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Energy-driven scheduling algorithm for nanosatellite energy harvesting maximization

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ABSTRACT

The number of tasks that a satellite may execute in orbit is strongly related to the amount of energy its Electrical Power System (EPS) is able to harvest and to store. The manner the stored energy is distributed within the satellite has also a great impact on the CubeSat's overall efficiency. Most CubeSat's EPS do not prioritize energy constraints in their formulation. Unlike that, this work proposes an innovative energy-driven scheduling algorithm based on energy harvesting maximization policy. The energy harvesting circuit is mathematically modeled and the solar panel I-V curves are presented for different temperature and irradiance levels. Considering the models and simulations, the scheduling algorithm is designed to keep solar panels working close to their maximum power point by triggering tasks in the appropriate form. Tasks execution affects battery voltage, which is coupled to the solar panels through a protection circuit. A software based Perturb and Observe strategy allows defining the tasks to be triggered. The scheduling algorithm is tested in FloripaSat, which is an 1U CubeSat. A test apparatus is proposed to emulate solar irradiance variation, considering the satellite movement around the Earth. Tests have been conducted to show that the scheduling algorithm improves the CubeSat energy harvesting capability by 4.48% in a three orbit experiment and up to 8.46% in a single orbit cycle in comparison with the CubeSat operating without the scheduling algorithm.

1. Introduction

Nanosatellites have become an affordable opportunity to reach the space. They are small satellites with total mass ranging from 1 to 10 kg with all the needed subsystems to satisfy a common satellite mission (including payloads). Through nanosatellites, universities may allow their students to work on real space application projects. Even small and medium size companies may have access to space technologies that until 20 years ago were mostly restricted to governmental space agencies. Presently, nanosatellites' launching ”low price” and short development time attracts space enthusiast. This growth in interest in small satellites was empowered by the CubeSat standard definition in 1999. The Stanford University and California Polytechnic State University (Cal Poly) proposed a modular 10 cm × 10 cm x 11.35 cm (1U) cubic shaped satellite intended for Low Earth Orbit (LEO) and designed mostly with commercial off-the-shelf (COTS) components. Since then, many other universities and companies around the world have been working on nanosatellites' development, testing, launching and tracking [1,2].

Motivated by the opportunity of allowing its students to work in a full space mission, the Federal University of Santa Catarina (UFSC) has started its own 1U-CubeSat development - The FloripaSat. The project's main goal is to empower undergraduate students which have been organized in the following teams: Electrical Power System (EPS), On-Board Data Handling (OBDH), Telemetry, Tracking and Command (TT&C), Attitude Determination and Control System (ADCS), Ground Station (GS), Verification and Validation (VV), Thermal Control and Structure (TCS) and Payloads (PL). The work presented in this paper has been developed in the FloripaSat EPS context.

A satellite electrical power system has three main functions: energy harvesting, energy storage and energy distribution. The EPS is a printed circuit board (PCB) which interacts with power sources (solar panels,

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thermoelectric generators, etc.), with storage units (batteries, supercapacitors, etc.) and with other satellite's subsystems (OBDH, TT&C, payload, etc.).

An ideal EPS should maximize energy extraction and manage the energy distribution to other satellite's subsystems in the most efficient manner. Mostly, these requirements conflict among each other or with other satellite subsystem's requirements. This work presents an elegant solution to maximize energy extraction only by controlling the satellite's tasks execution. Nanosatellites may be considered low power devices when compared to satellites with more than 100 kg. Therefore, the energy harvesting maximization must be addressed differently. Also, the applications for LEO nanosatellites drastically differs from the Medium Earth Orbit (MEO) and Geostationary Orbit (GEO) satellites' applications. LEO nanosatellites may not be continuously receiving solar energy, which makes the energy management highly dependent on orbit inclination. Also, nanosatellites may decay only few months after their launch, reducing mission time, which also impacts on the energy distribution strategy.

The satellite's tasks shall be somehow organized in order to accomplish the mission requirements. Since the tasks to be performed may have different priorities, execution time, resources, etc., a satellite task scheduling algorithm may be a key element to achieve a successful satellite mission. Once the scheduling algorithm may define which (and how) the satellite's tasks are going to be executed, there shall be a relation between the algorithm and the EPS, after all, tasks execution demands energy.

