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The First-Ever Asteroid Fly-By Performed by a CubeSat: Outcomes of the LICIACube Mission

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ABSTRACT

Transported onboard NASA Double Asteroid Redirection Test (in short, DART) spacecraft developed by Johns Hopkins Applied Physics Laboratory (APL), the Italian Space Agency (ASI) Light Italian CubeSat for Imaging of Asteroids (in short, LICIACube) played a crucial role in the homonymous mission that took place in September 2022. Its main purpose has been to document the effects of the intentional impact of DART probe with Dimorphos, the minor-planet moon of the 65803 Didymos asteroid system. Along this first-ever planetary defense mission against Near-Earth Objects (NEOs), LICIACube successfully completed the first-ever asteroid fly-by performed by a CubeSat.

With a maximum Earth distance of approximately 14 million km during its operative phase, LICIACube is currently one of the nanosatellites that operated the farthest from our planet in a robotic exploration mission. Once separated from DART, the micro-satellite followed its mothercraft along its approach trajectory: its optical system, composed by two digital cameras, is the core of the Autonomous Attitude Control System which allowed to gather images of the two asteroids during a very fast fly-by. This paper discusses how LICIACube behaved in flight, with a focus on the embedded real-time hardware-accelerated imaging capabilities and the Autonomous Attitude Control System as a whole. These technologies allowed the CubeSat to simultaneously operate its two optical payloads both for tracking and science purposes. During the approximately 5-minute-long fly-by, tracking has been performed using the primary telescopic grayscale camera (LICIACube Explorer Imaging for Asteroid, LEIA) to provide rapid feedback to the satellite Autonomous Attitude Control System controlling its attitude, thus maintaining the pointing towards the target. The telescope was exploited to track the main body (Didymos) during the initial phases of the fly-by, switching then to Dimorphos in the vicinity of the closest approach, which occurred with a distance of about 50km and a relative speed of approximately 7 km/s. On the other hand, the secondary payload allowed to capture and store wide-angle images of DART impact with the asteroid, by means of the secondary RGB camera (LICIACube Unit Key Explorer, LUKE) and with a maximum image acquisition rate of 3 pictures per second.

In the first section of this paper, the LICIACube CubeSat System is introduced in the DART mission context. In second place, Argotec's all-in-house HAWK-6 platform upon which LICIACube was built is discussed in detail. Followingly, LICIACube in-flight performances are examined with a focus on the Autonomous Attitude Control System. Mission results are included, with real-time telemetry data collected during operations and images of DART captured before and after the impact with Dimorphos.

1. INTRODUCTION

The first-ever planetary defense space mission against Near-Earth Objects (NEO) started on November 24th, 2021, when the National Aeronautics and Space Administration (NASA) Double Asteroid Redirect Test (DART) spacecraft lifted off from the Vandenberg Space Force Base. The mission goal was to deliberately deflect the course of Dimorphos, the minor-planet moon of the 65803 Didymos asteroid system, by colliding with it.

A secondary spacecraft was transported aboard, the Light Italian CubeSat for Imaging of Asteroids (LICIACube), designed, built, tested and integrated by Argotec under contract with, and the coordination of, ASI. LICIACube, which main extent was to document the effects of the impact of DART with Dimorphos, was piggybacked on the primary spacecraft reaching a maximum distance from Earth of more than 14 million km before being released. Equipped with two high-performance optical cameras, the CubeSat continuously captured pictures of the approaching asteroid system before and after the impact.

At its closest approach to the Didymos asteroid system, LICIACube performed the first ever fly-by performed by a CubeSat with a distance of about 58 km and a relative speed of 7 km/s circa. To succeed in such a complex scenario, the platform embedded a sophisticated Autonomous Attitude Control System. This mechanism included an on-the-fly hardware accelerated imaging system elaborating the pictures of the asteroid system acquired by the primary optical payloadto obtain the position of Dimorphos, a trajectory recognition routine to reconstruct the actual trajectory of the Cubesat with respect the nominal one, a tracking loop to adjust the platform attitude to center the target and to select the desired one, an attitude controller to provide the attitude control torques and, finally, an Attitude Determination and Control System (ADCS) to measure the attitude and to actuate the reaction wheels, granting sensors feedback to the attitude controller.

In this paper, the LICIACube mission context will be presented along, with a brief description of the all-in-house concept that led to the development of Argotec's own Cubesat HAWK-6 platform.

