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DYNAMIC SIMULATION OF ELECTRICAL AND THERMAL SYSTEMS FOR RAPID DESIGN ITERATION AND VALIDATION OF POWER PROFILES FOR 3U IMAGING CUBESAT

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Abstract

Traditional simulation of CubeSAT subsystems involved separate analysis of subsystems followed by a heavy, multi-physical co-simulation using large FEA solvers. This approach, while very accurate, is not suitable for the rapid design and validation iterations of small satellite teams due to lengthy simulation times and complex setups, which often require a lot of vacillating between the EPS and STS teams. This type of development is also heavily centered around the thermal side of the simulation, with little effort put into developing both systems in tandem on the electrical side of the design. Presented here is a novel approach to utilizing transfer-function modeling in Simulink to couple electrical and thermal models. This permits faster iterations and indications of design limitations in early stage integration studies, which often lack the time and attention dedicated to more complete co-simulation strategies in primarily FEA software suites like ANSYS and Siemens NX. The component variation efficiency due to temperature changes and thermal component life degradation is taken into account, especially for the sensitive solar panels. This thermal model is developed from a coarse sweep of FEA solutions through a mathematical system which yields a comprehensive approximation of thermal characteristics of the CubeSAT subject to various power profiles, integrated with existing electrical models in Simulink .The electrical distribution model provides the thermal dissipation of the various components. Faster iterations were achieved and early design limitation indications were overcome by coupling electrical and thermal models in Simulink to optimize the electrical system design of a 3U multi-spectral imaging CubeSAT.

Keywords

CubeSAT, Co-Simulation, Satellite Power system, Equivalent circuits

Acronyms/Abbreviations

Commercial Off the Shelf(COTS)
Finite Element Analysis(FEA)
Thermal Equivalent Circuit(TEC)
Printed Circuit Board(PCB)
On-Board Computer(OBC)
Telemetry, Tracking and Command(TTC)

1. Introduction

CubeSats are standardized 10 cm cube satellites that have democratized space access, enabling rapid, low-cost missions for education, research, and technology demonstration while providing hands-on experience for students in spacecraft development[1]. They have become increasingly popular due to their cost-effectiveness and and versatility in meeting diverse mission requirement. They can be developed by small teams quickly to suit a wide range of mission requirements[2].

CubeSats are primarily constructed using Commercial Off-The-Shelf (COTS) components [3], which may not always be optimally suited for the space environment. Several studies investigating various power system architectures for CubeSats have emphasized the challenges of meeting power requirements while adhering to strict mass constraints[4]. Furthermore, the operational longevity of electrical components is significantly influenced by the thermal characteristics of the CubeSat [5].The interdependent nature of the Thermal, Orbital, and Electrical systems forming a loop in which on affects the other is also crucial as shown by studies considering the effect of thermal and orbital aspects on the power subsystem[6]. Validation of such components during the design phase is essential in avoiding expensive mistakes in the future.

1.1 Modelling techniques

The design procedure to accommodate all aspects involves repeated analysis of power profiles to check the power budgets and the thermal limits of the system. Repeatedly performing FEA does lend itself to small teams and fast iterations[7]

Co-simulation, defined as the dynamic simulation of multiple interconnected processes, is crucial to the design process as it addresses various integration issues and is essential for verifying the appropriateness of selected components. In the context of CubeSATs a co-simulation would primarily link the orbital, thermal and power systems[6].
The primary method is to use a proprietary full system design toolkit[8]. Although several alternatives have emerged developing analysis tools[9–11] primarily using a permutation of any two of orbital, thermal and power simulation, these tools have different focuses and capabilities. The power simulation tool by [9] integrates orbital data from STK with power analysis in MATLAB. The CubeSat power modeling tool by [10] combines orbital simulation using GMAT with power calculations in MATLAB.The studies conducted in [11] integrates orbital mechanics and power generation modeling in MATLAB Simulink. However, none of these tools attach all three aspects - orbital, thermal, and power simulation - together in a single comprehensive package. Each tool focuses on specific combinations of orbital and power analysis, leaving room for further integration of thermal modeling to create a more complete satellite simulation environment.
Building upon these findings, it is evident that conducting FEA analysis can be computationally expensive, particularly when multiple iterations are required. FEA simulations with 5,212 elements required 5.5 hours for obstruction computation and 16.2 hours for cyclic temperature field solution[12]. In another study, transient thermal analysis with 20,816 elements took 1-2 hours for convergence using primarily 2D elements[13]. These results highlight that while FEA provides detailed 3D temperature distributions, the computational demands can be significant when numerous analysis runs are needed to evaluate different design iterations and test cases.

