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Optimization strategies for a 16U CubeSat mission

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Abstract. The surge in small satellite and CubeSat deployments has led to a diversification of feasible missions, driving a shift from emphasizing simplicity and low-cost to prioritizing performance while maintaining cost-efficiency. Integration of small payloads and advancements in technology have enhanced CubeSat capabilities, enabling the development of high-performance platforms. EXCITE, a 16U CubeSat mission, will demonstrate five different technologies in the LEO environment, including propulsion systems, a reconfigurable antenna, and on-board processing capabilities. To maximize EXCITE's capabilities and accommodate diverse payloads for various mission scenarios, multiple optimization strategies have been implemented. This includes thorough orbit analysis to determine the most suitable orbit for mission objectives, considering factors such as beta angles and eclipse time. The use of a chemical thruster provides flexibility in mission design by allowing adjustments to orbital altitude and ground-track patterns. Additionally, careful scheduling of orbital maneuvers is crucial for maximizing access time to specific ground stations and optimizing data downlink opportunities. Managing complex interactions between design variables necessitates advanced optimization techniques like gradient-based algorithms. OpenMDAO offers a robust framework for tackling multidisciplinary design optimization problems efficiently, facilitating exploration of trade-offs between competing design objectives.

Introduction

In recent years, there has been a remarkable surge in the deployment of small satellites and CubeSats into orbit annually. This proliferation has naturally expanded the variety of feasible missions achievable with these spacecrafts, encompassing in-orbit demonstrations, remote sensing, and scientific experimentation. Consequently, there has been a growing demand for improved performance across various aspects such as pointing accuracy, power generation, and data downloading [1]. This evolving demand has prompted a departure from the original attributes of CubeSat projects, which emphasized simplicity, low-cost, and high-risk, towards a new paradigm that prioritizes performance while still maintaining cost-efficiency.

Moreover, the compact nature of CubeSats, combined with advancements in technology, has enabled the integration of small payloads [2]. This addition further enhances the capabilities of CubeSats as IOD/IOV platforms, eventually equipped with propulsion systems which extend the possible mission design options [3]. Following this trend, a 16 U Cubesat mission named EXCITE has been developed by a collaborative effort led by the University of Pisa and four SMEs based in the Tuscany region: CRM Compositi, MBI, IngeniArs and Aerospazio Tecnologie. EXCITE will host 5 different technologies for Cubesat to be demonstrated in the LEO environment:

- *(CHIPS) Green monopropellant thruster*: a hydrogen peroxide propulsion system capable of performing moderate delta-V manoeuvres on a Cubesat, under development at UniPi.

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- *(PPT) Pulsed plasma thruster*: a miniaturized electric thruster from Aerospazio Tecnologie S.r.l., capable of delivering very low impulse bits, for proximity operations or fine attitude control.
- *(REISAN) Reconfigurable integrated S-band antenna*: an electronically steerable antenna based on exciters distributed on suitable spacecraft surfaces, developed at UniPi.
- *(IoT-GPU) Internet-of-things GPU demodulator*: a technology by MBI S.r.l, based on the utilization of a COTS GPU for on-board processing of advanced IoT waveforms and VDES protocol.
- *(PHP) Pulsating heat pipes*: high throughput heat pipes under development at UniPi, based on unsteady fluid flow, especially suited for high heat flux applications (e.g., thermal management of high-power microsatellites).

Optimization Strategies

Since its early development, our focus has been on transforming EXCITE into a high-performance platform, driving us to implement multiple optimization strategies. Our goal is to maximize its capabilities and accommodate various payloads for diverse mission scenarios.

To address this process, we conducted a thorough analysis of potential orbits for the mission. Given its dimensions, EXCITE is likely to be hosted as a secondary payload on a VEGA-C launcher and placed into a Sun-Synchronous Orbit at approximately 550 km altitude. Such orbits are ideal for Earth Observation and provide global coverage [4].

However, the nature of Sun-Synchronous Orbits introduces considerations regarding beta angles, which significantly impact power generation and eclipse time. There are two extreme cases in this sense: dawn-dusk orbits, where the satellite traverses the termination line, minimizing eclipse time, and noon-midnight orbits, where eclipse time is maximal. Each option has its advantages and drawbacks. While no eclipse maximizes power production from solar panels, it may pose thermal management challenges. Conversely, a longer eclipse creates a dynamic thermal environment and reduces power production per orbit. Anyway, most SSO satellites for Earth observation are placed into orbits with a local time of ascending node (LTAN) around 10 A.M or 2 P.M [5]. This is optimal for having not too long shadows and good illumination conditions.

Considering EXCITE's role as a secondary payload, our spacecraft design must account for all possible Right Ascension of the Ascending Node (RAAN) values in which we could be deployed, which in turn will affect the eclipse time, as shown in Figure 1.

The possibility for EXCITE to use a chemical thruster gives us lots of possibilities regarding the mission design. In particular, by using the thruster to lower or elevate the orbital altitude it is possible to obtain different ground-track patterns. Figure 2 shows how orbits with periods which are dividers of a daytime, have repeated ground track patterns, and are suitable for example to fly over specific targets every day at the same hour, while different altitudes provide better coverage over a region for interest, for example the North of Italy. This proves how a propulsion system on a Cubesat improves the mission design flexibility and also provides adjustability to any orbit insertion error after the deployment of the satellite [6]. For this reason, the amount of propellant and the orbital maneuvers schedule will be crucial design variables for the optimization of EXCITE.

