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Engineering Notes

Optimal Distribution of Electronic Components to Balance Environmental Fluxes

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Nomenclature

A	=	area of panel/face, m^2
f	=	number of faces
N	=	total number of satellite components
n	=	number of components on each face
obj	=	objective function
$\bar{P}$	=	orbital-averaged power, W
$\bar{q}''_{\text{env}}$	=	orbital-averaged environmental heat flux, W/m^2
$\bar{q}''_{\text{gain}}$	=	orbital-averaged heat gains from environmental and component sources, W/m^2
T	=	temperature, K
α	=	surface solar absorptivity
ε	=	surface long-wave emissivity
σ	=	Stefan–Boltzmann constant, 5.67×10^{-8} $W/m^2\text{-}K^4$

Subscripts

i	=	face index
j	=	component index

I. Introduction

ROBUST satellites are required to handle a wide variety of missions. As a result, the underlying thermal control subsystem must be robust enough to maintain acceptable thermal conditions for satellite components under the most severe (hot and cold) environments. Investigation has revealed that this could be accomplished, in part, with an isothermal bus concept [1,2]. In effect, the isothermal bus concept provides for heat sharing components. As a result, gradients across the satellite are minimized, thus reducing temporal variations in temperature. This goal could be achieved in numerous ways. These include embedded heat pipes and integrated pumped fluid loops. One method that can reduce the requirements for active solutions and that has not received much attention is simply optimized component distribution. Optimized component distribution relies on intelligently placing components on specific faces of a multisided structure in order to improve overall global performance. To date, inertial optimization through intelligent placement has been studied [3–7]. However, only Jackson and Norgard [8] included thermal effects, and they did not consider the effects of nonuniform external heating environments.

The present work develops and demonstrates a simplified approach for determining the optimal distribution of electronic components between various exterior spacecraft panels to achieve a more balanced distribution of heat flux. Although developed in response to a robust satellite need for isothermal conditions, the method could also be applied to traditionally designed spacecraft. Other applications of this work include use as a trade tool to quickly assess and evaluate several proposed component distributions (e.g., assessing the implications of component relocation as a result of design change). Note that this approach is not a replacement for detailed analysis work. It is intended as a thermal optimization tool for use in early design stages. The current Note assumes that heat fluxes are uniform on individual panels. A companion paper [9] addresses the problem of placing individual components within individual panels.

II. Optimization Problem

Consider a satellite panel (i.e., face) i of area A_i that receives a uniformly distributed averaged heat load from the environment $\bar{q}''_{\text{env},i}$ and dissipates energy to the surroundings via long-wave radiation. A total of n_i components is placed on each face, each with orbital-averaged power $\bar{P}_{i,j}$ $(1 \le j \le n_i)$. Therefore, each face has a total power generation from discrete component sources of $\sum_{j=1}^{n_i} \bar{P}_{i,j}$, which is assumed to be evenly distributed. Component heat gains occur on one side of the face, whereas environmental heat loads and dissipation occur on the opposite side. Assuming negligible panel thickness, a surface energy balance for the ith face yields

$$\sum_{j=1}^{n_i} \bar{P}_{i,j} + \bar{q}''_{\text{env},i} \cdot A_i = \varepsilon_i \cdot \sigma \cdot T_i^4 \cdot A_i \tag{1}$$

The goal of the present work is to isothermalize this structure, such that the temperature of each face is the same. Further, it is assumed that each face has the same optical properties. Therefore,

$$\sum_{j=1}^{n_i} \bar{P}_{i,j} + \bar{q}''_{\text{env},i} \cdot A_i = \varepsilon \cdot \sigma \cdot T^4 \cdot A_i \tag{2}$$

Consider a structure consisting of f faces. At isothermal conditions, conductive and radiative coupling between faces can be ignored. Summing Eq. (2) for all faces yields the following:

$$\sum_{i=1}^{f}\left(\sum_{j=1}^{n_i} \bar{P}_{i,j}\right) + \sum_{i=1}^{f}(\bar{q}''_{\text{env},i} \cdot A_i) = \sum_{i=1}^{f}(\varepsilon \cdot \sigma \cdot T^4 \cdot A_i) \tag{3}$$

