SSC21-II-03

LICIACube Mission: The Fastest Fly-by Ever Done by a CubeSat

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ABSTRACT

As SmallSats are gathering an ever-increasing importance for all types of space missions, they are asked more often to operate in harshest environments and to complete the most complex tasks. One of these demanding technical challenges arises in the frame of the planetary defense. Space missions towards asteroids have garnered the due attention in recent years and, in this regard, NASA has developed the Double Asteroid Redirection Test (DART) mission, in which the Italy will lend its contribution. While DART acts as a kinetic impactor deflecting the orbit of the asteroid Dimorphos, the moon of the targeted binary system Didymos, the Light Italian CubeSat for Imaging of Asteroid (LICIACube) collects and gathers valuable images of the effect of the DART impact on the rocky body. LICIACube will allow to study the structure and evolution of the ejecta plume resulting from the impact, and to model both impacted and non-impacted sides of Dimorphos. LICIACube is an Italian Space Agency (ASI) project, whose design, integration and testing have been assigned to the aerospace company Argotec. The scientific team is enriched by University of Bologna team, supporting the orbit determination and the satellite navigation, Polytechnic of Milan, for mission analysis support and optimization and INAF (National Institute of Astrophysics), which provides support in the scientific operations of the satellite, instrument calibrations and data exploitation. This work focuses on the fly-by of LICIACube which will be accomplished using the imaging capabilities provided by the Argotec HAWK-6 platform and by the autonomous navigation system. In order to acquire high-resolution images, LICIACube approaches Dimorphos at a relative distance of 55 km. The very close fly-by, the high relative velocity of ~7 km/s with respect to the asteroid and the need to keep LICIACube camera pointed at Dimorphos make the mission very challenging. In addition, since the binary asteroid system is ~10 million kilometers away from Earth, the fly-by has to be performed with no real time commanding. As a result, LICIACube shall be able to autonomously analyze all information from its sensors to track the asteroid. The evaluation and subsequent solutions to this problem are presented in this paper, as well as a unit-level description of the parts included in the autonomous navigation system. Finally, an overview of the verification of both unit-level and system-level strategies is outlined.

INTRODUCTION

Thousands of asteroids orbit the proximity of Earth. Given the possibility that they could cross Earth orbit and pose a significant threat, multiple international space agencies and defense departments of different countries monitor these celestial objects to predict their possible impact on Earth. Different solutions to avoid the impact, such as asteroid deflection or fragmentation, are currently investigated by NASA, ESA, and other government space agencies [1][2].

The Double Asteroid Redirection Test (DART) mission, part of the Asteroid Impact and Deflection Assessment (AIDA), will be the first mission aimed at demonstrating the kinetic impact technique [2]. In order to perform this test, DART will target 65803 Didymos, a synchronous binary system consisting of a larger body, with an average diameter of 780 m, and a small minor-planet moon, Dimorphos, with diameter of 164 [3]. DART mission will impact the smaller asteroid Dimorphos to change its motion. Any variation in the orbital parameters of the binary system will thus be registered and studied. DART will be launched in late 2021 and it will reach its target in 2022, after a journey of maximum 11 months.

DART spacecraft will impact Dimorphos at a relative speed of 7 km/s [4]. Ground-based telescopes will record any change in the binary system orbit, enhancing the knowledge about the kinetic impact technique. Dimorphos, characterized by an orbital velocity of 17 cm/s, is expected to have a shift in its speed by 0.5 mm/s, changing its rotation period around the primary body by about 200 seconds.

In order to acquire relevant scientific data in the form of pictures to confirm the impact, DART spacecraft will carry the 6U LICIACube - Light Italian CubeSat for Imaging of Asteroids - as a piggyback. LICIACube will be deployed from the probe to assess and document the success of the impact, its effects and the evolution of debris generated by the collision [5]. The LICIACube platform, designed, produced, and qualified by Argotec, is an augmented version of the ArgoMoon HAWK platform, which is designed to withstand hard deep-space environment [10]. The CubeSat weighs approximately 14 kg and it will be equipped with the Argotec On-Board Computer & Data Handling (OBC&DH), Power Conversion and Distribution Unit (PCDU) and subsystems and components that are both in-house-built and Commercial Off-The-Shelf (COTS) properly modified and adapted.

