THE EXTREMA ORBITAL SIMULATION HUB: A FACILITY FOR GNC TESTING OF AUTONOMOUS INTERPLANETARY CUBESAT

Alessandro Morselli (1), Gianfranco Di Domenico (1), Eleonora Andreis (1),
Andrea Carlo Morelli (1), Gianmario Merisio (1), Vittorio Franzese (1), Carmine Giordano (1),
Paolo Panicucci (1), Fabio Ferrari (1), Francesco Topputo (1)

(1) Politecnico di Milano, Dipartimento di Scienze e Tecnologie Aerospaziali,
via La Masa 34, 20156 Milano, Italy
email: alessandro.morselli@polimi.it

ABSTRACT

This paper presents the EXTREMA Simulation Hub (ESH), an integrated infrastructure that reproduces dynamic simulations of the spacecraft-environment interaction, allowing high-fidelity testing, validation, and verification, through Hardware-In-the-Loop (HIL) simulations, of deep-space autonomous GNC systems for CubeSats. 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 control from ground. 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.

First, we describe the modeling of the optical navigation and low-thrust propulsion systems. Contextually we introduce the different ESH components: the optical facility, the thruster-in-the-loop test bench, and the attitude simulator. We then describe the integrated infrastructure, focusing on the interfaces with on-board camera and on-board computer models, and the corresponding simulation approach to test the robustness of navigation and guidance algorithms. Finally, we present the case studies involving mission profiles that are tested with the ESH, the performances, and outcomes of the simulations, concluding with the potential impacts and future possible improvements.

1 INTRODUCTION

The last decade has seen the flourishing of the space sector. CubeSats, shoebox-sized satellites equipped with payloads capable of carrying on different activities, fueled this growth thanks to their reduced manufacturing costs and launch weight. However, their employment has been mainly focused on the part of space closer to the Earth. Only a few missions employed CubeSats to reach and explore furthest locations in the Solar System, namely the MarCO (Mars Cube One) mission [1], while others are planned other in preliminary design phases (e.g., M-ARGO [2] [3]). While CubeSats allow for reduced manufacturing and launch budgets, the cost for operating deep-space CubeSats barely differs from that required to operate larger probes. As deep-space missions are usually long-lasting, with durations varying from a few months to entire 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 the space not surrounding Earth. A solution to the problem is represented by the development of autonomous capabilities for interplanetary CubeSats. In this context, the ERC-funded EXTREMA project, directed by Prof. Francesco Topputo from Politecnico di Milano, aims to further foster research in the field, ultimately triggering a paradigm shift from the current methods of operating deep-space projects [4]. The project has been awarded a five years grant from the European Research Council and is planned to last five years. It aims to answer a fundamental Research Question:

To what extent can we navigate the Solar System free of human supervision?

In order to answer it, the EXTREMA project builds on three main Pillars:

- **Pillar I: Autonomous Navigation.** The research activities falling within this pillar focus on the development of a CubeSat-safe navigation algorithm to enable deep space probes to locate themselves in deep space in complete autonomy.
- **Pillar II: Autonomous Guidance and Control.** Currently, trajectory planning is performed on ground due to the limited computational resources available on board. Moreover, also correction maneuvers have to be planned from ground, employing huge resources in terms of time and human personnel. EXTREMA aims to develop a lightweight guidance algorithm that exploits the knowledge of the spacecraft position obtained through the algorithms developed in Pillar I to accurately compute a time-definite thrust profile and achieve the mission objectives in complete autonomy.
- **Pillar III: Ballistic Capture.** Cruising in deep space involves phenomena happening on large time scales; on the contrary, orbiting celestial bodies in close proximities presents further challenges due to faster dynamics and higher accelerations. The current technology on electric propulsion does not allow spacecraft to carry on expensive orbit insertion maneuvers; for this reason, the phenomenon of ballistic captures is here explored and engineered. Specific conditions in the state-space are individuated: these make up the capture set and subsequently define the ballistic capture corridors. When the spacecraft finds itself in a ballistic tunnel, it can exploit the multi-body dynamics of the Solar System to remain in the proximity of the celestial body for a prolonged period of time.

The outcome from each Pillar is meant to be integrated into a series of experiments and, ultimately, brought together in the EXTREMA Simulation Hub: a hardware-in-the-loop testing facility that would allow testing integrated guidance, navigation, and control (GNC) systems and algorithms.

The paper is structured as follows: in Section 2 the Pillar I will be described. An overview of the current paradigm for spacecraft navigation will be given in Section 2.1; the EXTREMA approach will be described in Section 2.2 instead. Section 2.3 will describe the EXTREMA Optical Facility and the experiment associated with Pillar I. Pillar II will be illustrated in Section 3, along with the current state of the art for spacecraft guidance (Section 3.1) and the envisioned approach (Section 3.2); again, the experiment associated to Pillar II will be described in Section 3.3. Section 4 will describe the Ballistic Capture and the approach employed to engineer it (Section 4.1). The integration of the three Pillars in the EXTREMA Simulation Hub will be discussed in Section 5, drawing a first architecture of the facility in Section 5.1 and giving some considerations on simulation time in Section 5.2. Finally, the potential outcomes of EXTREMA will be discussed in Section 6.

