Available online at www.sciencedirect.com

ScienceDirect

IFAC Papers Online
CONFERENCE PAPER ARCHIVE

IFAC PapersOnLine 58-16 (2024) 1–5

The EXTREMA Thruster-In-The-Loop Experiment: a facility for hands-on testing of spacecraft guidance algorithms ⋆

Alessandro Morselli * **Francesco Topputo** **

* *Dept. of Aerospace Science and Technology, Politecnico di Milano,*
Via La Masa 34, 20156 Milano, Italy (e-mail:
alessandro.morselli@polimi.it).
** *Dept. of Aerospace Science and Technology, Politecnico di Milano,*
Via La Masa 34, 20156 Milano, Italy (e-mail:
francesco.topputo@polimi.it)

Abstract: The EXTREMA THruster-In-the-Loop Experiment (ETHILE) is a facility designed for testing the effectiveness and robustness of spacecraft guidance algorithms through hardware actuation. Initially designed to simulate in an accelerated framework the actuation of interplanetary transfers with low-thrust, the system is highly configurable as it can simulate different thruster behaviours with a thruster balance equipped with a compressed air nozzle. An overview of the system and its performance is given, highlighting through a practical example its possible use for research and educational purposes.

Copyright © 2024 The Authors. This is an open access article under the CC BY-NC-ND license (https://creativecommons.org/licenses/by-nc-nd/4.0/)

Keywords: Hardware-in-the-loop simulation, Guidance, navigation and control of satellites, Embedded computer control systems and applications, Autonomous systems, Micro-nano-satellites.

---

1. INTRODUCTION

Over the past twenty years, CubeSats have revolutionized space access, making low-Earth orbit missions more and more affordable and enabling new actors. This trend is expected to extend to interplanetary missions: NASA's MarCO CubeSats (Schoolcraft et al., 2017) were released near Mars in 2018 and missions concepts like M-ARGO (Walker et al., 2017; Topputo et al., 2021) are currently under study. However, deep space exploration with miniaturized satellites is impacted by ground-based operations since these missions are operated like standard, monolithic spacecraft, hence requiring costly human oversight. Additionally, the availability of antenna time for communication with interplanetary probes is extremely limited since the deep space networks are close to saturation. These limitations are hampering the spread of CubeSats in outer space.

The Engineering Extremely Rare Events in Astrodynamics for Deep-Space Missions in Autonomy (EXTREMA) project aims to enable autonomous CubeSats for deep-space missions, reducing ground control reliance. Funded by an European Research Council (ERC) Consolidator Grant, the project focuses on three Pillars: Autonomous Navigation, Guidance and Control, and Ballistic Capture. These areas involve experiments with hardware mimicking current CubeSat capabilities, using a distributed flatsat system (Di Domenico et al., 2023).

Pillar II of the project seeks to develop a lightweight guidance algorithm for autonomous thrust profiling. To validate this, hardware-in-the-loop simulations are being performed through a dedicated facility at the DART lab of Politecnico di Milano: the EXTREMA THruster-In-the-Loop Experiment (ETHILE) simulates low-thrust propulsion in an accelerated framework (Morselli et al., 2022). As the objective is to assess autonomous Guidance, Navigation and Control (GNC) capabilities of deep-space CubeSats, these algorithms are embedded and executed on relevant hardware (i.e., with performances and capabilities in-line with the ones nowadays available for such satellites).

ETHILE is integrated in the EXTREMA Simulation Hub (ESH), a complete infrastructure which is composed of a *distributed flatsat* (a hardware representation of the satellite subsystem, including the on-board computer), a navigation facility (that simulates on high-definition screens a realistic scene as observed from the satellite and is equipped with actual cameras for image acquisition), an attitude simulator, and a workstation which is orchestrating the whole simulation execution. The ESH will allow the validation of interplanetary transfers to near-Earth asteroids or to planets, the latter exploiting ballistic capture corridors to cope with the limited control authority of CubeSats.

While designed to perform testing and validation of algorithms to demonstrate autonomous guidance and navigation capabilities for interplanetary CubeSats, the ESH has also proved to be suitable for educational purposes. In this work we provide an overview of such educational cases and a few possible future educational applications.

⋆ This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 864697).

2405-8963 Copyright © 2024 The Authors. This is an open access article under the CC BY-NC-ND license.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2024.08.452

This article is organized as follows: first an overview of the ETHILE facility is provided in Section 2 while in Section 3 the experimental approach used for testing and validation of guidance algorithm is given. Section 4 describes the possible experimental activities that could be performed during master thesis works, highlighting the achievable educational objectives and some possible future activities. Finally, some final remarks and conclusions are provided in Section 5.

