(Preprint) AAS 23-188

SPESI: A REAL-TIME SPACE ENVIRONMENT SIMULATOR FOR THE EXTREMA PROJECT

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EXTREMA is a project, funded by the European Research Council, that aims towards a paradigm shift in the spacecraft Guidance, Navigation, and Control, by enabling probes able to reach their destination in a totally autonomous fashion. Within the project, the EXTREMA Simulation Hub will be exploited to carry on dynamic simulations of the spacecraft-environment interaction, allowing high-fidelity testing of deep-space autonomous GNC systems. This work presents the EXTREMA's space environment simulator (SPESI). SPESI has the aim to propagate forward the spacecraft trajectory and generate the surrounding scene to be fed by the spacecraft sensors in real time.

INTRODUCTION

Space economy is booming. Integrated, space-based services will soon benefit mankind at unprecedented levels. Private companies are establishing several artificial constellations composed of thousands of satellites. The momentum characterizing the near-Earth space will soon affect outer space as well. At this pace, a multitude of miniaturized probes will soon pervade the inner solar system. The abundantly variegated minor bodies (asteroids and comets) will be destination of numerous missions. Rocky planets will feature networks of artificial satellites to support science and operations. A shift from space exploration to systematic space exploitation will take place due to the steady reduction of natural resources on Earth. All in all, evidence is mounting that the near future will be characterized by a large number of deep-space missions.

Since the beginning of the space era, interplanetary probes have been operated from ground. Operations are conducted by flight control teams and involve performing a number of routine tasks. Governing the space flight consists of determining the spacecraft position, planning its trajectory, and controlling its motion. Accordingly, these activities are known as a whole as Guidance, Navigation and Control (GNC). The acute increase of deep-space missions will shortly lead to saturation of ground-based facilities, inducing the urgency of granting autonomy in GNC to deep-space probes.

The EXTREMA project (Engineering Extremely Rare Events in Astrodynamics for Deep-Space Missions in Autonomy), funded by the European Research Council, aims towards a paradigm shift on how deep-space GNC is performed, enabling CubeSats with autonomous capabilities. In this perspective, self-driving spacecraft become the main focus: machines that can travel in deep space and reach their destination in a totally autonomous fashion. These systems are used to engineer ballistic capture, an extremely rare event in astrodynamics that is characterized by high sensitivity,

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thereby proving the effectiveness of autonomy in a complex scenario. Validating this technology will be a step toward uncharted territories in space exploration: missions will no longer be limited by our capability to operate spacecraft. Space and ground systems will be unchained. It will be a disruptive innovation in access to outer space, especially when combined with system miniaturization, such as CubeSats, nanosatellites made of cubic modular units (10 cm edge, 1.3 kg mass[1]), that can grant access to space to institutions and small companies.

Although the success of CubeSats for Earth observation is unquestionable, deep-space exploration is still dominated by conventional, monolithic spacecraft. Several technological gaps prevent realizing interplanetary CubeSats: with their minute budgets, power production, communication, micro propulsion, attitude pointing, orbit control, and radiation shielding become extremely challenging. However, the recent success of the two MarCO CubeSats[2] indicates that interplanetary CubeSats are bound to thrive in the near future. Nevertheless, it can be proven that the overall cost for interplanetary missions scales with the system mass, except for what concerns operations: under the current paradigm, operating a 1-kg spacecraft requires the same effort as operating a 1-ton one. Self-driving interplanetary CubeSats have the potential to demolish this last barrier, favoring full mission scalability. A reduced effort required for operation will further lower the overall mission cost, making it even easier for small institutions to access outer space.

THE EXTREMA PROJECT

The EXTREMA project 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, EXTREMA wants to enable deep-space, limited-budget spacecraft to determine their position using information embedded in the environment, to plan their trajectory using on-board available computational resources, and to govern their motion using on-board low-thrust propulsion, for the whole duration of an interplanetary mission. As a consequence, the spacecraft has to:

(a) infer information from the surrounding environment to determine the state;

(b) generate a plan for the trajectory that reaches the target mission destination;

(c) execute the plan and correct for possible deviations arising from unmodeled disturbances.