2 PILLAR I: AUTONOMOUS NAVIGATION

Performing navigation operation is critical in guaranteeing the reaching of typical objectives of deep-space missions. Navigation is performed whenever the state of the spacecraft - usually intended as its position and velocity with respect to a particular reference frame - is needed, such that operations as trajectory reconstruction or orbital guidance can be performed.

2.1 Current paradigm

The current paradigm for deep-space navigation relies on the communication between the space probe and the ground segment. In particular, radiometric tracking techniques are employed to track spacecraft in deep space: such techniques are able to obtain the spacecraft's position and velocity by processing range and range rate data. Until the 1970s, only range and Doppler information were used to infer the position of the spacecraft in the interplanetary space [5]; then, better accuracies were obtained exploiting a technique known as Very Long Baseline Interferometry (VLBI) [6]. The current systems are able to obtain accuracy up to the order of meters for close-Earth applications and in the order of kilometers for deep-space ones. However, these techniques are usually heavy on mission budgets. Indeed, extensive antennas are required for communicating with deep-space probes. The current paradigm relies on a few networks distributed across the globe, as the DSN (Deep Space Network), a set of three ground stations located in Madrid (ES), Goldstone (CA), and Canberra (AU) [7]. Since the availability is limited, operations need to be scheduled in advance, and only a few spacecraft at a time can be tracked [8]. This approach will unavoidably lead to the saturation of slots for deep-space communication, resulting in the hampering of the growth of deep space missions and applications.

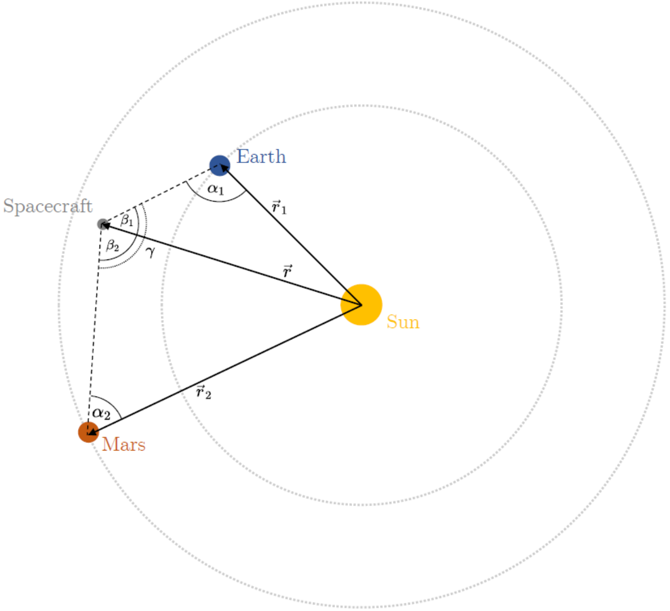

Figure 1 - Overview of a triangulation scheme. The position vectors $\vec{r}_1$ and $\vec{r}_2$ are known from the knowledge of the planets' ephemeris. The line-of-sight extraction allow to obtain the angle γ, and the spacecraft position vector $\vec{r}$ is then inferred by completing the geometry of the problem.

2.2 The EXTREMA approach for navigation

The EXTREMA project departs from this paradigm by envisioning autonomous navigation capabilities on board of CubeSats. In particular, the approach of radiometric tracking seems unsuitable to such applications because of

1. The high operational costs, that jeopardize the savings brought by CubeSat technologies;
2. The limited capabilities of typical CubeSat systems, that result in low data rates.

In our vision, the spacecraft is instead able to extract information on its position and velocity directly using its on-board sensor suite, requiring no communication with the ground segment. In particular, optical navigation techniques are envisioned to achieve the goal. Such techniques have already been widely investigated in different conditions. Close-proximity applications include feature-based navigation, in which the sharp variations in the brightness of an image (e.g., related to a surface feature as a crater) are used to estimate the position of the observer and retrieve the geometry of the celestial body [9, 10]. Mid-range navigation exploiting optical data has also been employed, with edge detection algorithms comparing the apparent shape of an object (e.g., the Moon) to its actual size and subsequently inferring the position of the observer [11]. Deep space navigation, instead, would employ optical navigation techniques to extract the line-of-sight celestial bodies. Thanks to the knowledge of the planets' position in the Solar System, it is possible to feed triangulation schemes to reconstruct the position of the observer [12, 13]. Of course, as optical data can be subject to measurements errors and outliers, filtering techniques are compulsory to build a robust system.