1.2 Thermal Equivalent Circuit (TEC) modelling

The utilization of Thermal Equivalent Circuits (TECs) for thermal analysis is a well-established methodology in the field of thermal engineering. Contributions have been made by [14, 15]to this area by developing techniques to generate medium-order electrical equivalent circuits for modeling complex thermal systems. These approaches utilize advanced computational techniques to divide complex thermal structures into simpler, interconnected parts. They then estimate the thermal properties of these parts based on physical principles, resulting in simplified yet accurate models of the overall system. The TEC model is fundamentally based on the concept of thermal nodes, where major components of a system (such as satellite subsystems) are represented as lumped thermal capacities with averaged temperatures. The thermal interactions between these nodes are modeled using equivalent thermal resistances, which are functions of the predominant heat transfer modes between the components. In satellite thermal modeling, radiative heat transfer often dominates these inter-nodal thermal couplings[16]. The main advantage of the TEC is that it can be analyzed and solved using the robust and fast tools of circuit analysis, leading to seamless integration with electrical design software(in our case, SIMULINK). Further, TEC are uniquely suited to model satellite systems, as the major downfall of TEC is their less than accurate handling of convection, and the complex modelling required to handle the same[14]. Conduction and radiation, however, are relatively simple to model.

2. Proposed modelling approach

Our thermal analysis employs a reduced 3D model for all Finite Element Analysis (FEA) simulations, incorporating essential CubeSat components and accurately representing major construction materials. The model includes copper-coated FR4 for PCBs, copper and aluminum standoffs for structural support, and coated germanium ceramic solar cells. For simulation purposes, we focus on four key thermal nodes: three Printed Circuit Boards (PCBs) and the chassis.The chassis node encompasses the structural framework and external surfaces, including solar panels. We have used this thermal model in conjunction with a comprehensive electrical model, composed of equivalent model resistors and power conversion circuitry[17], and simplified the electrical model to lumped functions that represent the averaged heat generation of the components.

Previous approaches to this problem have used varying degrees of simplification, but we have found that for our case, the number of nodes and level of detail was enough to make reasonable conclusions about the temperatures of critical components. We have also taken care to ensure that all major heat transfer modes are accounted for, but have for reasons of simplicity, neglected effects such as radiation from standoffs and conduction through adhesive joints.

2.1 Thermal modelling

The satellite is represented by thermal nodes corresponding to major components like the On-Board Computer(OBC), Telemetry, Chassis, and Payload. These nodes are modeled as lumped thermal capacitances with averaged temperatures. Thermal interactions between nodes are represented by equivalent thermal resistances based on the dominant heat transfer modes. Two key simplifications are typically made in this modeling approach. First, the outer chassis and solar panels are treated as a unified thermal body with an averaged temperature. Second, due to the stacked PCB construction in CubeSats, only non-occluded radiative connections between boards are considered, as middle PCBs shield radiation between outer boards[18].

Table 1. Thermal quantities and their electrical equivalents

Quantity	Symbol	Equivalent	Symbol
Temperature	T	Voltage	V
Heat flow	q	Current	I
Heat Capacity	C	Capacitance	C
Heat Energy	H	Charge	Q

The simplified thermal model is shown in the figure below:

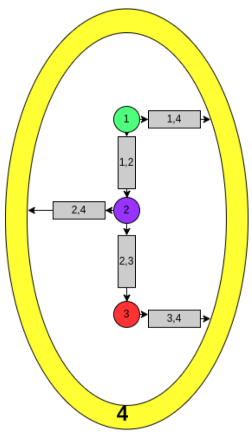


Fig. 1. Simplified thermal model

Each part is represented as an average-temperature node in the model. Between nay 2 nodes, the heat flow can be described as a differential equation[19]:

$$q_{ij} = C_i \frac{dT_i}{dx} = K_{ij}(T_i - T_j) + R_{ij}(T_i^4 - T_j^4) \quad [1]$$

where q_{ij} is the heat transferred between nodes, C_i is the heat capacity of the node i, T_i and T_j are the temperatures of the nodes and R_{ij} and K_{ij} are the coefficients of heat conduction and radiation between the nodes. C_i, R_{ij} and K_{ij} are all solely dependant on physical and materials composition of the parts.