It is assumed that the three actions are executed recursively during the cruise, until the mission destination is reached. The conceptual logic of the research hypothesis introduces two actors: the spacecraft and the environment. They interact by virtue of the information inferred by the former and through its dynamics, which in turn alters their relationship. This paradigm is challenging because the deep-space environment is scarce of information, and the spacecraft has limited control authority. The logic is executed in a totally autonomous fashion; no intervention from ground is contemplated in the research hypothesis.

The project is built on three pillars:

1. **Pillar I** deals with autonomous navigation, and aims to develop algorithms and techniques to determine the state of the spacecraft through optical navigation in complete autonomy;

2. **Pillar II** deals with autonomous guidance and control, and aims to develop state-of-the-art trajectory computing algorithms under a closed-loop guidance paradigm, in which a new trajectory is re-computed on board together with a time-definite thrust profile, in order to achieve the mission objectives in complete autonomy;

3. **Pillar III** faces autonomous ballistic capture, and aims to validate the previous algorithms in a complex scenario that is also appealing for CubeSats missions.

As a matter of fact, 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.

Three experiments are foreseen, one within each pillar. The experiments will produce intermediate results, and are instrumental for the EXTREMA Simulation Hub. The outcome from each Pillar is meant to be integrated 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.

An overview of the 3 pillars will be provided in the remainder of this section, since it will be instrumental for the core of this work.

Pillar I

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 is needed, such that operations as trajectory reconstruction or orbital guidance can be performed.

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.[3] 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, large and expensive antennas are required for communicating with deep-space probesm with only a few networks distributed across the globe, as the DSN (Deep Space Network).[4] Their limited availability 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.

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. 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.[5,6]

To assess the robustness of the developed navigation algorithms, the EXTREMA project envisions the development of an Optical Facility 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:[7]

1. a high-definition screen, on which an image of the surrounding environment will be cast;
2. a lens system that will make sure that the image will be seen as if it was at an infinite distance;
3. a camera, that will mimic the properties of typical cameras as found on CubeSats;
4. 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.

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. Moreover, the 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.

Pillar II

A deep space probe will never follow its prescribed path due to uncertainty in the dynamics, navigation, and control. In order to reach the mission targets, a set of correction maneuvers, coping with the estimated deviations, must be computed, in the so-called spacecraft guidance.

Currently, spacecraft guidance relies heavily on the communication between the spacecraft and the ground. The current practice is to compute a new trajectory on ground, and upload to the spacecraft a set of commands, in the form of determined impulsive maneuvers or future history of the thruster pointing and actuation, such that the spacecraft is able to track the nominal trajectory or to follow an entirely new one. Of course, this approach is expensive and in some cases can jeopardize the entire mission (e.g., in case of prolonged periods of communication blackouts).

EXTREMA envisions deep-space CubeSats cruising in the Solar System powered by low-thrust engines characterized by high specific impulses, due to their higher efficiencies in terms of mass consumption. Thus the guidance algorithm will be based on the continuous low-thrust transfer problem. A closed-loop guidance approach is selected due to its robustness and flexibility. Under this approach, once the spacecraft state is reconstructed through the navigation algorithm, it would re-compute a new trajectory and generate a new thruster actuation command history. The onboard trajectory computation algorithm must guarantee robustness against uncertainty, optimality to better exploit the limited on-board resources, and computational efficiency, so that it can be run on a CubeSat on-board computer. To this aim, 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) with good convergence properties.[8] Convex optimization does not guarantee the final solution to be optimal, but only sub-optimal.[9] Despite that, this approach is seen as the best trade-off between computational sustainability, robustness, and optimality.

In order to test the robustness of the guidance algorithm, EXTREMA adopts a hardware- and processor-in-the-loop experiment. The EXTREMA Thruster-In-the-Loop Experiment (ETHILE) is meant to validate the computational sustainability of the algorithm and its robustness to unmodeled perturbations,[10] by exploiting a CubeSat-like system-on-a-chip to simulate the on-board computer, a cold-gas with similar performances to a low-thrust CubeSat thruster, and a complete sensing suite to record the exerted thrust.

Pillar II

Limited availability of resources on CubeSats heavily influence also the possibility to perform some kind 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 about major celestial bodies. These events are usually known as ballistic capture. A ballistic capture happens when the spacecraft achieves naturally a temporary orbit around a celestial body and remains in close proximity to it for a prolonged period of time, usually performing a certain number of revolutions around it.[11]

Ballistic captures offer great benefits in terms of mission costs and flexibility; however, they are complicated phenomena observed in highly sensitive regimes. According to the algorithm described in,[12] 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.[13] The aim of EXTREMA is to engineer ballistic capture, and enable CubeSat to recompute them, or a high-fidelity approximation, if required, and achieve them autonomously.