2. ETHILE FACILITY OVERVIEW

The facility ETHILE is designed to allow the execution of thrust commands, obtained by means of trajectory optimization algorithm using a pneumatic line fed with compressed air. The thrust command can be obtained both by direct and indirect methods providing fuel optimal solutions which are therefore characterized by alternated thrust and coast arcs (Morelli et al., 2024; Mannocchi et al., 2022). The magnitude of the thrust force has to vary throughout the simulation since it is connected with the available power, which is dependent from the Sun's distance. For this reason it is not possible to just fix a predefined pressure level but it is necessary to regulate and adapt the pressure level.

The thrust test bench is composed of three parts:

(a) the *thrust balance*, where the thruster and the load cell are positioned;
(b) the *pneumatics feeding system*, which provides compressed air at the required pressure level to the thruster;
(c) the *Single-Board Computer (SBC)*, which computes the optimized trajectory, applies the scaling, and actuates the thruster by acting on the solenoid valve and pressure regulators.

The experimental setup is portrayed in Fig. 1. The thruster is capable of generating up to 2.2 N force, which is measured only in the vertical direction. Torques and forces in other directions are not affecting the measurement due to the particular design of the hanging system, which employs two knuckle eyes connection with axis perpendicular to each other (see zoomed-in layout in Fig. 2). Further details of each ETHILE part can be found in Morselli et al. (2022).

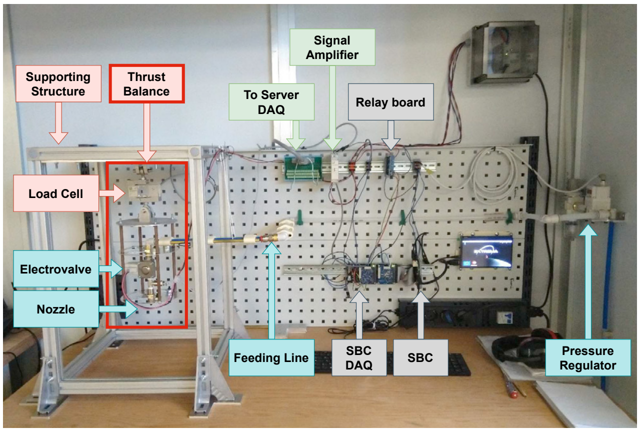

Fig. 1. Layout of the ETHILE facility. The vertical thrust balance is marked in red, the data acquisition chain to the simulation server in green, the pneumatics components in light blue, while the single-board computer and its interface boards and actuators in gray.

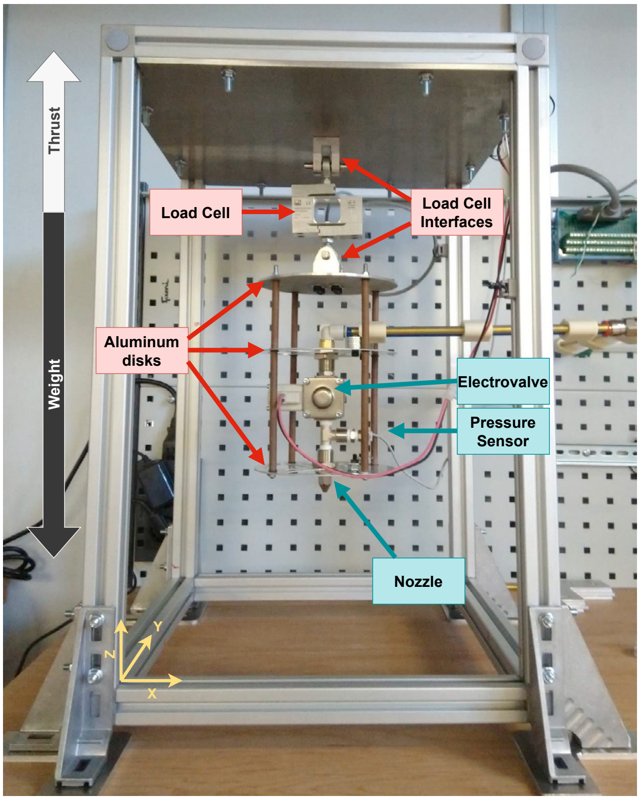

Fig. 2. Thrust balance detail: thrust and weight act on the same direction but with opposite sign. The design of the load cell interfaces avoids transferring of any momentum resulting from tiny misalignment to the load cell.

