LICIACube on DART mission: an asteroid impact captured by Italian small satellite technology

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ABSTRACT

In the frame of the Planetary Defense program, NASA developed the Double Asteroid Redirection Test (DART) mission and the Italian Space Agency joined the effort. DART's spacecraft will act as a kinetic impactor by deliberately crashing into the moonlet of Didymos binary system (i.e. Didymos-B) while the effects of the impact will be observed by a small satellite, the Light Italian CubeSat for Imaging of Asteroid (LICIACube) and ground-based telescopes. LICIACube, an Italian Space Agency (ASI) mission, will fly with a relative velocity of approximately 6.5 km/s and it will document the effects of the impact, the crater and the evolution of the plume generated by the collision. LICIACube will have to maintain the asteroid's pointing at an angular speed of approximately 10 deg/s to fly-by the asteroid close to the Didymos-B surface. The images acquired by LICIACube will be processed onboard through the autonomous navigation algorithm to identify the asteroid system and control the satellite attitude. They will also help the scientific community and provide feedback to the Planetary Defense program, pioneered by the Space Agencies. This deep-space mission is based on a small scale but highly technological platform, whose development is involving both the Italian technical and scientific community.

INTRODUCTION

Nowadays scientific community and international space agencies are focusing their attention on the Near-Earth Objects (NEO) intending to localize the ones that have the potential to impact the Earth in the near future. Known asteroids usually orbit inside the main belt of asteroids lying between the orbits of Mars and Jupiter or are co-orbital with the latter. However, there are other orbital families with significant population numbers, which include objects close to Earth. To avoid the heavy consequences of an impact with the planet, the Space Agencies and the states' defense departments monitor these objects to try to forecast a possible threat. Many studies are carried on by both NASA and ESA for asteroid impact avoidance using different solutions, among which the fragmentation and deflection strategy. The first one destroys the object in smaller parts, which will then burn when they enter the Earth's atmosphere. The second strategy involves diverting the orbit of an asteroid to avoid its impact with the Earth. Lately, the latest one involving the kinetic impactor technique gained the favor of the Near-Earth Objects (NEOs) science community. Unfortunately, not all NEOs are known and even of those known, their composition is not well understood.

DART MISSION

The Double Asteroid Redirection Test (DART) mission is part of the plan developed by NASA for the Planetary Defense program. DART is a spacecraft acting as a kinetic impactor that will deflect the orbit of a binary asteroid by crashing itself into the moonlet of the Didymos binary system. To increase the accuracy of the deflection measurement, the ASI 6U Light Italian CubeSat for Imaging of Asteroid (LICIACube) will be carried on DART and released by the main probe in the proximity of the target. The effects of the impact will be observed also from ground-based telescopes. LICIACube, an Italian Space Agency mission, has been designed, integrated and tested by the assigned aerospace company Argotec. The primary objective of LICIACube is to capture photographs of DART impact ejecta plume over a span of times and phase angles in order to confirm the DART impact on the secondary body of the Didymos binary asteroid system and to observe the ejecta plume dynamics. After the deployment from the DART spacecraft, LICIACube will perform braking manoeuvers, to increase the relative velocity with respect to DART spacecraft, allowing LICIACube to perform the scientific phase and fulfil the mission objectives. Following this phase, the LICIACube satellite will continue on its path for a few months, transferring scientific data and performing radio-science experiments. Scientific objectives can be accomplished by using the autonomous navigation algorithm and the imaging capabilities provided by the baseline platform, based on the heritage of the Argotec company. The images acquired by LICIACube will help the Italian involved scientific community and the American partners to obtain relevant data about the binary asteroid system. The scientific team is enriched by University of Bologna team, supporting the orbit determination and the satellite navigation, and Polytechnic of Milan, for mission analysis support and optimization.

LICIACUBE MISSION

Mission Overview

LICIACube is a 6U CubeSat that will be launched inside a dedicated dispenser mounted on DART external panel and deployed from it in a heliocentric orbit after a cruise phase trajectory of approximately 15 months.