The EXTREMA Simulation Hub

The EXTREMA Simulation Hub (ESH) is an integrated infrastructure to carry on dynamic simulations of the spacecraft-environment interaction, allowing high-fidelity testing of deep-space autonomous GNC systems for CubeSats.[14] The outcomes from each one of the three pillars will be validated with a tailored experiment featuring the model of the associated CubeSat subsystems. However, this does not guarantee the functionality of the interactions between the latter. For this reason, an integrated experiment involving all the components of a CubeSat GNC system is required. This experiment will be carried on in the EXTREMA Simulation Hub, an integrated facility that will simulate an interplanetary transfer with a hardware-in-the-loop setup. The EXTREMA Simulation Hub will represent the validation and success of the EXTREMA project. Figure 1 represents a functional scheme for the integrated simulation. The ESH is made by some blocks simulating the spacecraft subsystems (indicated in blue in Figure 1) and a block that simulates the surrounding environment (in red), that is the EXTREMA SPace Environment SImulator (SPESI).

The core of the facility is represented by the guidance unit, that will run the GNC algorithms and the software developed to find and target ballistic capture events, using as input the rendering of a deep-space scene to be cast on the high-definition screen of the optical facility and sensed by the

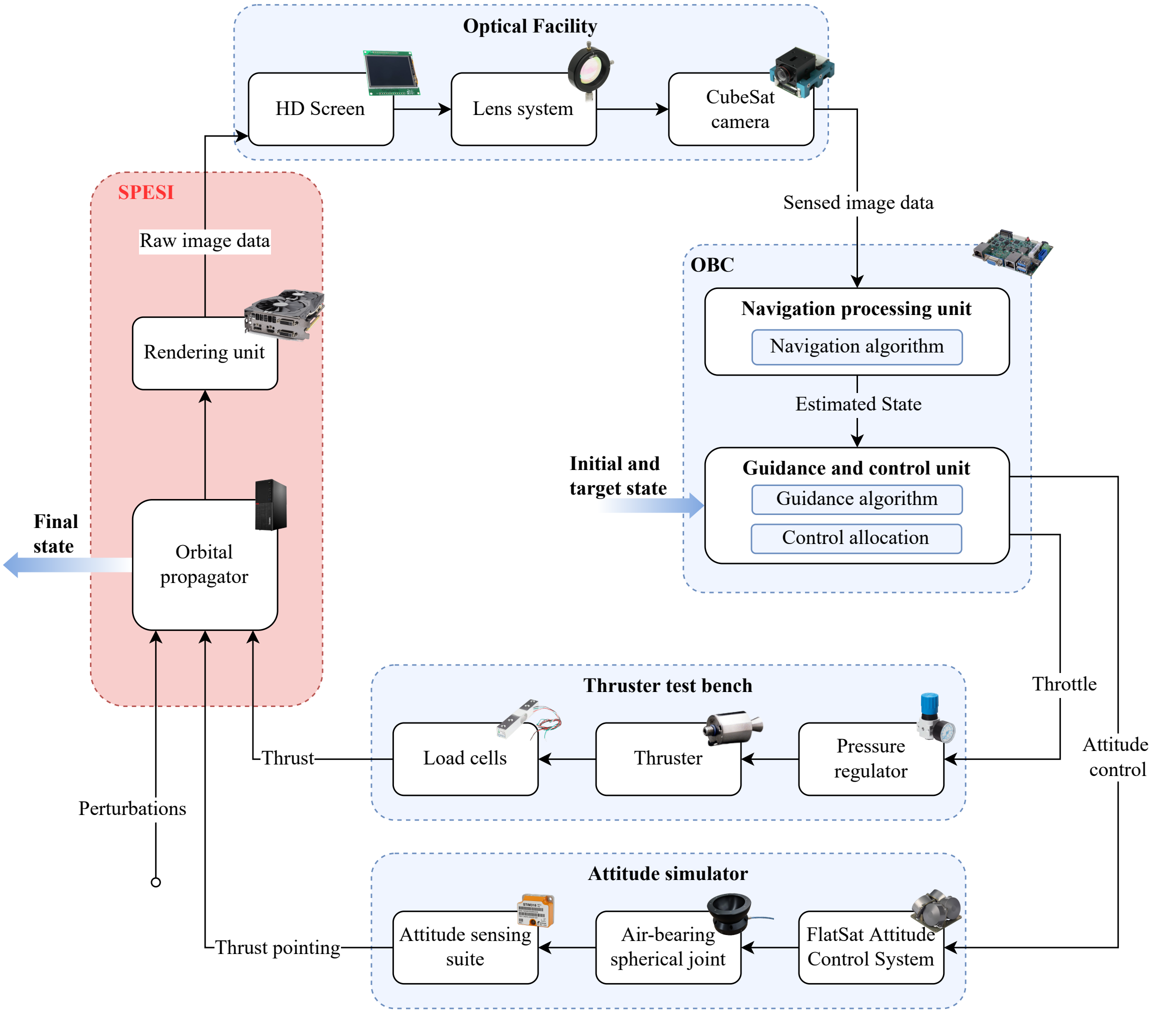

Figure 1: Functional logic of the ESH.

navigation camera. A cold gas thruster will actuate the commands sent by the guidance unit and a force transducer will read the magnitude of the thrust. 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. Generally speaking, 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. SPESI will oversee the process, since it simulates the space dynamics and environment, taking as inputs the real spacecraft thrust and attitude and giving as output a high-fidelity rendering of scene the spacecraft will see as it is in deep-space. 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 hard real-time constraints.

It must be noted that interplanetary transfers, especially the ones involving low-thrust and ballistic capture, are usually characterized by transfer times in the order of months or even 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.[15] 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 (i.e., 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 2), attainable with thrusters that are easier to employ in a lab environment. The need to have dynamics faster-than-real is accounted in the ESH design.

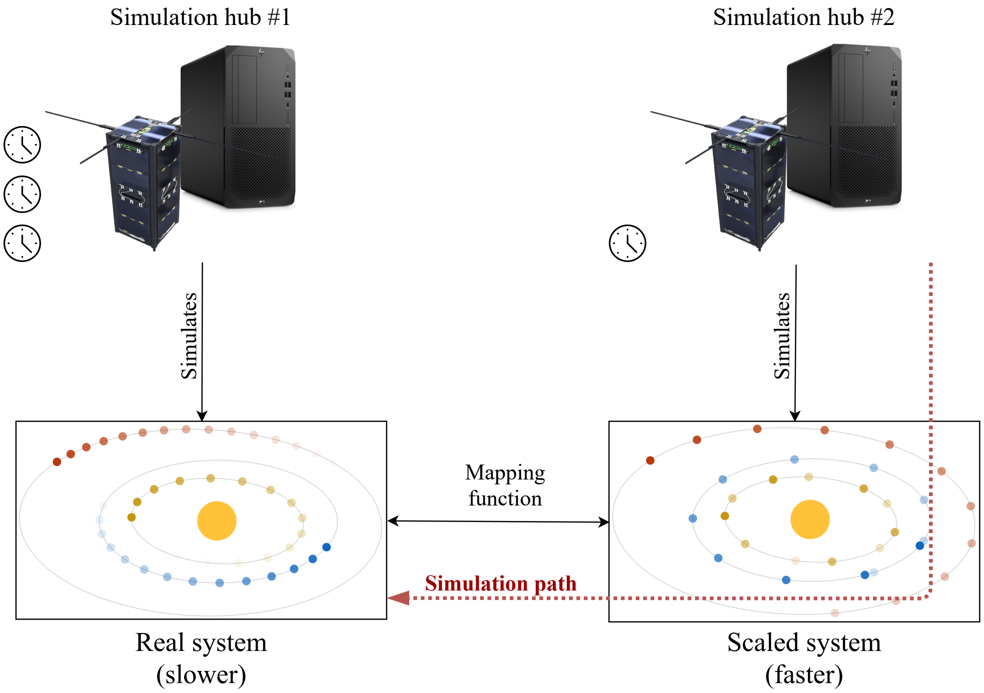

Figure 2: Conceptual scheme of the mapping approach.