The functional schematics of the ETHILE is portrayed in Fig. 3, framed within the EXTREMA complete experiment, hence including the navigation experiment. Once a target orbital state is given, a guidance solution is computed on a SBC representative of on-board resources and thrust arcs and thrust pointing vector are obtained as an output. The arcs are then actuated by ETHILE and the thrust force is measured by means of a load cell and fed to the orbital propagator. The orbital propagator is run on a dedicated workstation which is responsible of orchestrating the full simulation and represents the only source of truth for the simulations. The workstation is also capable of generating the scene as observed by the spacecraft cameras which could be then acquired and processed by a navigation algorithm that estimates the orbital state. The execution in a loop of thrust arcs and navigation arcs closes the GNC on-board loop: reaching the target state of the interplanetary transfer will demonstrate the autonomous capability of deep-space CubeSats.

Whenever the testing and validation focus is only on guidance algorithm, the navigation block can be replaced by a statistical model. The estimated orbital state can be sampled from an error distribution instead of performing autonomous orbital state estimation. This scenario is the one considered in this work.

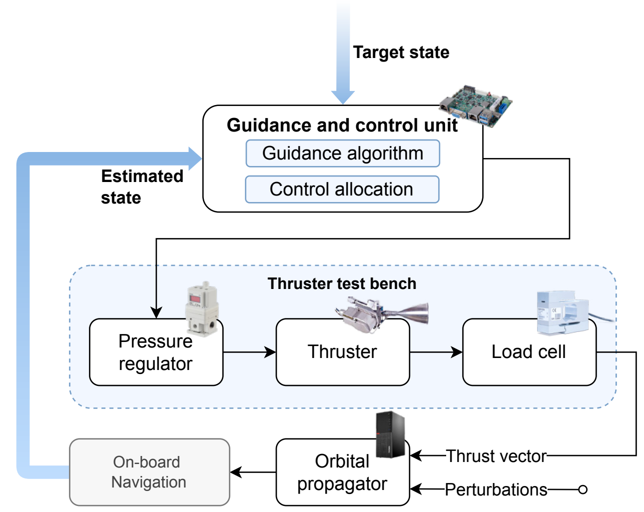

Fig. 3. Guidance algorithm validation approach within the EXTREMA framework.

3. VALIDATION AND TESTING APPROACH

A key issue in the execution of hardware-in-the-loop simulations for interplanetary transfer is the time scale. A real-time simulation of such transfers is practically unfeasible: transfers to planets or asteroids require months or more likely years to be carried out. This would make the development and testing of the models a task spanning decades. Luckily, this issue can be cleverly avoided by employing particular mathematical tools. In particular, the dynamic similarity, already known in simulation engineering for applications related to aerodynamics (Bayındırlı et al., 2016), fluid dynamics (Glicksman et al., 1994), electronics (Meliopoulos et al., 2009), and hydraulics (Heller, 2011) can be exploited for deep-space simulations too. The idea is to map the original system, represented by the original spacecraft and the original environment as they are in the real world, to a faster-evolving system, linked to the original by a set of definite mathematical relationships involving the quantities of interest (Fig. 4).

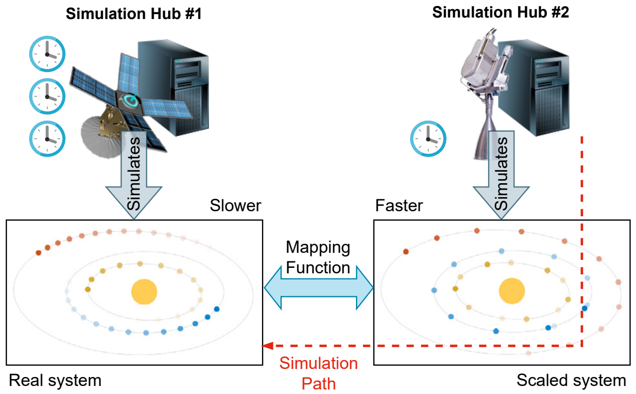

Fig. 4. Conceptual scheme of the mapping approach. The information on the original system is retrieved from the simulations performed on the scaled one through a defined mapping function, following the simulation path highlighted in red.