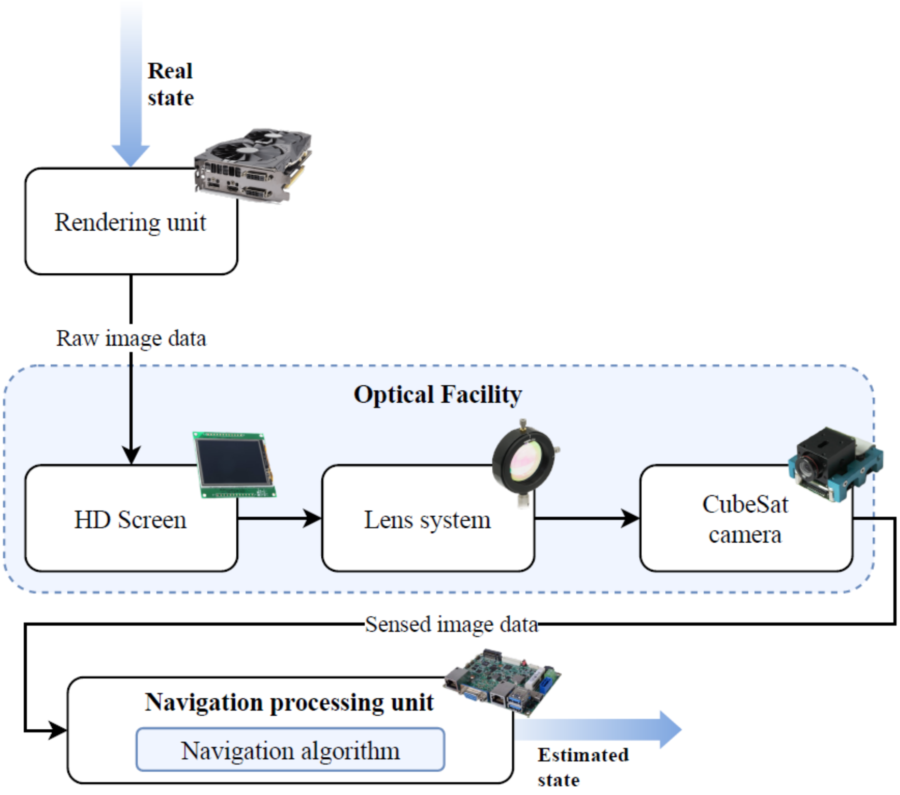

Figure 2 - Conceptual scheme of the logic to implement in RETINA

2.3 RETINA: The EXTREMA optical facility

To assess the robustness of the developed navigation algorithms, the EXTREMA project envisions the development of an Optical Facility (Figure 2) in which the uncertainties and perturbations associated with a real-world physical optical system can be taken into account. The EXTREMA optical facility RETINA (Realistic Experimental faciliTy for vIsion-based NAvigation) counts the following components:

1. a high-fidelity deep-space scene renderer, capable of producing an image given the information on the spacecraft position, velocity, and orientation;
2. a high-definition screen, on which the image will be cast;
3. a lens system that will make sure that the image will be seen as if it was at an infinite distance;
4. a camera, that will mimic the properties of typical cameras as found on CubeSats;
5. a processing unit, that will receive the raw image data as captured by the camera and will process them according to the desired navigation algorithm.

RETINA will be integrated inside the EXTREMA Simulation Hub, as it will be described in Section 5, and therefore it will need to run in real-time to comply with the requirements of the integrated simulation. To ensure the developed algorithm to be as general as possible and robust enough to work with different hardware and in multiple observing conditions, RETINA will employ a system of lenses that will be able to adapt the light incoming from the screen to different cameras and fields of view. In order to guarantee the on-board computational sustainability of the algorithm, a processor-in-the-loop experiment will be set up. A processing unit will be selected to mimic the traditional performances of onboard computers (OBC). The algorithm must be able to reconstruct the position of the spacecraft and an associated measure of uncertainty within a certain amount of time, complying with the memory and clock limitation of typical radiation-hardened devices. The accuracy of the algorithm, instead, will be assessed with the original data used to generate the rendered image in the first place.

3 PILLAR II: AUTONOMOUS GUIDANCE

In case the tracking of a deep space probe results in the spacecraft departing from its nominal trajectory, a set of correction maneuvers is required to ensure the reaching of the mission targets. The computation of a new trajectory is typically known as spacecraft guidance.

3.1 Current paradigm

Again, the current paradigm relies heavily on the communication between the space asset and the ground segment. The current practice is to compute the new trajectory on Earth, and relay to the spacecraft a set of information, being these in the form of specifics of impulsive maneuvers or the future history of the thruster pointing and actuation commands, such that it is able to re-align to the nominal trajectory or to follow an entirely new one. Of course, this approach can easily lead to issues that could eventually lead to mission failure. Indeed, in case of prolonged periods of communication blackouts - being these caused either by unfortunate positioning of the spacecraft with respect to the Earth [14], strong electromagnetic perturbations in the environment [15], failure of on-board (or ground) systems, or simply a communication schedule limited by budget constraints nothing guarantees that the spacecraft will have enough fuel or control authority to reach of its target. Historically, deep-space missions have been carried on employing bigger, monolithic spacecraft [16]. These were characterized by chemical engines designed to be fired impulsively. The employment of low-thrust engines has been investigated only recently to reach targets outside Earth’s sphere of influence, as in the case of the MARGO mission [2].

