Guidance Navigation and Control Challenges for the ESA Asteroid Impact Mission

By Massimo CASASCO,[1)] Jesus GIL FERNANDEZ,[1)] Guillermo ORTEGA,[1)] and Ian CARNELLI[2)]

[1)]*European Space Technology Centre, Noordwijk, The Netherlands;*
[2)]*European Space Agency Headquarters, Paris, France*

The Asteroid Impact Mission (AIM) is a small mission of opportunity of the European Space Agency. Launched on a Soyuz-Fregat from Kourou, AIM will reach the binary asteroid system Didymos after only 1.5 years of cruse. AIM will demonstrate new technologies, carry out fundamental asteroid research and assess the capabilities of a kinetic impactor for planetary defence. The AIM main spacecraft is designed to carry three smaller spacecraft – the MASCOT-2 asteroid lander, provided by DLR, and two CubeSats (COPINS). The distances to Didymos during close proximity operations impose significant challenges on the Guidance Navigation and Control (GNC) subsystem in terms of performance, reliability, and autonomy. Deployment of MASCOT-2 drives the GNC performances. MASCOT-2 has no means of propulsion and needs to fully rely on the AIM spacecraft for being injected into a ballistic trajectory that achieves successful landing on the secondary asteroid Didymoon. Uncertainties in the ephemeris of the asteroids require that relative navigation techniques are used. The baseline is to use vision-based navigation to either determine the asteroid centre of brightness or track unknown features on the asteroids' surface. This paper addresses the challenges encountered in the trajectory and navigation design for AIM and describes the adopted design solutions.

Key Words: relative navigation, NEOs, trajectory design, data fusion

1. Introduction

The Asteroid Impact Mission (AIM),[1)] is a small mission of opportunity of the European Space Agency, currently undergoing preliminary design and intended to demonstrate new technologies, to carry out fundamental asteroid research and to assess the capabilities of a kinetic impactor for planetary defence (the latter performed in collaboration with the NASA-led DART spacecraft as part of the AIDA mission). Launched from Kourou on a Soyuz-Fregat, AIM will reach the binary asteroid system 65803 Didymos after only 1.5 years of deep-space ballistic cruse. Figure 1 shows a schematic of the AIM mission reference profile. Scientific characterisation of Didymos (focusing in particular on the smaller asteroid - informally called Didymoon - of the two asteroids composing the binary asteroid system) will be performed by means of remote sensing instruments (high-resolution cameras in visual and infrared wavelengths together with radars) as well as in-situ instruments (on-board of the MASCOT-2 small lander). The close proximity operations near the Didymos system will include an early characterization phase (ECP) at distances in the order of 35 km, two detailed characterization phases (DCP1 and DCP2, before and after kinetic impact by DART) at distances in the order of 10 km and special operations for ballistic deployment of MASCOT-2 (at less than a few hundred meters from Didymoon) and for deployment of the COPINS CubeSats. An inter-satellite link is implemented to allow communication between AIM and MASCOT-2 and between AIM and the COPINS, which will impose constraints on the close proximity operations. Such distances and constraints impose significant challenges on the Guidance Navigation and Control (GNC) subsystem of AIM in terms of performance, reliability and autonomy, that will be discussed in the following chapters of this paper.

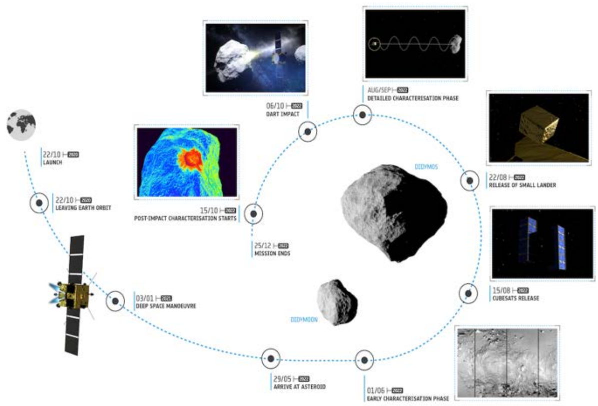

Fig. 1. AIM mission reference profile

2. Overview of AIM's GNC system

The European Space Agency has been developing on-board Guidance, Navigation, and Control (GNC) technologies for all types of missions to small bodies, namely characterisation, sample-return, and deflection missions to asteroids and comets (Rosetta, Don-Quijote, Marco-Polo, Marco-Polo-R),[2)]. Experience from designing these missions allowed for efficient selection of the baseline sensor and actuator suite for AIM: star trackers, IMUs, sun sensors and navigation cameras are the sensors measuring inertial attitude and relative position with respect to Didymos, while reaction wheels and chemical thrusters are the actuators providing 6 degrees-of-freedom controllability.

