Design and challenges of an IOD/IOV 12U Cubesat mission

Matteo Gemignani[1,a] *

[1]Dept. of Civil and Industrial Engineering, University di Pisa, Italy

[a]matteo.gemignani@phd.unipi.it

Keywords: CubeSats, Propulsion, Demonstration, Validation

Abstract. EXCITE (“EXtended Cubesat for Innovative Technology Experiments”) is a technology demonstration mission selected by ASI in 2021 in the frame of the "Future Cubesat Missions" call. Based on a custom-designed 12U CubeSat platform featuring a full-composite structure, EXCITE is aimed at in-orbit demonstration / in-orbit validation of a number of innovative small spacecraft technologies in the domains of chemical and electric onboard propulsion, thermal management of significant heat loads in limited volumes, COTS GPU computing for IoT applications, and steerable, integrated S-band antennas. In this paper we describe the EXCITE platform design, outline the main expected technological innovations, and discuss the possible methodologies for a multi-disciplinary optimization approach.

Introduction and Background

Recent years have seen an exponential increase in the quantity of small satellites and CubeSats launched into orbit each year. As a natural consequence, the variety of types of missions that can be performed with these spacecrafts, such as in-orbit demonstrations, remote sensing, or scientific experimentation, has also grown [1]. This variety led to an increasing demand for enhanced performance, for instance, relatively to pointing accuracy, power generation, and data downloading. Thanks to this increased performance requirements, CubeSat project design is gradually detaching from its original attributes, such as simplicity, low-cost and high-risk, going towards a new philosophy which is more performance oriented, but still cost-efficient. With this background and this demands, new challenges emerged for the design and project strategies for CubeSats, in particular regarding optimization techniques, which until now were mostly devoted to large scale projects [2].

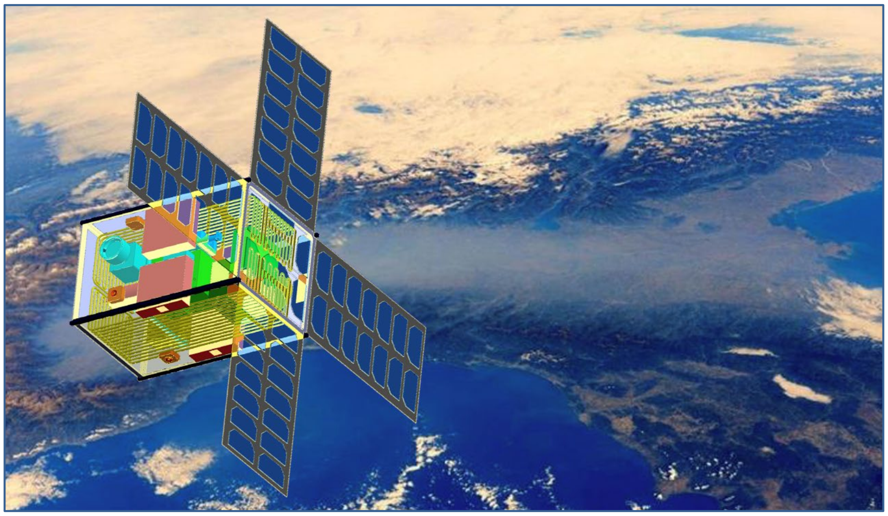


Figure 1: The EXCITE 12U Cubesat

In the frame of this context, in this paper a 12U CubeSat mission named EXCITE ("EXtended Cubesat for Innovative Technology Experiments") (Fig. 1) for in orbit demonstration/validation is presented, illustrating its main technological challenges, with a focus on optimization strategies that can be adopted in order to maximize the performance of this platform.

The EXCITE mission is jointly developed by a team including the University of Pisa as team leader. The proposal was submitted in 2020 in response to the Italian Space Agency's "Call for Future CubeSat Missions" and was selected for funding. The mission proposal was prepared in late 2020 in response to ASI's call for Future Cubesat Missions and was selected in 2021. Four SMEs based in the Tuscany region act as industrial partners: Aerospazio Tecnologie, a small company of the Siena/Livorno area with a strong background in space propulsion and testing; CRM Compositi, a structural workshop specialized in composite materials in Livorno; IngeniArs, a spin-off company of UniPi, dedicated to space electronics; and MBI, a telecom company located in Pisa, active in satellite telecommunications and networking. The consortium is a working example of a regional-scale initiative leveraging on Cubesat technology for local development. Activities will start in mid-2023 in the frame of ASI's Alcor programme [3], with flight planned for 2026.