This work primarily focuses on the autonomous navigation strategy of the LICIACube satellite and its corresponding performance assessment for performing close proximity fly-by and operations near the Dimorphos asteroid. Implementation of this strategy greatly increases the mission flexibility and responsiveness of the system to perform the fly-by of an asteroid using a CubeSat while ensuring high fidelity observation and scientific data collection. LICIACube mission will be the first CubeSat to support the characterization of a kinetic impact technique on an asteroid while operating under a significantly uncertain environment.

In the next sections, the background of the LICIACube Mission is discussed. Then, the autonomous navigation system is firstly presented in detail and then the validation preliminary results, at unit and system levels, are reported.

BACKGROUND

Mission Background

The primary objective of the LICIACube mission is to acquire multiple images of the Dimorphos asteroid, during and after the impact, along with the ejecta plume, with different phase angles to allow the reconstruction of the mass-velocity distribution and the size distribution of the ejecta [6][7], as well as the real shape of the asteroid. LICIACube imaging includes the non-impact hemisphere of the Dimorphos, the side not imaged by DART.

LICIACube satellite will be deployed by DART spacecraft roughly 240 hours before the Dimorphos impact time, with a relative velocity with respect to DART of 1.14 m/s [8]. Once deployed in a heliocentric orbit, LICIACube will start its commission phase, during which it will power on all its subsystems and reconstruct its attitude to start performing in-orbit tests and calibrate the equipment. Once the propulsion subsystem reaches the expected operational temperature and pressure, it is enabled to perform a manoeuvre to change its orbit and avoid impacting the asteroid. Then, approximately 200 seconds after its release from DART, LICIACube will be on the optimal trajectory toward the asteroid to fulfil the mission objectives.

The scientific part of the mission starts 240 seconds before the nearest distance from Dimorphos, the so-called Close Approach (C/A), since it is the first moment in which the optical payload is capable to recognize at least one body in the image.

The satellite will be at the C/A at a nominal distance of 55 km from the impact region. Although during the first mission phase the satellite will be tracked through Ground Stations (GSs), the uncertainties about the orbits will make it unfeasible to fully plan the attitude maneuvers needed to track the target during the fly-by from Earth. Both the distance and the time of the C/A cannot be predicted with enough accuracy and the asteroid tracking shall be autonomously performed during the fly-by.

Technical Challenges

The technical challenges and the limitations of a deep space 6U CubeSat platform make the fulfilment of the scientific objectives extremely complex. One of the first hurdles to overcome is the long cruise to reach the Didymos binary system. In fact, during the maximum 11 months of cruise required to reach the target, LICIACube will face a harsh environment, being subjected to extreme temperature changes and to a significant radiation dose. Once the satellite will be deployed by DART, LICIACube will start its approach to Didymos, taking about 10 days in the nominal scenario. The asteroid flyby will require a very high satellite body rate, being the most demanding part of the mission in terms of platform required power, pointing and computational capabilities. Such body rate can reach a peak of 7 deg/s, with a 3σ uncertainty of 0.32 deg/s, which must be achieved only by means of the satellite reaction wheels.

In addition, in order to autonomously perform the flyby, image-based target recognition is necessary, to provide real-time feedback to the tracking and control system. Moreover, the presence of the not-well-known dust plume produced by the high-speed DART impact puts an additional challenge to the image recognition algorithm robustness.

Concerning the required pointing capabilities, it should be considered that, during the scientific activities, the target shall be tracked and maintained inside the camera horizontal Field of View (FOV) of 2.9 deg from a distance at C/A of about 55 km. By means of a simple trigonometric calculation, given that Didymos has a diameter of 780 m, it is proved that the required pointing accuracy at C/A is less than half of the FOV. For this reason, in addition to the attitude control loop aimed at tracking the asteroid exploiting the feedback of the imaging subsystem, a dedicated algorithm will help reconstruct the correct satellite trajectory, allowing to reduce the distance and time uncertainties and increase the pointing accuracy. Due to the autonomous activities and to the reduced available time to perform the fly-by, the system is highly sensitive to the on-board time accuracy. In fact, since the flyby operations shall be executed at particular time instants, particular attention shall be put in the time synchronization.

Finally, one of the hardest challenges is to implement the required technology and algorithms in the very limited resources of a 6U CubeSat. The Argotec's HAWK platform, designed and built to be resilient in the extreme conditions of such a journey, has been exploited to achieve the necessary performance, implementing some parts of the described functionalities in the available hardware processing system while others are performed by the On-Board Software (OSW).