The primary objective of the LICIACube mission is to provide multiple images of the DART mission, over a span of times and different phase angles.

Specifically, the images acquired by LICIACube after the DART impact on the asteroid will help the scientific community to study the structure and evolution of the ejecta plume generated by the impact, so to improve the determination of the momentum transferred obtained by DART's impact. The CubeSat will also capture scientific observations of the non-impact hemisphere of Didymos-B.

To summarize, the LICIACube mission primary and secondary objectives are the following:

1. To obtain images of the ejecta plume;
2. To obtain multiple images of the impact region at a high-resolution so that crater's size and morphology can be analyzed;
3. To obtain multiple images of the non-impact hemisphere of Didymos B;

   To acquire images of the asteroid to characterize its spectral class;
4. The imaging of the crater is a nice to have mission objective since it is strictly related to its dimension that is not predictable *a priori*.

For the sake of clarity, the latter is a function of the resolution to be reached during the mission, according to the release and approaching trajectories. The achievement of the LICIACube primary and secondary mission objectives is pioneering the evolution of the nanosatellite technology for deep space.

Mission Description

LICIACube will be deployed by DART, 240 hours (i.e. 10 days) before the Didymos-B impact time, with a relative velocity with respect to DART of 1.14±0.07 m/s, with two "release angles" denoted as φ and θ of φ=38.5° and ϑ=-64°, respectively, with respect to DART reference (Figure 1).

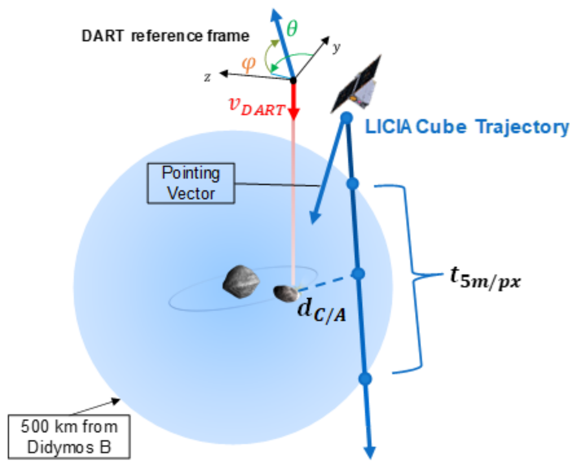

Figure 1 DART Reference Frame

Once deployed, the LICIACube satellite will not execute any ΔV maneuver using the main propulsion within 30 min of release from the DART spacecraft and will inhibit the cold gas propulsion system activation for at least 30 seconds after release. This delay is designed to prevent recontact with the DART spacecraft, as well as to ensure that DART's optical instruments and sensors do not become contaminated with thruster plume products.

Following a successful deployment from the DART spacecraft, LICIACube will power on all its subsystems, except for the TT&C subsystem, to perform in-orbit testing, during the Commissioning phase, to check the health status of the subsystems, calibrate the equipment necessary to fulfil the mission objectives, reconstruct the satellite attitude and start heating the PS unit. The LICIACube ground operators will coordinate with the DART team to assist in providing initial orbit state information and predicted orbit information.

Not earlier than 45 minutes after the deployment from DART, LICIACube will turn on the TT&C subsystem aimed at locking first signals from the Ground Stations for ranging operations of the satellite.

Approximately 55 hours from the deployment time, the main thruster is enabled to perform a braking maneuver (OM1) and increase the relative velocity with respect to DART spacecraft.

The expected ΔV for the braking maneuver is 1.319 m/s, to be applied with 112.08° and -36.12° of Azimuth and Elevation angles, in-plane and out-of-plane angles in EMO2000 reference frame.