Mission Overview

The project concerns the IOD/IOV of five innovative technologies:

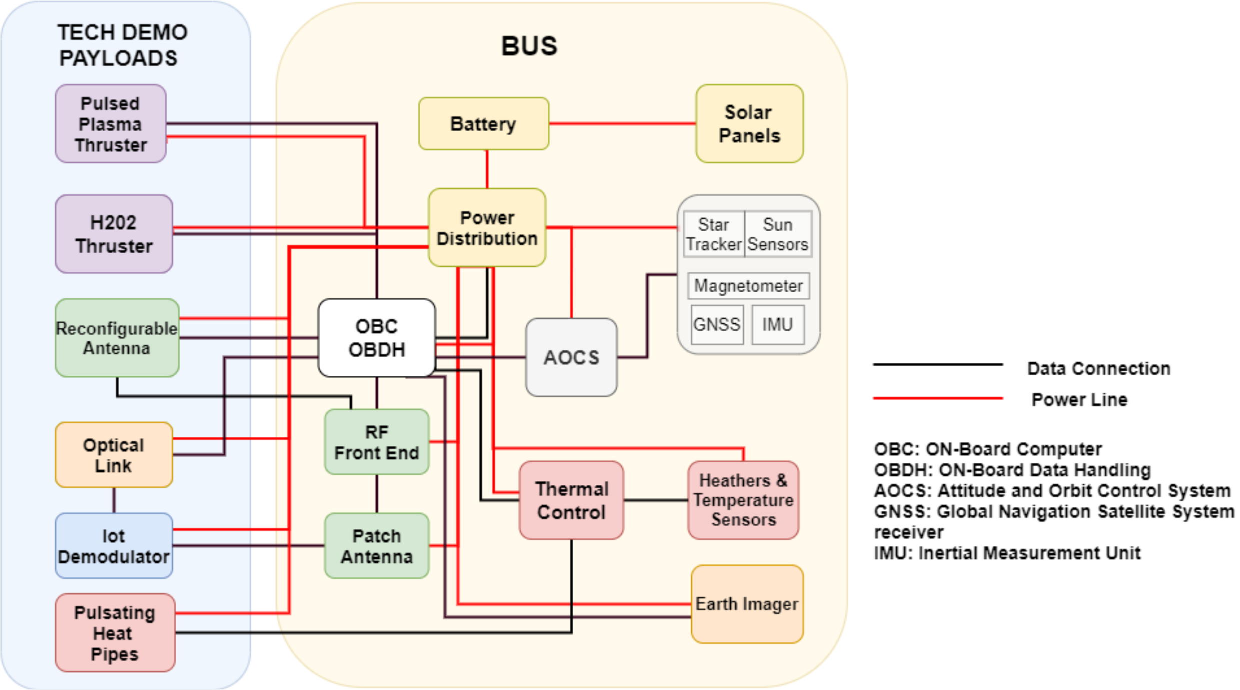
- *Green monopropellant thruster*: a hydrogen peroxide propulsion system capable of performing moderate delta-V manoeuvres on a Cubesat, under development at UniPi [4].
- *Pulsed plasma thruster*: a miniaturized electric thruster from Aerospazio Tecnologie S.r.l., capable of delivering very low impulse bits, for proximity operations or fine attitude control.
- *Reconfigurable integrated S-band antenna*: an electronically steerable antenna based on exciters distributed on suitable spacecraft surfaces, developed at UniPi [5].
- *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.
- *Pulsating heat pipes*: high throughput heat pipes under development at UniPi [6], based on unsteady fluid flow, especially suited for high heat flux applications (e.g., thermal management of high-power microsatellites).

The mission has the following additional objectives:

- To develop a high-performance 12U bus equipped with deployable solar panels.
- To integrate a commercial optical sensor as an onboard source of a data stream representative of real applications.
- To set-up a ground station at UniPi to be used for satellite operations but also as a valuable teaching tool.

Two of the experiments hosted on EXCITE belong to the IOV category (chemical and electric propulsion); the other three are extended scope IOD experiments (pulsating heat pipes, IoT GPU demodulator, reconfigurable integrated antenna).

The mission is based on a 12U CubeSat platform featuring a full-composite structure, deployable solar panels, 3-axes attitude control, and S-band telecommunications. Some of the subsystems (Fig. 2) will be procured on the commercial market as COTS, while some high performance, critical elements (power generation, thermal control, structure and deployables) will be entirely designed and manufactured by the EXCITE team.



