LICIACube: the eyewitness of an asteroid deflection

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## ABSTRACT

LICIACube is an Italian Space Agency (ASI) project, whose design, integration and testing have been assigned to the aerospace company Argotec, with the scientific coordination by INAF (National Institute of Astrophysics). 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, together with CNR-IFAC to study the dynamical evolution of the plume.

LICIACube has been launched on 24th November 2021 and it is currently hosted as secondary spacecraft on board of DART, on its way to the asteroids. The autonomous mission will start with the separation from DART, planned few days before the impact, expected in late September 2022.

This work focuses on the LICIACube spacecraft design, as driven by the imaging capabilities provided by the Argotec HAWK-6 platform and by the autonomous navigation system. In order to acquire high-resolution images, LICIACube will approach Dimorphos at a relative distance of approximately 55 km. The very close fly-by, the high relative velocity of about 7 km/s with respect to the asteroid and the need to keep LICIACube cameras pointed at Dimorphos make the mission very challenging. In addition, since the binary asteroid system is approximately 10 million km away from the 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 Mission Control Centre, located in Argotec premises in Italy, will be the user terminal for TT&C and also Data collection and distribution to the scientific community.

## INTRODUCTION

CubeSats are increasingly becoming a key player in space missions, providing a cost-effective solution for scientific and commercial applications. The development of CubeSats started in universities to support research activities and allow students to experience first-hand the design and development of objects that will fly in space. In recent years, space agencies and private companies have entered the CubeSat market, increasing the capabilities and reliability of these satellites and making them suitable for more complex missions. In this context, LICIACube, a 6U CubeSat developed by Argotec under a contract from the Italian Space Agency and embarked on the DART spacecraft as a secondary payload, is aimed to provide an eyewitness account of the spacecraft's impact on the natural moon of the Didymos binary asteroid system and support scientific observations of the ejecta generated by the impact itself. [1].

LICIACube, as part of the DART mission, was launched on November 24, 2022 from Cape Canaveral with Falcon 9 and is currently on a heliocentric orbit on its way to the asteroid.

This paper focuses mainly on the challenges and constraints that were overcome during the design of the mission. It is organized as follows: the mission overview is reported in section 1, the mission drivers in section 2 and the design solutions used to overcome the technical challenges and meet the design drivers are reported in section 3.

### Mission Overview

The Double Asteroid Redirection Test (DART) mission will be the first demonstration of the kinetic impact technique to change the orbit of an asteroid in space. The DART spacecraft will achieve kinetic impact by deliberately crashing into the asteroid at a velocity of about 7 km/s. 10 days before its impact on the asteroid, DART will release LICIACube. The primary objective of LICIACube is to obtain multiple images of the ejecta plume from the DART impact over a time frame and phase angles such that reasonable expectations for the ejecta mass-velocity distribution and ejecta size distribution can be obtained.

In addition, secondary objectives are to:

* Obtain multiple images of the DART impact site.
* Obtain multiple images of the non-impact hemisphere of Dimorphos.
* Obtain images of the ejecta plume and asteroid target to characterize color and spectral variations.

Once deployed into a heliocentric orbit, LICIACube will begin the commissioning phase, during which it will switch on its subsystems, reconstruct its attitude, perform calibration activities and orbital maneuvers to achieve the correct flyby trajectory.

The start of the science mission begins 240 seconds before the Closest Approach (C/A) with Dimorphos, as this is the maximum distance at which the imaging subsystem will be able to recognize at least one of the two asteroids. The CubeSat will be at the C/A at a nominal distance of approximately 55 km from the impact region. Although during the mission the CubeSat will be tracked through Ground Stations (GSs), asteroid tracking will be performed autonomously during the fly-by due to uncertainties about orbits and the round-trip communication time between the satellite and the GS of more than 30 seconds.

After the fly-by, the mission will last 6 months and LICIACube will downlink all acquired scientific images to the GS for scientific analysis.

### Mission Phases

The following image depicts the main mission phases of LICIACube.

A satellite in space

Description automatically generated with low confidence

Figure 1. LICIACube Mission Phases

During the cruise phase, the LICIACube has all subsystems turned off except for the External Battery Charger (EBC), which is connected to the DART spacecraft power bus and allows the LICIACube battery to be charged and the CubeSat temperature to be maintained within the operating range. Once the LICIACube is released, detumbling operations are required to reconstruct the satellite attitude and the commissioning phase begins. All subsystems and performances are tested according to the specific in-orbit test plan, such as the calibration of the PLs to correctly set the exposure for science image acquisition during the asteroid approach and calibration of the ADCS subsystems to best match the approach trajectory to the asteroid.

Prior to the flyby, LICIACube will perform a predicted maneuver planned for the correct flyby of the asteroid. Two additional stochastic maneuvers are planned to reduce flyby uncertainties. All maneuvers will be performed within a communication window to allow ranging operations and increase the accuracy of orbit determination.

