AN OVERVIEW OF THE EXTREMA DEEP-SPACE OPTICAL NAVIGATION EXPERIMENT

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Abstract. *Space economy is growing and an increasing number of satellites is expected to orbit in the Solar System. Current Deep-Space Network infrastructure can not manage the increasing workload expected in the next decade. Spacecraft need to be more autonomous to reduce ground contact, thus reducing the overall deep-space missions cost. Motivated by these concerns, the EXTREMA project aims at developing and validating autonomous deep-space CubeSats. In this work an overview of EXTREMA vision-based navigation algorithm, validation approach, and hardware-in-the-loop integrated experiment is presented with a particular focus on the different elements composing it and their interconnections.*

Introduction. In the last decades, the number of spacecraft launched per year has increased dramatically enhancing the access to space to private and public actors of the space sector. Earth orbits are populated by fleets of satellites to support the increasing number of services which are ensured from space. Beside the Earth orbits, this momentum has paved the way to a more programmatic exploration and exploitation of the Solar System. Amongst other reasons, a driving factor which enabled this trend has been the use of CubeSats as a standardized, small size and low-cost platforms to access the space economy. Although Cubesats have been historically used for Earth orbits, their application to Solar System exploration is gaining interest in the community due to launch opportunity as secondary payloads and to their use as technological demonstrators. As a consequence, interplanetary CubeSats missions are conceived, designed and flown to the Solar System inner planets,[1] small bodies[2,3] and the Moon.[4] Even though CubeSats have proven that platforms cost scales with system mass, the same reasoning cannot be extended to spacecraft operations as their cost is mass-independent. This is because small and big probes are controlled and navigated with the same paradigm: satellites communicate with Deep-Space Network (DSN) antennas and, then, the orbit determination problem is solved by engineers on ground to determine the spacecraft state and the needed maneuvers. For interplanetary CubeSats potential actors, this is a major drawback as operations cost limits to big companies and space agencies the access to the space sector. Moreover, the increasing numbers of probe will cause an increase of DSN workload and DSN communication slots will saturate by limiting the number of operated probes. In this context, a possible solution to reduce human-in-the-loop-related costs and to limit DSN saturation is spacecraft autonomy.

The EXTREMA project. Prompted by the aforementioned considerations, the ERC-funded project EXTREMA (Engineering Extremely Rare Events in Astrodynamics for Deep-Space Missions in Autonomy)[5] aims at enabling deep-space self-driving CubeSats, along with the potential impact of applying the same techniques to large spacecraft as depicted in Figure 1. EXTREMA project is based on three pillars:

- **Pillar 1** deals with autonomous vision-based navigation (VBN) algorithm design and its validation in a hardware-in-the-loop (HIL) experiment;
- **Pillar 2** realtes with autonomous guidance and control algorithm design and its validation in a HIL experiment;
- **Pillar 3** faces autonomous ballistic capture, and it aims to validate the previous algorithms in a complex dynamical scenario.

These three pillars are part of a unified simulation framework: the EXTREMA Simulation Hub which is an integrated infrastructure to carry on dynamic simulations of the spacecraft-environment interaction, allowing high-fidelity HIL testing of deep-space autonomous Guidance Navigation Control (GNC) systems for CubeSats.
This work aims at depicting in more details EXTREMA Pillar 1, along with the current status and future development of the different elements composing it.

Deep-Space Vision-Based Algorithm. During spacecraft cruise, a satellite can take images of the stars and Solar System bodies to gather information of its position and orientation with respect to the inertial reference frame by exploiting celestial triangulation[6] and attitude determination algorithms.[7] These pieces of information are then provided to a navigation filter to solve the orbit determination problem and fully determine the spacecraft state. This solution is completely autonomous as no information is required from ground as Solar System bodies ephemerides can be stored efficiently on board. This implies that the optical data registration in the inertial reference frame can be easily performed once the observed planet is detected in the image.
The VBN algorithm is composed in two main blocks: the image processing pipeline and the orbit determination algorithm. The image processing pipeline is in charge of determining the spacecraft attitude using state-of-the-art centroids and star asterisms identification methods.[8] From the determined attitude, the visible planets can be identified from statistical considerations.[8] The planets are used as inertial beacons to solve for the observer position in a navigation filter by correcting for planetary aberration which could induce biases.[7]

Deep-Space Rendering Engine. VBN requires images for design, testing, and validation. Although images are available from past missions, they are generally constrained to mission observational geometry which limits their applicability. A solution to this drawback is to design rendering engines which provide images of the observed space scene by setting the scene configuration and the camera characteristics. Space rendering engines, such as SurRender,[9] exist in the literature but they are generally proprietary software. Due to this limitation, a dedicated deep-space rendering engine is developed within the EXTREMA project. The deep-space rendering engine is a enhanced version of the one presented in Reference 10. The current version of the engine can work in two modes: HIL simulations and software simulations. On the one hand, in the HIL simulation mode the scene is modified to compensate the errors identified during the calibration process. On the other hand, in the software simulations mode the engine renders images of the deep-space sky without considering any warping but by adding the camera noises. These two modes are crucial for the correct execution of Pillar 1 as the first is used for VBN validation while the second one is used for VBN design. An image rendered in the software mode is shown in Figure 4 with the Earth at the center of the image.