The Autonomous Attitude Control System implemented on board the platform is then described in its constituent elements, detailing both hardware and software implementations.

As third portion of this work, real-time telemetry data and pictures shot by LICIACube during its fly-by will be shown, portraying the mission outcomes and results.

Conclusions will be eventually drawn at the end of this paper.

2. THE LICIACUBE MISSION CONTEXT AND ARGOTEC'S HAWK-6 PLATFORM

NASA's DART mission was the first-ever demonstration of the kinetic impact technique to modify the motion of an asteroid in Space, thus providing the scientific opportunity to register any variation in the orbital parameters of the asteroid. The target of the mission has been the 65803 Didymos asteroid binary system, that transited close to Earth at about 0.07 AU (11 million km) in September 2022. The choice of this target is linked to the opportunity to record the variation in the orbital parameters affecting a binary system instead of a single asteroid. On September 26th, 2022, DART impacted Dimorphos with an approximate 7km/s speed to deflect its orbit.

DART released LICIACube 360 hours before the impact on the asteroid, which was piggybacked during its travel. In this framework, the LICIACube spacecraft was able to obtain multiple images of the DART impact ejecta plume over a span of 15 minutes, being successful in its scientific objectives [1]:

- testifying the DART impact;
- obtaining multiple (at least 3) images of the ejecta plume taken over a span of time and phase angle, that, with reasonable expectations concerning the ejecta mass and particle size distribution, could potentially:
    - allow measurement of the motion of the slow (<5 m/s) ejecta: this requirement was intended as the possibility to acquire images at spatial scale better than 5 m/pixel, with the possibility to distinguish the movements of the slowest particles of the plume by the sequence of images.
    - allow estimation of the structure of the plume, measuring the evolution of the dust distribution;
- obtaining multiple (at least 3) images of the DART impact site with a sufficient resolution to allow measurements of the size and morphology of the crater. These images were taken sufficiently late after the impact that the plume can be reasonably expected to have cleared;
- obtaining multiple (at least 3) images of Dimorphos showing the non-impact hemisphere, hence increasing the accuracy of the shape and volume determination.

In addition [2], the LICIACube project was an important demonstrator for new small technologies used in Deep Space, which lifetime expectation was more than 6 months.

LICIACube was developed based on Argotec's proprietary Cubesat HAWK-6 platform, which for this specific mission included the following subsystems:

- Primary (codename, LEIA) and Secondary (codename, LUKE) Payload (PL), optical cameras with monochromatic and Red-Green-Blue (RGB) digital sensors, designed to capture images of the DART mission. More details to follows in section 3;
- Telemetry Tracking & Command Subsystem (TT&C), that allowed the satellite to transmit data to Ground Segment, including images and telemetry, as well as receiving of commands from Earth;
- Structure Subsystem (SS), which provided physical support for the required hardware and withstood launch, deployment and operational mechanical loads;
- Thermal Control Subsystem (TCS), which kept all the subsystems' components in their prescribed temperature range;
- Argotec's FERMI On-Board Computer & Data Handling Subsystem (OBC&DH), which included the On-Board Software (OSW) and the Image Recognition Subsystem (IS), and which provided communication between the subsystems and guaranteed their right interaction, performing satellite operations;
- Electrical Power Subsystem (EPS), which included the Argotec's VOLTA Power Control and Distribution Unit (PCDU), the Solar Panel Assembly (SPA) and the battery (BAT), and which provided, managed and stored the required electrical power for the spacecraft. Moreover, it converted and distributed the electrical power coming from the SPA to the BAT;
- Attitude Determination and Control Subsystem (ADCS), aimed to determinate and to control LICIACube attitude, considered where the satellite pointed and therefore oriented it;
- Propulsion Subsystem (PS), which guaranteed the capability of the satellite to perform both attitude and orbital maneuvers.

Table 1 lists the main characteristics of the LICIACube spacecraft, while Figure 1 shows a picture of the satellite in its deployed configuration.

