University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document
Optical Thermal Regulation System
(OTheRS)

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Approvals

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1. Problem Statement

1.1. Project Motivation

Thermal regulation is important for successful operation of any system and is even more important in space systems because components are subjected to extreme and widely ranging thermal environments. In the past two decades, electronic technologies in aerospace applications have improved and expanded, while at the same time growing smaller and more compact. This makes regulating these heat sensitive components more critical than ever before. Current thermal management technology requires numerous physical temperature sensors to monitor the increased number of heat sensitive components at the cost of added weight, wiring complexity, and number of telemetry inputs not related to scientific data. Each of these increases the technical difficulty and cost of placing a satellite in a desired orbit.

1.2. Project Overview

In an attempt to solve this problem, General Atomics and the Ann & H. J Smead Aerospace Engineering Department undergraduate senior design team are proposing the use of a non-contact, optical thermal sensing solution. The proposed solution would reduce wiring complexity and provide comparable performance to traditional thermal sensing systems. This project will focus on assessing the feasibility and practicality of such a system in small satellite applications. In order to validate the proposed system, a test bed will be developed to directly compare the proposed optical thermal regulation system (OTheRS) to traditional systems. The OTheRS system will utilize a thermal camera to image satellite hardware and process the thermal image data to determine the necessary command and control required to keep satellite components within acceptable temperature ranges.

2. Previous Work

Thermal management is a critical need for aircraft, small-scale satellites, and aerospace industry projects. On-board electrical components, even when not exposed to near-space environments, go through fluctuating temperature changes that can cause damage to the electrical equipment without proper thermal protections. Since electrical damage would surely detract from science experiments, protecting on-board components is a critical design element to ensure a successful mission. Current industry methods for thermal management can be active or passive schemes.[2] An open-loop system for thermal management is often not as helpful to ensure longer-life of on-board electrical components due to the lack of feedback control in the design. It is not simply enough to interpret temperature readings for electrical components or thermal hot spots, which is why active thermal management for small-scale satellites and cubesats has become a large new focus of research in the aerospace industry. However, passive thermal management technologies can still be beneficial when they do not involve additional on-board electronics which can add weight and consume valuable space.[3]

NASA is currently developing a passive thermal management technique that is employing and repurposing a technology not used on spacecraft since the 1960s - louvered flaps. These flaps are passively actuated and behave similarly to Venetian blinds. Using bimetallic springs, the louvers will open and close depending on whether an instrument needs to shed or conserve heat. As an added benefit, this technique requires no additional power for thermal control.[4] Looking ahead, this passive control technology will be flight-tested on-board the Goddard-developed Dellingr spacecraft, a 6U CubeSat.[3] Additional thermal management technologies used in industry today include deployable radiators, heat pipes, electrical heaters, mini-cryocoolers, thermal straps, and many more.[2] In developing new aerospace technologies, it is more important than ever to find innovative methods for building on previous techniques of temperature control and thermal management for spacecraft.

Starting in the latter half of the 20th century, IR cameras found a niche in aerospace applications. Most of these applications were designed for an IR camera to look down to earth from LEO and be able to accurately measure temperature on the ground. One of the earliest examples of this is from 1967, when NASA was able to use IR cameras to successfully measure the surface temperature of the Columbia River.[5] Although Thermal cameras have been in space for over 50 years, most of their applications have been restricted to space to ground functionality. This is due to a combination of the fact that current thermal management systems are successful in managing heat on satellites, alongside various problems that Thermal cameras encounter in a satellite configuration, such as the ability to handle reflectivity and surface roughness.[6]

3. Specific Objectives

The main objective of this project is to provide a feasible alternative to traditional satellite thermal management systems. Specifically, this design will use an optical means of temperature sensing that will be directly compared to traditional sensing in order to determine the viability of the system in terms of accuracy, complexity, and cost.

A minimum level of success for this project is to sense two or more spatially separated, heat sensitive objects, and independently send command signals to an actuator at or near each object in order to regulate their temperatures. These objects will take the form of stacks or trays in the satellite, which will house various electronic components.

