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ETHILE: A THRUSTER-IN-THE-LOOP FACILITY TO ENABLE AUTONOMOUS GUIDANCE AND CONTROL OF AUTONOMOUS INTERPLANETARY CUBESATS

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As the number of interplanetary space missions keeps increasing thanks to the reduction of spacecraft development and integration costs, there is the urge of avoiding the saturation of the ground infrastructure required to operate satellites. The aim of the EXTREMA project, which has received fundings from the European Research Council, is to solve the aforementioned issue by enabling deep-space autonomous spacecraft. This work presents the EXTREMA Thruster in The Loop Experiment (ETHILE), a facility under development at the DART laboratory of the Politecnico di Milano. Its aim is to test and validate novel guidance algorithms tailored for satellites traveling autonomously in deep space. Therefore, it shall model the real actuation of low-thrust propulsion systems, measure the produced thrust, and feed the measurements to a high-fidelity numerical propagator. It is worth noting that a true real-time simulation would require an extremely long time: to complete an interplanetary transfers many months or even years are needed. EXTREMA aims at exploiting a scaled model of the physical system, and to correlate the results with the original one thereafter. Through a mapping between the original system and a fast-evolving one, it will be possible to execute the guidance and control simulations in a shorter time frame, which will last only a few hours or days. Once detailing the mapping principle, the paper describes the layout and characteristics of the ETHILE facility, followed by an overview of the guidance and control algorithms, developed in the framework of EXTREMA. Finally, some preliminary results are given and future developments are outlined.

1 Introduction

In the last two decades CubeSats have revolutionized the utilization of space, allowing more and more actors to gain access to low-Earth orbit. The same trend is now foreseen for interplanetary missions: In 2018 the two NASA's MarCO CubeSats [1] were operated in Mars proximity, and more are expected to being launched in the next few years (e.g., M-ARGO [2, 3]). A bottleneck for further exploration of deep space is represented by the ground segment: interplanetary CubeSats are operated, navigated and controlled with the supervision of the Flight Dynamics experts, like regular, monolithic spacecraft. As deep-space missions are usually long-lasting, with durations varying from a few months to some years, human-in-the-loop operations result to be heavy on mission budgets. Moreover, even with higher budgets, the number of ground slots to communicate with interplanetary probes is saturating, hampering the spread of CubeSats in outer space. The EXTREMA (Engineering Extremely Rare Events in Astrodynamics for Deep-Space Missions in Autonomy) project aims towards a paradigm shift on how deep-space GNC operations are performed. The goal is to enable self-driving CubeSats, capable of traveling in deep space without requiring any interaction with ground [4]. The project has received a Consolidator Grant from the European Research Council (ERC), a prestigious acknowledgment that funds cutting-edge and disruptive innovation research in Europe. The project builds on three main Pillars: Autonomous Navigation, Autonomous Guidance and Control, and Ballistic Capture. Each of the Pillars foresees the execution of a physical experiment that should test the associated cutting-edge algorithms and models. As the objective is to assess autonomous Guidance, Navigation and Control (GNC) capabilities of deep-space CubeSats, relevant hardware (i.e., with performances and capabilities in-line with the ones nowadays available for such satellites) will be used. The experiments will be thus interfaced with a hardware representation of the satellite subsystems, a *distributed flatsat*, and algorithms will be installed on the equivalent on-board computer. The validation will be performed by simulating interplanetary transfers to near-Earth asteroids or to planets, also exploiting ballistic capture corridors at Mars to cope with the limited control authority of CubeSats. The collection of the flatsat, the experiments

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interfaces, workstation, and the secondary subsystems (e.g. the power generation device) form the EXTREMA Simulation Hub (ESH). This work provides details on the development and execution of the experiment related to Pillar II, whose goal is to develop a lightweight guidance algorithm that exploits the knowledge of the spacecraft state to accurately compute a time-definite thrust profile and achieve the mission objectives in complete autonomy. To validate and assess the operational performances of the algorithm, a dedicated facility is under development at the Deep-space Astrodynamics Research and Technology (DART) laboratory of the Politecnico di Milano. This thruster-in-the-loop facility will model the real actuation of low-thrust propulsion system therefore allowing testing and validating the autonomous guidance algorithm conceived within Pillar II of EXTREMA.

This paper is structured as follows: An overview of ETHILE will be initially given, focusing first on the functional requirements, and then detailing the facility design and realization. Subsequently, an outlook of the guidance algorithms will be provided, emphasizing the characteristics that allow their use on CubeSats on-board computers and defining the interfaces between ETHILE and the flatsat prototype. Some preliminary simulations and their corresponding results will be presented thereafter. To conclude, a critical analysis of the current performances of ETHILE will be made and possible improvements in the design and algorithm validation will be finally outlined.