Table 1: LICIACube main characteristics

Field	Value
Dimensions	10 cm × 20 cm × 30 cm; (3.9 in × 7.9 in × 11.8 in)
Mass	12.98kg
Generated power	Up to 80 W (BOL)
Downlink rate	Up to 256kbit/s (X-Band)
Propulsion	Cold gas based on R-236fa
Optical payloads	±2.07° FoV (LEIA) ±5° FoV (LUKE)

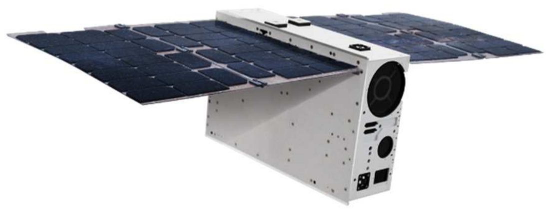

Figure 1: LICIACube deployed configuration

The integration with DART took place during the month of September 2021 in the clean rooms of the Applied Physics Laboratory (APL) of the Johns Hopkins University in Laurel, MD, USA. Figure 2 shows the CubeSat attached to the surface of the main spacecraft from which it was later deployed more than a year later, on 11 September 2023 at 23:14 UTC, after a cruise of almost 10 months and about 14 million kilometers from Earth.

Figure 2: LICIACube integrated with the DART spacecraft at APL in September 2021

3. AUTONOMOUS ATTITUDE CONTROL SYSTEM DESCRIPTION

As previously introduced, the LICIACube satellite included two optical payloads to succeed in its main mission. The primary one (LEIA, LICIACube Explorer

Imaging for Asteroid) was composed of a narrow field panchromatic (i.e., visible and near-infrared part of the spectrum) camera able to acquire images of the ejecta plume and of the target asteroid. The secondary PL (LUKE, LICIACube Unit Key Explorer) acquired coloured pictures with a wide field RGB camera, allowing a multicolor analysis of the Didymos system environment. The collected images were utilized as an input for the on-board implemented software for imaging recognition (IS). Table 2 and Table 3 show the main characteristics for LEIA and LUKE.

Table 2: LEIA main characteristics

Field	Value
Diagonal FoV	±2.07°
IFoV	24.71µrad/pixel
Focal Length	222.55 mm
F/N	3
Colour Filters	Panchromatic (400-900 nm)
Mass	800 gr
Sensor	CMOS CMV4000
Number of Pixels	2048 x 2048
Pixel Size	5.5 µm
Pixel Reading Resolution	10 bit or 12 bit
Integration Time Range	From 0.1 ms up to seconds
Operability	Up to 6 frame/s
Storage	Up to 1GB

Table 3: LUKE main characteristics

Field	Value
Diagonal FoV	±5.16°
IFoV	78µrad/pixel
Focal Length	70.5 mm
F/N	2.2
Colour Filters	Panchromatic (400-900 nm)
Mass	392 gr
Sensor	CMOS CMV2000
Number of Pixels	2048 x 2088
Pixel Size	5.5 µm
Pixel Reading Resolution	10 bit
Integration Time Range	From 0.1 ms up to seconds
Operability	Up to 15 frame/s
Storage	Up to 16GB

The LICIACube Autonomous Attitude Control System was designed and developed based on the mission challenges and the derived requirements for the attitude control system, which can be resumed as follows:

- the satellite shall be able to identify and track Dimorphos from optical images;
- the Autonomous Attitude Control System shall be able to keep Dimorphos in the camera Field of View (FoV) for at least the 90% of the fly-by time;
- assuming the worst-case trajectories, the Autonomous Attitude Control System shall still keep Dimorphos in the camera FoV for at least 90% of the fly-by time;
- the satellite shall be able to reach a peak of 7 deg/s body rate.

A functional diagram of the Autonomous Attitude Control System is depicted in Figure 3 at page 5.

The Autonomous Attitude Control System, described in detail in [8], was composed by four main software modules that run on the OBC&DH subsystem that had two interfaces respectively with the Primary Payload and the ADCS. The main software modules were the Imaging Subsystem (IS), the Trajectory Recognition, the Tracking Loop and the Attitude Control. IS processed the image acquired from the payload to recognize the two asteroids, and to give feedback to the Trajectory Recognition module. For every object it recognized, the IS provided the offset of the centroid with respect to the center of the image. The Trajectory Recognition module estimated the actual trajectory on which the satellite was traveling. Each possible trajectory was defined by the time at which the satellite would be at closest approach (C/A) and its distance from the asteroid. The purpose of this module was to compensate for the uncertainty arising from on-board time and ephemeris. Tracking Loop module took as input IS results and the angle between the payload axis and the asteroid in the nominal or estimated trajectory, deriving the desired pointing quaternion to track Dimorphos. Finally, the Attitude Control module controlled the angular velocity of the ADCS reaction wheels by means of a PD controller. It got the current quaternion and body rate from the ADCS and it calculated the torque to control the ADCS. It has to be noticed that it was not possible to use the ADCS internal controller for the fly-by because it was too slow for the estimated body rate of 7 deg/s at the C/A.