To further specify project objectives, the team created levels of success based on different aspects of the thermal regulation system. Team OTheRS will be trying to reach the maximum level of success for each aspect of the project but if issues are encountered throughout development the first level of success will still meet all the requirements given by the customer.

Criteria	**Camera**	**Image Processing**	**Electronics/Comm/Control**	**Test Bed**
Level 1	Camera will sense temperatures between -30°C and 60°C and will fit within the interior of the given satellite	Software can differentiate between module trays in the stack being monitored while recording their temperature.	The control system will command actuator(s) based on thermal data from the image processing system and will handle 2.5A. The entire system will also be able to operate on 28V of unregulated power	The test bed will have two different heated objects, whose temperature is read by both the thermal camera and TBD traditional sensors in an ambient air, room temperature environment. This is a minimum to help ensure the camera can differentiate and monitor multiple components
Level 2	The mounted camera will have a FOV that can capture TBD number of trays	-	Communication system makes use of TBD communication protocol	System operates successfully when tested in thermal chamber between -20°C and 50°C
Level 3	Camera will sense temperatures at an accuracy of ±TBD °C and be comparable to TBD traditional sensing system	Software can facilitate spatial and thermal calibration of the system	-	A range of reflectivity coatings will be tested to determine effect on temperature readings

4. Functional Requirements

1. System shall return thermal data map for multiple components between -30°C and 60°C with TBD accuracy.
2. System shall provide regulatory commands when components are outside -20°C to 50°C
3. System shall operate on 28V unregulated power provided by the spacecraft.
4. Supporting systems electronics shall fit within a standard GA nanotray.
5. System shall be able to switch a 2.5A load as needed to control an externally powered heater.
6. The thermal camera shall be placed such that it can image critical stack electronics

4.1. Functional Block Diagram

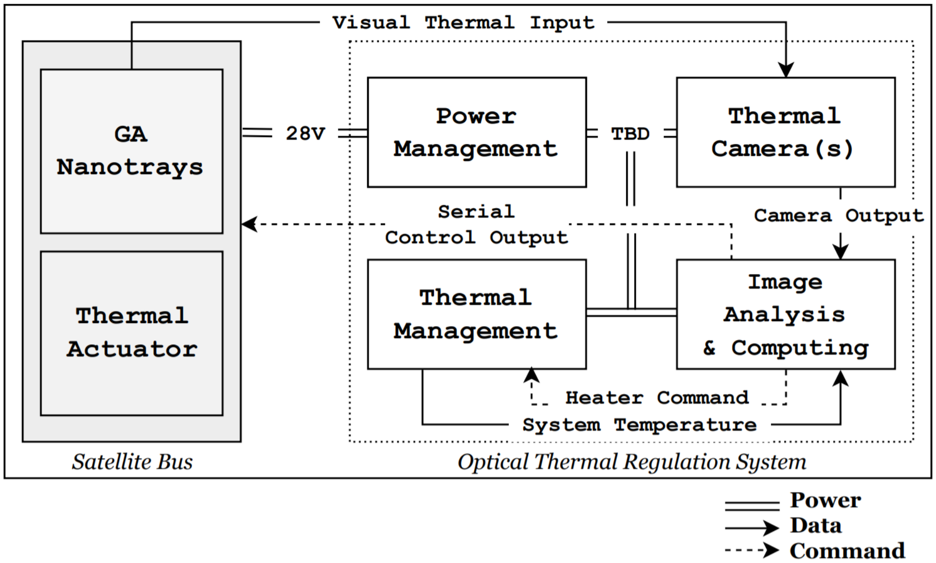

Figure 1. Major functional elements of the system

The satellite bus is not a project element, but will supply the system with an unregulated 28V power output and receive a TBD serial output from the system. The overall system itself contains four elements: a power management system, one or multiple thermal cameras, a processing unit, and a thermal management system. The power management system is responsible for regulating and transforming the 28V volts into a desired TBD voltage required by the other components. The thermal camera receives a thermal image of the desired sections of the satellite bus and outputs the digital data to the processing unit which will use that data to create a TBD serial output sent to the satellite bus. A thermal management system is required to keep the processing unit and the thermal camera at operating conditions, and will consist of a temperature sensor, thermal actuator, and control unit.