The technology developments carried out in the frame of those projects allowed the identification of critical technologies and preliminary design solutions for AIM. The AIM mission requires prolonged operation in proximity of the Didymos system: the small relative distances to the asteroids impose demanding performance requirements on the relative navigation function and impose the need of autonomous collision avoidance manoeuvring capability as a safety measure. The unknown environment at Didymos and the effects on the environment following DART's impact also need to be addressed to the maximum possible extent.

Deployment of MASCOT-2 drives the spacecraft design due to the combination of GNC performance, reliability and level of autonomy required to successfully and safely carry out the deployment. Autonomous on-board relative navigation is the enabling technology for MASCOT-2 deployment.

During the ECP and DCP phases, the navigation accuracy, autonomy and safety requirements are more relaxed and the baseline approach is to use a ground-based navigation approach, making maximum reuse of the techniques, processes and tools developed for Rosetta.[3)]

2.1. Challenges on GNC hardware

The need to operate in Didymos proximity after DART's impact, when the impact ejecta will form a cloud surrounding Didymos,[4)] has parallels with the operations of ESA's Rosetta mission at comet 67P/Churyumov-Gerasimenko, which generated significant amount of dust particles around perihelion passage. Also, natural presence of dust in the Didymos environment cannot be excluded.

Dust particles proved to be a significant challenge for the CCD-based Rosetta star trackers. The attitude determination algorithms of the Rosetta star trackers were designed specifically to use a pattern recognition algorithm that improves robustness to persistent objects (i.e. non-SEU objects) in the star tracker's field-of-view (FOV).[5)] Nevertheless, loss of tracking has been experienced in flight at close distance from the comet and during phases of high comet activity. While some limited improvement can be expected by using the last generation APS-based star trackers, the issue of robustness to dusty environments needs to be addressed at GNC system level.

For this reason, the AIM GNC system design includes the following:

- A gyro-stellar estimation function capable of sustaining prolonged gyro-only attitude propagation,
- A star-tracker-less survival mode to ensure ultimate spacecraft safety,
- The FDIR function is designed to always attempt attitude acquisition when tracking is lost,
- The gyro-stellar estimator innovation check within the FDIR function is specifically tuned for presence of dust.

A separate challenge with impact on hardware results from the need to minimize parasitic ΔV (in turn dictated by the need for accurate trajectory reconstruction to achieve the demanding performance requirements on relative navigation in asteroid proximity). This drives the selection of the thruster layout, which has been designed to implement a so called pure-force/pure-torque configuration, whereby actuation for attitude control nominally produces a null force. In addition, the safe mode has been designed to autonomously switch to using reaction wheels as soon as possible, thus minimising thruster usage.

With respect to ΔV estimation, given the performance limitation of the baseline accelerometers selected for AIM, and the intrinsic limitation of all accelerometers in accurately determining accelerations below a certain threshold, a pulse count method has been included in the GNC baseline design. As a consequence, accuracy and repeatability properties of the thrusters are of importance since the accuracy of the pulse count method depends on the repeatability of thruster pulses and relies on accurate modelling of the thruster transient behaviour.

Selecting the navigation camera to support all mission phases using relative navigation has also proved to be a challenge, since the design goal was to use a single camera for both asteroid recognition and tracking during approach and rendezvous with Didymos (distances up to approximately 1 million km) and for relative navigation (both ground-based and autonomous) during all close proximity operations (distances between 35 km and a few hundred meters). Cameras with 1 megapixel detectors have been considered, for qualification status and reliability reasons. The camera field of view has been subject of trade-offs and a range of viable FOVs for AIM identified. Cameras with the same design as the Dawn Framing Cameras,[6)] have been selected, which satisfactorily comply with the suitable FOV range. Trade-off on the camera spectral bandwidth (i.e. multispectral solutions that include near infrared – NIR - and/or thermal infrared wavelengths together with visible wavelengths) have been performed, which led to the decision to have a camera in visible spectrum as baseline navigation camera, together with the optional possibility to fuse information from payloads operating in NIR or thermal infrared (see Chapter 2.7).