2 Thruster-in-the-loop facility

Historically, the modeling of interplanetary transfers has heavily relied on mathematical approximations, system decoupling, and numerical and computational tools to build models for predicting and analyzing the evolution of the quantities of interest. Statistical approaches have been employed to guarantee the robustness of the outcomes against effects not included in the original models. Given the advances in the capabilities of microcomputing and technologies for embedded systems, a different kind of models, mixing numerical tools with physical implementations of the systems of interest, emerged. Depending on which parts of the systems were physically represented, these have been named hardware-in-the-loop (HIL), processor-in-the-loop (PIL), or even human-in-the-loop simulations. The advantages of such approaches can be seen in terms of:

(a) **simulation fidelity**, since the approximations brought by numerical models of physical elements do not introduce errors in the simulations;

(b) **resources required**, as it is possible to relieve the numerical integrators from the need to propagate the evolution of physical systems; this benefits, in particular, those simulations involving phenomena happening at very different time scales;

(c) **simulation flexibility**, as it is possible to obtain a faithful simulation of harsh environment and phenomena employing tailored sets of sensors and actuators, without leaving the safety of the lab environment.

In particular, ETHILE represents a HIL facility as it integrates hardware in the orbital simulation, namely the thruster.

2.1 The accelerated framework

In the past years, multiple frameworks for HIL simulations have been proposed. However, they all were characterized by a single, critical drawback that would make them unsuitable for deep-space applications. As the evolution of physical models is subject to certain time scales, the synchronization of the virtual part of the model with the physical one hinders all the speed advantages brought by numerical simulation: no matter how powerful the computing platforms are; since they need inputs from the real world to go on with the simulation, they are bounded to the time scale of the physical models. As interplanetary transfers are usually long-lasting, this means that a single simulation could span months, if not years: 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 [5], fluid dynamics [6], electronics [7], and hydraulics [8] 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. 1). The simulation models can mimic the behavior of the scaled system, benefiting from shorter simulation times while still keeping all the advantages brought by HIL simulations. Moreover, by manipulating the mapping-defining parameters, a significant advantage in terms of experiment feasibility can be achieved. Indeed, applying the mathematical relationships governing the dynamic similarity results in higher thrust levels in the lab environment: this frees the experiment from the employment of complex, expensive electrical engines that also require ad-hoc setups to be operated (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 the lab environment and to adapt the *scaled thruster* to the technological limits and safety requirements of the lab environment.

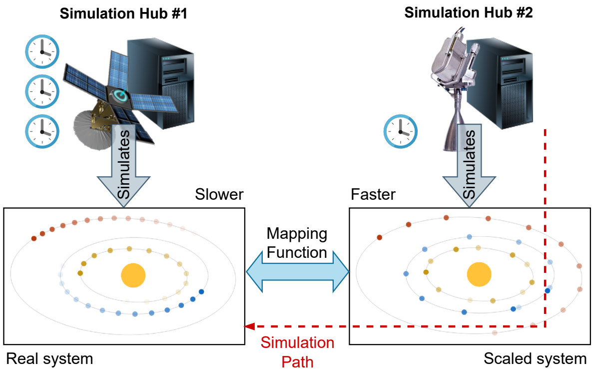


Fig. 1: Conceptual scheme of the mapping approach. The information on the original system is retrieved from the simulations performed on the scaled one through a defined mapping function, following the simulation path highlighted in red.

By properly fixing the remaining mapping degrees of freedom, the requirements on the specific impulse of the thrusters can be lowered: while this translates in levels of fuel mass consumption that cannot comply with a CubeSat, these can be achieved with simple laboratory equipment such as pressurized tanks or supply pipes. By selecting compressed air as fuel, even the need for tanks is removed, since it is possible to directly compress the surrounding air with a mechanical compressor and regulate it with a tailored pipeline before feeding the fuel to the thruster. Of course, the feeding system and the thrusting test bench shall take into account the fundamental differences in the typical thrust profiles of ion and cold gas thrusters. While the dynamic similarity allows to freely choose the thrust level and the specific impulse of the thruster, additional requirements on multiple parameters and characteristics of the thrust profile - like rising and fall times, oscillations, and stability of response - cannot be avoided nor neglected, calling for a careful design of the thrust test bench.

In this context, we can express the philosophy behind the realization of ETHILE as follows:

> *To map a high-efficient, low-thrust ion engine into a higher-thrust technology like a cold gas thruster in an accelerated framework, guaranteeing at the same time high levels of fidelity.*

2.2 ETHILE: functional overview

The functional layout of Experiment 2 is represented in Fig. 2. The target state and the one estimated by the navigation algorithm [9] are fed as inputs to the Guidance and Control (GC) algorithm, which runs on a Single-Board Computer (SBC). The output of the GC process is used to actuate the cold-gas thruster that is installed on the test bench. The produced force is measured by the load cell and then transmitted to the orbital propagator which runs on the workstation that controls the whole simulation.