EXTREMA HIL facility: RETINA. A major concerns once a VBN algorithm is designed is how to prove its robustness to off-nominal scenario. To perform verification and validation, in the space sectors it is possible to use real images from past missions, high-fidelity rendering engines images, or ground-based hardware-in-the-loop facility simulations which reproduce space-borne observational conditions.[11] Within EXTREMA, this latter solution is used because it is more representative of the real hardware errors. Moreover, thanks to a high-fidelity dynamical simulation, a wider set of observational conditions can be reproduced in this framework. Thus, a HIL optical facility is under development: RETINA (Realistic Experimental faciliTy for vIsion-based NAvigation). The main goal of RETINA is to provide the VBN algorithm with an image as it would be acquire from the same hardware in space. RETINA is composed of a high resolution miniaturized screen, a lenses system which collimates the screen light, an optical camera consistent with CubeSats hardware, and a processing unit to embed the VBN algorithm. The camera, the system of lenses, and the screen are mounted on an optical breadboard and placed in a dark box. For the sake of completeness, the CAD model of RETINA is shown in Figure 3. Beside the hardware components, dedicated software is developed to estimate the camera intrinsic matrix, the calibration distortion model, and the camera-screen misalignment.[11]

Workflow of EXTREMA Deep-Space HIL Experiment. The core of Pillar 1 is the integration of its different elements in an unified experiment to test and assess HIL VBN performances. A functional breakdown of the experiment is shown in Figure 2. The experiments performs by executing the following steps:

1. The true spacecraft pose is provided to the rendering engine to generate a deep-space image consistent with the spacecraft pose.
2. Thanks to the calibration software, the image is warped to remove HIL errors. The warped image is displayed on the high-resolution screen which stimulates the camera through the lenses system.
3. The camera takes images of the projected deep-space sky and sends them to the processing board which is responsible for the VBN execution.

This set-up developed in Pillar 1 will provide not only a comprehensive analysis about the performances of the VBN algorithm errors and operational limits by varying camera parameters , e.g., the exposure time or the objective defocus, but it will also set up an adaptable simulation framework where different hardware and algorithms can be designed, tested and validated.

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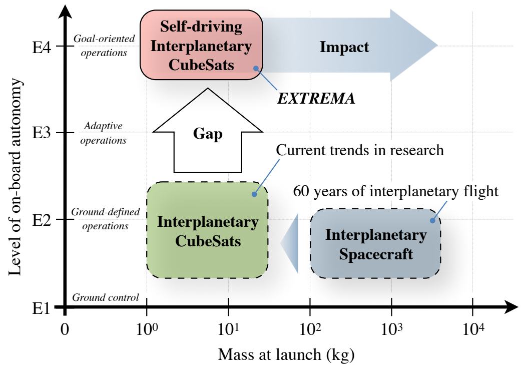

Figure 1. Qualitative overview of the potential impact of EXTREMA

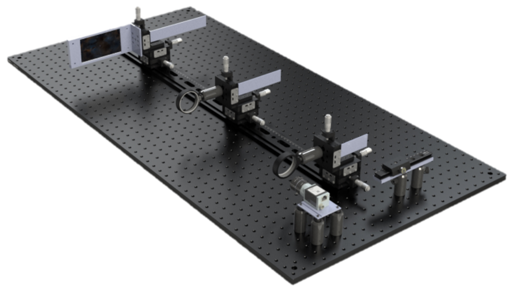

Figure 2. The CAD of RETINA.

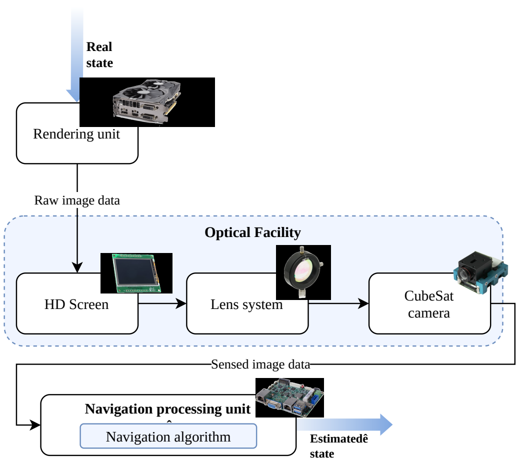

Figure 3. Logic of the Optical Facility to test the navigation algorithms.

Figure 4. An example of an image rendered by the deep-space rendering engine. The bright dot in the center is the Earth.