3.2 The EXTREMA approach for guidance

EXTREMA envisions deep-space CubeSats cruising in the Solar System powered by low-thrust engines characterized by high specific impulses. Indeed, given the limited capabilities of their on-board systems in terms of performance and their reduced launch mass, it is paramount to exploit the thrusting technologies with higher efficiencies in terms of mass consumption. This choice leads to a first characterization of the autonomous guidance operations to be performed: the reference problem is the continuous low-thrust transfer problem. Different approaches to tackle the problem are available:

- An *open-loop* guidance paradigm implies the computing of a reference trajectory, with an associated control actuation history and the religious following of the latter. This approach is not robust to external perturbations and can easily lead to mission failure in case of unmodeled effect in the transfer dynamics.
- A *fly-the-wire* approach, or *perturbation guidance*, envisioning the spacecraft following a nominal trajectory and a set of correction maneuvers to force it to remain in close proximity to it. This approach is better in terms of robustness and is also computationally efficient considering that it is possible to approximate the dynamics of the system in the proximity of the nominal trajectory [17]. However, it is still sensible to higher perturbations making the spacecraft depart from the neighborhood of the nominal trajectory and does not guarantee the optimality of the solution under a generic set of external unmodeled perturbations.

- A *closed-loop* guidance approach. This approach exploits the capability to re-compute new nominal trajectories according to the information given by the navigation system. According to a set of pre-determined conditions - being them met when the spacecraft departs from the previous nominal trajectory of a certain amount, or according to a fixed time schedule - the spacecraft state is exploited to compute a new, optimal nominal trajectory. The robustness of this approach is directly inherited from the robustness of the trajectory computation algorithm and guarantees the optimality of the overall spacecraft path under a generic set of unmodeled perturbations.

The aim of EXTREMA is to maximize the efficiency of the closed-loop guidance approach by enabling CubeSats with autonomous guidance capabilities. Once the spacecraft state is reconstructed through the navigation algorithm, in case the trigger conditions are met, it would re-compute a new trajectory and generate a new thruster actuation command history. Of course, both the navigation and the trajectory computation algorithm must guarantee a high level of robustness. Since EXTREMA wants to achieve no communication between the probe and the ground, the following requirements for the onboard trajectory computation algorithm must be guaranteed:

- **Robustness.** The algorithm must guarantee that a feasible solution is achievable at any moment; the situation of the guidance algorithm not converging cannot be tolerated in the envisioned paradigm.
- **Computational Efficiency.** The algorithm must be sustainable for an on-board implementation given the reduced performance of typical CubeSats’ OBC and limited power resources.
- **Optimality.** A cost function is to be minimized (usually the fuel consumption); indeed, CubeSats have usually access to limited amounts of fuel and resources.

Moreover, the two-fold interaction between the navigation and the guidance system must not be neglected: the computed trajectory should ensure the trackability requirements of the navigation system at multiple points along its path.

In EXTREMA, multiple approaches to the solution of the continuous low-thrust transfer problem will be investigated. Direct methods work by solving the full nonlinear optimization problem [18], but are not suitable for on-board applications due to their high computational burden and poor robustness; indirect methods exploit the Pontryagin principle [19] and guarantee the optimality of the solution through a set of dynamic equations involving auxiliary variables; they are usually sensitive to initial guesses and therefore do not guarantee the robustness requirements. Research in EXTREMA is currently focused on a convex optimization (CP) approach, in which the original non-convex interplanetary transfer problem is transformed into a convex one. The latter can then be solved with polynomial-time algorithms. The solution of the original problem can be obtained through iterative techniques (e.g., sequential convex programming, SCP [20]) with good convergence properties [21]. Differently from indirect methods, convex optimization does not guarantee the final solution to be optimal, but only sub-optimal [22, 23]. Despite that, this approach is seen as the best trade-off between computational sustainability, robustness, and optimality.

3.3 ETHILE: The Extrema thruster test bench

In order to test the robustness of the guidance algorithm, EXTREMA adopts a hardware- and processor-in-the-loop experiment (Figure 3). The EXTREMA Thruster-In-the-Loop Experiment (ETHILE) is meant to validate the computational sustainability of the algorithm and its robustness to unmodeled perturbations. It will propagate the state of a spacecraft according to the actuation history as returned by the guidance algorithm.