Concerning the IS module, images acquired by the primary PL were transmitted to the OBC&DH subsystem via a high bitrate SpaceWire (SpW) interface. Streamed data were processed in a hardware-accelerated environment, composed by image processing algorithms performed on-the-fly in a Microsemi RTG4 Field Programmable Gate Array (FPGA) [6]. These algorithms composed a processing chain with the following functional cores:

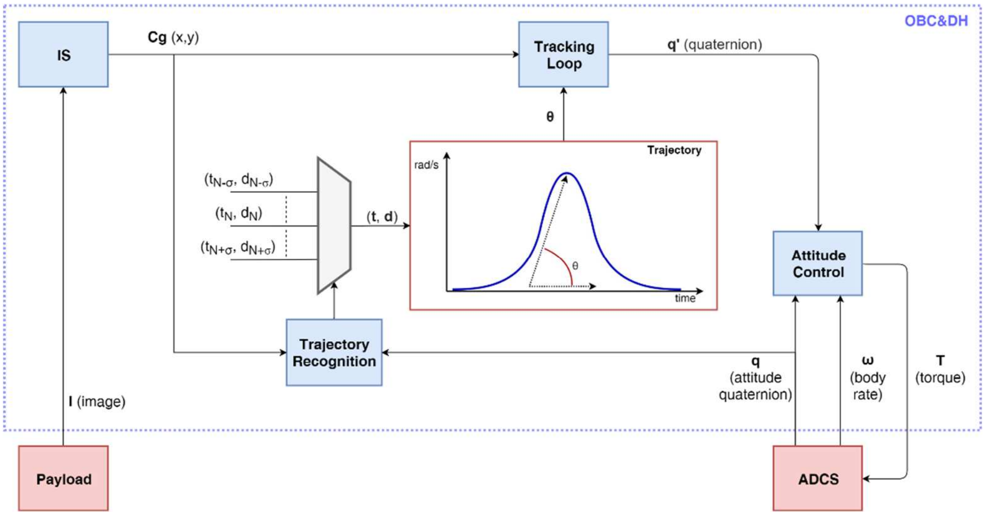

Figure 3: Autonomous Attitude Control System functional diagram

1. Pixel binning;
2. 2-D convolutional Low-Pass Filter;
3. Luminance Histogram generation with threshold calculation;
4. Binarization;
5. Multi-Target Identification.

The first element, pixel binning, allowed to reduce by a factor 4 the size of the input image, thus reducing the time to process it. Operating with 2048x2048 pixel pictures, the pixel binning brought down the scale to 512x512 pixels.

The second core, Low-Pass Filter (LPF), performed a two-dimensional convolution between the binned image and a 3x3 user-programmable kernel, with the resulting effects of smoothing objects edges in the pictures. Moreover, background noise is filtered – thus, small objects such as one-pixel-dimensioned stars, typical of the Deep Space environment, are removed.

The next item was composed of the Luminance Histogram (LH) generation which lead to the calculation of the binarization threshold.

As a result of this step, binarization was performed on the image. The resulting picture was a black-and-white scheme, that leveled pixels with a lower value than the threshold to the background and flattened the pixel dynamic to a single value to minimize the effort for object recognition.

The outcome of the FPGA-based image processing algorithm was the Multi-Target Identification (MTI), which labeled each non-void pixel as a single object in the stream and combined multiple non-void adjacent pixels as a single entity, thus speeding the process of the identification of the Didymos asteroid system in real-time.

Figure 4 shows the feedback output from the FPGA-based IS datapath. The resulting data were transferred to the COBHAM Gaisler GR712RC Central Processing Unit (CPU) for the following elaboration by the On-Board Software (OSW).