4.2. Concept of Operations

OTheRS is working to improve the thermal management system for satellites. During the mission for General Atomics, the system will be monitoring the temperature of two or more trays in a stack contained within a portion of the shell. The trays house various electronic components including mission critical hardware. With these infrared images, the on-board processor will determine the temperatures of these stacks to see if they are in the given operating range. The satellite will encounter extreme temperature swings in operations as it orbits the earth. At some times it will be in direct sunlight, imparting excess heat to the satellite. At other times, the earth will shield the satellite from the sun, creating an extremely cold environment. This makes the temperature regulation extremely important; as such, the OTheRS project, the control system will command heaters to turn on and off as the temperature swings or turn tray electronics off if need be.

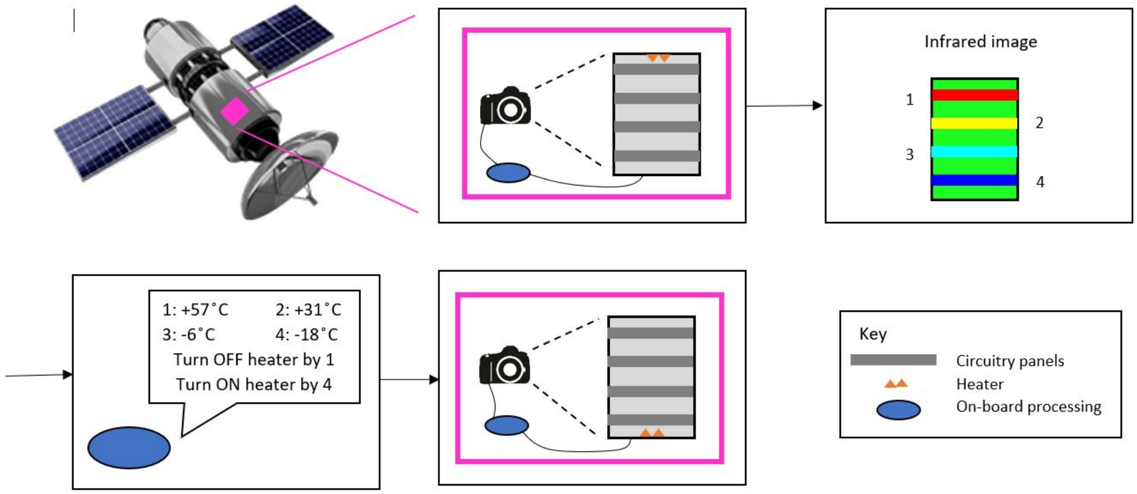

Figure 2. Mission overview: OTheRS will thermally manage the internal systems of the satellite

The test bed will consist of an outer aluminum shell, where the camera will be mounted, with two or more power resistors contained within a portion of the shell. The camera will periodically image the aluminum structure to determine whether or not the resistors fall within the required temperature bounds (-30°C to +60°C). The image processing will use a TBD technique to spatially map objects of interest and isolate temperature measurements in those areas. This data will be fed into a control system, which will command heaters at or near the objects of interest in order to maintain operational temperatures. During testing, the temperatures of the resistors will also be measured using thermistors. After measurements are taken, values taken from the camera will compared to those taken by the thermistors. This process is illustrated in figure 3 below.