Unmodeled perturbations can be distinguished into two groups: the one arising from the environment and the one arising internally from the spacecraft. In order to model the ones arising from the physicality of the spacecraft engine, a thruster test bench employing a real mock-up of the spacecraft engine will be employed. The specifics of a low-thrust ion engine will be mimicked by the cold gas thruster thanks to an accelerating framework based on dynamic similarity and through the implementation of a system of pressure regulators and fast response solenoidal valves. A force transducer measures the axial force arising from the thruster, and this will be mapped to a thrust value to be fed to the numerical propagator. Thrust misalignment errors will be introduced a) by the attitude sensors themselves, which estimate the FlatSat pose on the attitude simulator, b) via simulation settings (e.g. when considering a systematic error or bias). Pressure and temperature sensors will be used to control the cold gas thruster performance, with the aim of compensating variations in the test environment (e.g., fluctuations in the supply pressure).

The propagator will be developed in-house and will also include the perturbations arising from the environment (i.e., Solar Radiation Pressure (SRP)). In order to comply with the hardware-in-the-loop requirement, the numerical propagator must adopt either explicit or semi-implicit integration schemes [24] (e.g., SDIRK [25]), as fully implicit schemes are not suitable to HIL simulations since they need information on time steps that still have to happen at the moment of computation.

The numerical integrator will propagate the spacecraft position in deep space and will simulate its attitude and navigation system; whenever a trajectory recomputation will be required according to the selected criteria, the guidance algorithm will be run on a single-board computer carefully selected to mimic the performances of a real spacecraft OBC.

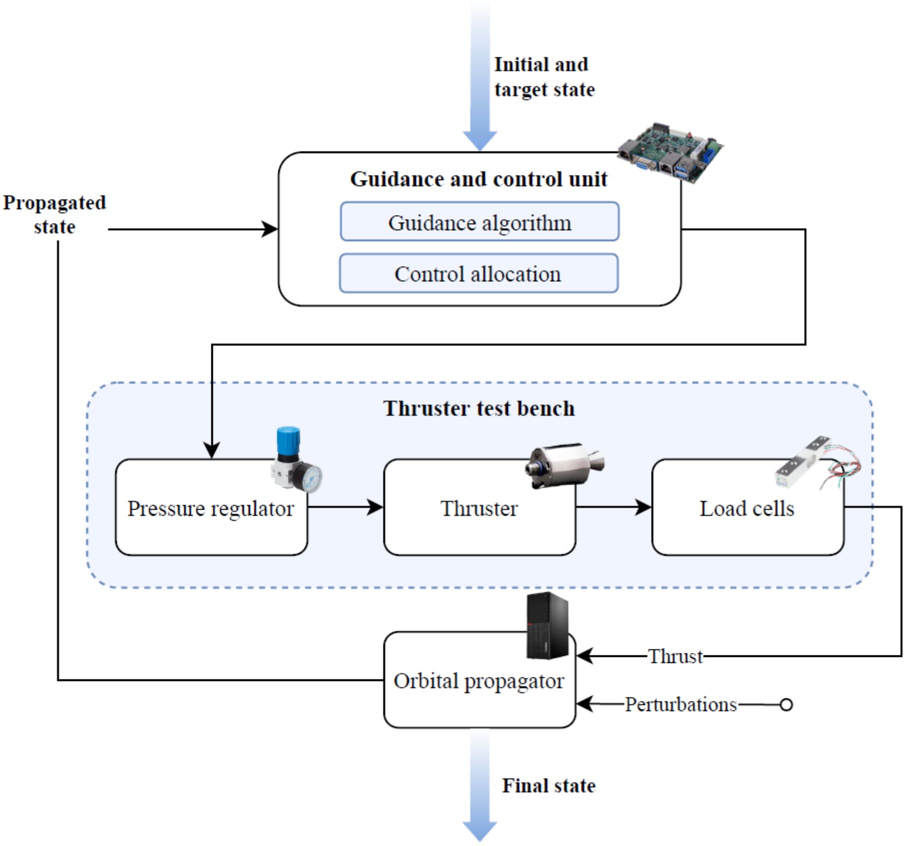

Figure 3 - Conceptual scheme of the thruster test bench ETHILE

4 PILLAR III: AUTONOMOUS BALLISTIC CAPTURE

The limited availability of resources on CubeSats has already been discussed. However, its effects have been presented only for what concerns the cruise phase of the interplanetary transfer; despite that, they heavily influence the availability of orbit insertion maneuvers, as the typical thrust magnitude values offered by electric engines do not offer enough control authority to perform such maneuvers.

In this context, the EXTREMA project investigates the possibility to exploit the natural dynamics of the n-body problem to achieve temporary captures around major celestial bodies. These events are usually known as ballistic capture. A ballistic capture happens when, after a certain powered trajectory and an insertion phase in which no additional maneuver is required, the spacecraft achieves a temporary orbit around a celestial attractor and remains in close proximity to it for a prolonged period of time, usually performing a certain number of revolutions around it [26].