OBC: ON-Board Computer
OBDH: ON-Board Data Handling
AOCS: Attitude and Orbit Control System
GNSS: Global Navigation Satellite System receiver
IMU: Inertial Measurement Unit

Figure 2: EXCITE Functional Block Diagram

A Sun-synchronous, 550 km Earth orbit is assumed as the baseline operational environment of EXCITE. The mission can however easily be adapted to different LEO locations, should a convenient flight opportunity arise. This provides ample flexibility in the choice of launch opportunities. Considering the relatively low ballistic coefficient of the platform when solar panels are deployed, de-orbit will occur naturally form the chosen orbit within the 25 years term mandated by the international debris mitigation guidelines. It is additionally foreseen to perform the last chemical thruster burn in such a way as to lower the orbital attitude and further accelerate re-entry. Space-qualified COTS will be used for the platform subsystems wherever possible, but the EXCITE mission will also provide an opportunity to develop and use operationally a number of advanced microsatellite bus technologies that are already under development at UniPi and partners:

- The structure will be made of carbon composite materials. This will allow for mass reduction with respect to metallic frames and to the possibility to build custom layers into the composite structure, e.g. for the Reconfigurable Antenna experiment.
- Deployable solar panels (Fig. 4) will be designed, manufactured, and integrated using the same composite manufacturing techniques as for the spacecraft body, integrating Shape Memory Alloy actuators developed at UniPi.
- Thermal control, a critical issue in such a high-power, small volume bus, will integrate with the PHP experiment.

Payload Demonstrations

The H2O2 propulsion system occupies a volume of about 2U, including a propellant mass of about 2 kg. The demonstration maneuvers are designed to change different orbital parameters in a sensible way, demonstrating both in-plane and out-of-plane maneuvers, while deviating minimally from the nominal flight trajectory. Starting from the nominal orbit at 550 km, the maneuvers envisaged are as follows:

1. apogee lowering to 500 km. The required consumption is about 22% of the initial propellant mass equivalent to 27 m/s of ΔV.
2. apogee raising back to 550 km; propellant consumption and ΔV approximately as before.
3. change of RAAN by 0.5 degrees; the maneuver is best performed providing a 65 m/s ΔV by firing at argument of latitude almost equal to 90 degrees, for a 50% propellant consumption.
4. the remaining propellant is used for the final de-orbiting maneuvering phase.

The PPT tests are designed to demonstrate the capability to carry out precision maneuvers. Four independent thrusters will be installed on EXCITE (Fig. 3), so to have the possibility to generate either pure thrust or pure torque by selecting thrusters in pairs.