Furthermore, the scheduling of orbital maneuvers is essential for maximizing access time on specific ground stations. By carefully planning and executing maneuvers, the CubeSat can align its ground track with the desired ground station passes, thereby maximizing communication windows and data downlink opportunities.

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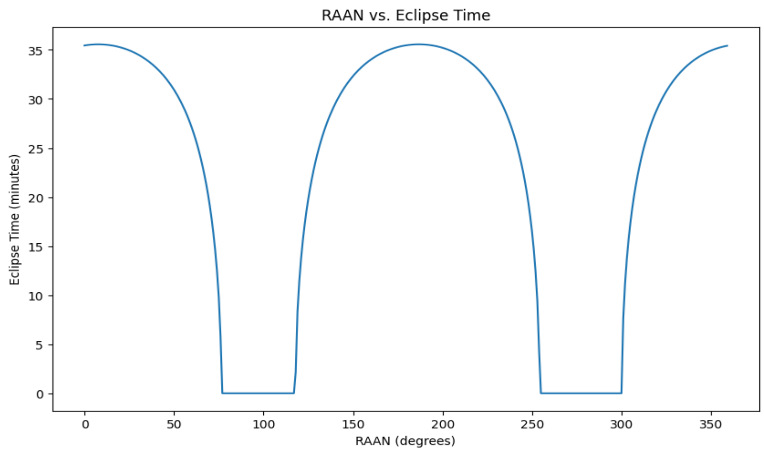

Figure 1: Eclipse time vs RAAN for a Sun-Synchronous Orbit at 550 km altitude

For example, using the CHIPS propulsion system, assuming 1 kg of propellant mass, it will be possible to perform a Hohmann transfer from 550 km altitude to 500 km, using about 40% of total propellant mass. Then the rest of the propellant might be used to compensate the drag losses, extending the mission duration, or for a faster de-orbit at the end of the spacecraft lifetime.

Thermal management is another critical aspect of mission optimization, ensuring that onboard systems operate within their specified temperature ranges for optimal performance. This is nowadays of great interest among small satellite manufacturers because, with higher available power on-board, thermal management for highly integrated and compact platforms has become difficult. Pulsating Heat Pipes (PHP) installed on-board of EXCITE will dispose of the heat building up on the body-mounted solar panel. Compared with other two-phase passive thermal devices, such as conventional heat pipes and loop heat pipes , PHPs have many advantages, including having a simple construction, being lightweight and flexible, and having no internal wick structure. Moreover, they can be embedded inside the composites structure of the Cubesat. For this reason, their layout is also a factor to be considered in optimization.

Power production, orbit changes schedule, thermal management, and the design of the composites structure of EXCITE will have a huge impact on the attitude control system, both on the design and operations schedule.

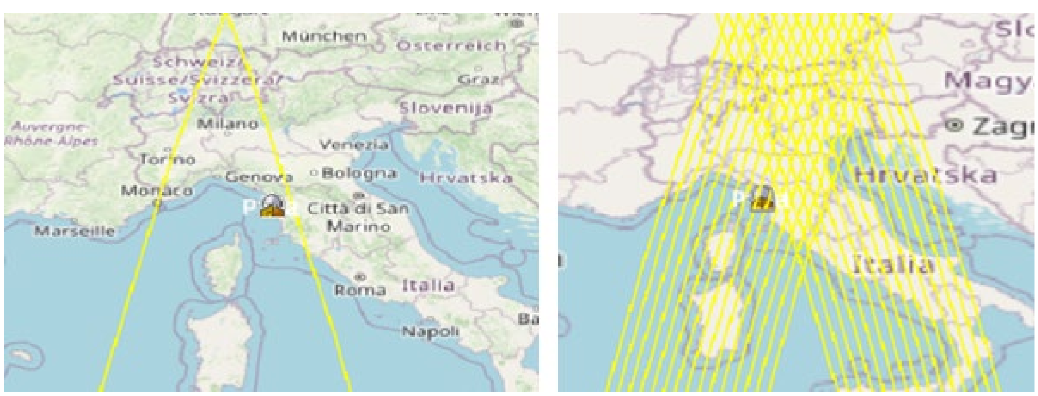

Figure 2: Ground Tracks over Italy propagated for 15 days at altitudes of 555 km (left) and 570 km (right). The tracks on the left image overlap.

Finding an optimal design for a system with so many highly coupled design variables result in a non-trivial mathematical problem. Managing such a high-dimensional optimization problem effectively requires advanced optimization techniques capable of handling large-scale, multidisciplinary design optimization (MDO) problems. Due to this fact, we are considering gradient-based algorithms, such as those provided by OpenMDAO (Open-source

Multidisciplinary Design Analysis and Optimization) [7] that offers a robust framework for tackling such optimization challenges. By leveraging gradients or derivatives of the objective function and constraints with respect to the design variables, gradient-based algorithms can efficiently navigate the design space to identify optimal solutions. This approach enables faster convergence to high-quality solutions and facilitates the exploration of trade-offs between competing design objectives.

Conclusions

Due to the diversity that EXCITE, and IOD Cubesats in general can accommodate, thorough optimization strategies, encompassing orbit analysis, propulsion system utilization, and thermal management, are crucial for maximizing mission effectiveness. Advanced optimization techniques, such as gradient-based algorithms offered by OpenMDAO, play a pivotal role in navigating the complex interplay of design variables and achieving optimal solutions. Ultimately, EXCITE serves as a testament to the integration of cutting-edge technologies and optimization methodologies, ensuring efficient and effective mission outcomes in the dynamic realm of small satellites design.

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