Ballistic captures offer great benefits in terms of mission costs and flexibility; however, they are complicated phenomena observed in highly sensitive regimes [26, 27]. According to the algorithm described in [28], only 1 in 10,000 explored initial conditions result in ballistic capture. These define the capture set, which is in turn used to define the concept of ballistic capture corridors: They are time-varying manifolds in the state space that guarantee the capture of the spacecraft by the planet [29]. The aim of EXTREMA is to engineer ballistic capture, and enable CubeSat to achieve it autonomously.

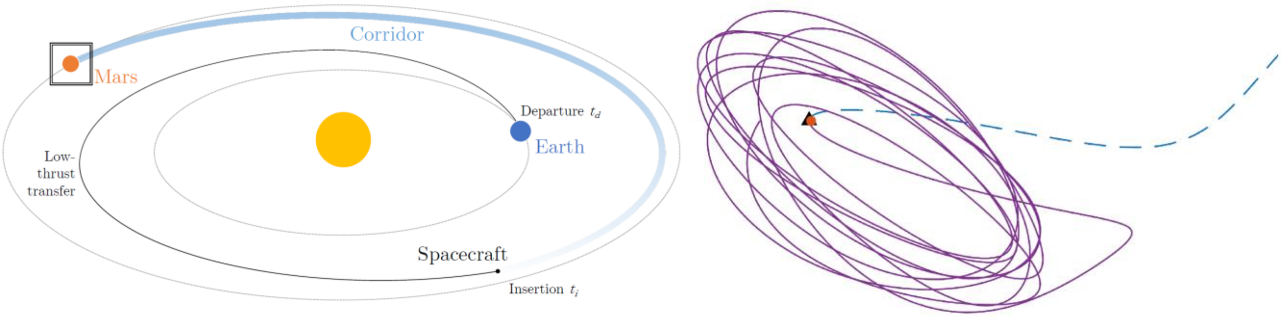

Figure 4 - Representation of a ballistic capture. On the left the trajectory followed by the spacecraft under low-thrust actuation is displayed. At t_i, the spacecraft enters the ballistic capture corridors and is able to reach Mars with no additional actuation. On the right the trajectory followed by the spacecraft after being captured by Mars is displayed, with the probe performing multiple revolutions around the planet.

4.1 Engineering ballistic capture

In order to engineer ballistic capture, a series of subobjectives have been defined in the EXTREMA project.

1. **Characterize the ballistic capture corridors**: understand their behavior in the state space and provide a classification framework [29].
2. **Develop a numerical approximation of them**: currently, high levels of computational power are required in order to find trajectories that culminate in ballistic capture. This approach is believed to be unsustainable given the limited computing performance of OBCs traditionally found on CubeSats. Therefore, EXTREMA defines the development of a catalog of numerical approximation of ballistic capture corridors as its objective, to implement it on board. Multi-dimensional interpolation will then be performed on-board, as in [30], to evaluate the attainability of ballistic capture from state-space conditions not covered by the catalog.
3. **Guarantee computational sustainability of the procedure**. The numerical approximation should guarantee that the spacecraft is able to find and target ballistic capture corridors in total autonomy. To this purpose, a set of processor-inthe-loop experiments has been envisioned employing computing boards whit performances similar to the ones found on space-graded OBC.

Would EXTREMA be able to achieve these three objectives, it would allow spacecraft to compute and target ballistic corridors in complete autonomy.

5 THE EXTREMA SIMULATION HUB

The EXTREMA Simulation Hub is thought of as a facility in which the outcomes of the three EXTREMA's Pillars and experiments are integrated. Its realization and validation will mark the success of EXTREMA. The ESH aims to provide a test environment in which to test autonomous GNC systems during interplanetary transfers. To this purpose, the navigation, guidance, and control units must be interconnected to test the validity and robustness of the developed algorithms in a fully functional facility that will simulate the transfer of a spacecraft from an initial condition towards a target located in deep space.