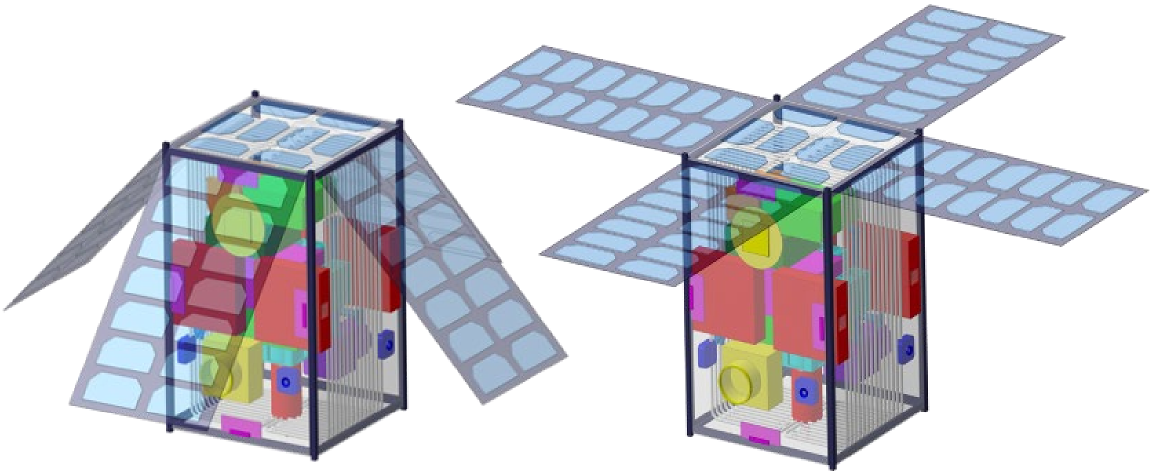


Figure 3: Solar panels deployment sequence

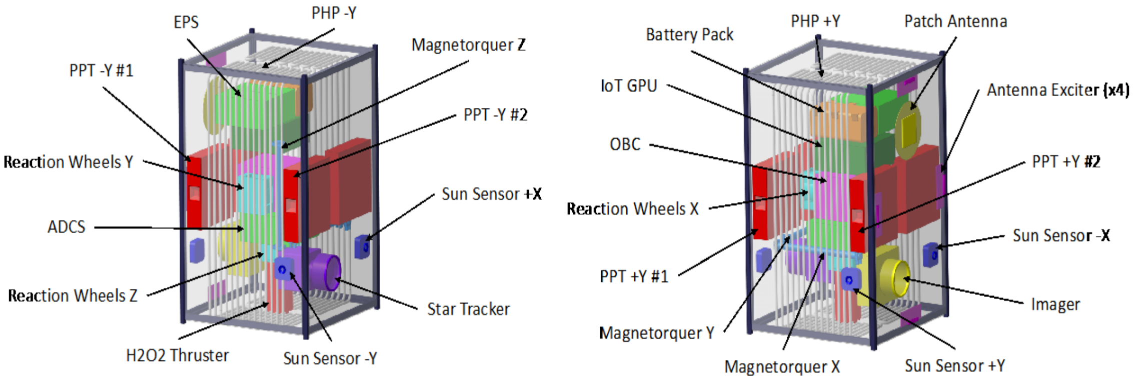


Figure 4: Schematics of the subsystem arrangement inside EXCITE

It is envisioned to perform three experiments:

1. validate the use of PPTs to control the attitude of the satellite in one axis , by spinning up the satellite using a pair of thrusters pairs on opposite sides of the spacecraft body. The burns last 5 minutes in order to reach a spin rate of about 0.8 deg/s. The resulting angular rate measured by the AOCS sensors provides a measure of the impulse delivered. The opposite pairs of thrusters are then fired to spin the spacecraft back to zero angular speed.
2. provide off-loading capabilities of reaction wheels of the on-board 3-axis AOCS, by momentarily taking over the task of the magnetorquers to provide de-saturation torque to the reaction wheel assembly.
3. provide translational thrust, needed e.g. for precise proximity operations (rendez-vous, close formation control), by firing thrusters on the same side of the spacecraft. In the latter case, the spacecraft orientation will be set so to have the thrusters oriented along the orbital velocity direction. Firing for a few minutes at nominal rate (1 Hz) and impulse bit (40 μN s) will provide enough delta-V to change orbital altitude by a few tens of meters, a change that can be easily detected by the onboard GNSS sensors.

The PHP experiment is totally passive; it will automatically start as soon as proper thermal conditions are established, which will occur almost immediately after acquisition of the nominal Sun pointing attitude and deployment of the solar panels.

Regarding the GPU demodulator**,** various demonstration activities will be performed:

1. generic utilization of the GPU for onboard data processing, anytime during flight.
2. a designed IoT signal is transmitted by MBI's IoT ground terminal when EXCITE is passing within its visibility area. In particular, an innovative spread-spectrum waveform named IURA (IoT Universal Radio Access) will be used. The signal collected by on-board telecommunication hardware is demodulated and stored by the GPU.
3. during a generic orbit, S-Band I+Q samples from different world areas are collected by the RF front-end radio, recorded by the GPU and processed onboard.
4. when the spacecraft is in view of the mission's ground station, or of another suitable receiving station located elsewhere, the GPU generates a Continuous Wave (CW) signal in S-band that is broadcast by the RF front-end. The receiving ground terminals can perform a detailed analysis of the received beacon for performance assessment and for additional auxiliary scientific purposes.

The reconfigurable antenna will be tested by rotating the spacecraft to different attitude angles with respect to the ground station and measuring the strength of the received signal. The experiment can be performed anytime, provided visibility with the GS is ensured and the instantaneous power balance on board allows for the RF front end operation. On basis of future risk analysis results, the telecommunication activities can be arranged to perform combined IoT GPU - ReconfAntenna experiments.