SPACE ENVIRONMENT SIMULATOR

The SPace Environment SImulator (SPESI) is the block within the EXTREMA simulation hub that generates and simulates the external environment. Figure 3 shows the functional breakdown structure for SPESI in its default mode. Specifically, in each cycle of the ESH, it

1. takes as inputs the FlatSat attitude and the thrust magnitude,
2. propagates forward in time the trajectory,
3. performs a rendering of the scene, and
4. feeds it to the HD screen.

These tasks must be performed in hard real-time, in order to provide to the spacecraft sensors the correct image and close the functional loop correctly. For this reason, within the EXTREMA project, SPESI is implemented on a workstation equipped with a Intel i9 10900X CPU working at 3.7GHz, 64GB DDR4 RAM, and two nVidia Quadro RTX4000, exploited for their fast rendering capabilities, running a Linux kernel version 5.10 customized with the PREEMPT_RT patch.[16]

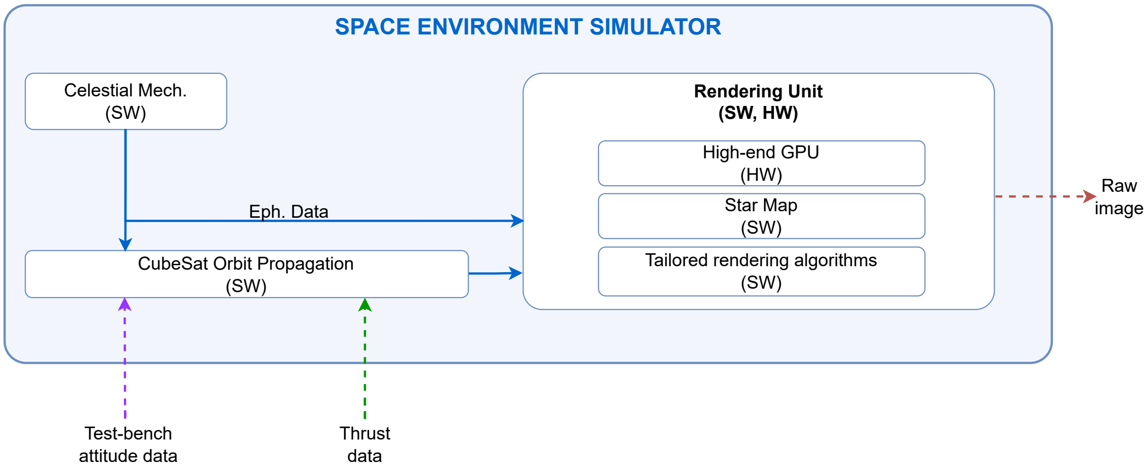

Figure 3: SPESI functional breakdown structure.

Figure 4 shows the typical time sequence that SPESI undergoes in each ESH cycle. For each ESH time-step of length h, SPESI integrates the state in the first τ_{int} seconds, reading the thrust T and the attitude θ in real-time, when requested by the integration scheme; then, in the last τ_{rnd} seconds, it performs the rendering. Just before sending the image to the HD screen, it reads the attitude in order to provide an image with the correct orientation. Of course, in order to have the most efficient algorithm, the constraint $\tau_{int} + \tau_{rnd} = h$ is enforced. In its default implementation, SPESI employs half a step for both tasks.
It must be noted that, even if SPESI can call the inputs several times, based on the integrator, inputs cannot be read after τ_{int}, reducing so the exploitable integration schemes. For example, implicit schemes or methods requesting the right-hand side beyond the time-step cannot be used.

From Figure 3, three main blocks can be identified and they are

1. the *orbital propagator*,
2. a tool for retrieving the *celestial mechanics*, and
3. the *rendering unit*.

Each of them is implemented not only to be flexible, but considering the specifics of the hardware and exploiting the preemption routines coming for the operating system kernel, in order to properly cope with the hard real-time constraints of the EXTREMA experiment.