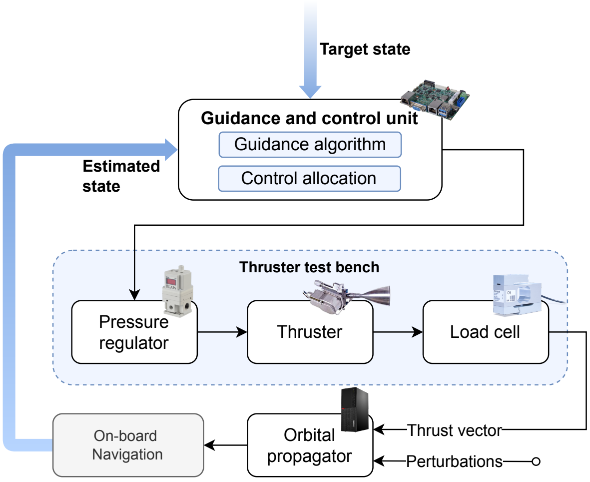


Fig. 2: Logic of the Thrust Test Bench to test the robustness of guidance algorithms.

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*, 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. 3 and described more in details in the following paragraphs.

Thrust balance The thrust balance measures the force generated by the thruster. As can be seen in Fig. 4, it is installed on a laboratory workbench and has a vertical layout, with the thrust vector that acts vertically from bottom to top, opposite to the weight of the hosting infrastructure and thruster. The two main drivers of this design choice are:

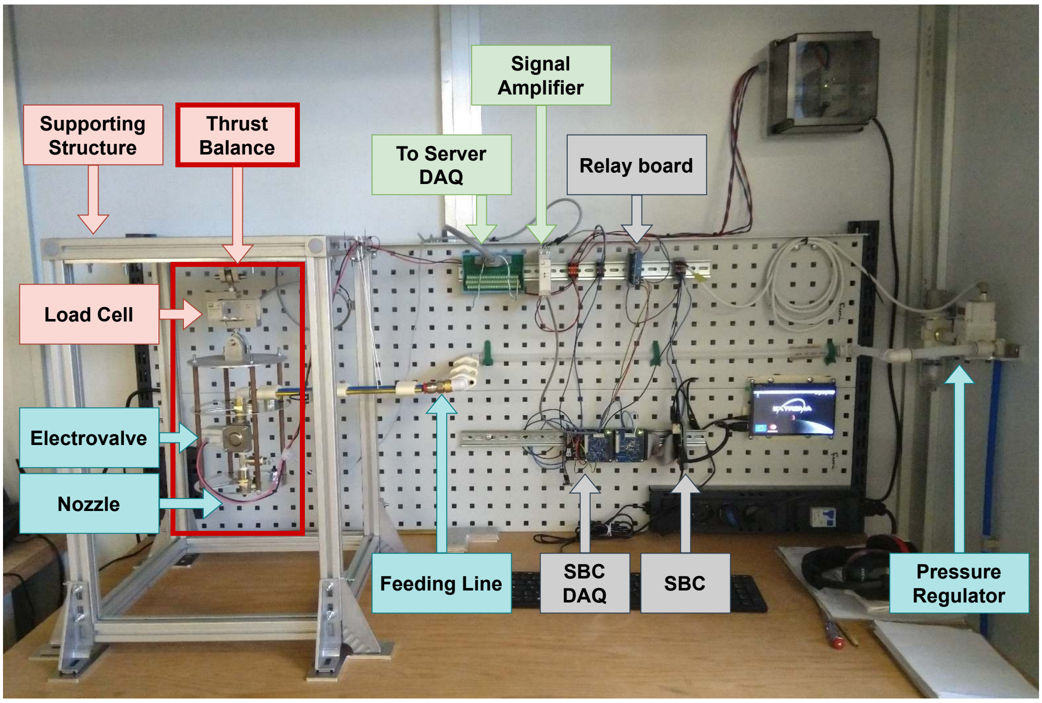


Fig. 3: Layout of the ETHILE facility. The vertical thrust balance is marked in red, the data acquisition chain to the simulation server in green, the pneumatics components in light blue, while the single-board computer and its interface boards and actuators in gray.

(a) the magnitude of the scaled thrust forces, which is of the order of a few Newtons instead of the mN or μN of a low-thrust engine;

(b) the simpler calibration process with respect to the horizontal or torsional thrust balances.