The simulation models can mimic the behavior of the scaled system, benefiting from shorter simulation times while still preserving all the advantages obtainable by hardware-in-the-loop (HITL) simulations. Additionally, a significant advantage in terms of experiment feasibility can be achieved by manipulating the parameters defining the mapping. Indeed, applying the mathematical relationships governing the dynamic similarity results in higher thrust levels in the lab environment. This avoids the need of employing complex, expensive electrical engines and in turn ad-hoc setups necessary for their operation (i.e., vacuum chambers or bulky pipes to avoid the interaction of the plume with the surroundings) and ultra-high-accuracy measurements rigs to sense the tiny thrust force output. In this way, it is also possible to tailor the simulation to better comply with the availability of resources in a laboratory environment and to adapt the *scaled thruster* to relax the safety requirements. Consequently, this simplified experimental setup results in an easier definition and execution of testing campaigns and is therefore extremely suitable for conducting teaching and formative activities with students.

4. EXPERIMENTAL STUDENTS ACTIVITIES

In this section, an overview of the activities already performed or planned for the near future is provided. First, an overview of the expected students background is provided, then the possible activities are briefly explained, and finally the expected learning outcomes are detailed.

4.1 Students background

The prerequisite for the experimental activities comprise notions of mechanical, electrical, thermal and fluid systems, as well as calculus (especially Ordinary Differential Equations) and numerical analysis, which the students shall be able to develop mathematical or implicit models of complex systems. Notions on automatic control are instead acquired during the bachelor studies at the Politecnico di Milano.

Students at the second year of Master studies at the Politecnico di Milano are the candidates for performing experimental and hands-on activities. In the study plan the courses of *Modeling and Simulation of AeroSpace Systems (MSAS)* and *Spacecraft Guidance and Navigation (SGN)* provide the theoretical framework for supporting the model-based design of aerospace systems and trajectory design via nonlinear programming and optimal control, which are key elements for the laboratory activities.

Notions on SBC programming and background on communications and commanding via hardware interfaces like General-Purpose Input/Output (GPIO) are not deemed necessary at the beginning of the activity since they can be acquired during the course of the master thesis work.

4.2 Current and foreseen activities

The hands-on activities that could be performed with the ETHILE facility can be grouped into three domains:

- *guidance algorithm validation*: the objective is to validate the robustness and effectiveness of on-board guidance algorithms. Algorithm based on direct and indirect methods can be tested via the facility and the students have the opportunity to deploy the designed algorithms on the SBC, hence facing with the limited computational capabilities that characterise the on-board applications. Students can develop the code using MATLAB/Simulink and make use of the embedded coder for the generation of the source C or C++ code optimized for target processor architecture.

- *simulation realism*: the objective of these activities is to increase the fidelity of the simulation, introducing whenever possible the modelling of effects such as beam-out and partial failures (e.g., power level reduction and malfunctioning). This activities leverage on the notions acquired through the MSAS course and elevates them to actual hardware application, hence giving the students the possibility to verify the assumptions and perform a validation of the modelled behaviours with actual hardware.
- *trajectory control*: the availability of simulated power readings and the use of other (real or simulated) sensors like gyros that could be available on board would allow for the introduction of a supervision logic that could constantly monitor the execution performance during thrust arcs. This could open the way for the definition and implementation of an active control that could autonomously determine the need to adjust the thrust level or interrupt an arc in case of large deviations from the commanded thrust profile. Activities on this research domain are currently at a very early stage but might become more significant in the future.

The first domain is more directly connected to the notions acquired during the SGN course but moves the focus from the classical on-ground applications and analysis (which could be run on powerful workstations) to on-board applications on processors and boards with limited power. Additionally, the presence of noise due to the thruster actuation provides the students the perspective of actual spacecraft operations. The noise generated by ETHILE is calibrated to reach a level compatible to those experienced during actual operations. Therefore, as in real cases, the trajectory actually flown or simulated deviates from the nominal one, requiring a re-optimization after each thrust arc to ensure that the spacecraft reaches the desired target. The thrust profile acquired during the actuation of a thrust profile is provided in Fig. 5.

An example of the second domain application is instead given in Fig 6. Here a thrust profile has been executed with ETHILE applying a polynomial thrust model. In this case the available power is computed by the power subsystem model based on the spacecraft distance from the Sun, therefore decreasing as the Sun's distance increases. By performing a pointwise comparison of the nominal thrust level with the actuated one it is possible to assess and characterize the error introduced by the HITL simulation in terms of orbital position and velocity. Whenever actual data is available, it is possible to fine tune such models to increase the fidelity of the simulations.