Orbital propagation

The first sub-block of SPESI is made by its orbital propagator. The spacecraft dynamics is modeled using an extended parameterized post-Newtonian formulation (PPN),[17] considering the gravitational accelerations, the general relativity correction, the Lense-Thirring precession, the solar

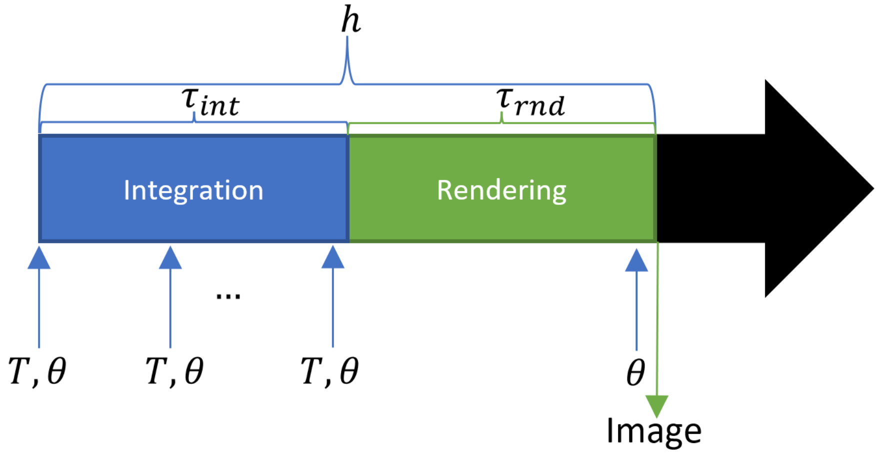

Figure 4: SPESI tasks time sequence.

radiation pressure, and the spacecraft thrust, i.e.,

$$
\begin{aligned}
\ddot{\mathbf{r}} = & \underbrace{-\sum_{i\in\mathbb{P}} \mu_i \frac{\mathbf{r}-\mathbf{r}_i}{\left\|\mathbf{r}-\mathbf{r}_i\right\|^3}}_{\text{Gravitational acc.}} + \underbrace{\sum_{i\in\mathbb{P}} \mu_i \frac{\mathbf{r}-\mathbf{r}_i}{\left\|\mathbf{r}-\mathbf{r}_i\right\|^3} \left[\frac{2(\beta+\gamma)}{c^2} \sum_{k\in\mathbb{P}} \frac{\mu_k}{\left\|\mathbf{r}-\mathbf{r}_k\right\|} + \frac{2\beta-1}{c^2} \sum_{k\in\mathbb{P}\setminus\{i\}} \frac{\mu_k}{\left\|\mathbf{r}_i-\mathbf{r}_k\right\|} + \right.}_{\cdots} \\
& \underbrace{\left. -\gamma \frac{\mathbf{v}\cdot\mathbf{v}}{c^2} + (1+\gamma) \frac{\mathbf{v}_i\cdot\mathbf{v}_i}{c^2} + 2(1+\gamma) \frac{\mathbf{v}\cdot\mathbf{v}_i}{c^2} + \frac{3}{2c^2} \left(\frac{(\mathbf{r}-\mathbf{r}_i)\cdot\mathbf{v}_i}{\left\|\mathbf{r}-\mathbf{r}_i\right\|} \right)^2 - \frac{1}{2c^2} (\mathbf{r}-\mathbf{r}_i)\cdot\mathbf{a}_i \right] +}_{\text{General relativity acc. according to PPN}} \\
& \underbrace{+ \frac{1}{c^2} \sum_{i\in\mathbb{P}} \frac{\mu_i}{\left\|\mathbf{r}-\mathbf{r}_i\right\|^3} \left[(\mathbf{r}-\mathbf{r}_i) \cdot \left((2+2\gamma)\,\mathbf{v} - (1+2\gamma)\mathbf{v}_i \right) \right] (\mathbf{v}-\mathbf{v}_i) + \frac{3+4\gamma}{2c^2} \sum_{i\in\mathbb{P}} \mu_i \frac{\mathbf{a}_i}{\left\|\mathbf{r}-\mathbf{r}_i\right\|}}_{\cdots} + \\
& + \underbrace{\frac{2}{m} \left[\frac{(1+\gamma)\mu_\odot}{2c^2 \left\|\mathbf{r}_i\right\|^3} \left(-\hat{\mathbf{J}} + \frac{3\left(\hat{\mathbf{J}}\cdot\mathbf{r}_i\right)\mathbf{r}_i}{\left\|\mathbf{r}_i\right\|^2} \right) \right]}_{\text{Lense-Thirring precession}} + \underbrace{\frac{QA(\tilde{\theta})}{m} \frac{\mathbf{r}-\mathbf{r}_\odot}{\left\|\mathbf{r}-\mathbf{r}_\odot\right\|^3}}_{\text{SRP}} + \underbrace{\mathcal{R}_{body}^{inert}(\tilde{\theta}) \frac{\tilde{T}}{m}}_{\text{Thrust}} + \mathbf{a}_{res}
\end{aligned}
\tag{1}
$$

