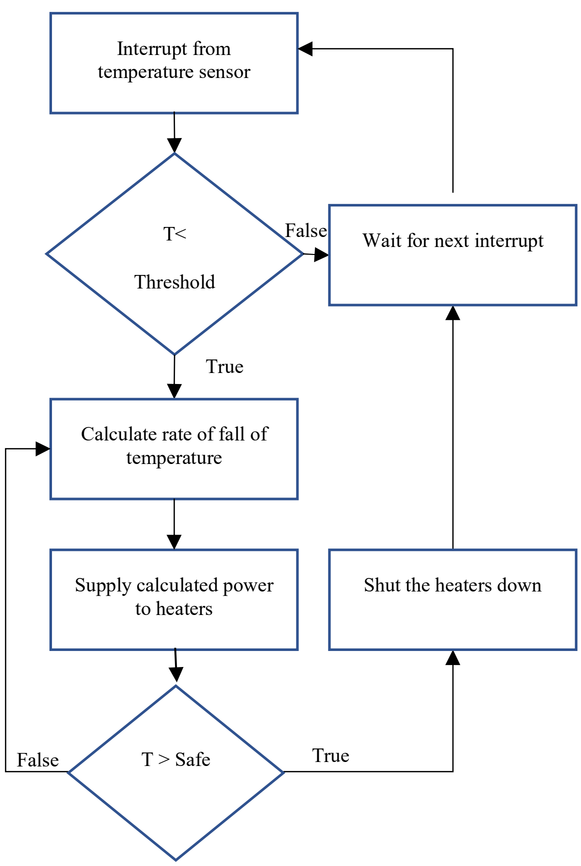

Figure 2: Flowchart of the Control System Algorithm

The dynamic control system is susceptible to the following types of failures:

1. Software failure.
2. Incorrect reading of the temperature sensors.
3. Single event failure of the EPS MCU.

Probability of failure of type-2 can be significantly reduced by the addition of multiple temperature sensors for redundancy. The heating would start when any one of the sensors records a value smaller than the threshold temperature. The heating would then continue until *most of the sensors* reach the safe temperature. In this arrangement, the power supplied would be calculated based on the mean of the rate of fall of temperatures recorded by all the sensors. When most of the sensors reach the safe value, any sensor which still records a value less than the threshold value would be considered faulty.

Failures of type-1 and type-3 will be overridden by the second control loop, which would be operated by thermostats. The thermostats for the battery would be calibrated for safe storage temperature range for the batteries, i.e. 0°C to 50°C as the battery would automatically heat when the satellite is subjected to solar radiation, meeting the requirements for charging. The thermostats for the imager would be calibrated to the operating range for the imager, i.e. 0°C to 50°C. This would ensure that the imager is always in the operating condition so that the image can be captured whenever required. The thermostats would be arranged in a quad arrangement to overcome both fail open and fail close type of failures, which are common in thermostats. The thermostats in both payload and battery heater circuits will be calibrated to engage at 5°C and cut off at 40°C.

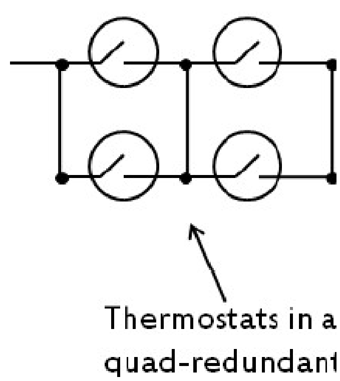

FIGURE 3: Thermostat arrangement Schematic Diagram

The considerations for deciding the threshold and safe temperature values for Payload and battery heating systems have been discussed. Based on these considerations, the decided values have been provided in table 2.

Critically Low Battery State of Charge

In this mode, the components of the satellite would be switched off in a pre-decided order. EPS MCU would be the last component to switch off in this mode, hence heating can continue. The battery would be maintained in its safe storage range of 0°C to 50°C with the safe temperature critically reduced. The payload would also be maintained in its storage temperature. Since the worst cold case of the satellite with no heater arrangement predicts a temperature that is 17.6°C more than the lower limit of payload storage, the payload heating circuit will be switched off in this mode

Battery Low Temperature

The battery must be maintained in its safe storage temperature. The thermostats would be calibrated such that they automatically engage to heat the battery when it falls under consideration for this mode. The payload heating circuit would be switched off to save power. The interrupt from the temperature sensors will be increased for the dynamic control system.

Payload Low Temperature

This mode was initially studied as a possibility. However, as per the thermal simulation results, the payload will never fall below its safe storage temperature range. Hence, this mode will not be of importance in designing the systems for the satellite.

Payload execution

In this mode, the component of major concern is the payload. The imager must be maintained in its optimal operating range throughout, which is between +10°C and +25°C. The satellite will not be in eclipse during image capture; hence, the battery must be maintained in its charging range i.e. +10°C to +45°C. The payload must be ready for image capture before the mode starts and hence, similar constraints also must be applied to the mode preceding it, which is the *Payload Pointing mode*.

Other Modes of the satellite

The control system also needs to be calibrated for other operating modes of the satellite. In all modes, using the dynamic control loop would save power. This is because of the temperature values to which the thermostats have been calibrated. The fast cycling of thermostats increases the chances of their failure and hence they have been calibrated accordingly. The dynamic loop will be calibrated to prevent the thermostats from engaging unless necessary.

Table 2: Safe and Threshold Temperatures for the Different Operational Modes

Mode	Payload Threshold Temperature	Payload Safe Temperature	Battery Threshold Temperature	Battery Safe Temperature
Critically Low Battery SoC	--	--	5°C	15°C
Battery Low Temperature	--	--	10°C	30°C
Payload Low Temperature	--	--	--	--
Payload Execution	15°C	20°C	15°C	30°C
Payload Pointing	15°C	20°C	15°C	30°C
Other Modes	10°C	30°C	10°C	30°C

FUTURE WORK

The future work for development of the system majorly includes simulation and testing. The thermal results must be validated after incorporating the modes of the satellite in the simulations. Further applications of this system to enhance the operation during some of the other modes must also be studied.

A study must be performed to gauge the viability of heating the battery from its storage to charging temperature during sun pointing. This can only be performed after a simulation environment that incorporates modes of the satellite is modelled.

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