Challenges and Optimization

EXCITE's mission philosophy is to provide affordable, effective in-orbit technology demonstrations by making use of COTS, wherever possible, but also dedicated developed hardware, while maintaining adequate best practices in documentation, product/mission assurance, verification, and testing, balancing the need for rigorous space project management with the limited resources of a Cubesat programme. In order to achieve such an ambitious goal, some points in the "traditional" approach to CubeSat need to be abandoned: for example, for this mission design we are going to give up the modularity of the CubeSats, preserving the 12U form factor but using the entire internal volume of the satellite for an integration that maximizes the space available for payloads for the eventual reuse of this platform as a test bed for innovative satellite technologies. The final goal is to develop new methodologies by merging optimization techniques in order to achieve an optimal design for the EXCITE mission. But first, it is important to clearly state which mission aspects has to be optimized.

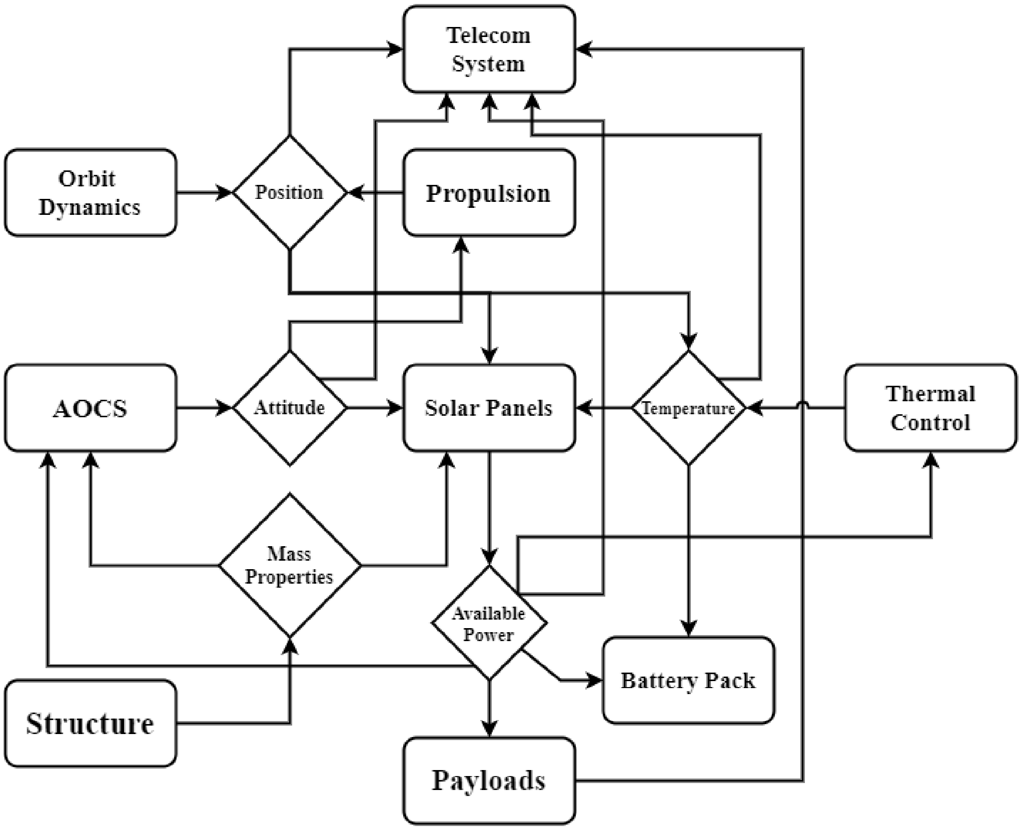


Figure 5: Schematics of the coupling between subsystems and parameters

For a space mission in general, the problem of optimization is never driven by a single objective but, rather, by a set of objectives that concur to achieve the mission statement most efficiently. In this case, validate the 5 embarked experiments so as to elevate their TRL. For this reason, the first step, as part of the design process will be to develop an opportune objective function. This objective function will be a sum of subfunctions each specifically tailored to the type of experimentation to be done on the relevant payload technology. For example, for the hydrogen peroxide engine, the success of the mission will depend crucially on the accuracy with which it can perform the scheduled maneuvers, while for the PhPs it will be the degree of efficiency in heat dissipation. Moreover, the success of the mission will depend on the total duration of the payload functionality. This objective function definition will be definitely a complex task to undergo, and will be affected also by the schedule of the mission operations that will essentially define the sequence of experiments.