where $\mathbb{P}$ is a set containing the Sun, 8 planets, Pluto, the Moon and a prescribed subset of asteroids in the main belt, μ is the planetary constant, β and γ the PPN parameters (considered equal to 1), c the speed of light, $\hat{\mathbf{J}}$ is the Sun angular momentum and Q the solar constant. The superscript tilde is used to indicate the inputs read from the ESH hardware, that the thrust magnitude T, and the attitude angles θ. The spacecraft mass m is integrated as well as

$$\dot{m} = -\frac{\tilde{T}}{I_{sp} g_0} \tag{2}$$

Moreover, uncertainty in the solar radiation pressure and in the residual acceleration are considered and modeled as Gauss–Markov processes. This means that a system of stochastic differential equation (SDE), summarized in the Itô form, as

$$\mathrm{d}Q_t = -\frac{1}{\beta}Q_t\,\mathrm{d}t + \sigma\,\mathrm{d}W_t \tag{3}$$

$$\mathrm{d}\mathbf{a}_{res,t} = -\frac{1}{\beta}\mathbf{a}_{res,t}\,\mathrm{d}t + \sigma\,\mathrm{d}\mathbf{W}_t \tag{4}$$

is added to Eqs. (1) and (2).
In conclusion, SPESI orbital propagator, in its default mode, integrates the random ordinary differential equation (RODE)

$$\dot{\mathbf{x}} = \mathbf{f}\left(t, \mathbf{x}, \boldsymbol{\omega}\right) \tag{5}$$

$$\mathrm{d}\boldsymbol{\omega}_t = \mathbf{g}\left(\mathbf{x}_t, t\right)\,\mathrm{d}t + H\,\mathrm{d}\mathbf{W}_t \tag{6}$$

where Eq. (5) represents Eqs. (1) and (2), and Eq. (6) containts Eqs. (3) and (4).
Thus, in its standard configuration, SPESI have to solve a 3-DOF RODE. To do so, SPESI exploits a fixed-step stochastic Runge-Kutta (SRK) method of order $(3.0, 1.5)$.[18] The RODE is converted in a stochastic differential equation (SDE), that is integrated with the following 3-stage SRK scheme

$$\boldsymbol{\chi}_{n+1} = \boldsymbol{\chi}_n + \sum_{i=1}^{s}\alpha_i h\,\mathbf{l}\left(t_n + c_i^{(0)}h, \boldsymbol{X}_i^{(0)}\right) + \sum_{i=1}^{s}\sum_{k=1}^{m}\left(\beta_i^{(1)}I_{(k)} + \beta_i^{(2)}\frac{I_{(k,0)}}{h}\right)H_k\left(t_n + c_i^{(1)}h\right)\frac{I_{(1,0)}}{h} \tag{7}$$

with $\boldsymbol{\chi} = [\mathbf{x}, \boldsymbol{\omega}]^T$, $\mathbf{l} = [\mathbf{f}, \mathbf{g}]^T$, h the step-length, m the number of noises, and

$$\boldsymbol{X}_i^{(0)} = \boldsymbol{\chi}_n + \sum_{j=1}^{s}A_{ij}^{(0)}h\,\mathbf{l}\left(t_n + c_j^{(0)}h, \boldsymbol{X}_j^{(0)}\right) + \sum_{j=1}^{s}\sum_{k=1}^{m}B_{ij}^{(0)}H_k\left(t_n + c_i^{(1)}h\right)\frac{I_{(k,0)}}{h} \tag{8}$$

The stochastic integrals I_k are computed exploiting the Wiktorsson approximation.[19] The extended butcher tableau for the method employed in SPESI is

$$\begin{array}{c|c|c|c} c^{(0)} & A^{(0)} & B^{(0)} & c^{(1)} \\ \hline & \alpha^T & \beta^{(1)^T} & \beta^{(2)^T} \end{array} \qquad \longrightarrow$$

With respect to the common integration schemes for SDEs with additive noise, it can be noted that the deterministic time-fraction coefficients (i.e., the column $c^{(0)}$) are lower than $1/2$, in order to satisfy the constraint on τ_{int}.