AUTONOMOUS NAVIGATION SYSTEM

The autonomous navigation system developed for the LICIACube mission has been designed according to all the requirements derived from the technical challenges described in the previous section.

A high-level functional scheme of the autonomous navigation system is reported in Figure 1.

The functional diagram shows how the modules involved in the satellite control interact with each other, highlighting the different domains of the OBC&DH, that hosts the processing units to run the algorithms, the primary Payload of the satellite, i.e. the camera, and the Attitude Determination and Control System (ADCS).

The main modules of the navigation system are:

- The Imaging Subsystem (IS) module, that processes and manages the image I acquired from the Payload, in order to recognize the two asteroids and to give a feedback to the Trajectory Recognition module, in terms of targets position within the image. For each target, the IS provides the offset of the object centroid (Cg) with respect to the centre of the image.
- The Trajectory Recognition module is aimed at estimating the actual trajectory on which the satellite is traveling using the Cg to minimize the error between the nominal orbit and the other 2σ trajectories. The time at which the satellite will be at C/A and its distance from the asteroid at C/A characterize the different trajectories, where the pair (tN, dN) identifies the nominal one. The set of $(2\sigma + 1)$ calculated trajectories constitutes the trends from which the Trajectory Recognition module will choose the best trajectory. The purpose is to compensate for the uncertainty arising from on-board time and ephemeris. Θ is the angle formed by the vector of the satellite velocity w.r.t. the asteroid at a certain time instant and the straight line connecting the satellite and the asteroid. The inputs of the block are Cg and the satellite attitude information provided by ADCS.
- The Tracking Loop module takes as input the IS result in addition to the angle Θ, in order to derive the desired pointing quaternion q0 to track Dimorphos.
- The Attitude Control module is designed to control the angular velocity of the reaction wheels of the ADCS via a PD controller. It gets the current quaternion (q) and body rate (ω) from the ADCS and,

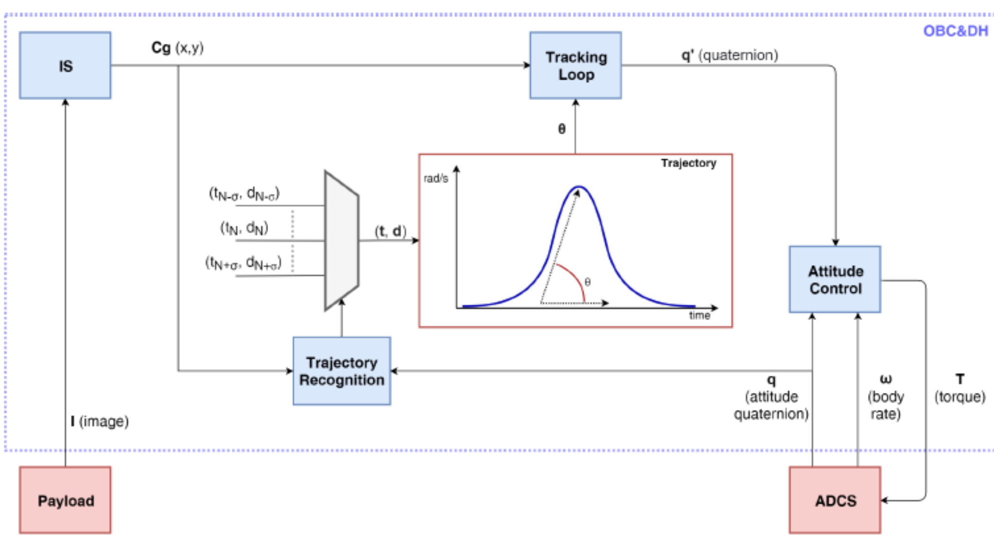


Figure 1: *Autonomous Navigation System Functional Scheme*

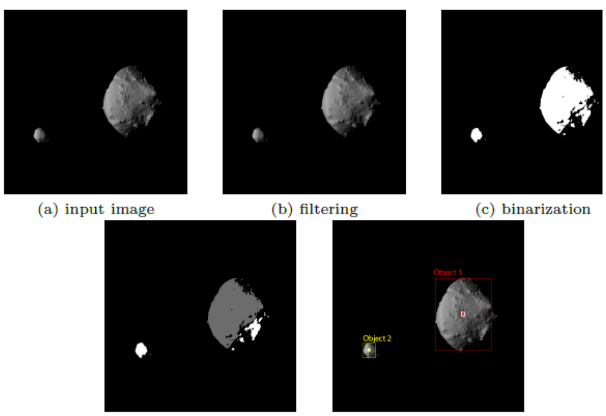
by combining them with q0, calculates the torque T to control the ADCS.