Table 1 Parameters for LICIACube release and braking maneuver

Maneuver	Epoch [hour]	ΔV [m/s]	Az [deg]	El [deg]
Release	T0 – 240	-	166.36	57.13
OM1	T0 – 185.91	1.318	112.08	-36.12

Continuing its path along a heliocentric trajectory, approximately 24 hours before DART impacts on the asteroid, the LICIACube satellite will have the chance to communicate with the ground to schedule a corrective maneuver (OM2) in order to get close to the nominal trajectory towards the Didymos-B close approach. The maneuver is a corrective (stochastic) maneuver to minimize the effect of perturbations on the final flyby location and time. The purpose is to minimize the effect of perturbation and to allow the longest DSN tracking possible to enhance orbit determination accuracy. At the same time, it is required to have some time between corrective maneuver and flyby to be able to cope with contingencies.

Given the achieved trajectory deviations and the accuracy from orbit determination, the corrective maneuver magnitude oscillates from 0 to 2.5 m/s, with a mean expected value of 0.83 m/s, as shown in Figure 2.

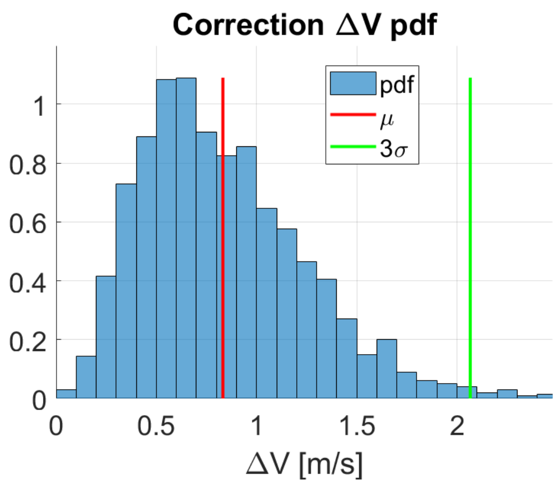

Figure 2 Probability density function for Corrective Maneuver magnitude

DART impact on the Didymos B will occur approximately 24 hours after the LICIACube satellite corrective maneuver. Approximately 165.3 seconds after DART impact, LICIACube will be at 55.3 km from the Didymos-B surface (Close Approach distance) to start performing the scientific phase and fulfil the mission objectives. The scientific phase will continue for additional 38.1 seconds, during which operations are devoted to science acquisition only.

The final uncertainty at the approach foresees a maximum deviation of the close approach distance of around 5-6 km and a delay time variation of 6 seconds, at most (Figure 3 and Figure 4).