Rearranging, Eq. (3) becomes

$$\frac{\sum_{i=1}^{f}\left(\sum_{j=1}^{n_i} \bar{P}_{i,j}\right) + \sum_{i=1}^{f}(\bar{q}''_{\text{env},i} \cdot A_i)}{\sum_{i=1}^{f} A_i} = \varepsilon \cdot \sigma \cdot T^4 \tag{4}$$

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For the kth face, Eq. (2) becomes

$$\frac{\sum_{j=1}^{n_k} \bar{P}_{k,j}}{A_k} + \bar{q}''_{\mathrm{env},k} = \varepsilon \cdot \sigma \cdot T^4 \tag{5}$$

Setting Eqs. (4) and (5) equal to one another yields

$$\frac{\sum_{j=1}^{n_k} \bar{P}_{k,j}}{A_k} + \bar{q}''_{\mathrm{env},k} = \frac{\sum_{i=1}^{f}\left(\sum_{j=1}^{n_i} \bar{P}_{i,j}\right) + \sum_{i=1}^{f}(\bar{q}''_{\mathrm{env},i} \cdot A_i)}{\sum_{i=1}^{f} A_i} \tag{6}$$

The right-hand side of Eq. (6) is an orbital-averaged heat flux for the entire satellite considering total environmental and component heat loads for all faces. Setting the right-hand side equal to $\bar{q}''_{\mathrm{gain}}$, this equation is simplified by

$$\frac{\sum_{j=1}^{n_k} \bar{P}_{k,j}}{A_k} + \bar{q}''_{\mathrm{env},k} = \bar{q}''_{\mathrm{gain}} \tag{7}$$

The left-hand side of the same equation is the average heat flux for a given face. This balance is based on an assumption of isothermality; departure from this balance will generate temperature nonuniformities across the structure. The goal of the present work is optimizing the distribution of $N = \sum_{i=1}^{f} n_i$ components over the f faces such that orbital-averaged heat flux from environmental and component sources approaches the orbital-averaged flux value of the entire satellite. That is, we want to identify the distribution of components over the discrete panels such that

$$\min\left[\sum_{i=1}^{f}\left(\bar{q}''_{\mathrm{gain}} - \left(\frac{\sum_{j=1}^{n_i} \bar{P}_{i,j}}{A_i} + \bar{q}''_{\mathrm{env},i}\right)\right)^2\right] \tag{8}$$

This optimization problem only addresses the problem of selecting panels for locating the N components and not the problem of distributing them within each panel. The latter problem is addressed in a companion paper [9]. The discrete problem represented by Eq. (8) quickly becomes unwieldy as the number of panels and components grow. The number of possible panel-component combinations is $\mathcal{O}(f^n)$. For a six-sided satellite with 36 components, this becomes $\approx 1 \cdot 10^{28}$ potential combinations. One class of methods suitable for handling this problem is that of bin-packing methods.

The problem presented here is a variable sized bin-packing problem in which bin size is proportional to face area (Fig. 1), with two significant differences. First, "overflow" (i.e., filling a bin past $\bar{q}''_{\mathrm{gain}}$) is allowed. Thermal penalties are the same if a bin is overfilled or underfilled (i.e., too hot or too cold, respectively). Second, the resulting heat flux contribution of a component is dependent upon which bin it is placed within. For example, an item placed on a larger face will yield a smaller heat flux than if it was placed on one that was smaller. As a result, power for a given component is "poured" into a given bin, as shown in Fig. 1.

The problem considered in this Note involves determining the best approach to filling bins using a discrete number of components. The solution produces the order and location of components that are poured into the bins. To solve this specific problem, a genetic algorithm (GA) approach with heuristics was developed.

Maximum fitness of the GA corresponds to the minimum of an objective function *obj*, based on environmental heat sources on each panel along with panel dimensions and component powers, as shown in Eq. (9):

$$\mathrm{obj} = \sum_{i=1}^{f}\left(\bar{q}''_{\mathrm{gain}} - \left(\frac{\sum_{j=1}^{n_i} \bar{P}_{i,j}}{A_i} + \bar{q}''_{\mathrm{env},i}\right)\right)^2 \tag{9}$$

A detailed presentation of method development can be found in Hengeveld's dissertation [10].