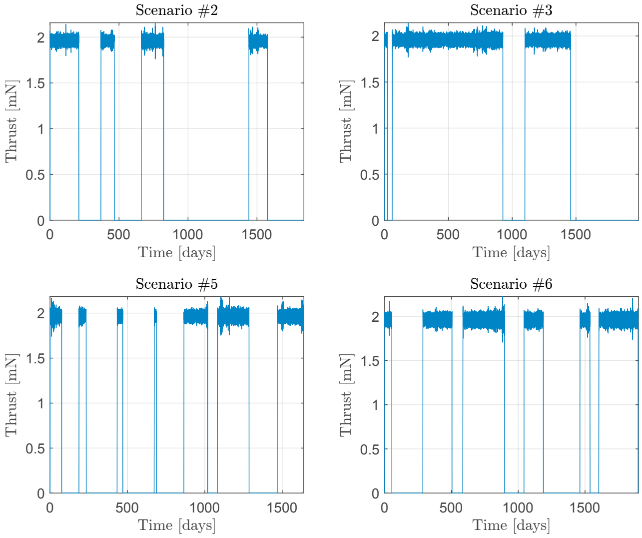

Fig. 5. Example of thrust profile execution with constant thrust level

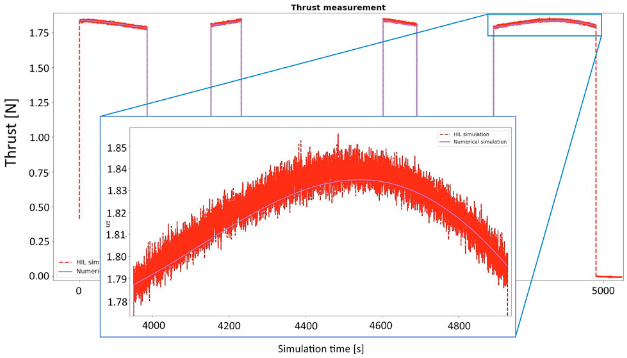

Fig. 6. Example of optimized thrust profile executed on ETHILE. The power and thruster were modelled with a 4-th order polynomial curve extracted from an experimental data points of a real thruster.

Finally, a functional diagram representing the logic and interfaces for the introduction of the trajectory control domain within the EXTREMA simulation framework is represented in Fig. 7. Here the execution of the algorithm for the computation of the optimal guidance solution is triggered and regulated by a *supervision layer*. Different control and monitoring logic which make use of sensors readings could be designed by the students and directly tested via HITL simulation. The supervision layer also implements a validation and verification step, which could, besides checking the exit flags of the optimizer, perform comparison against previously computed solutions or verification of mission operational constraints. This approach guarantees that only validated solution are passed to the on-board computer for the thruster actuation.

Currently, the definition of the power subsystem and thruster models have involved only simple polynomial or analytical models. Future development will involve the introduction of acausal modelling of such subsystems, therefore increasing even more the fidelity of the simulation. Simscape and Dymola could be employed to model the power and thruster subsystems and integrated in the simulations. It is worth noting that in case the computational burden would be not compatible with the execution on a

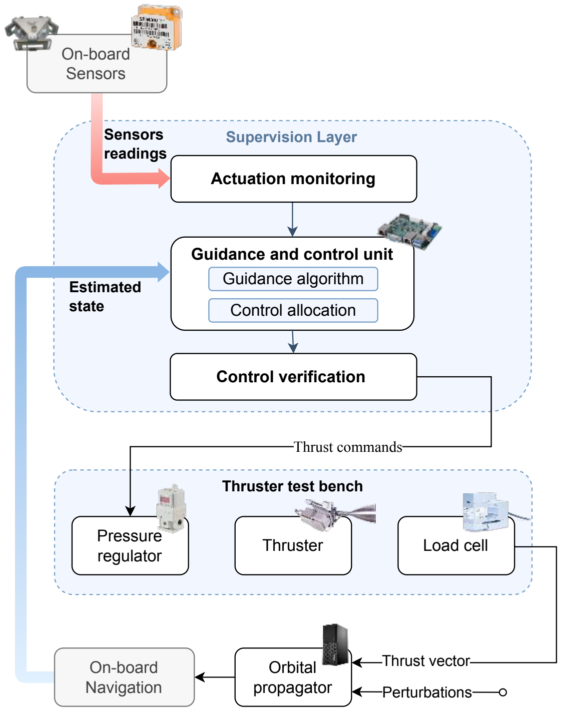

Fig. 7. Schematics of a trajectory execution supervision and control approach within EXTREMA simulations.