The satellite scheduling problem is not new. It has been formulated with a variety of perspectives, with numerous proposed solutions (Section 2). Although there are distinct manners for defining and solving problem [3–5], the goal is mostly the same: to optimize tasks execution from some perspective (maximize communication quality [6], minimize system response time [7], etc.).

As described in Section 2, most of recent satellite scheduling algorithms are not designed for nanosatellites. Besides this, none of them aims energy harvesting maximization. Energy aware task schedulers have been widely discussed for wireless sensor networks (WSN) applications [8,9]. Although some of these works focus on reducing energy consumption to extend the nodes lifetime, the problem is totally different. Most wireless sensor networks have no energy input. Also, the periodicity (both in tasks execution as in power input) imposed by the orbital motion is not verified in most WSNs. Some authors, even when considering energy harvesting embedded systems, propose algorithms based on dynamic voltage and frequency scaling technique [10]. This approach is restricted to reducing the processor power consumption only. Thus, this work tries to solve the satellite scheduling problem with a different approach for an emerging class of low power satellites.

2. Related work

The task scheduling problem in satellites is not new, referring to the late 50s and early 60s, during the Space Race, where military artificial satellites started being developed and launched. At that time, the main concern was to maximize communication time. The system factors pertinent to the scheduling problem used to be classified into three categories: satellite availability, communication requirements and quality of communication. Linear programming approach has been one of the solutions to solve a set of mathematical equations in a maximization problem. Due to the computational limitation at that time, dynamic scheduling was considered an overhead [11].

With the increasing number of launched satellites and the development of new channel access methods, the scheduling problem has become more sophisticated. For instance, scheduling algorithms have been applied to satellite systems communicating through time division multiple access (TDMA) to a channel. In this case, the proposed scheduling algorithm goal was to avoid or to reduce message conflict from ground stations when occupying a time slot. Also, the idea was to minimize the assignment procedure to shorten assignment time delay [12]. No power constraint is mentioned in this solution.

Later, scheduling techniques have been applied to Earth Observing Satellites (EOS). Some of these works considered energy constraints in their scheduling algorithms. The Landsat 7 from National Aeronautics and Space Administration (NASA), for instance, implemented the so-called duty cycle constraint. A sensor should be limited to its operating time for a given period [13]. For the Landsat 7 a sensor should not be used for more than:

1. 34 min in any 100 min period,
2. 52 min in any 200 min period, or
3. 131 min in any 600 min period.

Since there is a correlation between the time the sensor is turned on and its power consumption, this can be considered an energy constraint. However, none of the evaluated algorithms solve the scheduling problem to reduce power consumption but to maximize the number of collected images from Earth.

An innovative work has considered fault-tolerant and real-time aspects to solve the task scheduling problem for multiple observation satellites [14]. In this innovative approach, the authors adopt the replication concept to ensure that a designated task is going to be executed. For this, they assume that a task primary copy is successfully allocated only if its corresponding task backup copy can be scheduled in another satellite. Otherwise, the primary copy shall be canceled. Even if one of the satellites fails in executing the task, the other one is able to execute it. Although the scheduling problem is rigorously well defined through a set of equations and assumptions that ensure the good performance of the algorithm, this work also does not mention power constraints or energy efficiency optimization.

Some recent works have been developed on solving the issue of ground station-satellite communication on multi-satellite missions. This problem also may be solved using scheduling algorithms. Recent ideas have emerged as applying mutation concepts of genetic algorithms to meet computation time and success rate mission requirements on satellite communication. Hybrid Dynamic Mutation has demonstrated outstanding performance in terms of speed and reliability when compared with other mutation strategies [15]. Although both algorithm have proved to be efficient they are focused on the ground station side. They do not consider the satellite tasks management nor its energy consumption impact on mission accomplishment.

A dynamic scheduling approach is proposed by Wang *et al.* for emergency tasks on distributed imaging satellites (a satellite constellation for imaging proposes). The authors defined a multi-objective mathematical programming model that contains five objects: tasks, resources, available opportunities, operational constraints and objectives [5]. Energy consumption minimization is classified as one of the scheduling objectives. The authors present a so-called merging tasks technique, which allows tasks being executed simultaneously, reducing energy consumption in comparison with other algorithms. However, authors state that the scheduling main goal is to maximize the priorities