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A Novel Nanosatellite Heat Management System via Actively Switched Thermal Pathways

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Abstract

This paper will outline a novel thermal management system for CubeSat-scale satellites utilising actively switched heat-conductive pathways, as well as a lumped parameter methodology that allows the rapid design of such systems. As CubeSats become more powerful and capable, regulating their thermal condition will become a growing challenge. The integration of heat-conductive pathways and actuated junctions into CubeSat structures can enable integrated control over the distribution of heat between subsystems during operation. In principle, local thermal spikes can be mitigated, excess heat can be moved to where it can most effectively be radiated away independent of spacecraft orientation. Moreover, critical subsystems can be better thermally regulated than with a passive system. These all serve to increase the reliability and capability of future CubeSat missions. Such a system would also have broad applicability to other satellite platforms as well as terrestrial use cases. An active thermal management system is potentially not only more flexible in both design and operation, but also more accurate in temperature regulation.

Due to the low-cost nature of CubeSat platforms, many missions are launched with limited thermal validation. High fidelity thermal models do not afford themselves to rapid design changes or parameter optimisation. Instead, by approaching the design as a thermal-analogue circuit, a lumped parameter model can allow for much greater flexibility and speed when quantifying mission performance, component sizing, and safety. The proposed methodology will be utilized to present the design of the thermal paths, as well as evaluating the performance benefits of the active switching system, if it were to be implemented on existing CubeSat platforms.

Keywords: nanosatellites, thermal management, CubeSat systems, lumped parameter modelling, system modelling

Acronyms/Abbreviations

OBC – On-Board Computer
IR – Infrared
PCB – Printed Circuit Board
MEMS - Microelectromechanical system

1. Introduction

1.1 The Need for Novel Thermal Solutions

Growth in payload requirements and CubeSat platform capabilities require smarter and more robust thermal management systems. As CubeSats create and consume higher quantities of power onboard, thermal dissipation of waste heat becomes a significant bottleneck that must be addressed for future missions.

Existing passive thermal dissipation methods heavily constrain the design and manufacture of these platforms and until very recently, active systems have not been viable for CubeSat-scale satellites.

For current-generation missions, the thermal design of CubeSat platforms is necessarily tied to its mission profile to most optimally radiate heat into space. This becomes an issue when the pointing requirements of platform subsystems and payload intersect, requiring trade-offs to be made in performance. The ability to decouple the spacecraft's attitude from its ability to radiate waste heat would greatly enhance the flexibility of the platform during both its design and operational phases.

1.2 Existing Thermal Solutions

Existing passive thermal systems heavily constrain the electrical and mechanical design of CubeSat platforms as the static design must withstand both the hot and cold temperature extremes over the course of the mission. Thermal systems must also direct heat towards faces where it can best be radiated away, must survive temperature spikes, as well as ensure that satellite safe-modes are reliable and robust, as shown in *Fig. 1*.

The use of active on-board heaters or Peltier units can provide flexibility, but are reliant on accurate sensor measurements as well as increasing power demands.

Passive modes of achieving desired thermal behaviour of CubeSats are achieved via careful design of the platform structure, the use of copper heat shunts to direct heat, and the use of phase-change material such as paraffin to smooth thermal fluctuations[1]. Thermal louvres common on larger satellites can also be considered, and their efficacy has been shown on CubeSat-scale form factors[2]. These have the benefit of

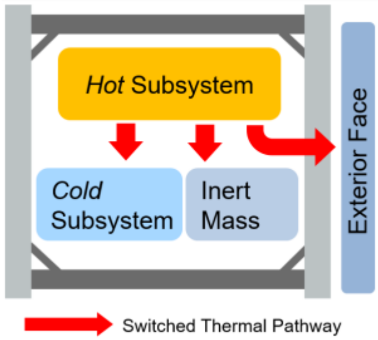

Fig. 1. Excess heat from a hot subsystem can be directed into systems below their design temperature ranges, into inert masses to smooth thermal spikes, or to faces where it can best radiate away

being autonomous and independent of the on-board computer, and generally simpler than electronic systems.

