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Thermal Management and Design of High Heat Small Satellite Payloads

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ABSTRACT

The size and mass constraints on small satellites provide a serious challenge for efficient heat dissipation from electronics. Incorporating thermal straps, or more sophisticated hardware, can put serious strain on mass budgets, if the placement of such devices is even feasible in the form factor of the satellite. The ability to use existing structures in small satellites, such as payload housings, can be an attractive alternative to provide thermal mass for integrated electronics. With appropriate materials and surface treatment, using an existing payload housing is shown to be a viable solution to dissipating heat from high-power components. This manuscript uses simulations to describe appropriate measures for effective heat removal from a high performance, space-based computational unit.

I. Introduction

Small satellites provide a unique platform for low-budget development of space missions with fast turnaround. With miniaturization of scientific payloads comes the challenge of thermal management, since a decrease in mass can steepen thermal gradients. The Multiview Onboard Computational Imager (MOCI) endeavors to use a graphics processing unit (GPU) in space to perform computations on-board the satellite, to mitigate high down-link rates. Between the small package size and high power draw of the GPU, this provides a thermal engineering challenge to manage the heat generated by the GPU.

The MOCI payload explores a design that uses existing structures as thermal management systems, as opposed to adding thermal straps which eat into tight mass budgets, and take up volume that might not always be available. Simulation is used to evaluate design parameters such as materials and surface finish during design, and testing of a development unit is used to confirm simulation results.

II. Design

MOCI uses an Nvidia Jetson TX2 GPU, which has a peak power draw of about 7 Watts, with a nominal power draw of around 3.5 Watts, determined through testing and benchmarking. Because radiation is a relatively slow mode of heat transfer, it can be difficult to dissipate high heat loads mechanically. Therefore the design of the GPU's heat management system involves using the mounting structure of the optical payload as a heat sink, and an interface between the GPU and the primary structural frame. Making use of existing structures in the satellite aims to limit taxing the mass or power budgets.

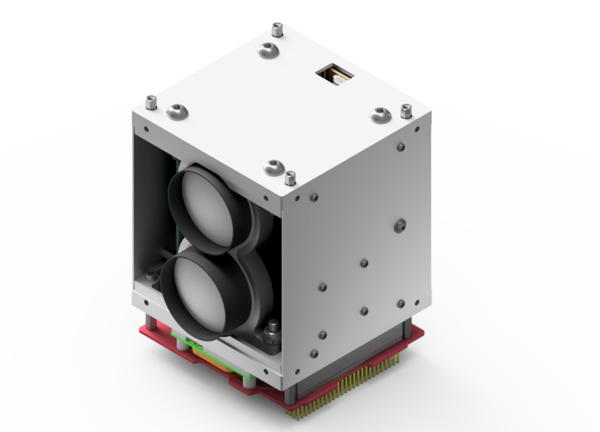


Fig. 1 Rendering of payload structure

A. Mechanical Design

The mechanical design of the payload consists of three primary parts: the optical mounting brackets, the structural housing, and the GPU. The rendering in Figure 1 shows how the GPU interfaces with the payload housing. The payload housing interfaces with the structural frame.

The GPU comes equipped with a metal thermal transfer plate (TTP) which serves as a passive heat sink for the electronics underneath. [5] Although shipped on a development board, with a fan and convection heat sink on the TTP, the GPU will be integrated into the payload on a custom core GPU interface (CORGI) board, which conforms to the PC/104+ standard. Removing the stock heat sink exposes threaded holes that are repurposed for mounting the payload housing to the TTP.

The payload housing is primarily made from machined aluminum 6061-T6, as is the primary structural frame of the satellite (not shown in Figure 1). All fastening of parts is done with stainless steel screws, secured by space-grade Vibra Tite, as well as a secondary thread-locking mechanism as back-out protection. This secondary mechanism is either a locknut, locking washer, or helicoil, depending on fastener size and thread sizes.

The optics are mounted on two brackets. The back bracket is the primary structural piece for mounting, with a threaded hole for the GOMSpace C1U Nanocam (top camera), and a clearance hole with side mounting screws for the Picocam (bottom). The front bracket is to provide additional support and remove the cantilever configuration. It has a plastic insert made from ULTEM 9085, a space-grade plastic that is easily 3D-printable. It will also help thermally isolate the lenses by providing a partially insulated contact between the payload housing and the optics.