More accurate and precise models of thrust balance, like the torsional and horizontal thrust balance, exists and are usually employed for accurate measurement of the performances of low thrust engines [10]. Anyway, their calibration and setup are much more complex and additional care must be taken in the preparation of the experiment. Additionally, they often require amplification mechanisms [11] which might also introduce non-linear effects if the force variation throughout the execution of the experiment varies and gets close to the full scale of the force sensor. The thrust balance hangs from a supporting structure, a 600 × 400 × 400 mm cuboid assembled with aluminum strut profiles which hosts on top a square aluminum. The supporting structure is raised 25 mm from the workbench top to let compressed air flow outside of the supporting structure from below, reducing the air interaction with the profiles at the bottom and thus limiting the onset of vortexes which might disturb the measurements of the thrust balance. The load cell is installed with two knuckle eyes, with the two connection pins inserted on the two adapters aligned with the X and Y directions. This guarantees that momenta acting around these directions, which might result from thruster misalignments errors, are not transferred to the load cell. The thrust balance consists of three aluminum disks: the top one is thicker and is connected to the load cell interface, the other two support instead the pneumatics feeding system, the electrovalve and the thruster. Lightening holes are present on the two lower disks to compensate the non-symmetrical weight distribution of the electrovalve and pressure sensor. The pneumatics feeding line is instead installed at the same level of the elbow connector present on the middle disk. In this way, the load cell is measuring only the weight of electrovalve, thrust balance, fittings, and pressure sensors when the thruster is off. Note that a constraint on the maximum thrust level is imposed by the facility design: the maximum thrust must be smaller than the weight of the thrust balance to keep the load cell working in tensile loading.

Note that the thrust balance can only measure the thrust along one direction. As a consequence, ETHILE could only introduce errors in the magnitude of the thrust. The errors in the directions of thrust are instead introduced by the attitude simulator of the ESH, which is also under development within EXTREMA [4].

Pneumatics feeding system The pneumatics feeding system provides compressed air to the cold gas

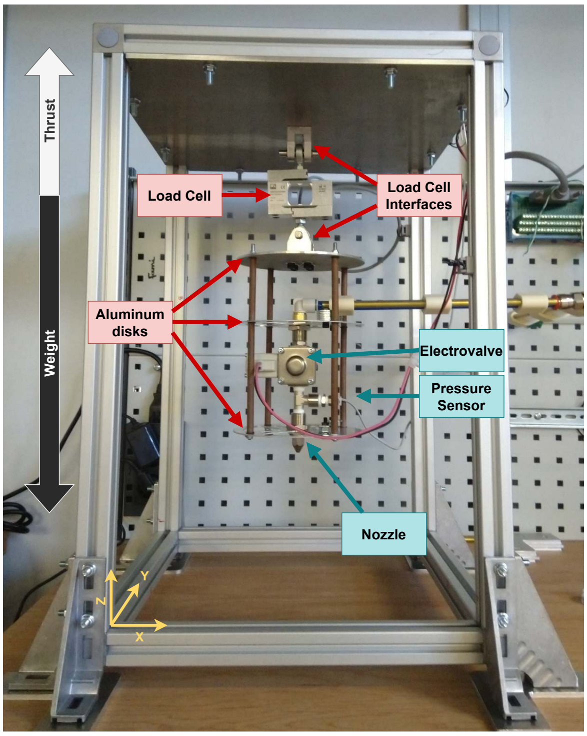


Fig. 4: Thrust balance detail: thrust and weight act on the same direction but with opposite sign. The design of the load cell interfaces avoids transferring of any momentum resulting from tiny misalignment to the load cell.

thruster. A simplified pneumatics circuit schematics is shown in Fig. 5. The feeding line is connected to the compressed air pipes of the laboratory, which provides a pressure up to 8.0 bars. A manual filter regulator is installed near the pressure regulator on the supply side. The filter was selected in accordance with the requirements on the filtration degree by the pressure regulator. The electro-pneumatic pressure regulator is voltage-controlled by an analog signal in the range 0-5 VDC, compatible with a SBC voltage output. The feeding line segments are nylon tubes with an internal diameter of 10 mm which are connected together by elbow tube-to-tube adaptors. This solution increases the mechanical degrees of freedom of the feeding line, since the adapters allow each tube to rotate along its axis. In this way, the feeding line can move and accommodate the small vertical displacement generated by the thruster actuation. In addition, this setup eases the levelling and height regulations of the feeding line by simple rotation along the axis of the tubes. The last two segments of the feeding line are kept straight by two brass tubes and are suspended to guarantee the alignment with the elbow connector on the thrust balance. The solenoid valve actuates the thruster and is controlled by the SBC. The selected electrovalve is lightweight and has quick response time (below 20 ms). The analog pressure sensor is placed on a T-joint after the solenoid valve. Its output signal is acquired by the SBC to perform closed-loop control of the pressure, ensuring that the required thrust is achieved. Finally, a convergent nozzle is placed at the end of the circuit. The nozzle diameter shall be such that the flow is chocked for the expected thrust range. Convergent-divergent nozzles were not considered as they would operate in adapted regime only for one single value of control pressure, which is non-ideal as we will modulate the control pressure. Indeed, possible issues might arise due to presence of shock waves in the divergent section or expansion waves at the exit of the nozzle. This would likely result in non-symmetrical flow as it is extremely hard to achieve a sufficient precision in manufacturing components with inner diameters of a few millimeters.