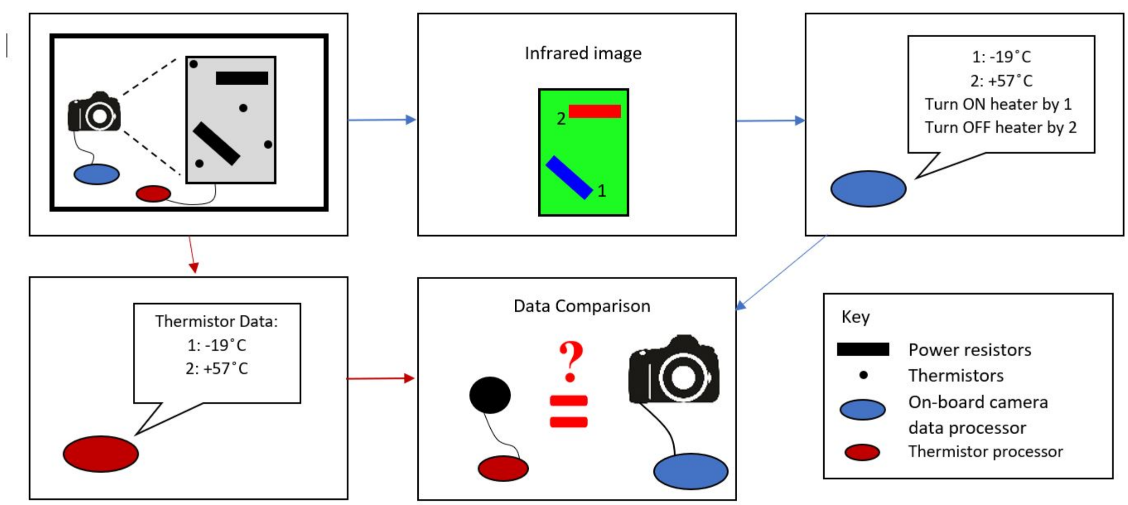

Figure 3. Testbed concept of operations

5. Critical Project Elements

The most critical item in our project is the thermal camera, which is the subject of our proposed testing. Most of the other critical elements are related to the test article and integration hardware. Software will also play an important role in image processing and communication with the rest of the satellite. For this project to succeed, we must have at least the following:

5.1. Thermal Camera

The thermal camera, our chosen solution to obtain thermal data, is critical to our success for all aspects of our project. The technical aspect is that without the camera in our system we will not reach any level of success. In addition, this component is perhaps the most important aspect of our system, as the customer requires a thermal management system built on this technology. The logistical aspect is minimal but should also be considered. Although this part is desired to be commercial off the shelf (COTS), a manufacturer still may need a few weeks to manufacture the product if the shelf stock is out. The final aspect of this element is the financial aspect. The camera cost can be quite high depending on the desired requirements, so our budget for other aspects of the system could be minimized. Also, there is some risk in testing the camera as breaking the camera would directly affect the budget of the system.

5.2. Software

Software, whether designed or purchased, is critical to our system as the system must process the images from the camera to make decisions for the command and control of thermal management systems. The software will have two primary functions in the systems. First, the software will need to process the images from the camera. This allows for the systems to identify hot or cold regions and classify them if action is needed. This leads into the second function, which is the command or control of a heater or representative system. Both elements are vital in the basic function of the overall system to meet the customer needs. The software has the possibility of being the most complex part of the system depending on the level of success met for image processing and the communication protocol needed to communicate.

5.3. Communication Electronics

The communication electronics are related to the software but are critical in their own regard. These components allow for the designed system to communicate with the satellite that the system will sit in. The communication is vital for regulating the temperatures in the satellite so this is determined as critical to the final designed system. Also, the choice of communication electronics could greatly increase the complexity of the system as some communication protocols are more difficult to implement than others.

5.4. Thermal Model

Raw camera data is useless without knowing what is being imaged. In order to be an improvement over current methods, our camera system should be calibrated so that it is suitably accurate for temperature regulation. Because our camera may have a restricted view of certain components, it will be advantageous to use a mathematical simulation of heat transport throughout the satellite or test bed that we use. This will allow us to infer more information about the heat of sources, sinks, and various components on the electronic boards.

5.5. Test Bed

Obtaining flight hardware to test with is extremely unlikely and also very challenging. Instead, the final thermal solution will be used with a simplified model of a satellite. A few heat sources, such as power resistors, will be added to the model in order to simulate actual electronic heat sources on a satellite, such as a processor chip. The entire test bed and thermal camera will be placed within a thermal chamber in order to simulate how heat is rapidly lost when radiated to space. This portion of the project is also to be used for verification and validation of the final project before use on flight hardware.