The science phase starts about 30 minutes prior to DART's impact on the asteroid, so that the satellite will have the opportunity to acquire images of the impact region and the location and initial development of the plume. After DART's impact on the asteroid, LICIACube will move close to the asteroid's binary system to capture DART's impact region and plume evolution while avoiding collision with the ejected plume. The science data will be stored in the satellite's internal mass storage before being downloaded to the ground during the remaining 6 months of the mission.

At the end of the mission operational lifetime, the LICIACube satellite, orbiting the Sun, will be passivated: the energy source stored on board will be exhausted as it is no longer needed for mission operations. Propellant depletion burns and cold gas release will be performed to minimize the occurrence of accidental collisions and the impact of a subsequent explosion.

## MISSION DRIVERS

This section focuses on the design of the main LICIACube mission drivers that led to the architecture and design of the mission. For the sake of clarity, this section does not report the entire list of drivers but only the most important ones:

1. DART's impact on the asteroid will generate ejecta from the asteroid's surface. Although the composition of the asteroid is not well known, several observations with ground-based telescopes and simulation have allowed to define an exclusion zone to avoid any type of ejecta impact. Consequently, the CubeSat trajectory, including Orbit Determination (OD) uncertainties, must avoid passing through the keep out zone.
2. Since the main objective of the mission is to take a series of photographs of the DART impact site, the evolution of the ejecta during the flyby and the non-impact hemisphere:
   1. The Field of View (FoV) size of the payload must be large enough to capture the entire plume.
   2. The payload must have sufficient resolution to capture the DART impact site.
   3. The albedo of the plume cannot be predicted with high accuracy, so the payload must be capable of acquiring sets of images with different exposure times.
3. Angular velocity during the flyby will be very high (approximately 7 deg/s) due to the close distance to the asteroid surface to increase image resolution, and high relative velocity due to the high impact velocity (approximately 7 km/s) of the DART to increase the kinetic energy to be transferred to the asteroid.
4. The mission will operate at a distance greater than 10 million km from Earth, so the CubeSat will need to be able to downlink, over its lifetime, all data acquired during the science phase.
5. DART's trajectory includes a long cruise phase to reach the asteroid so the CubeSat must be maintained in the desired temperature range and have a charged battery at the time of deployment from DART.
6. The CubeSat will operate in deep space so it will have to provide high reliability and be able to withstand the radiation environment.

## MISSION ARCHITECTURE & DESIGN

The drivers described in previous section bring a wide set of technical challenges. These challenged have been identified and faced. In the following subsections these challenges are briefly described, as well as the implemented solutions.

### Mission Analysis

To increase the resolution of the images, LICIACube should be very close to Dimorphos during the flyby. This poses the risk of impacting some of the ejecta particles, following the DART impact on the asteroid. The consequence of particles impact on the CubeSat could lead to partial or total degradation of the system, depending on the size and velocity of the impacting particles. In order to set a safe distance for a very low probability of having an impact with the ejecta particles, an analysis was performed on three different materials, Monolithic Basalt, Weakly Cemented Basal, and Sand/Fly Ash [2]. The outcome of this analysis showed that a minimum distance of approximately 55 km with a delay time of approximately 160 seconds respect to the DART impact would allow to drastically reduce the possibly of the ejecta particles impact.

### Pictures of the Impact and of the Plume

The CubeSat needs acquire scientific pictures of the plume and impact region, as well as navigation images for autonomous navigation (described in subsection 3.3). According to ground-based simulations, the plume may generate a high cone, so a payload with a large field of view is required to fully acquire it. On the other hands, to acquire high resolution pictures of the asteroid and the plume, a narrow field of view payload is required. As results, LICIACube mounts two Payloads, Liciacube Explorer Imaging for Asteroid (LEIA) and Liciacube Unit Key Explorer (LUKE).

LEIA allows the acquisition of high resolution images since it has a diagonal FoV of ± 2.06° with respect to the sensor side, resulting in a spatial resolution of 1.38 m/px at the LICIACube closest approach that allows scientific requirements in terms of spatial resolution to be met. It is a catadioptric camera composed of two reflective elements and three refractive elements designed to work at focus between 25 km and infinity and the detector is a monochromatic CMOS sensor with 2048x2048 pixel.

LUKE is a camera with a FoV of ± 5° and an RGB Bayer pattern filter, designed to work in at focus between 400 m and infinity. The sensor unit is designed to contain the image sensor and interface with a NanoCU, and the optics consists of a ruggedized, mission configurable aperture, lenses and required spectral filters.

### High Angular Rates during Science Mode

The scientific phase of this mission consists of acquiring pictures of the asteroid Dimorphos after the impact with DART. LICIACube will navigate very close to it, with a shorter distance of about 55 km. This poses the first technical problem: pointing a target during a high angular rates maneuver (~7deg/s). To address this challenge, an ad-hoc attitude controller was developed. It was first modelled in a Simulink environment and validated with an extensive HIL validation campaign. This controller was tailored for this delicate phase and proves capable of maintaining pointing even with the high angular rates involved.

The distance between Earth and LICIACube (~10 million kms), which delays the communication to an extent where automatization is fundamental. For this reason, the autonomous navigation system was designed to identify and track Dimorphos from optical images, keeping it inside the FoV during the fly-by time.