Ephemerides retrieval tool

In order to build the dynamics, Eq. (1) requires SPESI to read several times the planetary ephemerides, in order to simulate the celestial mechanics. For this reason, the need of a fast interpolation algorithm for the ephemerides, able also to provide also the accelerations, is of paramount importance.
To this aim, the Fast Ephemerides Retrieval Tool (FERT) has been implemented within SPESI. FERT is able to read SPICE kernels[20,21] and exploits CPU instruction sets and a single instruction, multiple data (SIMD)[*] implementation to speed up the ephemeris data retrieval and interpolation.[22]
It is composed by two layers:

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[*] For additional information on SIMD instructions on Intel platforms: `https://www.intel.com/content/www/us/en/docs/intrinsics-guide/index.html` (Last retrieved January 5, 2023).

1. the *initialization layer*, where the SPICE kernels are memoized and re-arranged in a proper way. This process has the twofold aim of eliminating the need of reading data from the disk when interpolating, reducing the access time, and prepare them for SIMD instructions;

2. the *interpolation layer*, where the ephemeris values are retrieved and made available to the user.

Thanks to the initialization layer, FERT does not need special kernels to exploit SIMD data, differently from the SIMD implementation by Arrieta.[22] Moreover, FERT is able to interpolate not only kernels of Type 2 and Type 3[*], based on Chebyshev polynomials and used for planetary and satellites kernels, but also Type 8 and 9, based on Lagrange interpolation, normally used for spacecraft state, and Type 20, based on Extended Modified Difference Arrays and used for the minor bodies ephemerides by JPL Horizons system[†].[23]
FERT is able to reduce from 5 to 15 time the ephemeris retrieving time with respect to SPICE. While the highest advantage is given by kernels of Type 2 and 3, other types of kernels benefits the same from SIMD implementation.

Rendering unit

The third block of SPESI is made by the rendering unit, that has been implemented to exploit the two GPUs. The rendering software takes as input the state provided by the orbital propagator, together with the attitude provided by the ESH sensing suite, then it exploits the CUDA platform, provided by nVidia, and the OpenGL libraries to create the environment scene as it would be seen by the spacecraft. It is able to create a scene containing the main solar system bodies and the stars from the Hypparcos catalogue up to magnitude 6, correcting their position for one-way light time and stellar aberration using a Newtonian formulation.

NON-DEFAULT MODES

In previous sections, the default mode of SPESI, that is the mode that is used in the EXTREMA integrated experiment, has been detailed. However, the ESH and SPESI are thought to be flexible enough to perform verification and validation of any GNC hardware and software. For this reason, the user can select a customized *non-default mode*, by simply changing the SPESI settings. Despite of the name, non-default modes are normal modes of SPESI, and do not imply the use of the software beyond its limits or scope. Moreover, the use of non-default modes is of paramount importance during the intermediate steps of the ESH development or during the testing and debugging.
For example in non-default modes, the noises can be neglected, or the attitude or the thrust can be provided as functions, and not read by the sensors suite. Or, alternatively, the user prefers to read the attitude control moments, since they are simulating contingency situations or they are not interested in the hardware-in-the-loop attitude simulation. In this last case, the orbital propagator is augmented with the attitude dynamics.
In order to cope with any kind of non-default mode, SPESI implements other integration schemes than the SRK, that are selected according to the dynamical system to be propagated. For example, in case of the deterministic 6-DOF, an ESDIRK[24] is exploited.

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[*] For additional information on ephemeris kernels: `https://naif.jpl.nasa.gov/pub/naif/toolkit_docs/MATLAB/req/spk.html` (Last retrieved on January 5, 2023).

[†] `https://ssd.jpl.nasa.gov/horizons/` (Last retrieved on January 5, 2023).

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.

A first asynchronous dry-run of the EXTREMA experiment, held at the and of November 2022, was successful and brought the aim of EXTREMA a step closer. It has also shown that SPESI is able to simulate correctly the dynamics and its hard real-time implementation is capable to have a proper interface with real-world sensors.

However, the challenges the project must still face are multiple and stem from different sub-fields of space engineering. However, its success, for which the Space Environment Simulator will play a relevant role, will be a key milestone for the future of space exploration and exploitation.

ACKNOWLEDGMENT

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).

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