Single board computer The Single-Board Computer has a dual function: it runs the guidance algorithm (described more in detail in Sec. 3) and controls the actuation of ETHILE. Currently, the SBC is a Raspberry Pi 4 Model B with 8 Gb RAM. The SBC functionality could be expanded by connecting physical hardware to the 40 pins GPIO (General Purpose Input Output) connector. Various Hardware Attached on Top (HAT) boards are also available for Raspberry Pi, with dedicated software libraries that ease up software development. The following boards are connected to the Raspberry:

- an environmental sensor to measure pressure and temperature inside the ESH;
- a Data Acquisition (DAQ) HAT to acquire the measurements of the pressure sensor and (optionally) the load cell. By means of these measurement, it is possible to perform a close-loop control to regulate to the desired level of thrust (e.g., counteract pressure deviations, introduce disturbances and simulate misperformance of the thruster).
- a HAT to provide analog voltage output in the 0-5 VDC range, used to control the pressure regulator.
- a 4-channel relay board, to switch on/off the pressure regulator and the electrovalve. These are operated with 24 VDC provided by a power supply and hence cannot be powered directly by the SBC.

This configuration has the advantage of simplifying the interaction between the guidance algorithm and the facility but has the drawback of requiring the execution of the guidance software on the Raspberry Pi. Therefore, it will be the baseline during the testing and validation phase of the ESH but it is foreseen to run the guidance algorithm on a dedicated SBC in the future.

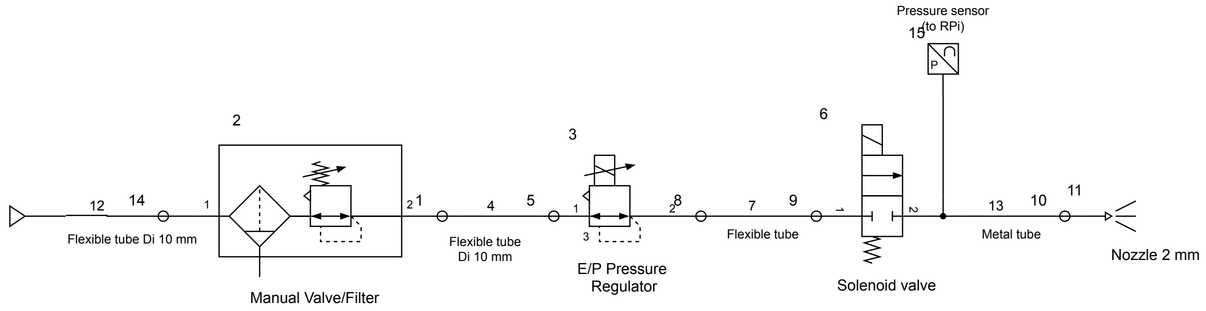


Fig. 5: Pneumatics feeding line schematics.

The described setup shall guarantee the repeatability and high fidelity of measurements. This is a key aspect in the EXTREMA simulations: an interplanetary or deep-space transfer has multiple thrust arcs, which are in turn interrupted by multiple navigation sessions. As a consequence, an activation of the cold gas thruster is needed per each thrust arc and it will not be advisable to perform intermediate calibrations during the execution of a simulation. The simpler design shall therefore guarantee an easier setup and smoother execution of the experiment.