6. Team Skills and Interests

Name	Skills/Interests	CPEs
Justin Alvey	Experience in software engineering, data analysis, and project prototyping. Software skills: Python, C/C++, Matlab, Linux, Git, Bash/shell scripting. Machine shop experience. Some SolidWorks and SolidCAM. Interested in mission operations, cubeSat deployments, and entrepreneurial ventures.	5.1, 5.2, 5.4, 5.5
Ryan Bennett	Experience in systems engineering, controls, project management, program planning, mechanical design, CAD. Software experience in MATLAB, VBA, SolidWorks and some Python. Interested in system integration,control systems, and manufacturing	5.1, 5.2, 5.4, 5.5
Emma Cooper	Experience in MATLAB, C++, SolidWorks, 3D printing, System Engineering, optical systems, and thermal testing. Interested in design modeling, control systems, systems testing, and manufacturing.	5.1, 5.2, 5.4, 5.5
Sean Ellingson	Experience in MATLAB, Python, Solidworks/CAD, image processing, design, manufacturing, testing environments, ; interested in manufacturing, testing, design safety, systems	5.1, 5.3, 5.4, 5.5
Pierre Guillaud	Interests in Electronics and Software. Experience in C, C++, Matlab, Python, Unit Testing, Computer Systems.	5.1, 5.2, 5.3, 5.5
Nash Jekot	Skilled in MATLAB and some Python coding and electronics (specifically microcontrollers), interested in image processing, testing, and manufacturing.	5.1, 5.2, 5.3
Jacob Killelea	C, C++, Ada, Rust, MATLAB, Ruby, Bash, ROS, Linux, Embedded computing with STM32 and AVR cores, Electronics design in KiCAD, Aluminum machining, and PID controls	5.2, 5.3, 5.4
Micah Svenson	Experience in MATLAB, Python, C++, modeling of optical systems, image processing, and project organization. Interested in project management, electronics, systems engineering, and control systems.	5.1, 5.2, 5.3, 5.5
Kendall Worden	Finance, system engineering, mechanical design, experience in MATLAB and Python. Interested in performing trade studies, cost analysis, and manufacturing.	5.1 5.2 5.3 5.5

7. Resources

Describe resources beyond team interest/skills needed to address the critical project elements defined above, and identify the source for each. These include specialized equipment, software, facilities, or outside expertise, and any additional financial support needed beyond the $5,000 project funds, along with the source.

7.1. Thermal Camera

- TBD thermal camera provided by GA (not necessarily final camera selection)
- Purchase of thermal camera(s)

7.2. Software

- Student Team will develop image processing and control software
- Campus library resources
- Existing methodology and protocols

7.3. Test Hardware

- Environmental test chamber provided by GA
- Simplified aluminum satellite structure provided by GA

- GA nanotray provided by GA

7.4. Communication Electronics

- Purchase of communication peripherals
- CAN assistance from GA
- Existing methodology and protocols

7.5. Thermal Modeling

- CAD Model of satellite provided by GA
- Thermal modeling software, starting from principals to Thermal Desktop
- Department help from Dr. Jackson, Dr. Nabity, Dr. Li
- Thermal chamber from GA or Dr. Nabity

7.6. Baseline test equipment

Critical Project Elements	**Resource/Source**
Thermal Camera	General Atomics or COTS parts
Image Processing Software	Student Team
Test Hardware	Student Team or General Atomics
Communication Electronics	COTS parts or fabricated by student team
Baseline test equipment (thermistors)	COTS Parts

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[3] Jenner, Lynn (2017), NASA Repurposes Passive Thermal-Control Technology for CubeSats. Retrieved September 6, 2018, from https://www.nasa.gov/feature/goddard/2016/nasa-repurposes-passive-thermal-control-technology-for-cubesats.

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[5] Eliason, J.R. Thermal mapping of the Columbia River at Hanford using an infrared imaging system. United States: N. p., 1967. Web. doi:10.2172/10173989.

[6] Sobrino, J. A., and J. Cuenca (1999), Angular variation of thermal infrared emissivity for some natural surfaces from experimental measurements