This complex system consists of the following sub-systems: the On-Board Computer (OBC), with the primary Payload (PL), i.e. the camera, the Attitude Determination and Control System (ADCS) and the Imaging System (IS). The IS is in charge of receiving images from the primary payload and performing image processing functions to recognize multiple objects in the camera FoV. This capability is used to recognize Dimorphos and evaluate its position. This information is provided to the rest of the autonomous navigation to keep the asteroid inside the FoV during the maneuver.

For the satellite to fulfill its mission, the processing pipeline achieves a latency of at most 4 seconds to provide the required feedback to the rest of the system. For this reason, the first steps are accelerated in hardware using an FPGA while the second part of the pipeline is performed by the on-board software.

A critical part of the development of this system was to calibrate and validate it, as extensively described in [3].

### Communication

LICIACube will not rely on DART for the communication with the ground thus the ground segment selection and the Telemetry, Telecommunication and Command (TT&C) design are two crucial aspects in order to communicate with a CubeSat from 10 million of kilometers.

The primary objective of the GS is to fully support mission operations, ensuring the possibility to control the spacecraft under every condition. Usually, Deep Space Network (DSN) and ESTRACK are used to communicate with the scientific deep space probe. Even in this case, DSN 34 meters antennae are used as ground stations. DSN provides to LICIACube not only the telemetry and telecommand services but also the ranging and doppler to allow the deep space navigation of the CubeSat. On the other hands, The LICIACube Mission Control Center (LICI-MOC) has been designed to meet the specific mission requirement to monitor and control LICIACube after deployment and during mission operations. All the TCs to LICIACube platform will be generated at the LICI-MOC and telemetry, scientific and ancillary data will be received by LICI-MOC for further processing and analyzing. Several tests with each antenna of the DSN asset have been successfully performed to test the compatibility of the LICI-MOC with DSN.

The TT&C Subsystem of LICIACube guarantees all the communications from and to the satellite. It is composed of a radio and a set of X-band patch antennae. The radio is fully compatible with the DSN and an extensive test campaign has been performed with JPL to check the compatibility of LICIACube with DSN. The antennae were designed to meet the specific mission requirements. They are four X-band patches coupled in two TX/RX pairs, placed onto two different faces of the satellite structure:

* The main couple has a TX antenna with 20 dB gain and a RX antenna with 6dB gain
* The secondary pair has a TX antenna with 12dB gain and a RX antenna with 6dB gain.

The selection of the DSN asset and the custom design on the TT&C allow for having a positive link margin every time after the flyby. 6 months of DSN support is required by the mission in order to downlink all the acquired pictures during the flyby since, in accordance with the acquisition strategy, LEIA will capture 202 pictures in total, while LUKE 228 pictures, by pointing out that each acquisition is composed by three shootings with different integration time.

### Long Cruise

For 10 months after its launch, LCC will cruise through space towards its destination installed on DART. The CubeSat shall have the battery fully charged at the power on to achieve the scientific objectives. The battery cannot remain at the full state charge from launch to the deployment of the CubeSat from DART because the battery degradation would be too high. Moreover, during the cruise phase, LICIACube will be exposed to the deep space environment and the expected temperatures varies in the range -20°C/+50°C.

For these reasons, a subsystem that oversees the charging LICIACube battery during the cruise phase and control the CubeSat temperature, called External Battery Charger (EBC), was designed and developed.

The EBC interfaces directly with the DART main power bus thus some design peculiarities were implemented to mitigate electrical faults and their potential propagations to DART:

* a diode will be included into the charge path to be used for in-flight charging to avoid inadvertent battery discharge due to external failures.
* a fuse will be included into the charge path to protect the battery against overcurrent conditions.
* a thermal switch will be used to interrupt the battery charge in case the battery temperature exceeds 37°C di ±2.8 °C.

### Deep Space Environment

CubeSats are typically used in LEO environment, and they use extensively the automotive and COTS components. Since LICIACube flies in deep space, a different approach shall be used. While COTS subsystems have been implemented in the design, some key systems have been developed or customized by Argotec to increase their performances and reliability. The COTS subsystems were selected among the ones that have flight heritage in deep space while the core, of the CubeSat which is the Power Conversion and Distribution Unit (PCDU) and the On-Board Computer and Data Handling (OBC&DH), takes the advance of the Argotec technology that were developed for the ArgoMoon deep space mission. These two subsystems are composed of high reliable deep space components. In addition, the PCDU provide the galvanic isolation and a dedicated latch current limiter for each power lines in order to avoid failure propagations and limit the effect of the radiation particles.

Finally, since the External Battery Charger (EBC) is exposed directly to the deep space environment during the entire cruise phase to the asteroids, it was designed with EEE space grade parts with a TID rating higher than 100 krad and a SEL onset above 75 MeV-cm2/mg.

## CONCLUSIONS

This paper presented the main drivers, challenges and the design choices used for the design and development of the LICIACube mission. The LICIACube mission requires high performance and a reliable design to successfully fulfil the mission objectives since it will perform one of the most challenging missions ever attempted by a CubeSat. Its design, 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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