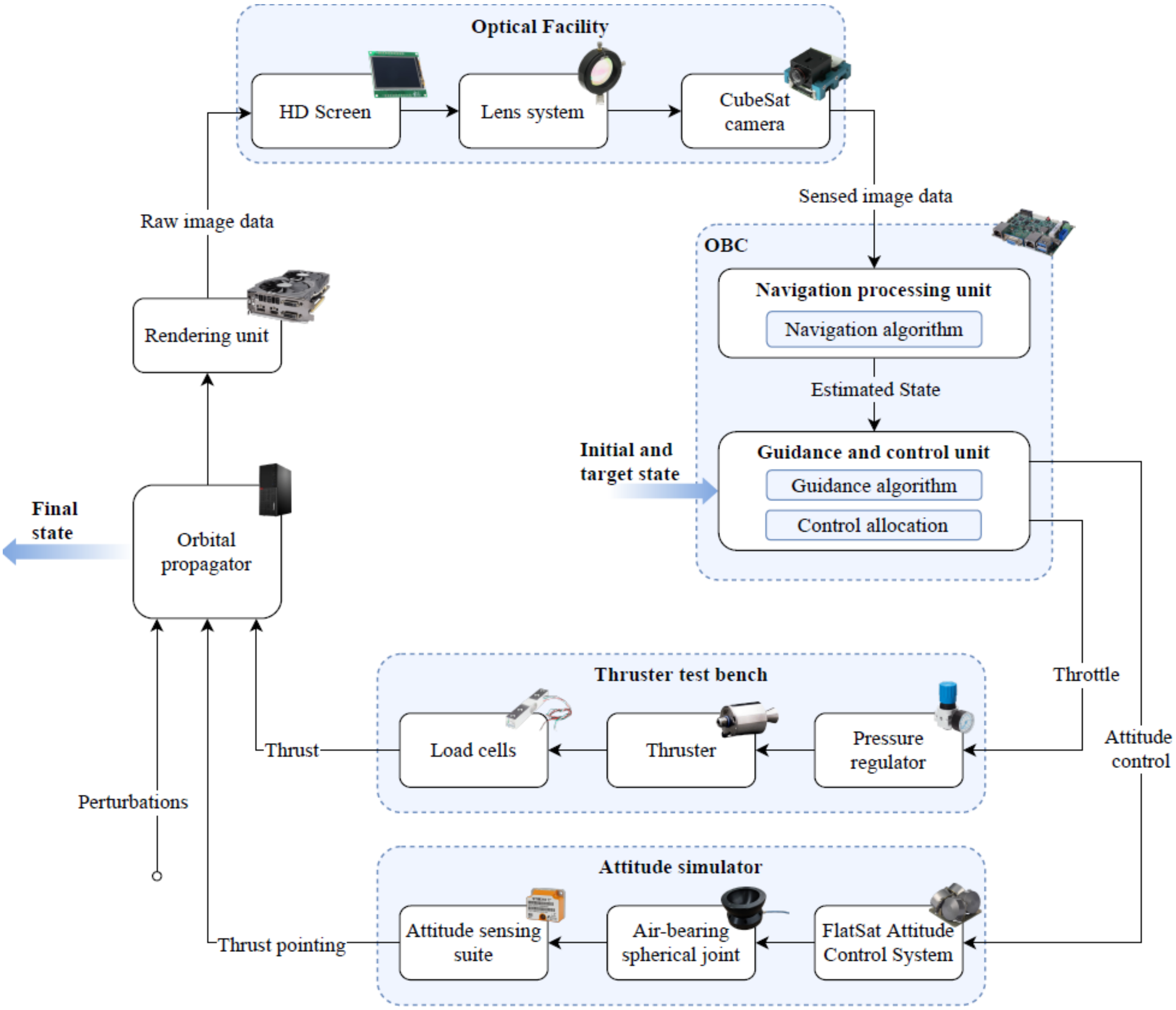

Figure 5 – Full logic scheme of the EXTREMA simulation hub.

5.1 ESH ARCHITECTURE

Figure 5 represents the architecture of the ESH. The core of the facility is represented by the guidance unit. The guidance unit will run the GNC algorithms and the software developed to find and target ballistic capture events. A similar setup to the one described for Pillar II is foreseen, with a cold gas thruster actuating the command as sent by the guidance unit and a force transducer reading the magnitude and orientation of the thrust before feeding them to the numerical propagator. Moreover, an attitude simulation system is envisioned: the guidance unit will be mounted on a FlatSat, and the whole assembly (together with a representation of the CubeSat's attitude determination and control system) mounted on top of an air-bearing spherical joint to obtain frictionless rotational motion around the center of mass of the system. A state-of-the-art sensing suite will be employed, reading the actual orientation of the FlatSat and feeding it to the numerical propagator to propagate the state of the spacecraft. At each timestep, the numerical propagator will trigger the rendering of a deep-space scene to be cast on the high-definition screen of the optical facility and sensed by the navigation camera. This closes the loop: whenever the OBC requests an image of the deep space scene to reconstruct its state (to be fed to the guidance unit), the camera will send the raw image data ready to be processed. If a trajectory recomputation is needed, the guidance unit will perform it and will then actuate the new control command history. The simulation will run in real-time to achieve maximum simulation fidelity. In order to guarantee the synchronization between the platform state and the spacecraft state in deep space, the set of operations required in a single step cycle must be performed with a hard limit on the computational time. This means that the filtering of the sensor suite, state propagation, and image rendering and casting procedures must be executed with a hard time constraint.