3 On-board guidance

Solving the low-thrust space trajectory optimization problem onboard poses several challenges. The requirements for a suitable real-time guidance algorithm include optimality (i.e. the ability of minimizing the fuel consumption), reliability (i.e. capability of converging even when poor initial guesses are provided), and low computational effort (due to the limited resources onboard, especially for CubeSats) [12]. State-of-the-art guidance algorithms divide into indirect and direct approaches [13]. The former are characterized by high precision, but are hardly usable for onboard applications since they have a very small convergence domain; on the other hand, classical direct methods are more robust, but they often require too much computational effort [14]. Convex optimization [15] represents an interesting direct approach as it assures robustness and computational affordability at the same time. It has been recently applied to solve the low-thrust space trajectory optimization problem [16], and it also represents the approach that we have selected in the context of EXTREMA to be tested on ETHILE. Several discretization methods methods have been developed, including pseudospectral convex collocation [17], Hermite interpolation-based arbitrary order discretization [12], and first-order-hold control parametrization [18]. As the low-thrust space trajectory optimization problem is originally nonconvex, an iterative technique called Sequential Convex Programming (SCP) is exploited to solve it using convex optimization solvers. It consists of considering a sequence of convexified subproblems whose solutions eventually converge to the solution of the original problem. A fundamental aspect of this strategy is the trust-region assuring that the problem convexification remains valid; we have developed several trust region update strategies and assessed their performance in extensive simulations [18]. To increase the robustness properties of the guidance algorithm, we have applied an energy-to-fuel homotopic path to the SCP algorithm [12]. Other works have also applied the homotopic strategy to account for operational constraints, real-thruster behaviour, and high-fidelity dynamics [19]. Finally, closed-loop guidance simulations using SCP have been performed to target different celestial bodies [20] and ballistic capture corridors at Mars [21]. Figure 6 shows a typical transfer trajectory from the Earth to asteroid Dionysus as computed by our convex guidance algorithm and the associated thrust profile. Note how the latter, in particular, has a bang-off-bang structure, meaning that a (sub)optimal solution to the problem has been found.

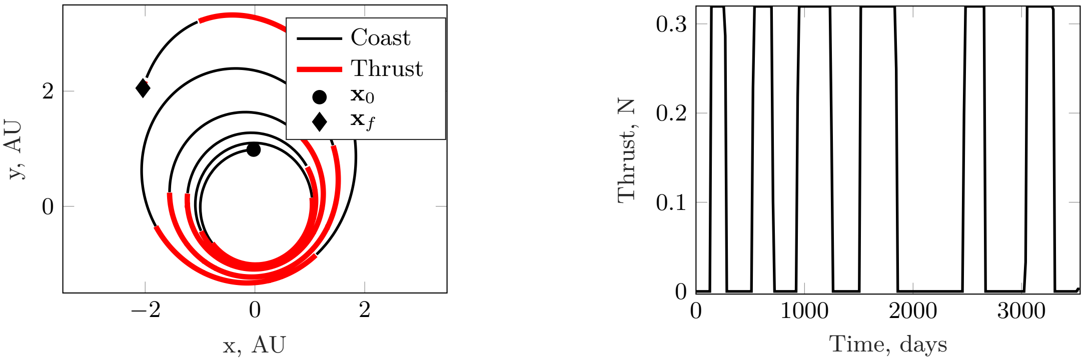
3.1 Guidance solution

As described in the previous section, the GNC algorithm will be embedded on a SBC and will run as if it was onboard a CubeSat. Therefore, it is necessary to define the interfaces with the flatsat and ETHILE. The output of the guidance solution shall therefore provide

(a) **thruster on/off epochs** (in physical variables).
(b) **thrust vector direction** during switch-on times.

After each guidance cycle, the above information shall be stored on-board and also transferred to the relevant satellite subsystems. In particular, the attitude control system (and the corresponding HIL facility) shall receive the thrust vector direction to properly orient the CubeSat while the thruster on-off times are needed by the on-board computer and ETHILE.

The SBC of ETHILE shall then map this solution (which is tailored for ion engine) into commands for the



(a) Trajectory

(b) Thrust profile

Fig. 6: Typical Earth-Dionysus transfer trajectory and corresponding linearly interpolated thrust profile.

cold gas thruster. In addition, the following information must be provided by the workstation in charge of the numerical simulation of the environment:

(a) currently available on-board power (related to the Sun distance)

(b) currently available fuel mass (to stop thrusting in case the propellant is used up).

During thrust arcs, the SBC will perform a reverse mapping to allow the on-board computer to generate telemetry concerning the thruster actuation. In particular, the actual thrust on-off times and estimated mass consumption will be monitored and stored for subsequent use.

4 Preliminary results

In accordance with the EXTREMA project planned schedule, the ETHILE facility is currently undergoing validation, calibration before being integrated with the other facilities. In the following, some preliminary results concerning the design validation are provided.

As stated in the previous sections, a scaling will be used to map a low-thrust engine into a cold gas thruster to perform accelerated simulations. The reference engine performance that was considered for the sizing of ETHILE is the miniaturized ion thruster model proposed for the M-ARGO mission [3]. The thrust level and specific impulse as functions of the distance from the Sun are plotted in Fig. 7a. By imposing a thrust scaling factor of $\lambda_T = 1e3$ the mapped thrust level reaches a magnitude range compatible with the thrust balance operative range. This value is also compatible with a simulation at least 100× faster that preserves the dynamical similarity between the real and accelerated systems. The mapped thrust is plotted in Fig. 7b, together with the inlet pressure that could provide the required thrust, assuming an ideal convergent nozzle (exit diameter $d_e = 2\ mm$) and that air is an adiabatic gas (specific $R = 282.62\ J/kg/K$ and $\gamma = 1.4$). The range of pressure is in line with the available compressed air pressure from the pneumatics feeding line at the laboratory.

