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Research Paper

Evolutionary design of a satellite thermal control system: Real experiments for a CubeSat mission

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HIGHLIGHTS

- GAs applied to automate design of CubeSat passive thermal control system (coating).
- Simulation adapted with real physical data (mockup experiment in vacuum chamber).
- Obtained coating patterns consistently outperform engineered solutions (by 5 K).
- Evolved coating patterns are far superior (by 8 K) than unpainted aluminum.

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ABSTRACT

This paper studies the use of artificial evolution to automate the design of a satellite passive thermal control system. This type of adaptation often requires the use of computer simulations to evaluate fitness of a large number of candidate solutions. Simulations are required to be expedient and accurate so that solutions can be successfully transferred to reality. We explore a design process that involves three steps. On a first step candidate solutions (implemented as surface paint tiling patterns) are tested using a FEM model and ranked according to their quality to meet mission temperature requirements. On a second step the best individual is implemented as a real physical satellite mockup and tested inside a vacuum chamber, having light sources imitating the effect of solar light. On a third step the simulation model is adapted with data obtained during the real evaluation. These updated models can be further employed for continuing genetic search. Current differences between our simulation and our real physical setup are in the order of 1.45 K mean squared error for faces pointing toward the light source and 2.4 K mean squared errors for shadowed faces. We found that evolved tiling patterns can be 5 K below engineered patterns and 8 K below using unpainted aluminum satellite surfaces.

1. Introduction

Genetic Algorithms (GA) are a form of stochastic optimization that involves intensive evaluation of candidate solutions (in the order of hundreds or thousands evaluations). This often restricts their domain of applications to problems that can be either represented by equational models or by time-saving computer simulations. GAs are starting to be applied to automate the design of satellite subsystems. In [1,2] GAs were proposed for the problem of satellite component placement or Satellite-Module Layout Design (SMLD). Evolutionary techniques such as Artificial Embryogeny [3] and Genetic Multi-Objective Optimization [4] have been recently proposed to address this challenging design problem as well.

SMLD is an example of a complex combinatorial problem in which GA are well suited due to their capacity to broadly search for solutions in highly nonlinear search landscapes. However it is also an example of a problem where representative computer simulations can be rapidly used to assess the performance of candidate solutions. Simulating a candidate module layout design simply requires a graphical verification of modules, their spaces, geometries and interference situations. This requires a reduced computing power and it is therefore convenient in the context of genetic search.

The experience shows that when applying GA to a particular design problem one should consider both, the intrinsic complexity of the target problem to be solved as well as the computational

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Nomenclature

ε_k	the emissivity factor
A_k	surface area of tile k
σ	Stefan–Boltzmann constant
$Q_{absorbed}$	heat incident to satellite surface (W)
$Q_{emitted}$	emitted heat from satellite surface (W)
$Q_{power\text{-}generated}$	radiation generated by the onboard electronics (W)
G_{DS}	solar constant (W/m^2)
G_{IR}	earth IR (W/m^2)
α	absorption of each material
γ	angle between an imaginary ray linking the sun and the satellite
a	Albedo factor
vf	view factor
A_{SD}	area pointing toward the sun (m^2)
A_E	area pointing toward the earth (m^2)
A_{out}	area pointing toward the space (m^2)
T	temperature (K)
q_0	energy flux (W/m^2)
q_s	contribution of a highly conductive thin shell in contact with the surface (W/m^2)
h	heat transfer coefficient used for modeling low thermal conductivity between thin shell and the surface
q_r	heat transfer due to radiation (W/m^2)
G	surface radiation from the faces to the environment (W/m^2)
C_p	heat capacity for each material (J/kg K)
ρ	density (m^3/kg)
k	thermal conductivity (W/m K)
v	variables en el dominio de búsqueda V
V	search domain for simulation
P_{lamp}	lamp power (W)
$A_{vc\_BasePlate}$	area of the vacuum chamber portion perpendicular to the light emission axis (m^2)

cost of the simulation to be used for testing each candidate solution [18]. We observe that most studies have been concentrated on problems of increasing intrinsic complexity but rely on simplistic computer simulations (like SMLD). In this work we want to give a step forward by exploring the use of GA on a satellite design task that is both, intrinsically complex and also requires a costly computer simulation to evaluate candidate solutions.

We focus our attention on the satellite thermal control design task. This problem is relevant to CubeSat design since engineers are often challenged with the problem of loading small satellites with expensive pieces of equipment, each having particular thermal characteristics and temperature requirements for successful operation. The right selection of materials and the proper placement of components is a problem of exponential complexity. Classical engineering methods have been exploited to provide acceptable, yet sub-optimal, solutions. Approaching optimality in material selection and component distribution is becoming a highly important, especially as the complexity of systems increases and constrains become stronger.

Evaluating the thermal behavior of a particular candidate solution involves the execution of a complex and expensive numerical simulation. These simulations often use a mesh representing the structure of the system to be simulated and proceed by numerically solving differential equations applying either finite difference time-domain (FDTD), finite element (FEM) or moments (MoM) methods as well as a set of boundary conditions of the problem. Analytical solutions can only be found for simple geometric scenarios that are not often representative of real satellite design situations.

In this work we use GA to explore combinations of surface painting materials that can be used to meet temperature requirements of a CubeSat. The idea is to find the right distribution so that all satellite sub-systems operate within their temperature range. We verify the process with temperature measurements performed on a 3U CubeSat mockup in a real physical setup. We are situating this problem in the context of our University CubeSat program [22]. The project "Satellite of the University of Chile for Aerospace Investigation (SUCHAI)" was the seed of our program in 2011. The satellite is 1U CubeSat carrying five proof of concept experiments about microgravity, space plasma and space technologies. The CubeSat is today ready and waiting launch. The University was recently granted funds to build and launch a couple of 3U CubeSats. For our next 3U satellite we foresee that 2/3 of the area of one face will be free of solar panels to allow deployment of booms of Langmuir probes and magnetometers. This setup motivates the present thermal design study.

The remainder of this paper is organized as follows: In Section 2, we describe a literature review related to satellite thermal problem. In Section 3, we describe the thermal control problem under analysis. Section 4 shows the process for the automated thermal design. In Section 5, we describe our results. Finally, Section 6 shows the conclusions of this study.

2. Related work

There are many related studies about the problem of modeling the thermal behavior of nanosatellites. The usual approach is to define a specific satellite layout (spatial disposition of components, heat emitters and materials, etc.) and then to model the thermal behavior under space representative conditions. Table 1 summarizes the methods and results obtained by different authors that have addressed nanosatellite thermal modeling problems.

In some studies thermal models have been validated with the aid of real physical experiments [6–12]. Corpino et al. [6] proposes finite differences for modeling the thermal behavior of LEO orbit satellites. They compared results with those obtained using ESATAN-TMS modeling software. Diaz-Aguado et al. [7] studied the thermal design of FASTRAC nanosatellite under vacuum conditions. Results were compared with those obtained using FEM. Bulut and Sozbir [8] analyzed the thermal behavior of a CubeSat using FEM. They tested different solar panel configurations. However, to the best of our knowledge there are no previous methods to automate the design of a CubeSat thermal control system using evolutionary computation, in particular for passive thermal systems.

3. Satellite thermal control problem

The purpose of a thermal control system is to maintain each satellite component within its nominal temperature limits over the entire lifespan of a satellite mission. This is especially important as we consider that in space, satellites are exposed to harsh conditions that can lead to catastrophic failures.