1.3 Thermal Management via Switching Thermal Pathways

The integration of heat-conductive pathways and actuated junctions into CubeSat structures can enable integrated control over the distribution of heat between subsystems during operation. In principle, local thermal spikes can be mitigated, excess heat can be moved to where it can most effectively be radiated away independent of the spacecraft orientation. Moreover, critical subsystems can be better thermally regulated than with a static system. Such a system would also have broad applicability to other satellite platforms as well as terrestrial use cases. An adaptive system is potentially not only more flexible in both design and operation but can also provide more stability in temperature for critical subsystems. The additional robustness of this system can greatly increase mission resilience to platform failure.

Switching pathways can be designed according to several methodologies. The first option is an integrated system whose sensor data passes through the OBC. The second involves a closed-loop sensor-actuator system, where each switch acts independently. Lastly is a system that uses solely mechanical components that operate as switches free of power and sensing requirements. These three modes are presented in *Figure 2.* A hierarchical system that passes all data through the OBC provides a high level of knowledge over the state of the satellite, but at the cost of reduced redundancy, increased harnessing requirements, and higher complexity. Local actuated junctions allow the thermal system to operate autonomously of the OBC and thus increase spacecraft resilience, but have the disadvantage of requiring increased testing during design phases to ensure suitable operation in all possible states of the spacecraft.

2. Thermal simulation tools

2.1 Lumped Parameter Thermal Model

To investigate the efficacy of novel thermal management systems a lumped parameter thermal model was developed. This model approximates the CubeSat platform as a series of nodes with given thermal characteristics, connected by thermal pathways of various types. This approach is more advantageous than a high-fidelity FEA approach due to the speed and ease with which new system-level solutions can be designed.

2.2 Thermal Modelling Strategy

Complex thermal models can be simplified by approximating each component as a single node with a given mass and specific heat parameters, connected to other nodes/systems in the network via thermal pathways. This allows the entire system to be represented by a concise series of simple equations. The rate of temperature change of a given node is determined by the lumped properties of the node and the net thermal energy entering it, summarised in *Eq. 1.1*.

$$dQ_{net} = mcdT, \qquad 1.1$$

where dQ_{net} is the heat required to raise a node with mass m and specific heat capacity c by temperature dT. This is equal to the net heat entering a node. *Eq. 1.2* then defines the 1D simplification of Fourier's equation for homogenous conductive materials, and in the lumped parameter model calculates the heat passing through each conductive link between nodes.

$$\frac{dQ}{dt} = kA\frac{dT}{dx} \qquad 1.2$$

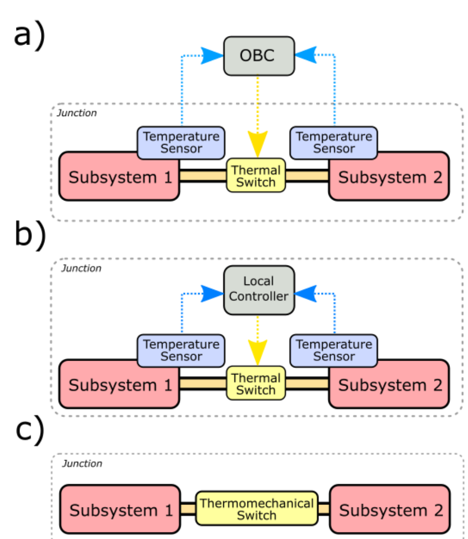

Fig. 2. Various approaches to thermal junctions. a) Sensor-actuator switching via OBC, b) Local sensor-actuator switching, and c) Thermomechanical Switching