Of course, the performance of the technologies will be affected by the degree of optimization of the overall platform, therefore in the sense of maximum available power, maximum achievable data rate, spacecraft agility and precise pointing. EXCITE is expected to generate a considerable amount of data, but the quantity that the communication system can send to the ground station is dependent on the amount of power this system has available to use. In general, the more power provided by the photovoltaic array and battery, the more data can be transmitted. Furthermore, if the ground station antenna is aligned with the satellite antenna, more data can be transferred with less power. However, to align the satellite antenna, attitude operation is required and, sometimes, the actuator power spent in aligning the antenna is more than the power used by communicating without the alignment. The attitude with respect to the Sun during an orbit will affect the Cubesat temperature, that in turn will affect the solar panels' efficiency and battery duration.

Is therefore self-evident (Fig. 5) how the coupling between disciplines in a spacecraft leads to the necessity of using multi-disciplinary optimization to maximize performances.

There are many optimization techniques, widely used in spacecraft engineering, that account for single discipline optimization (SDO). One typical characteristic of SDO is the usage of gradient-free optimization with indifferentiable design variables that originate from detailed modelling. The detailed and complex modelling often includes discrete or indifferentiable variables that cannot be handled with gradient-based optimization. These variables can only be handled with gradient-free optimization such as Genetic Algorithm (GA) or Particle Swarm Optimization (PSO). Hence, many single discipline optimization researches focus on gradient-free optimization Another characteristic is that most SDO applications have a small number of design variables because the gradient-free optimizer cannot handle a large number of design variables. Even with the gradient-based optimization, the number of design variables is less than 100 due to the limited characteristic posed by a "single" discipline. Many aerospace system designers have applied multidisciplinary approaches to their system design projects. However, most MDO efforts have focused on the design of aircraft structures and space launch vehicles, and very little work has considered the MDO application to the space system with complex constraints, such as a small satellite. Gradient-based methodologies will be probably most suited for this particular case, because for these methods the number of function evaluations is nearly constant with respect of an increase of design variables, while for gradient-free methods the number of function evaluations grows exponentially. Therefore one of the biggest challenges of such an approach will be the development of differentiable models that would allow the usage for derivative-based optimization, in order to have reasonable computational times.

Conclusions

An introduction and an overview of the EXCITE mission has been presented. The main technical challenges related to the demonstration of 5 technological demonstration/validation experiments have been reported together with a possible schedule for the operations. The optimization problem for such a platform has been discussed, with a focus on how disciplines related to different spacecraft systems are strongly coupled in space missions and will be of special importance in a high integrated, compact, high power CubeSat such as EXCITE. Moreover, the performance of the mission will be strictly related to the In-orbit demonstration of the payloads, therefore to the spacecraft operations schedule which will be considered in the optimization formulation.

For this reason, in order to maximize the overall performance, a multi-disciplinary approach that unifies the design and the operations will be adopted. On the other hand, the complexity and the computational cost of such an approach will have to be evaluated and justified in terms of the expected gains with respect to more traditional design philosophies.

References

[1] Bryce and Space Technology, SmallSat by the Numbers, 2022, https://brycetech.com/reports/report-documents/Bryce_Smallsats_2022.pdf

[2] B. Yost, S. Weston, State-of-the-Art: Small Spacecraft Technology, 2022. https://ntrs.nasa.gov/citations/20220018058

[3] EXCITE (EXtended Cubesat for Innovative Technology Experiments) https://www.asi.it/tecnologia-ingegneria-micro-e-nanosatelliti/micro-e-nanosatelliti/il-programma-alcor/excite/

[4] A. Pasini, L. Sales, E. Puccinelli, L.Lin, A. Apollonio, R. Simi, G. Brotini, L. d’Agostino, Design of an Affordable Hydrogen Peroxide Propulsion System for CubeSats, AIAA 2021-3690. *AIAA Propulsion and Energy 2021 Forum*, 2021. https://doi.org/10.2514/6.2021-3690

[5] S. Genovesi, F. A. Dicandia, Characteristic Mode Analysis for the Design of Nanosatellite Reconfigurable Antennas, 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-3. https://doi.org/10.23919/EuCAP48036.2020.9135534

[6] M, Mameli, A. Catarsi, D. Mangini, L. Pietrasanta, N. Michè, M. Marengo, P. Di Marco, S. Filippeschi, Start-up in microgravity and local thermodynamic states of a hybrid loop thermosyphon/pulsating heat pipe, Applied Thermal Engineering, Volume 158, 2019, 113771,ISSN 1359-4311. https://doi.org/10.1016/j.applthermaleng.2019.113771