B. Thermal Interface

An important consideration in the thermal modeling of discontinuous conduction models is thermal contact resistance (or its inverse, conductance). Microscopic roughness of material reduces the effective area for heat transfer on any interface. Endo-atmospherically, this would be partially mitigated by convection through the interstitial gas. In vacuum, this is limited to radiation, making the process even less efficient.

This design relies entirely on the conductance of heat from the GPU to the payload housing where more thermal mass and surface area is available to dissipate the heat. In vacuum, control over conductance between joined parts can be difficult as it depends on the surface roughness of interfacing parts and the interface pressure (Figure 2). While surface properties can be controlled in machining, this is often time-consuming and expensive, thus moving away from the benefits offered by small satellites.

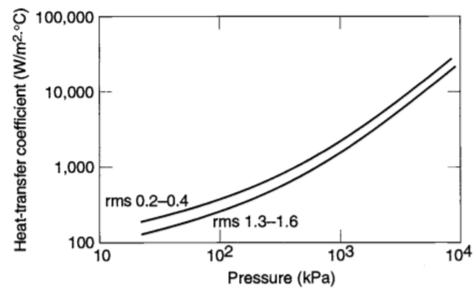


Fig. 2 Aluminum contact conduction coefficient in vacuum. Src: [3]

Instead, thermally important interfaces will include a thermal interface material (TIM) such as a gap filler pad or thermal tape to promote conduction heat transfer. An important requirement is that these materials conform to the offgassing requirements set by NASA, dictating a less than 0.1% collected volatile condensable materials ($\leq$ 0.1% CVCM) and less than 1% total mass loss ($\leq$ 1% TML). [7]

A survey of commercially available materials lead to the comparison table below, where all materials conform to the offgassing criteria

Table 1 TIM comparison

Product	Thickness (mm)	Conductance ($Wm^{-2}K^{-1}$)
Parker T412 Attachment Tape	0.23	1,772
Parker Therm-a-gap 579 filler pad	0.25	1,017
Carbice Space™	0.065	13,330

Table 2 concludes the Carbice Space™ to be the optimal product to use as interface material, as it provides the highest contact conductance value. As a safety margin, all simulations in the next section are run using the Parker T412 Attachment Tape value.

C. Optical Properties

Machined, bare aluminum is typically a poor emitter of radiation, with emissivity values being less than 0.2, but retaining high absorptivity. This poses a problem for this high-heat application where high emissivity is desired to increase the efficiency of heat transfer. Preliminary models assumed the thermo-optical properties of Aeroglaze Z306 [1], which showed promising results.

For a more realistic scenario, since painting surfaces comes with contamination hazards, and because aluminum is corroded by atomic oxygen in the upper atmosphere, the more crucial components of the payload will be anodized. [2] Clear anodized aluminum surfaces have improved thermo-optical properties that, while not ideal, are a drastic improvement over bare aluminum, with the added benefit of preventing atomic oxygen corrosion. Sources tend to report different values for achieved radiative properties, based on anodizing specifications used. For the purposes of this analysis, an emissivity, ε, of 0.78 and an absorptivity, α of 0.38 were chosen, based on a Type II Class 1 anodization. [4, 8].

III. Simulation Results

Finite element analysis was used extensively to prove the design of the payload, both for structural integrity during launch, and as a thermal management system. ANSYS was used for initial simulations, due to its ability to run different iterations quickly. At the end the design process, the payload was also analyzed using Thermal Desktop, to simulate dynamic orbit heating and assess what a day in the life would look like, thermally.

A. ANSYS

Initial benchmarking simulations were performed in ANSYS with interface temperatures determined from preliminary one- and six-node analyses. This analysis serves as a design guide, and proving the concept before more detailed simulations are run. Preliminary analyses have shown that the satellite will run too hot outside of eclipse to make data processing viable. For this reason, the ambient temperature for this analysis is set to 10°C; the approximate interface temperature of the frame in eclipse at the time the payload would be turned on.

The analysis begins with an imported CAD file, similar to Figure 1, with fasteners and certain details removed for the stability of the mesher. The ANSYS model is set up to model internal radiation with surface-to-surface boundary conditions on all (open) enclosures. Notably, the thermal interfaces between the TTP and the payload housing, as well as the TTP and the primary GPU circuitry, are manually set to the Parker T412 Attachment Tape value.

The model used in this analysis contained just under 900,000 elements. ANSYS makes these types of analyses easy to perform with high accuracy. This makes them ideal for use during the design process, as the design can be evaluated frequently, providing feedback to the designer on how the design might be improved to meet thermal, or structural requirements.