Imaging Subsystem (IS)

The IS is in charge of receiving images from the primary payload, with a resolution of 2048x2048 or 1024x1024 pixel and performing image processing functions on the received data. The IS allows to recognize multiple objects in the camera FoV.

The IS is composed by a series of algorithms which cooperate to acquire the position and size of the framed objects. The image processing pipeline (Figure 2) for the LICIACube mission includes the following functions:

- **Filtering**: downsample (binning) images from 1024x1024 down-to 512x512 12-bit/pixel and filter with colour depth compression down to 8-bit/pixel.
- **Binarization**: compute luminance histogram and binarize image.
- **Object Detection**: label regions and identify objects.
- **Feature Extraction**: extract area and centroid of target objects.



(a) input image (b) filtering (c) binarization
(d) object detection (e) merging

Figure 2: *Example of the image processing pipeline*

Steps 1 to 3 are hardware accelerated by the LICIACube the FPGA included into Argotec FERMI OBC, whereas step 4 is performed by the on-board software running on a dual-core SPARC-V8 processor.

Tracking and Trajectory Recognition Module

Asteroid tracking and trajectory recognition has the purpose of understanding the satellite relative motion with respect to the target asteroid and to build the satellite attitude in order to keep the asteroid within the camera FoV. The developed strategy has assumed two major uncertainties, which are the ones affecting the distance from the asteroid at the C/A and the time instant at which the C/A will happen.

Up to 30 seconds before the C/A, the spacecraft uses the “best estimation (or nominal) trajectory" sent by Earth to navigate and applies corrections to its attitude using the IS feedback. The autonomous tracking exploits a second order control loop minimizing pointing error. The choice of such closed loop controller has been driven due to its very low resources utilization and its extremely simple integration in the flight software. Furthermore, this type of loop controller fully corrects pointing errors during the first phase of the fly-by.

In fact, the first part of the approach, also called acquisition phase, is characterized by a small angular velocity and a small uncertainty region due to the relatively high distance between the satellite and the asteroid. During this first phase, the uncertainty on the position of the asteroid within the camera FoV is less than a quarter of the entire FoV span. For what concern the escape rate from the centre of the satellite camera, this is smaller than 0.4 deg/s.

The selected controller is capable of fully correct any initial pointing error and is capable to compensate for a constant body-rate acceleration error. The loop filter response is tuned controlling the pointing overshoot and cantering the asteroid with enough time margin while approaching the fly-by manoeuvre. Pointing accuracy is evaluated exploiting the information about the asteroid pointing vector derived using centroids and data and the satellite orientation in space. In order to evaluate the pointing vector from camera acquisition, the picture can be divided in four quadrants and considering the body reference frame orientation, the asteroid position can be computed on the basis of the distance from the centre of the picture as the projection of the pointing vector on the XY body reference plane.

At every IS feedback, the software computes the rotation of the pointing vector from the body reference frame to the inertial reference frame. The transformation to the inertial reference frame is to account for both asteroid motion within the camera FoV and the satellite attitude evolution. In other words, all the computations are referenced to the inertial reference frame and the only term that is evolving is the quaternion describing the satellite orientation time by time. Such a quaternion is an outcome provided directly by the ADCS. Acquiring information on the relative motion of the satellite with respect to the asteroid, the Trajectory Recognition algorithm selects the best fitting trajectory, on the base of a minimum mean square error computation between the acquired relative motion information of the actual trajectory and each trajectory within the pre-computed trajectory dataset. So that, while approaching the C/A, LICIACube will be able to perform autonomous navigation using the identified “best fitting" trajectory.

During the second phase, the satellite exploits the recognized asteroids motion within the images frame gathered during the first phase to set-up the attitude controller on the run-time computed best trajectory.

Attitude Control Module

The aim of the Attitude Control module is to implement a strategy to analytically determine and control the attitude of the LICIACube satellite in order to achieve the assigned mission requirements and perform the fly-by.