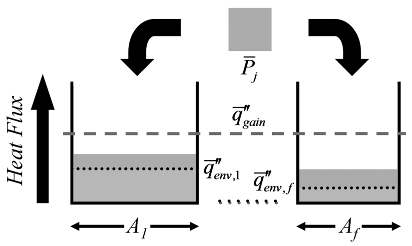

Fig. 1 Illustration of methodology.

III. Algorithm Demonstration

To demonstrate the tuned algorithm, a numerical model was developed, consistent with current robust satellite architectures [11]. A $1.0 \times 1.0 \times 1.0$ m six-sided frame-and-panel-construction satellite was used, with a honeycomb panel construction having 0.00127 m-thick Al 6061-T6 face sheets and a 0.0254 m-thick Al 5052 honeycomb material. Material properties were based on Gilmore [12]. A uniform heat flux source was placed on the interior of each panel, which represents electrical components with uniform heat flux spreading. Heat generation of all internal components was conducted to the panel only (i.e., not coupled through radiation), with a contact conductance of 110 $\mathrm{W/m^2}$-K [12]. Panel-to-panel conductance was 12 W/K, in order to simulate panel-to-panel longerons and bolted joints [13]. All heat generation was ultimately dissipated to a deep space environment (0 K) through radiation from the exterior of the panel surfaces. Exterior panel surfaces were modeled as a solar reflector ($\alpha = 0.1$ and $\varepsilon = 0.8$) for the analysis included in this Note.

The numerical model was evaluated using Thermal Desktop as a CAD-based interface to the SINDA/FLUINT finite difference thermal analyzer. As a first step, a study was conducted in order to determine the appropriate nodal resolution. Based on this effort, each panel was modeled using a 51×51 in-plane nodal resolution (i.e., 2 cm spacing between nodes). Additionally, panel-to-panel conductance was modeled using Thermal Desktop edge contactors.

To test the algorithm and evaluate results, characteristic component design cases for 18, 36, and 54 components were developed based upon Williams [14], Young [15], and a representative military satellite. Orbital parameters were based on the hot-case thermal environment detailed by Hengeveld et al. [16].

A. Examination of Algorithm Performance

Because the solution algorithm is stochastic in nature, the tuned algorithm was run 99 times in order to provide insight into any variability between runs. Results from the 99 runs are shown in Table 1. Computational requirements, on average, were approximately 12 s or less for up to 54 components over a six-sided structure using a 2.5 GHz dual-core computer. The maximum computational requirements were less than approximately 22 s for up to 54 components using the same machine. The thermal performance was also evaluated over the 99 runs. For the maximum, minimum, and median objective function results, the maximum temperature difference between components was evaluated using Thermal Desktop and summarized in Table 1. Thermal performance results varied less than 0.3 K between maximum, minimum, and median objective function values.

Optimized distributions were compared with even and worst-case distributions for the nominal component distribution for 18, 36, and 54 components in the hot-case environment [16] for 600 W of total component power. An even distribution was generated by running the optimization algorithm assuming uniform environmental fluxes on all faces. A worst-case distribution was obtained by applying all component power to the nadir facing panel. The resulting thermal performance for these cases is shown in Table 2. Performance is presented in terms of the maximum temperature difference between any two panels on the satellite. The optimized distribution provided a reduction in maximum temperature difference of 12.8 to 13.1 K over even and 84.3 to 84.9 K over worst-case component distributions. The worst-case distribution results are slightly different for the different cases, due to slight differences in total power.

Table 1 Computational time and maximum temperature difference results for optimized component distributions of 18, 36, and 54 components at 600 W of total power

	Computational time, s			Maximum temperature difference,[a] ΔK		
Number of components	Maximum	Minimum	Median	Maximum	Minimum	Median
18	4.2	0.9	1.6	8.2	7.9	8.2
36	14.1	4.2	7.0	8.0	8.1	8.1
54	22.3	11.8	12.3	8.1	8.1	8.1

[a]Based on maximum, minimum, and median objective function results.