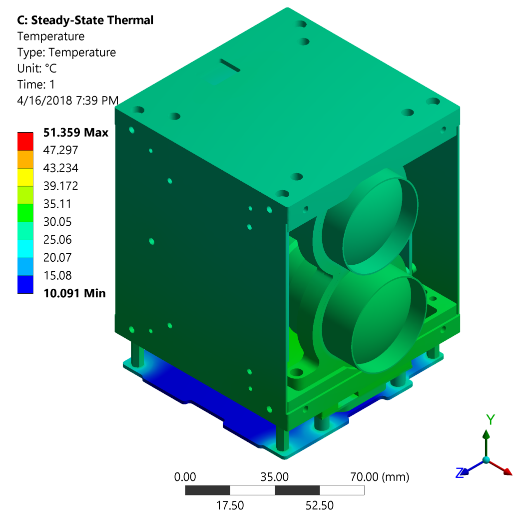


Fig. 3 Steady-state thermal results, ANSYS

Figure 3 shows the results obtained from the initial analysis model in ANSYS. This analysis uses the maximum power draw of 7 Watts on the GPU, assuming 0% processor efficiency, so all power is directly converted to heat. These assumptions model a worst-case scenario in power draw. The model predicts a maximum temperature around 51°C (cross section shown in Figure 4), which are then corrected by 11°C in post-processing to bring them within a 2-σ confidence interval. [6] This puts the maximum predicted temperature of the GPU at 62°C, which is within the operating temperature range of -25 to 80°C. [5]

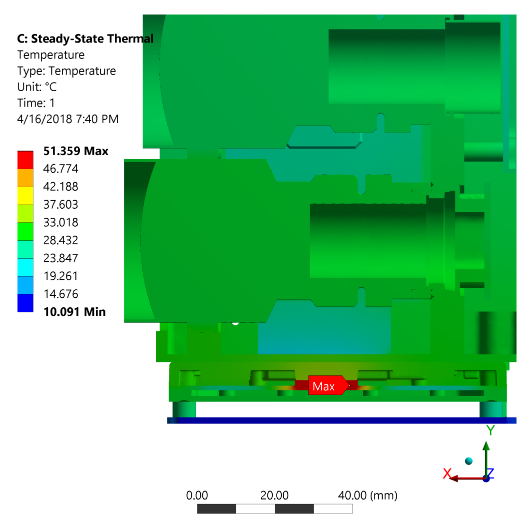


Fig. 4 ANSYS detail view

B. Thermal Desktop

To capture full dynamic behavior of the satellite, the payload design was also simulated in Thermal Desktop. While all components besides the payload will be hidden in these figures, they are fully modeled in this simulation. The dynamic temperature behavior will include a study of temperature over various beta angles seen by the satellite.

The same assumptions used for the ANSYS model in the previous section hold for this analysis, with the addition of the various other components on the satellite. The majority of which are modeled with the optical properties of Aeroglaze paint. However, proper optical values are used for the photovoltaics, and all additional aluminum parts modeled. The analysis is run in both hot and cold cases, dependent on season, with solar flux values of 1322 and 1414Wm^{-2}, respectively. [3] Appropriate Earth albedo and IR parameters are used according to [3] with respective beta angles.

The analysis produces a similar temperature gradient as the ANSYS simulation, as shown in Figure 5. To validate the interface temperatures used on the ANSYS model, the temperature of the structural frame and solar panels were a point of interest in the results of this analysis. The mean range is found to be between 0°C and 20°C across all cases, which validates the 10°C assumption on the ANSYS analysis.