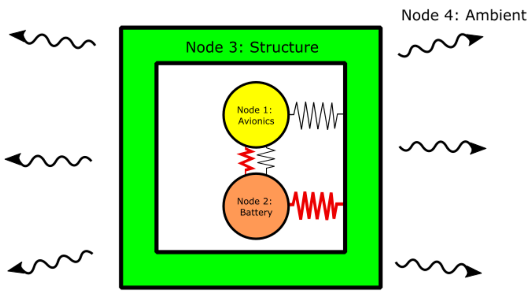

Fig. 3: Example network for lumped parameter modelling. Radiative heat transfer from structure to ambient, with internal heat transfer conductive. Switched pathways regulate battery temperature

Where k and A are the material conductivity and cross-sectional area of conductive transfer respectively. Then, *Eq. 1.3* defines the net radiative heat flux from a surface of a given temperature and is used to calculate the heat radiated to deep space from faces and radiators, as well as additional heat transfer between certain components inside the satellite.

$$\frac{dQ}{dt} = \sigma\varepsilon A(T_2^4 - T_1^4) \qquad 1.3$$

Where T_1 and T_2 are the temperatures of the radiator node and target node respectively, and A is the effective radiator surface area. The Stefan-Boltmann constant σ and the emissivity of the radiative surface ε are assumed to be constant in every thermal pathway.

2.3 Governing methodology

Once built, this entire network can be expressed by a series of simultaneous differential equations, constructed using equations for Fourier’s law, the Stefan-Boltzmann law, and the simplified heat equation. This series of equations is propagated forward in time using a Runge-Kutta integrator, minimizing numerical errors. This approach is general and can be applied to thermal networks of any size, though the speed of the solution will decrease with more nodes.

Small components within the satellite are not modelled as nodes, but rather as additions to the thermal resistances of adjacent subsystems. This is also the case for components with loose contact conductance between them. Subsystems consisting of multiple materials are assigned conductivities and specific heat values based on weighted averages according to their mass.

3. Example Thermal Network

Presented in *Figure 3* is a simple four-node thermal model representing a CubeSat in orbit. Two internal nodes representing the avionics stack and a separate battery node generate heat, and are connected to an external structural node, which radiates heat into deep space. The thermal connections between all internal

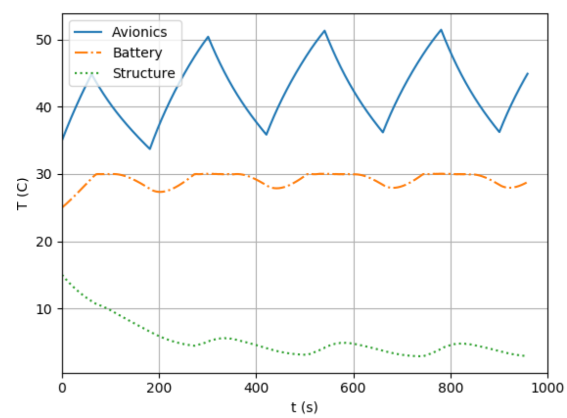

Fig. 4. Temperature profiles for CubeSat nodes in 4-node thermal model

subsystems are conductive, though between the battery and the structural nodes there is a temperature-dependent switch, activating once the battery exceeds 30 degrees Celsius. As shown in *Figure 4*, once the battery exceeds this design temperature the actuated heat shunt expels thermal energy into the structural node where it can better radiate away. If this path were always connected, then the battery may end up reaching too low a temperature, and if there were no heat path at all, the temperature would rise to a temperature detrimental to the battery itself. The actuated junction allows the battery’s temperature to be stabilized, even with a switched thermal pathway of moderate conductivity.

4. Discussion

Depending on their complexity, switched thermal pathways could connect not just to exterior faces, but also to other subsystems, radiators, and inert structural masses. These all serve to create an adaptive system that is both flexible in design as well as secure against unseen operational thermal spikes. Many subsystems, such as the battery and communication arrays, can even operate more efficiently in narrow temperature ranges, which can be maintained using advanced thermal networks. This can lead to even more performance savings, and allow lower factors of safety during design.