Raspberry Pi 4, these models could run on the workstation in charge of orchestrating the simulation.

4.3 Expected learning outcomes

The main expected learning outcomes for the experimental activities carried out with ETHILE are the following:

- acquire confidence in programming SBC like Raspberry Pi for control applications
- improve skills in modelling, also choosing a suitable level of complexity for the application and use case to analyze
- work with physical hardware which combines different domains (mechanical, fluidic, electrical) hence applying the theoretical knowledge gained throughout the university courses
- deal with multiple sensors, including calibration and measurement chain setups
- familiarize with communication protocols and exchange of data structures with protocols like User Datagram Protocol (UDP) (e.g., required for thrust profile commands transfers)

5. CONCLUSIONS

In this paper we presented the ETHILE facility and provided a very brief overview of its integration within the EXTREMA Simulation Hub. Some details on the types of activities carried out by Master thesis students were outlined, together with an overview of the expected background and an indication of the expected learning outcomes. Finally, a few possible future developments involving acausal modelling techniques are identified.

ACKNOWLEDGEMENTS

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 864697).

REFERENCES

Bayındırlı, C., Akansu, Y.E., and Salman, M.S. (2016). The determination of aerodynamic drag coefficient of truck and trailer model by wind tunnel tests. *International Journal of Automotive Engineering and Technologies*, 5(2), 53–60. doi:10.18245/ijaet.11754.

Di Domenico, G., Andreis, E., Carlo Morelli, A., Merisio, G., Franzese, V., Giordano, C., Morselli, A., Panicucci, P., Ferrari, F., and Topputo, F. (2023). *The ERC-Funded EXTREMA Project: Achieving Self-Driving Interplanetary CubeSats*, 167–199. Springer International Publishing, Cham. doi:10.1007/978-3-031-24812-2_6.

Glicksman, L., Hyre, M., and Farrell, P. (1994). Dynamic similarity in fluidization. *International Journal of Multiphase Flow*, 20, 331–386. doi:10.1016/0301-9322(94)90077-9.

Heller, V. (2011). Scale effects in physical hydraulic engineering models. *Journal of Hydraulic Research*, 49(3), 293–306. doi:10.1080/00221686.2011.578914.

Mannocchi, A., Giordano, C., and Topputo, F. (2022). A Homotopic Direct Collocation Approach for Operational-Compliant Trajectory Design. *Journal of the Astronautical Sciences*, 69(6), 1649 – 1665. doi:10.1007/s40295-022-00351-x.

Meliopoulos, A.S., Cokkinides, G.J., Mohagheghi, S., Dam, Q.B., Alaileh, R.H., and Stefopoulos, G.K. (2009). A laboratory setup of a power system scaled model for testing and validation of EMS applications. In *2009 IEEE Bucharest PowerTech*, 1–8. IEEE. doi:10.1109/ptc.2009.5282224.

Morelli, A.C., Morselli, A., Giordano, C., and Topputo, F. (2024). Convex trajectory optimization using thrust regularization. *Journal of Guidance, Control, and Dynamics*, 47(2), 339 – 346. doi:10.2514/1.G007646.

Morselli, A., Morelli, A.C., and Topputo, F. (2022). ETHILE: A thruster-in-the-loop facility to enable autonomous guidance and control of autonomous interplanetary CubeSats. *Proceedings of the International Astronautical Congress, IAC*, 2022-September.

Schoolcraft, J., Klesh, A., and Werne, T. (2017). MarCO: interplanetary mission development on a CubeSat scale. In *Space Operations: Contributions from the Global Community*, 221–231. Springer. doi:10.2514/6.2016-2491.

Topputo, F., Wang, Y., Giordano, C., Franzese, V., Goldberg, H., Perez-Lissi, F., and Walker, R. (2021). Envelop of reachable asteroids by M-ARGO CubeSat. *Advances in Space Research*, 67(12), 4193–4221. doi:10.1016/j.asr.2021.02.031.

Walker, R., Koschny, D., Bramanti, C., Carnelli, I., Team, E., et al. (2017). Miniaturised Asteroid Remote Geophysical Observer (M-ARGO): a stand-alone deep space CubeSat system for low-cost science and exploration missions. In *6th Interplanetary CubeSat Workshop, Cambridge, UK*, volume 30.