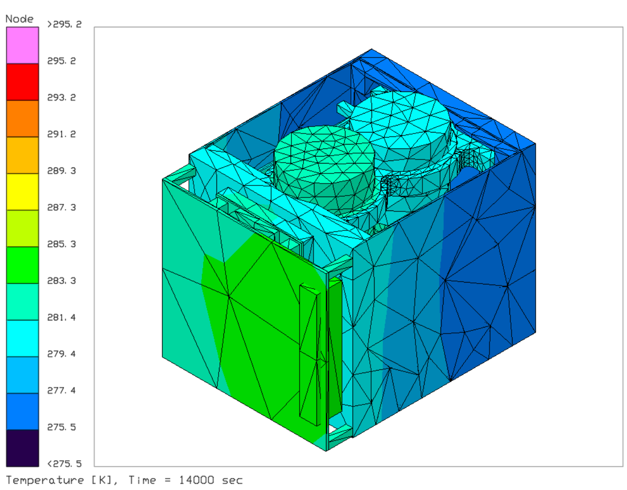


Fig. 5 Results, Thermal Desktop

The complete result set from this analysis consists of temperature and beta-angle data for each node in the model. To determine whether the temperature of the GPU and various payload systems remain within their operating temperatures, the maximum temperature over time is plotted against the beta angle set evaluated. These are presented in Figure 6. As with the ANSYS analysis, they are corrected by 11°C for the 2-σ confidence interval per [6], represented by the dotted black lines. Between the hot case and cold case extrema, the GPU only exceeds its operating temperature range of -25°C at low beta angles.

The payload generally runs at a lower temperature than the ANSYS model. While their heat load is 7 Watts in both cases, the GPU does not reach steady-state in the Thermal Desktop model, as it is only drawing power for 15 minutes in the middle of eclipse.

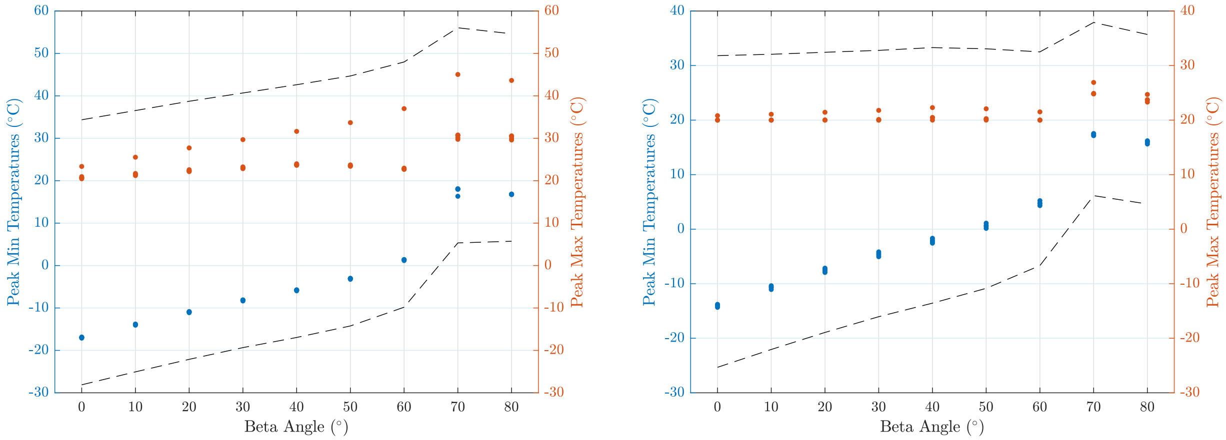
The other systems of interest in this model, are the two optical systems. While operating temperature ranges can be found for the sensors, the effects of temperature changes on the system can be hard to characterize. As part of the future work of this system, a structural-thermal optical performance (STOP) analysis will be necessary to determine how the thermal expansion of the lens will affect the optical performance of the system. The results in Figure 6b show a hypothetical temperature swing from around -25 to 40°C, although these show extremes over the entire orbit. In reality, this temperature swing is about half given the optimal range of time to image.

IV. Conclusion

While the GPU's high power draw is a an area of concern for MOCI's payload, the additional material and surface area provided by attaching the GPU to the structural payload housing is showing promising results in simulation. Even with temperature correction, the operating temperatures are only exceeded on the low end of the range, and only for extremely low beta angles.

A development model of the payload will be manufactured and tested in thermal vacuum. With power systems in place, this will be used to obtain a more realistic temperature model and help aid in future design of the payload.

The optical performance of the payload under temperature fluctuations remains an area of concern. While the best course of action would be to thermally isolate the optics, which would keep the optical train at nominal distances by mitigating thermal expansion, this would also inhibit the optics from dissipating heat. Performing STOP analyses will be part of future work and acceptance testing.



(a) Jetson TX2 GPU **(b) Camera system**

Fig. 6 Temperature extrema

Appendix

Table 2 Material properties

Material	Conductivity k ($\mathrm{Wm^{-1}K^{-1}}$)	Specific Heat c_p ($\mathrm{Jkg^{-1}K^{-1}}$)	Density ρ ($\mathrm{kgm^{-3}}$)
Al 6061-T6	167	896	2700
SS 304	16.2	500	8000
FR-4	.294	1150	1900
Silicon	124	794	2329
ULTEM 9085	0.184	1200	950

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