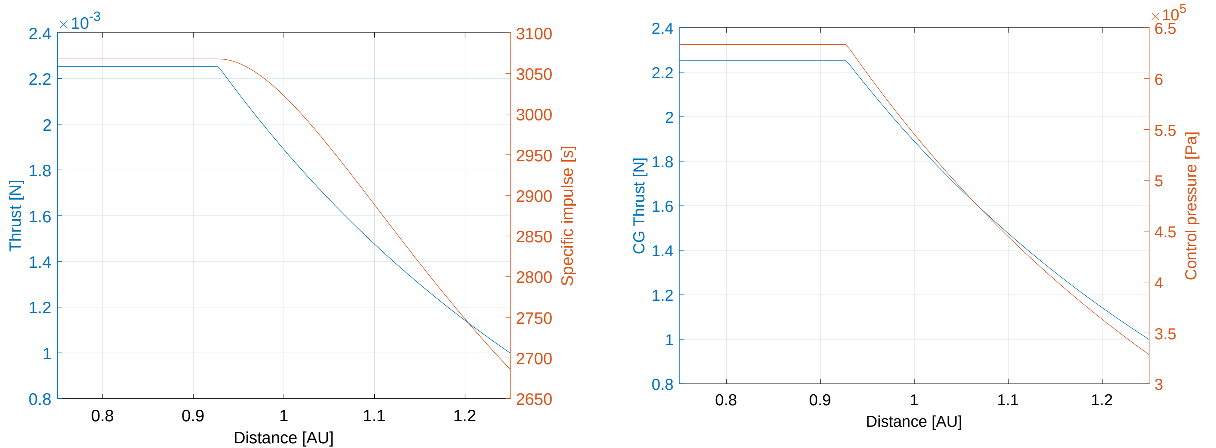
The ideal thrust level was verified once the facility was assembled. In Fig. 8 the average thrust values and the corresponding 3σ standard deviations are represented as function of the pressure at the nozzle inlet. These thrust and pressure measurements were acquired for different pressure levels and the mean was computed over a time interval of 5 seconds once the thrust stabilized (transients resulting from electrovalve actuation and pressure regulation were excluded). The standard deviation is below 5% of the maximum thrust level, a value that is compatible with the thrust of ion thrusters [22]. While the actual thrust is lower than the ideal curve, the required thrust range is fully covered by ETHILE. Since the relationship is linear it can be easily expressed as a first order polynomial and used on the SBC to perform open loop control of the thrust level.

Finally, the thrust resulting from an accelerated simulation is provided in Fig. 9. The simulation was performed using both control modes of ETHILE:

(a) actuation through the electrovalve (**EV mode**). The SBC regulates the thrust level by setting the control pressure on the regulator, according to the distance from the Sun (which determines the available power). The thrust arcs are mapped into a set of pulses and commanded by the GPIO interface to open and close the electrovalve.

(b) actuation through the pressure regulator (**PR mode**). The electrovalve is kept open during the whole simulation. During thrust arcs the pressure is regulated in the same way of the previous but the output voltage is set to zero during coasting arcs (hence switching off the thrust).

The EV mode is faster in actuation (< 30 ms reaction time) but the thrust is clearly noisier. Since the pneumatics line is pressurized at around 6 bars, the opening



(a) Specific impulse and maximum thrust level vs Sun distance (miniaturized ion thruster).

(b) Mapped (ideal) cold gas thrust level and corresponding control pressure at nozzle inlet. (Convergent nozzle, exit diameter 2 mm, adiabatic gas with air properties).

Fig. 7: Graphical representation of the miniaturized ion thruster model considered (left) and the mapped high-thrust model (right).

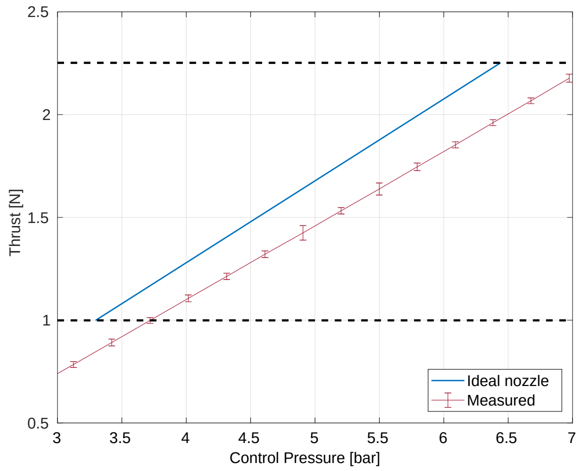


Fig. 8: Comparison of thrust computed for an ideal convergent nozzle and measured force as function of inlet pressure. The lower force of real thruster behaviour is compensated by the higher pressure available, which allows to cover the full range of the mapped thrust model (black dashed lines).