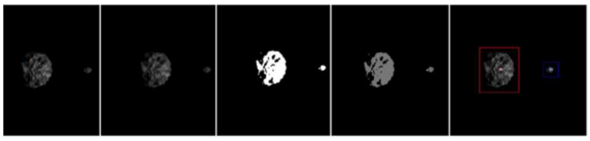

Figure 4: FPGA-based IS feedback output

With a pipelined elaboration, implemented with low device resources occupation (5% Look-Up Tables, 3% Flip-Flops, 15% Block Random-Access Memories), the hardware-accelerated IS portion provided high performances (up to 50Mpixel/s) and low latency (~650ms) results. These results were applicable to the implementation in Argotec's FERMI On-Board Computer FPGA This advanced elaboration was undisputedly the most important feature for allowing a rapid adjustment to the satellite attitude control system.

Cascaded to the IS execution, and by using its input, the 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 software modules that implemented this attitude control feature has been developed with a specific purpose in mind: to be able to update their parameters during the mission, after a calibration and measurement phase that could reduce the uncertainties modeled by this system.

In fact, for the tracking and trajectory estimation algorithm, the developers have assumed two major uncertainties: the distance from the asteroid and the time of the C/A. The mission analysis gave preliminary estimation for these two uncertainties, yet fortunately it had been possible to update the parameters of the whole attitude control system, given the different trajectory and speed, due to the anticipated LICIACube release from DART. Argotec developed an optimization system based on genetic algorithms and a fly-by simulation software that has been leveraged, once the in-orbit measurements were known, to compute the final parameters to uplink to the satellite.

4. MISSION RESULTS WITH REAL-TIME TELEMETRY DATA

During the planning and execution of the image acquisition timeline for the flyby, the different optical and electronic characteristics of the two cameras, as well as the image purpose, were considered.

Firstly, some pictures from LEIA were utilized for initial attitude control adjustments. These images allowed for accurately framing the asteroid within the camera's view, ensuring precise positioning and alignment for data collection.

Figure 5 shows that the first image acquisition for LEIA, that could frame the asteroid because of its smaller field of view, despite the expected distance from the target being greater than 1380 km, was scheduled 240 seconds before the closest approach.

As LUKE had a wider field of view, its image acquisition was programmed to start later once it approached the asteroid sufficiently to capture meaningful frames.

During the closest approach, both cameras acquired images at a higher frequency to acquire detailed information about the consequences of the impact of DART on Dimorphos.

In the approach and departure phases, where the distance and field of view did not require a high frequency of image acquisition, a lower acquisition rate was planned for both cameras. This enabled efficient management of the internal storage of the cameras and preserved space for the most relevant data. Considering the different storage capacities of the cameras, special attention was given to evenly distributing the images between the two cameras. The camera with a larger storage capacity captured a greater number of high-resolution images during the flyby, while the other camera captured a sufficient number of images with a quality suitable for scientific requirements.

Furthermore, both camera parameter values were updated during the last communication window using the information resulting from the analysis of the calibration images acquired in the previous days. This process involved fine-tuning the camera settings to optimize image quality and ensure accurate scientific measurements. By incorporating the updated parameters, the cameras were able to capture images with improved clarity and enhanced scientific relevance.

The sum of attitude control and science pictures of both cameras is greater than 600. Table 4 summarizes the number of images captured during tracking control loops.

Table 4: Image Acquisition Number

Control Loop # (6s each)	Attitude Control Picture #	Science Picture #	
	LEIA	LEIA	LUKE
0	1	1	0
6	1	3	3
16	1	3	6
34	1	3	6
37	1	3	18
42	1	3	6
45	1	3	3
65	1	1	3

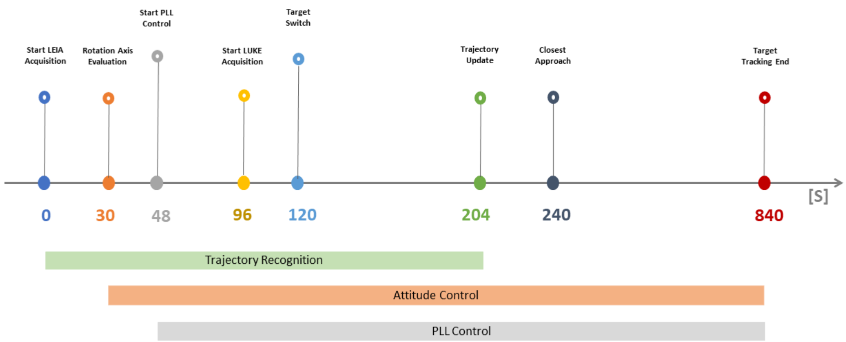

Figure 5: Asteroid Tracking Event Timeline

Figure 6 shows three images acquired in key moments of the tracking: the first image acquired by LEIA (up), the image acquired when the target switched from the main to the smaller body (down-left) and the image acquired at the trajectory recognition parameter update (down-right).