Table 2 Results for optimized, even, and worst-case component distributions at 600 W of total power

	Maximum temperature difference, ΔK		
Number of components	Optimized distribution	Even distribution	Worst-case distribution
18	8.2	21.3	92.5
36	8.1	21.0	93.0
54	8.1	20.9	92.8

B. Effect of Increasing Component Power

A study was conducted in order to determine the effect of increasing total power on optimized results. Optimized, even, and worst-case distributions for 36 components in the hot-case orbit were found for total power of 100 up to 1200 W. Maximum and minimum panel temperatures were determined using Thermal Desktop and are shown in Fig. 2. On average, optimized component distributions reduced maximum temperatures by 5.4 K over evenly distributed components. The largest and smallest maximum temperature reductions were 8.2 K at 400 W and 2.8 K at 100 W, respectively. Optimizing component distribution increased minimum temperatures by 7.1 K, on average, over evenly distributed components. The largest and smallest temperature increases were 9.3 K at 400 W and 5.7 K at 1200 W, respectively.

The maximum temperature differences are shown in Fig. 3. On average, optimized component distributions reduced maximum temperature differences by 12.6 K over evenly distributed components. The largest and smallest maximum temperature difference reductions were 17.8 K at 400 W and 9.5 K at 100 W, respectively.

As total power increases, components were distributed in an attempt to provide equal heat flux to all faces. Consequently, more components were placed on cold faces (i.e., faces receiving the least environmental heat flux), whereas fewer components were placed on hot faces (i.e., faces receiving the most environmental heat flux). As more components (i.e., heat flux) were placed on the cold faces, cold face orbital-averaged temperatures approached those of the hot faces.

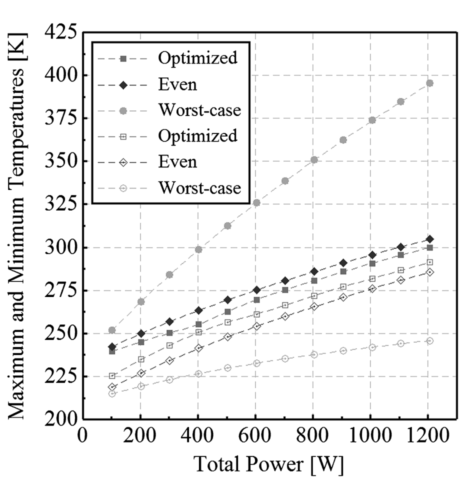

Fig. 2 Maximum and minimum temperature versus total power for optimized, even, and worst-case component distributions for 36 components in the hot-case thermal environment.

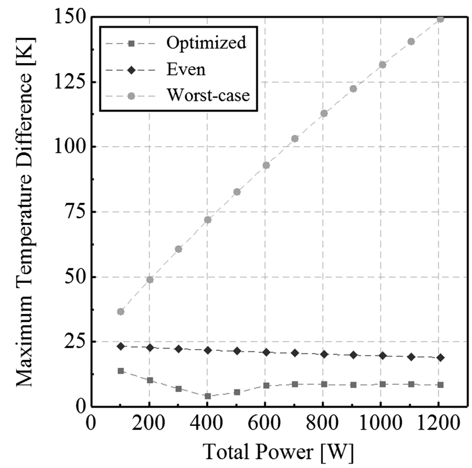

Fig. 3 Maximum temperature difference versus total power for optimized, even, and worst-case component distributions for 36 components in the hot-case thermal environment.

Although maximum temperature difference across all faces was eventually minimized (i.e., approximately 400 W in Fig. 3), orbital-averaged flux on each face was not equal at this same condition. This was due to cold and hot faces receiving most of their heat flux from components located on the inside and environmental sources on the outside of the bus, respectively. As total power increased and components were redistributed such that orbital-averaged flux on each face was nearly equal, cold face components operated slightly hotter than hot face components due to this thermal gradient. It is recommended that future study includes the effects of panel conductivity in order to improve algorithm performance.

IV. Conclusions

A computational tool was developed that provides rapidly optimized component distributions over multisided structures, each with unique environmental loading. Computational requirements are small; on average, approximately 12 s was required using a 2.5 GHz dual-core computer for 54 components over a six-sided structure. Optimized, even, and worst-case distributions for 36 components in a hot-case orbit were found for total power of 100 up to 1200 W. On average, optimized component distributions reduced maximum temperatures by 5.4 K, increased minimum temperatures by 7.1 K, and reduced maximum temperature differences by 12.6 K over evenly distributed components. The largest and smallest maximum temperature difference reductions were 17.8 K at 400 W and 9.5 K at 100 W, respectively.

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