In this regard, the closed control loop algorithm is required to perform a proper asteroid pointing in a stable way, considering both the nominal and the worst-case trajectories, just using the reaction wheels actuators. In particular, the employed reaction wheels are characterized by a maximum mentum storage of 0.1 Nms and a maximum torque of 0.007 Nm.

According to the last mission analysis, during proximity operations around the impact region, the worst-case scenario foresees a closest approach with a relative distance of ~50 km. During this period, the peak of required body rate to perform the fly-by can reach 7 deg/s. Considering also the narrow field of view of the payload the satellite requires a robust and very responsive control law to maintain the target in the FoV. Preliminary simulations were performed in a dedicated Simulink™ validated model in order to test the response of the system under different control laws. Complex attitude control strategies have been discarded since the computational power did not allow to perform complex mathematical operations.

The preliminary results have shown that the integrative contribution of the PID controller does not improve the pointing accuracy in the proximity of the C/A. For this reason, it was decided to use a simple PD Controller as baseline. The PD gains were firstly tuned by simulation, exploiting a dedicated Simulink™ validated model of the attitude controller, satellite dynamics and kinematics, and ADCS. It should be highlighted that, for reliability's sake, the chosen gains shall guarantee the success of the mission for all the possible trajectories. Thus, only one set of gains shall be obtained.

Starting from a first assumed guess, the gains were tuned for the worst-case trajectory dynamics, i.e. the nearest C/A, in order to minimize both the proportional and the derivative errors, guaranteeing the required pointing accuracy. The worst-case dynamics trajectory was chosen since it represents the case in which the required body rate is the highest one, representing the most demanding case for the reaction wheels torque. The obtained gains were then used for the simulations with all the other identified significant trajectories, reported in the next section.

SYSTEM VALIDATION AND RESULTS

In order to validate the autonomous navigation system and evaluate its performance, Argotec developed several components: a test platform for the Imaging Subsystem, MATLAB™ simulators for the Trajectory Recognition and the Attitude Control and a Hardware-in-the-Loop (HIL) setup for the system integration.

Imaging Subsystem Results

In order to verify the correct functioning of the Imaging Subsystem in a selected set of critical scenarios, the IS pipeline was tested in a software test bench, using batches of sequential frames generated with the PANGU tool [9] to simulate the fly-by.

Test images have been generated varying the following set of parameters: trajectory, time shift, asteroids illumination and model, plume shape, background noise.

For each of the described use cases, the test is considered passed as far as two objects are detected at most after 30 frames from the start of the simulation, time at which Dimorphos should be big enough to be detected as a valid target, and until the 45th frame.

In order to validate the IS capability to properly detect the target objects present in the simulated images, results have been compared to the ones obtained by an independent object detection algorithm developed using the OpenCV library.

The test on an image is considered passed if two targets are identified and the centroids of corresponding objects computed by the IS and the OpenCV function are less than 15 pixels distant.

The results have shown that the distance between corresponding objects computed by the IS and by the OpenCV function has never been observed greater than 8 pixels.

Trajectory Recognition Results

In order to build a test model fully representative of the mission environment, an accurate analysis was aimed at identifying the major error contributions that have an impact on the trajectory recognition module. Both systematic and random errors have been considered.

The main systematic errors are centroid shift due to filtering, binarization and unfavourable illumination conditions, thermoelastic effects and mechanical misalignment.

The main random errors are camera sensor discretization, optic distortion, noisy satellite attitude, picture lost during the acquisition phase.

A Montecarlo simulation was used to validate and to assess the algorithm performance.

1000 simulations were performed for each trajectory within the 3σ interval of confidence.

The results have shown that the major impact on the overall performance is given by the attitude determination error, which has a fundamental contribution to the estimated trajectory. Indeed, a large attitude estimation error gives a very noisy trajectory information which in turn produces a less accurate time and distance correction estimation.

Attitude Control Results

In order to develop and test the Attitude Control module, a model has been created using the Simulink™ software. As represented in Figure 3, the model is composed of five main blocks. The Desired Satellite Attitude block computes the set-points for the attitude and angular velocity, starting from a data set of the spacecraft and the asteroids orbit.