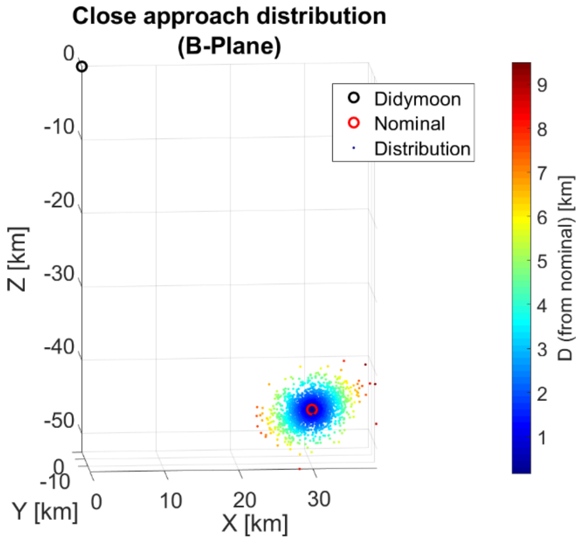

Figure 3 Flyby uncertainty ellipse on B-Plane

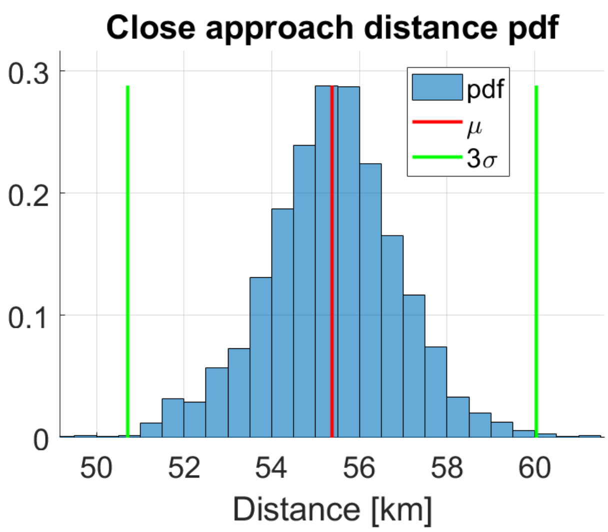

Figure 4 Distance distribution at Close Approach

The flyby distance and delay time have been set in a tradeoff to reduce the load on the attitude control system and to increase the resolution of the acquired pictures. The time of science is defined as the time between the first ejecta image at an acceptable distance and spatial scale (about 5 m/px, at 200 km), and the last acceptable image of the backside at the end of the flyby (about 2 m/px, at 80 km).

Following this phase, LICIACube satellite will continue on its path for a total of about 6 months, during which it will be able to communicate with Earth and exchange scientific data by the means of radio frequency (RF) communication.

Platform Overview

LICIACube platform (HAWK) is a 6U CubeSat with a weight of approximately 12 kg (Figure 5). In order to fulfil the mission objectives, it will be equipped with the following subsystems:

- Payload (PL), two optical cameras (LEIA with 4.12° and LUKE with 10° diagonal FoV) that allow acquiring significant photographs and evidence of the mission fulfilment;
- Structure Subsystem (SS), that provides the necessary physical support to place the hardware and to withstand all the loads that LICIACube will experience during the mission (e.g. launch, deployment, operational mechanical loads);
- Thermal Control Subsystem (TCS), that is the one in charge to keep all the subsystems inside their prescribed temperature ranges;
- Electrical Power Subsystem (EPS), that provides, converts and conditions the power to all the subsystems. It includes the Battery (BAT), the Solar Panel Array (SPA) and the Power Conversions and Distribution Unit (PCDU), which is in charge to convert and distribute the power coming from the SPA to each subsystem or store it in the BAT;
- On-Board Computer and Data Handling (OBC&DH), that provides communication among all the subsystems allowing their interaction;
- On-Board Software (OSW), that is hosted in the OBC&DH, managing the system's commands and telemetries. Representing the main core of the autonomous navigation of the satellite, one of its parts is represented by the Imaging System (IS), that provides the target identification, recognition and pointing;
- Attitude Determination and Control Subsystem (ADCS), that is able to determine and control the satellite's attitude, in order to properly orient it;
- Propulsion Subsystem (PS), which provides orbital manoeuvres and corrections, station keeping and RWs desaturation;

Figure 5 LICIACube Satellite

- Telemetry Tracking & Command (TT&C), which is constituted by an X-Band Transponder connected to a Solid-State Power Amplifier (SSPA) and a Low Noise Amplifier (LNA), providing power and signal to the 4 patch antennas. They are located on two opposite sides of the satellite (i.e. SPA side and radiator side), to exchange command and telemetry with the ground;
- Harness (HNS), that is an assembly of electrical wires required to connect the subsystems, to transmit signals or electrical power.

Platform Description

All the mentioned subsystems were designed to withstand the environment that LICIACube will experience during the mission, in terms of thermal, radiation and mechanical harsh environment.

The PL design was developed in order to be fit into a 6U CubeSat size and to be capable to fulfil the mission objectives. The primary payload is a catadioptric camera composed of two reflective elements and three refractive elements with an FoV of ± 2.06° on the sensor diagonal. The optic is designed to work in focus between 30 ± 5 km and infinity and the detector is a monochromatic CMOS sensor with 2048x2048 pixel.

While the primary PL name LEIA will take greyscale images of the ejecta plume and the asteroid target, the secondary payload LUKE may acquire colored images. It is an RGB camera with an FoV equal to ±5º and a focal length equal to 70.55 mm.