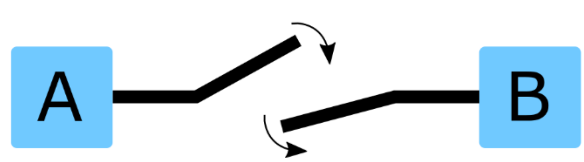

Fig. 5: Thermal switch in series. Heat is only transferred when A is above nominal temperature, and B is below. This is equivalent to a $\mathbf{A} \cup \mathbf{B}'$ *logic gate*

4.1 Passive Switching

The idea of passive, or analogue, switching junctions is of great interest. Though many methods exist to achieve it, these mechanisms provide fundamental advantages over electrical sensor-actuator systems. Previous investigations into magnetic switches [4] have shown promise but are largely impractical for nanosatellites due to interference with Earth's magnetic field. Better candidates include bimetallic mechanisms, shape-memory alloys, MEMS-scale droplet technologies, or phase-changing spacers such as paraffin.

These can be installed as single mechanisms and are simpler, more likely to survive high launch loads and the space environment, and could ensure that some spacecraft systems continue to operate autonomously in the case of catastrophic failure. Further research in the area will focus on the mechanism design. Additionally, with a network made up of a sufficient number of thermomechanical junctions, a rudimentary form of analogue computing can result.

4.2 Emergent Analogue Behaviour

Regardless of the switching mechanism, a sufficiently advanced network of switched thermal pathways can exhibit emergent or even quasi-intelligent behaviour. MEMS-scale logic gates and computing have shown great promise [5]. On CubeSat scales, heat paths can be designed to prioritise travel in certain directions, and research into the use of purely thermomechanical logic gates opens up opportunities for analogue computing. Simple switching behaviour with moderate conductivity ratios can create very complex behaviour as the number of interconnected nodes increase. For example, *Fig. 5* presents a junction of two thermal strips, in series. Since the actuation of each strip is dependent on its connected node, heat only transfers from one node to another when the former is above a given design temperature and the latter is below a design temperature. This would be used to prevent components from overheating even further by connecting to a subsystem that is also overheating. Assuming a binary of 'hot' and 'cold' states, this junction can be described by the logic expression: $A \cup B'$. Combining these in parallel could allow junctions to transfer heat bidirectionally. *Either* node could behave as heat sink or source depending on the spacecraft state. The junction in *Fig. 6* would be roughly equivalent to the logic expression: $(A \cap B') \cup (A' \cap B)$.

5. Conclusions

Networks of switched thermal pathways have the potential to greatly increase the performance and efficiency of CubeSats, as well as other nanosatellite platforms. These networks are being explored using lumped parameter thermal models, which can enable rapid design iteration as well as the analysis of large, interconnected networks. These large networks are required to explore the emergent behaviour that can result from the rules, logic, and actuation of very simple junction mechanisms. Route prioritisation, logic gates, and other forms of emergent behaviour are all promising areas of research, which will require robust tools such as lumped parameter modelling to explore.

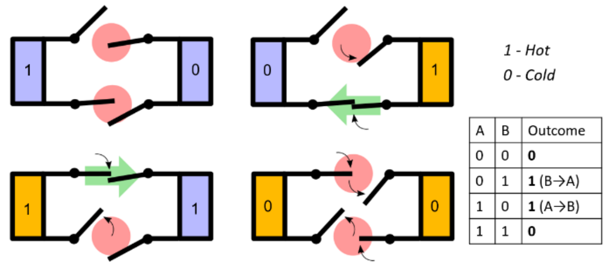

Fig. 6: Conditional heat transfer junction. Heat is only moved through junction when one can operate as a source and the other a sink. Equivalent to $(A \cap B') \cup (A' \cap B)$

Lastly, the use of purely thermomechanical switches can deliver autonomy, resilience, and flexibility of new CubeSat platforms, which will invariably become more powerful and require more advanced thermal systems as a result.

Further research will analyse more complex switching networks as well as the use of purely analogue switch junctions.

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