5.2 Considerations on Simulation Time

Interplanetary transfers, especially the ones involving low-thrust and ballistic capture, are usually characterized by prolonged transfer times [3, 32, 33], usually in the order of months or years. Since EXTREMA aims to simulate interplanetary transfers from their beginning until ballistic capture is achieved, a framework to execute the experiments in reduced time frames is required [31]. To this purpose, a set of mathematical caveats can be exploited. The underlying framework that allows this to be done while maintaining high simulation fidelity is based on the dynamic similarity; it sees the mapping between the original system (represented by the actual Solar System and spacecraft) to a scaled one, in which phenomena happen faster. The resulting system is characterized by reduced times and distances and higher levels of thrust (Figure 6), attainable with thrusters that are easier to employ in a controlled lab environment. The quantities of interest are then derived through a set of mathematical relationships.

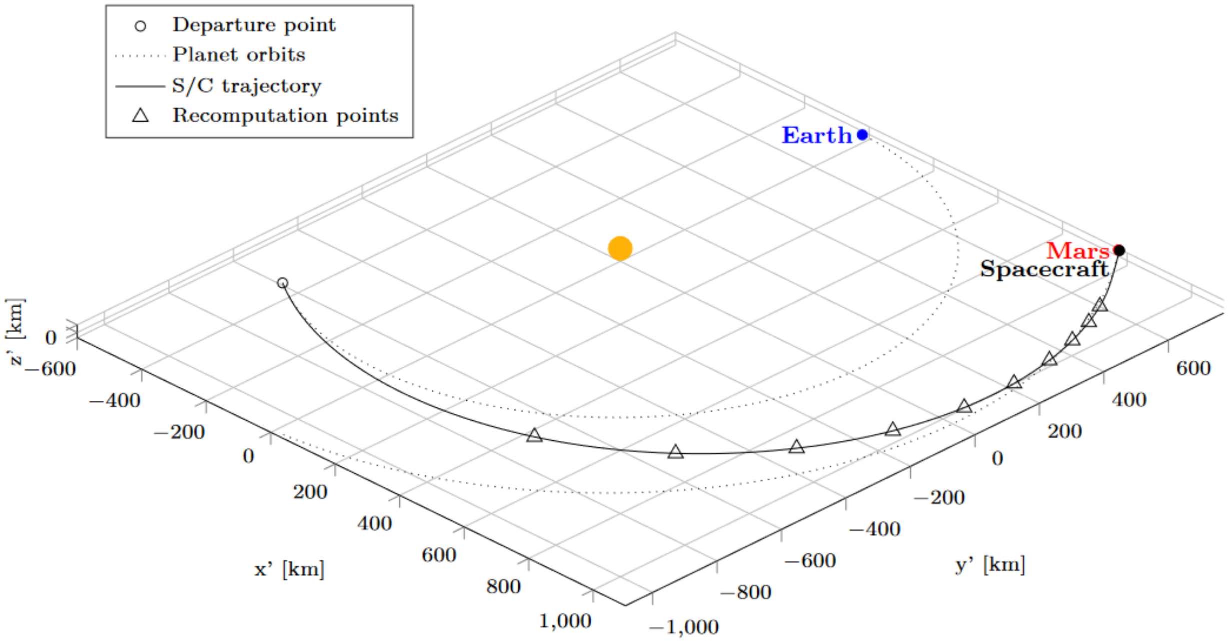

Figure 6 - Example of a trajectory obtained with a closed-loop guidance approach [31]. In this case, the spacecraft performs ten trajectory recomputations according to a logarithmically-spaced recomputation schedule. The recomputations have been performed with a simple shape-based

method. The simulation has been run in real-time on an accelerating framework that also resulted in the scaling of distances, as it is possible to see from the axes ticks.

6 POTENTIAL OUTCOMES

Evaluating the potential outcomes of EXTREMA is not trivial. The project's success would be of great benefit to the scientific community; indeed, the approach to space missions has always followed a cautious mindset due to the large budgets required. Despite the dramatic reduction of manufacturing and launch costs seen in recent years, operations still represent an important obstacle to access deep space for smaller companies, universities, and institutions.

Moreover, by focusing on CubeSats, typically characterized by smaller, cheaper, and less performing systems, the outcomes from the project would be seamlessly transferrable to bigger monolithic spacecraft as well. This means that EXTREMA has the potential not only to improve the current knowledge of the Solar System by easing the exploration of major and minor bodies: as bigger spacecraft are nominally characterized by higher budget, better-performing systems, and a more diverse gamma of payloads, the project could be the key to finally achieve autonomy on any type of interplanetary spacecraft and open the doors to a new era of space *exploitation*.

7 CONCLUSIONS

The EXTREMA project is ambitious. It targets an emerging problem in astrodynamics, aiming to free interplanetary spacecraft from ground supervision. To do that, it attacks the fundamental research question by addressing what are considered to be three key aspects for enabling autonomous CubeSats: ensuring autonomy for navigation, guidance, and ensuring these in a complex scenario as the one of ballistic capture.

The challenges the project must face are multiple and stem from different sub-fields of space engineering. However, the outcomes discussed in the previous section totally define the project as a high-risk/high-gain one and predict its potential success to be a key milestone for the future of space exploration and exploitation.

8 ACKNOWLEDGEMENTS

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