Although a first principles approach to computation of thermophysical parameters is feasible through rigorous analytical methods, a better approach would be to use techniques produced by [15]. This methodology brings about compact thermal models of IC components by implementing parametric model order reduction on high-fidelity numerical thermal models, shrinking the system's scale while preserving parametric dependencies and solution accuracy. To reduce the complexities associated with differential equations, The system is abstracted into a thermal equivalent circuit to mitigate the complexities inherent in differential equations. Within this framework, thermal conduction is represented by thermal conductances, while radiative heat transfer is modeled using dependent current sources. This, the equation Eq. 1 can be written as the electrical form :

$$I_{ij} = R_c(V_i - V_j) + G_r(V_i^4 - V_j^4) \quad [2]$$

where all the thermal quantities have been replaced by their electrical equivalents as given in Table 1. Now, we can see that the thermal model in Fig. 1 becomes the electrical model in Fig. 2 and the constants R_c and G_r are directly equivalent to the values of R_{ij} and K_{ij}. For clarity, the heat capacity equivalents at each node are not shown, but are present and are modeled as a capacitor, whose capacity is calculated either by manually adding up heat capacities, or using CAD software, and ensuring both results match. The controlled current sources represent the equivalent radiation coupling and the resistors represent the equivalent conduction coefficient. The current sources represent volumetric(evolved) heating and radiation, both from the sun and the emission from the surface of the panels.[14]

The values are computed by averaging multiple simultaneous solutions to Eq. 1, taking the values of q_{ij}, T_i and T_j pairwise from the FEA simulations and solving for R_{ij} and K_{ij}.

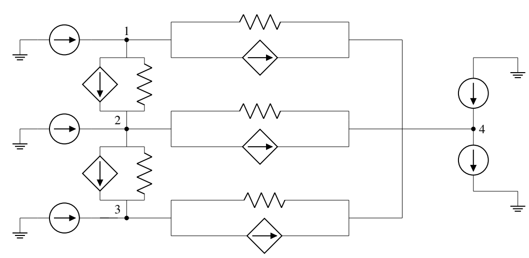


Fig. 2. Equivalent thermal circuit

2.2 Electrical modelling

The electrical model used in this study is based on the framework outlined by [17], which has been adapted and updated to meet specific requirements, as shown in Fig. 3. In SIMULINK, electrical components were modeled as resistive loads and enhanced with additional features such as limiting circuitry and protection mechanisms. The model incorporates various flight modes or states, each requiring specific electronic components to be either active, in power-saving mode, or inactive[20]. To improve the input for the thermal model, the electrical data is coupled with extreme solar irradiation cases. The worst-case hot and cold scenarios, with solar irradiation values of 1423 W/m² and 1323 W/m² respectively, as demonstrated by [9, 19], are considered in the calculations. This data is then passed onto the Electro-Thermal solver model, which can return the temperature data.

The lumped reduced form the the model is calculated by taking the average power dissipation for all the components on an particular board in a given operation mode, account for any temperature coefficients, and writing a function to calculate the effective heat current from the components, using the conventions in Table 1

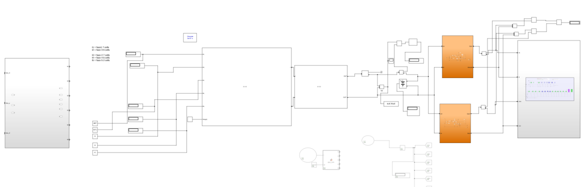


Fig. 3. New model used to compute power profiles

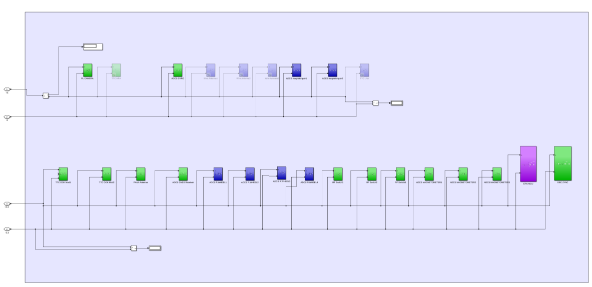


Fig. 4. Modelling of components[17]

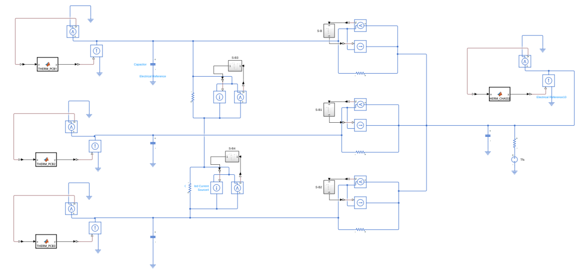
2.3 Orbit Propagator

The orbit propagator, developed by adapting the approach presented in [10]and [21]. The GMAT script is modified using Contact Locator[22] to include line-of-sight events between the CubeSat, Ground Station, and target. Two primary attitude control modes are considered: Nadir-pointing and Sun-pointing [23], with the former employed during Ground Station and target passes, and the latter used otherwise. These modes significantly influence power generation through changes in solar irradiation and refine power utilization by switching power profiles, as shown by [4, 24, 25].