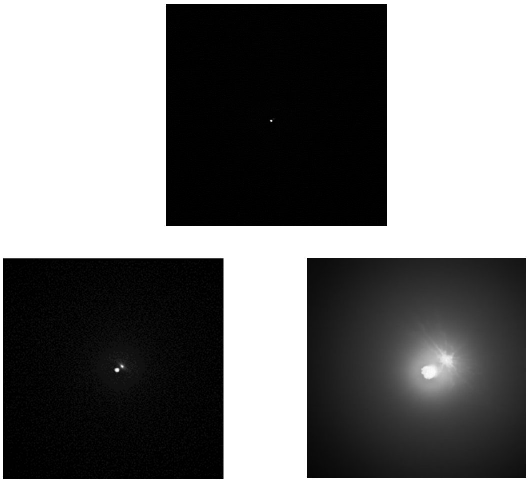

Figure 6: Acquired images from LEIA (credits ASI/NASA)

5. TRACKING AND TRAJECTORY RECOGNITION RESULTS

The LICIACube Autonomous Attitude Control System, widely discussed in [7], was composed of two main building blocks: a target tracking module and a trajectory recognition module. The target tracking module aimed at keeping the asteroid within the camera FOV since the first picture of the acquisition timeline. During an initial calibration and before any actuation, this module identified the best rotation axis (with respect to the spacecraft body reference frame) to efficiently control the spacecraft attitude correction.

Figure 7 reports the scatter plot of the centroids location with respect to the camera FOV starting from 240 seconds before the closest approach (T_0) up to the trajectory update (T_0 + 204 seconds, 40 seconds circa before closest approach). The centroid locations are referred to the main body, that was the biggest object within the acquired picture. The six blue dots show (each dot represents an acquisition) how fast the target would have left the camera FOV in case of no active control at T_0. With the target tracking and attitude control running, the target was effectively kept very close to the center of the picture (orange dots).

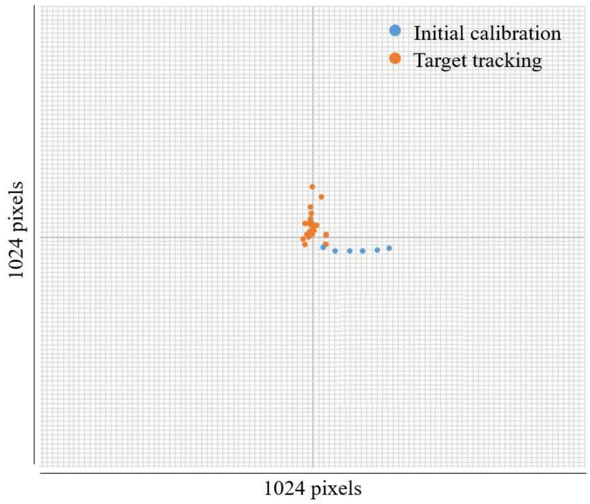

Figure 7: Scatter plot of target centroids

The active target tracking adjusted the spacecraft attitude minimizing the pointing error (the distance of asteroid centroid in terms of pixels with respect to the center of the images). The attitude correction translated into a rotation of the body reference frame. Figure 8 shows the body rate in rad/s on the main rotation axis, which had the most relevant impact on the pointing accuracy. These data represent real body-rate measurement acquired by the ADCS subsystem.

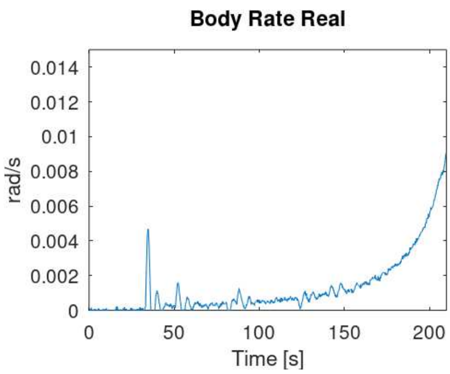

Figure 8: LICIACube body rate [rad/s] Main rotation axis

The impulsive behavior visible at 35 seconds was to correct the large initial pointing error. After that, additional corrections happened every 6 seconds (attitude control images acquisition time step). The body-rate increased as the LICIACube spacecraft approached the asteroid.