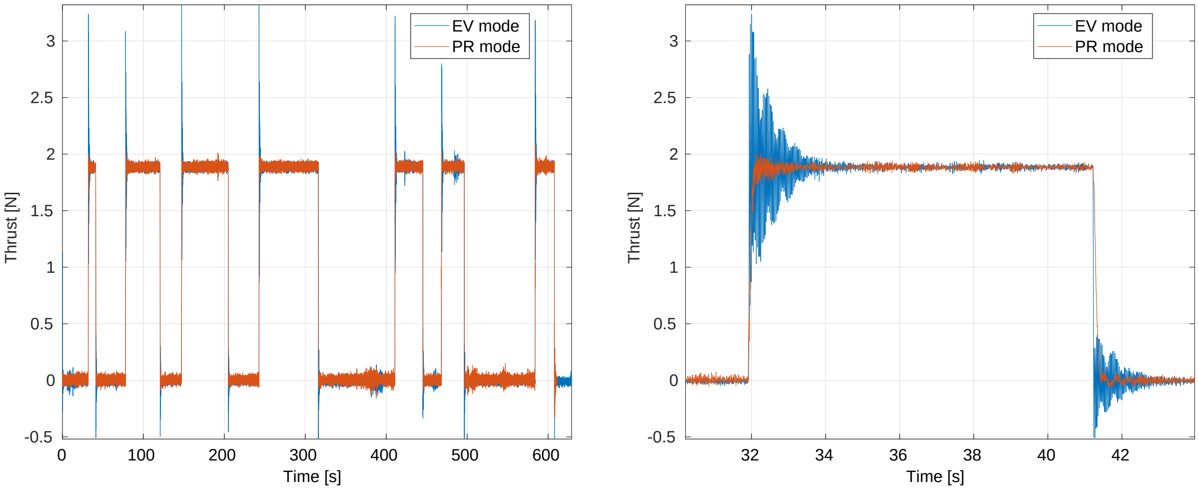
of the valve suddenly puts the fluid in motion, introducing turbulences and generating oscillations of the thrust balance. This behaviour shall be compensated through a review of the thrust balance design, e.g. introducing a dampening system. On the converse, the actuation in PR mode provides a smoother profile but has a longer transient (∼ 1 s). Anyway, this behavior could be partially compensated via software, e.g. advancing the pressure on/off command. In addition, the PR mode could allow a more accurate modelling of the ion thruster ignition phase.

The oscillations during coasting arcs can be neglected because in those time intervals the force measurements are not processed by the orbital propagator. It is worth noting that the force measurement could become negative: the reason is that the thrust balance measures the thrust in differential mode. The weight of the thruster and its support is always larger than the thrust force, thus keeping the load cell in tension.

5 Conclusions

This paper describes the thruster-in-the-loop facility ETHILE under development at the DART laboratory of the Politecnico di Milano within the framework of the ERC-funded project EXTREMA. An overview of the facility has been provided, detailing the main components and highlighting some of the key characteristics and design features of the facility. The results of the preliminary validation of the facility are given, showing that the cold-gas thruster is capable of achieving a thrust larger than 2.2 N, a value which allows a scaling of 1000× of the considered ion thruster model in accordance with the design requirements.

The facility will be further tested and validated in the coming months. In particular, the efforts will be directed towards the realization of a closed-loop pressure control (to allow for the introduction of thruster misperformances, beam-out events, etc.), to cope with disturbances arising from the electrovalve actuation (which causes a transient with small oscillations of the thrust balance), and to characterize and properly represent also the transient behaviour of the ion thruster and not only the thrust at regime. In parallel, the guidance algorithm will be installed on the SBC and tests will be per-



(a) Comparison of the thrust measurements.

(b) Zoom on first thrust arcs.

Fig. 9: Example of thrust measured with ETHILE. The guidance solution used in the simulation refers to an interplanetary transfer to Dionysus. The HIL simulation is accelerated by a factor of $5e5$. The blue curve represents the measured thrust when ETHILE is actuated in *EV mode*, the orange one in *PR mode*.

formed, actuating the commands to perform a transfer to an asteroid or Mars in open-loop. At a later stage, the facility will be fully integrated with the workstation and the other facilities of the ESH to finally test and validate the navigation and guidance algorithms and progress towards the objective of EXTREMA: enabling autonomous deep-space CubeSats.

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