The LICIACube structure was designed to minimize mass and maximize usable volume and offering the highest possible reliability at the same time. Since it shall ensure that the satellite is able to withstand the mechanical environment and space operational one, the SS can be is subdivided into:

- A primary structure, that provides the interface for all the satellite's subsystems:
- A secondary structure, that provides support to the internal subsystems.

The Thermal Control Subsystem (TCS) has the aim of keeping all the subsystems within the required temperature range during the overall mission according to the changing thermal loads and environment. The TCS exploits a completely passive architecture due to the very compact configuration and the absence of eclipses. Thus, thermal paint is applied on the external part of the structure to lower the absorption coefficient and to increase the emissivity to the deep space sink. Besides, gap fillers and thermal spreaders will be inserted.

As already mentioned, the EPS consists of the PCDU, SPA and BAT. Using three regulated voltages, the primary power source is provided by two wings of solar panels and the BAT will store enough energy to sustain non-Sun pointing operating modes and face events of increased demand from the subsystems. The PCDU extracts the maximum electrical power available from the SPA, converting it to distribute the energy to the subsystems, protecting them from overcurrent.

The OBC&DH subsystem represents the core of the satellite since it runs the OSW in order to monitor and control the LICIACube satellite. In addition, the OBC&DH interface the PL and the platform subsystems for Telemetry and Telecommand to properly manage the satellite and acts as the satellite mass-memory.

The OBC&DH embeds also the IS, that drives the LICIACube autonomous navigation that will be described in the following subsection.

The ADCS main function is to stabilize and direct LICIACube in the desired direction despite the external torques acting on it. Three-axis control is necessary to correct the execution of the photographic shooting and the relative maneuvers in the proximity of Didymos-B. Such a technique allows reaching a very accurate pointing and stability required not to deteriorate the acquired pictures. The LICIACube ADCS is composed of a star tracker, IMU and two Sun sensors, that provide their input to the Attitude Determination Block, whose task is to reconstruct the satellite's attitude. That block also feeds the Momentum Control Block, that maintains the spacecraft's momentum within a safe dead band for the RWs. If the limit is exceeded, the PS is required to desaturate the wheels.

The PS is also required since LICIACube will have to perform both braking and correction maneuvers to reach the nominal baseline, approach the impact scene and perform the scientific phase during the asteroid's fly-by. Thus, a cold gas PS will be embarked on LICIACube; it has four double canted thrusters for attitude control and two axial thrusters for orbital maneuvers.

The TT&C Subsystem will manage all the communications to/from the satellite. The involved signals will provide the following information:

- Telemetry and remote-control data (e.g. health and status, in-orbit corrections);
- Payload data (i.e. scientific data);
- Ranging (i.e. pure tones for phase-based distance estimation).

The subsystem includes an X-Band transponder that manages downlink and uplink communications and is connected to four X-Band patch antennas. The set of antennas consists of:

- The main pair composed by a transmitting antenna, with 22 dBi gain, and a receiving antenna, with 6 dBi gain, both placed in the solar side structural panel;
- The secondary pair composed by a transmitting antenna, with 12 dBi gain, and a receiving antenna, with 6 dBi gain, both placed at the opposite side of the main pair.

Autonomous Navigation

As anticipated, LICIACube mission involves a proximity flyby of the binary asteroid system Didymos, composed of a main, bigger body (i.e. Didymos-A or *Didymain*) and a smaller secondary body (i.e. Didymos B or *Didymoon*).

The mission aims at obtaining images of Didymoon at close range shortly after the impact of DART spacecraft.

During that phase, LICIACube satellite shall be able to track the target. Such operation turned out to be highly critical due to the relatively high angular speed in correspondence of the closest approach. Moreover, since the round-trip light time for communication between the satellite and the ground station is of the order of magnitude of the duration of the most critical observation phase, the asteroid's tracking shall be performed autonomously, otherwise, the required maneuvering would be unfeasible.

LICIACube will exploit the feedback coming from the Imaging System (IS) to recover its position relative to the target, collect data and apply a tracking strategy to keep the asteroid in the payload's FoV during the whole process.