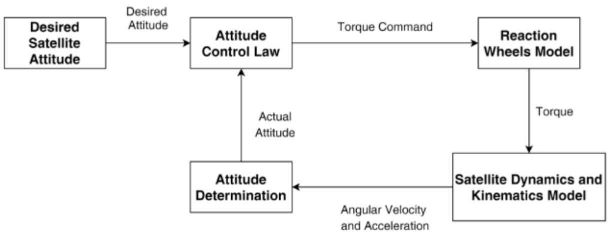


***Figure 3**: Attitude Controller Model Architecture*

The core of the model is the Attitude Control Law block, whose input are the attitude and angular velocity of the satellite as well as the set-points. The quaternion-based controller described in previous section calculates the torque command needed to achieve the desired target.

The torque output is provided to the Reaction Wheels Model that implements the RW Torque-Angular Velocity law, extracted by the real hardware after the data obtained by different tests.

The Satellite Dynamics and Kinematics Model block receives the torque produced by the Reaction Wheels Model and evaluates the satellite angular acceleration using the Euler's equations of motion. The angular acceleration is integrated in order to obtain the angular velocity of the satellite. Angular velocity and acceleration are the output of this block, which are used by the Attitude Determination block to compute the attitude quaternion and close the loop.

The controller gains identified during the design phase has been tested with the different trajectories. Both the pointing error and the angular velocity have been computed, verifying that the first never exceeds half of the camera FoV and that the satellite is able to reach the requested body rate of 7 deg/s.

System Results

The final test is performed on the integrated system. The OSW is executed by the OBC&DH and the rest of the system, together with the environment, is simulated. The OBC&DH is connected to a Payload Emulator that simulates the on-board camera and provides images to the flight software on demand. High resolution images are generated using the PANGU software, in which 3D models of the asteroids, their state vectors and the payloads model are implemented in a simulated environment that reflects the expected mission conditions.

The spacecraft dynamics is directly controlled by the OBC&DH through its Attitude Control module, that sends torque commands to the connected ADCS. Sensors and actuators are simulated by a Universe Dynamic Simulator (UDS), that also simulates the space environment and the spacecraft dynamics. Through the UDS interface, PANGU retrieves the satellite trajectory and attitude, to generate images from the proper point of view. Figure 4 shows a block diagram of the HIL setup.

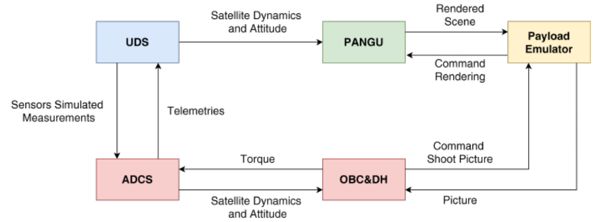


***Figure 4:** HIL Test Setup Diagram*

The test campaign was performed on the nominal case scenario and then on worst case trajectories, in order to test the limits and the robustness of the developed system.

Preliminary results confirm that the nominal trajectory is the best-case scenario in which the system performs at its best estimating a trajectory and the system still keeps the asteroid in the FoV for 98% of the time, as requested to fulfil the mission objectives.

Concerning the worst-case trajectories, the system is capable to fulfil the mission objectives too, keeping the asteroid in the FoV for more than 90% of the time.

CONCLUSIONS

This paper presented the autonomous navigation system of the LICIACube satellite. The mission scenario has been discussed in order to highlight the performance required to successfully fulfil the mission objectives, and the additional technical challenges related to the implementation of such a system using a 6U CubeSat have been presented. The autonomous navigation system has been detailed in all its parts, describing the Imaging Subsystem, the Trend Recognition and the Attitude Control modules. Extensive optimization activities, documented in the previous sections, are required to fulfil the mission with such kind of spacecrafts, and the role of the Argotec's HAWK platform in this process has been highlighted.

Extensive analysis and unit-level testing showed the system is able to achieve the desired results both in terms of performances and functionality. The IS, leveraging a highly optimized hardware pipeline, is able to correctly process images as requested.

The Trajectory Recognition module is able to predict the satellite trajectory even with uncertainties of several km in distance.

The Attitude Control module is able to provide a pointing error of less than half camera FOV and control the satellite angular velocity with a peak higher than 7 deg/s.

System-level simulations executed so far, by means of the developed HIL setup, showed the system is able to correctly perform the y-by and track the target asteroid for more than 90% of the time, both in the nominal and the worst/case scenarios.

In conclusion LICIACube will attempt to perform one of the most challenging missions ever attempted by a CubeSat. Its autonomous navigation system, proven to be robust to the challenging conditions and compliant with the mission requirements, can be considered the state-of-the-art in the field of deep-space robotic exploration using small-satellite platform.

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