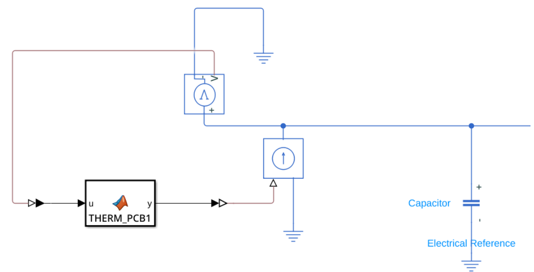
3. Validation using the Team Anant CubeSAT

3.1 Description of the model

Team Anant, the satellite team of Birla Institute of Technology and Science, Pilani is developing a 3U Cube-



(a) The layout of the SIMULINK model



(b) Individual thermal node in SIMULINK

Fig. 5. SIMULINK model overview and individual thermal node

SAT with a Multi spectral camera as the primary payload.The parameters regarding the electronic components and the Structural characteristics have been extracted from[17, 20, 23] The CAD model shown in Fig. 6 has been simplified by merging complex components and segmented into chassis, solar panels and PCB. Orbital parameters mentioned in Table 2 taken from [21].

In the thermal modeling process, material properties of the satellite components were averaged to simplify the analysis and streamline calculations. Rather than modeling each component's detailed and distinct thermal properties, an average of key material characteristics—such as thermal conductivity, specific heat capacity, and emissivity—was computed. This approach reduces computational complexity while maintaining a sufficient level of accuracy[27].

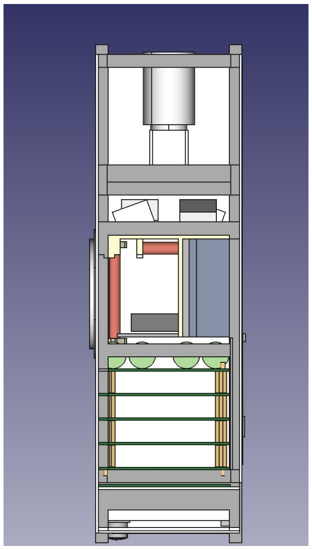


Fig. 6. Section of the CAD model[26]

Table 2. Orbital characteristics obtained from [21]

Quantity	Value
Type	Sun-synchronous
Start date	01/01/2018 00:00
Semi-Major Axis	6945 km
Eccentricity	0.0°
Inclination	60.0°
RAAN	0.0°
True Anomaly	0.0°
Period	5765 s

3.2 Steady state analysis

For testing purposes, three PCBs as heat sources are placed in the domain, as shown in Fig. 6. A standard power profile was applied to these PCBs. The comparison between the steady-state behaviors of the FE model (using NX) and the EC (performed in SIMULINK) is shown in Table 3. The average relative error in steady-state temperature was 2.8%.

Table 3. Results for theoretical simple power profiles (Steady State tempratures)

Test Case 1				
Component	Power	FEA	TEC	Error
PCB 1	4W	313 K	306 K	2.2%
PCB 2	8W	340 K	332 K	2.3%
PCB 3	4W	372 K	363 K	2.4%
Test Case 2				
Component	Power	FEA	TEC	Error
PCB 1	5W	323 K	313 K	3.1%
PCB 2	10W	350 K	334 K	4.5%
PCB 3	5W	383 K	372 K	2.8%

3.3 Transient Analysis

The FE simulation was commisioned on NX was used to verify the results obtained from the model.Fig. 7 compares the Percentage error in the TEC model versus the FEA model.

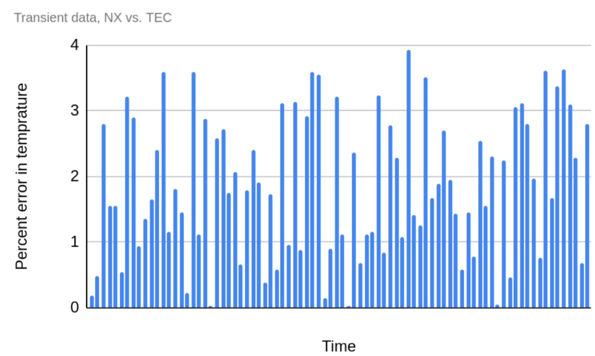


Fig. 7. Percentage error of FE versus TEC analysis

4. Summary and Conclusions

The findings of this work underscore the utility of using thermal equivalent circuits for the analysis and design of space missions. Given the constraints of small teams and tight development timelines, full mission designs are often limited by insufficient time, specialized expertise, or access to proprietary software. Through the development of this method using widely available software, this study demonstrates a practical method that significantly lowers the barriers to satellite design. Notably, the core aspects of this approach can be implemented using open-source software alternatives, such as Python and SPICE in place of MATLAB and SIMULINK. The methodology outlined herein can be readily replicated by teams with limited experience in advanced simulation tools (The generation of the TEC does not require full fledged transient simulations), and provide valuable data to estimate life cycles and validate flight plans. The approach also lends itself well to extension and modification to analyze specific parts of the satellite

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