During the active tracking, the trend recognition module used all the information on the pointing error to update the trajectory parameters in terms of "time to the closest approach" and LICIACube-to-Dimorphos distance at closest approach. The trajectory recognition module autonomously computed the fly-by parameters specified in Table 5.

Table 5: LICIACube autonomously computed parameters at fly-by

Field	Expected value	Trajectory recognition estimation	Effective value [2][9][10]
LICIACube to Didymos distance at closest approach	57560 m	59940 m	57940 m
Closest approach time (UTC):	2022-09-26 23:16:39	2022-09-26 23:16:40	2022-09-26 23:17:11.4869

All the pointing error information were collected based on the position of the main visible body. Hence, the trajectory parameters refer to Didymos, which was always detectable since the beginning of the acquisition timeline. The result of the trajectory correction is visible in the spacecraft body rate reported in Figure 9.

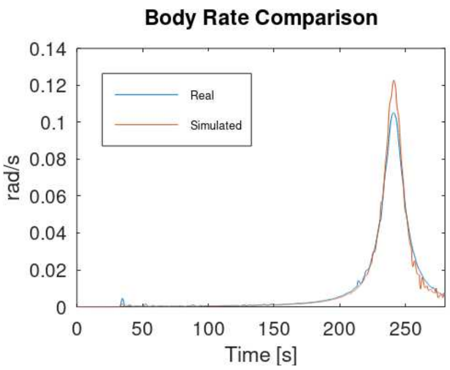

Figure 9: LICIACube body rate [rad/s] Entire fly-by

The real trajectory had a distance at the closest approach slightly larger with respect to the expected one, which resulted in a smaller body rate (in the order of 0.01 rad/s). Based on trajectory parameters corrections, the spacecraft successfully performed its mission acquiring stunning pictures pre, during and post fly-by.

Figure 10 shows a post-processed image of the ejecta plume of Dimorphos acquired by LICIACube, within which each rectangle represents a different level of contrast to better see fine structure in the plumes.

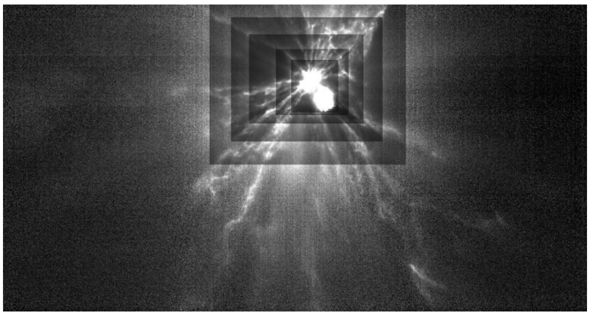

Figure 10: Plume of ejecta from Dimorphos (credits ASI/NASA)

6. CONCLUSIONS

In this paper, the results of the LICIACube mission have been presented with specific insights on its subsystems integrated in Argotec's HAWK-6 platform. Details on the Autonomous Attitude Control System implementation have also been enlisted, offering a spotlight on the outstanding mission results accomplished. In particular, the hardware-accelerated image processing algorithms allowed rapid feedback to the on-board software. This element was in charge of controlling the attitude of the satellite in real-time, with adjustments performed by a high-performance custom-designed control module.

The described outcomes have also shown that the behaviour of the satellite met the expectations, despite their extreme challenges, in terms of functionalities and performances. In fact, the large number of pictures acquired (more than 600) and the precision the satellite performed the Didymos asteroid system fly-by with, confirmed the quality of the mission analyses and algorithmic simulations.

Images shot with the LICIACube optical payloads at close distance allowed to provide remarkable details of the DART impact with Dimorphos to the scientific community, integrating Earth-based observations. Both monochromatic and RGB pictures were transmitted to Earth from the satellite, with impressive specifics on the ejecta plume and the effects on the asteroid system. Never before a CubeSat platform had been able to witness an event of such importance, and such a long distance from Earth.

As a conclusion, the LICIACube satellite capabilities have been a striking opportunity to demonstrate the suitability of the CubeSat platform technology for present and future Deep Space missions.

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