The IS allows processing the acquired pictures with payload, in order to recognize multiple objects in the field of view and autonomously support trajectory adjustment. It is composed of a series of two algorithms that cooperate to acquire the consciousness of the framed objects. The LCC algorithms for image recognition can, therefore, be subdivided in:

- IS1, that merges the information commanded to the OBC&DH for the shooting with the pictures' metadata, giving confirmation the target is in view, providing the On-board Software (OSW) with the feedback on the presence of objects in the camera's FoV, by comparing the luminance channel with respect to a threshold evaluated from the OBC;

- IS2, that is able to ensure the level of pointing required by the mission, once the object is confirmed to be in view and the rough position has been estimated. Each photograph is filtered and analyzed to detect the center of the area of the target and the associated dispersion.

Once the IS has provided its feedback, the tracking strategy can be implemented. The strategy includes a first acquisition phase, characterized by a small angular velocity and small uncertainty region, during which the software collects information about the actual trend of the asteroid, build a fingerprint ad identify the best curve that fits the collected data.

Once the outcomes of this phase are obtained and the best curve is identified, the implemented closed-loop controller can determine the required attitude maneuvers to point the asteroid.

The developed controller can actuate the required torques through the satellite's Reaction Wheels (RWs), to point the target within the required accuracy.

To perform such operation, the desired spacecraft's attitude shall be chosen from the onboard pre-loaded data exploiting the results obtained from the trend recognition algorithm. Such data (i.e. the desired attitude) were derived by imposing a continuous pointing of the satellite's Z-axis to the asteroid.

Once the LICIACube desired attitude, in terms of angular velocity and quaternion, is defined, the closed-control loop can compute the errors in relation to the actual satellite's attitude provided by the ADCS.

These errors are used as input in the implemented control law, capable to define the required torque to achieve the aforementioned desired attitude.

A functional scheme of the closed-loop controller is shown in Figure 6.

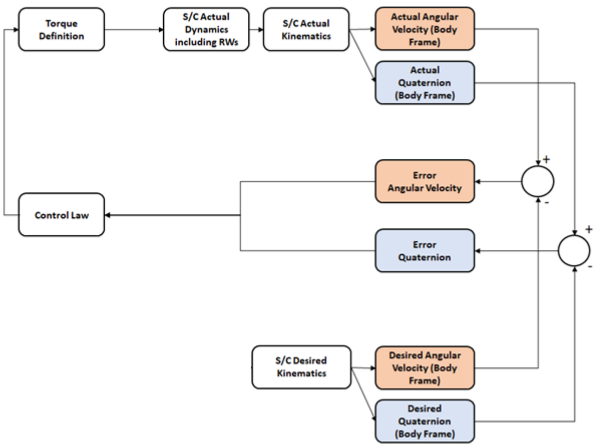

Figure 6 Closed Control Loop Functional Scheme

Being able to provide images as input, such property will be exploited to give the desired input (i.e. images of the target) to the IS, in order to simulate the acquisition of the pictures through the satellite's payload. Then, the capacity of the trend recognition algorithm to recover the real satellite's position and the following target pointing exploiting the developed ADCS controller will be verified.

CONCLUSIONS

The LICIACube mission will be implemented by the 6U CubeSat based on the Argotec HAWK platform, whose main design features and functionalities have been above described.

The HAWK platform is a combination of reliability and resistance, allowing it to take on the harsh environment of deep space missions. The HAWK platform can be customized according to the payload's mass, volume, launcher and mission objectives: it is able to reach Deep Space destinations, as well as performing a mission in Earth's orbit thus greatly increasing the operational life of the mission. The use of commercial components and the interfaces' standardization in the HAWK platform allow the development of relatively cheap CubeSats in a short timescale, so increasing the competitiveness of CubeSats for scientific missions, also in Deep Space.

As time went by, the space community realized the great potential hidden behind such CubeSat. LICIACube satellite and its advanced technologies are the testimonials demonstrating the real potential of the CubeSat sized probes, enlarging their application in much more complex mission scenarios, and potentially towards more distant targets.

References

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