2.2. Autonomous navigation concept for AIM

As mentioned at the beginning of this paper, the unique mix of performance, reliability and autonomy requirements that needs to be satisfied to ensure successful MASCOT-2 landing on Didymoon, calls for the need of autonomous on-board relative navigation. Autonomous GNC systems for descent and landing missions has been developed under several ESA contracts with GMV Innovating Solutions,[7)] mainly to address the needs of the Marco Polo and Marco Polo-R missions, and have been adapted to AIM in support of the descent towards Didymoon for MASCOT-2 release.

The objectives of the autonomous GNC system are to enable flexible, robust proximity operations for different strategies and to minimise space segment development and operational costs. The GNC system is based on advanced algorithms fitting into existing flight processors, and low-cost, European navigation sensors (optical camera, star tracker, IMU).

These advanced algorithms entail two different navigation strategies: pure relative navigation and enhanced relative navigation. Both strategies are based on the tracking of unknown features on the surface of the asteroid. The difference lies in the initialisation procedure. In pure relative navigation, ground produces a trajectory prediction at the start of the D&L sequence and uploads it to the spacecraft. Relative navigation is then performed autonomously using the ground-based trajectory prediction to initialise the navigation filter. In enhanced relative navigation, a landmark database (generated in a previous asteroid characterisation phase, following the approach used in Rosetta) is used on-board to initialise the spacecraft position in the navigation filter relative to asteroid-fixed frame.

Pure relative navigation is the selected baseline for AIM: navigation filters are initialised by ground using on-board measurements (by the navigation camera, star tracker, and IMU), sent to ground and used to propagate the spacecraft state vector until the time when autonomous relative navigation is engaged. When the navigation is switched to autonomous mode, feature tracking is used to measure change in spacecraft pose between images. The image processing techniques employed for this purpose are Harris corner detector (feature detection) and KLT algorithm (feature tracking).

2.3. Trajectories and closed loop attitude guidance

Relative trajectories for ECP and DCP are defined with the primary objective of ensuring spacecraft safety. Following the operational experience from Rosetta,[8)] the decision is taken to always fly AIM on hyperbolic arcs, whereby the spacecraft is never on a collision course with any of the asteroids. For safety reasons, the arcs are designed to have a pericentre velocity at least 40% larger than the escape velocity from the Didymos system at that pericentre radius. These hyperbolic arcs are patched together with the objective of achieving repeatable patterns that satisfy maximum and minimum distance limits (e.g. 15 km and 10 km respectively in DCP), suitable phase angles for navigation (and science) purposes (e.g. phase angles below 60 deg) and intervals between manoeuvres that are compatible with the operation team shifts. Figure 2 shows a typical trajectory solution respecting the constraints described above and satisfying the needs of payload observations.

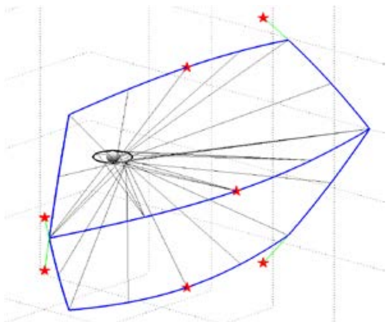

Fig. 2. AIM trajectory in DCP

Again based on Rosetta operational experience, ΔV manoeuvres are designed to be split into two legs in order to avoid that any incomplete manoeuvre execution could reduce the spacecraft velocity below the escape velocity. These robust manoeuvres give rise to a small additional cost in ΔV, which is considered acceptable.

For proper tracking of these trajectories it is of utmost importance that Didymos is always kept in the navigation camera FOV. Achieving this objective requires that the attitude guidance is well synchronised with the trajectory evolution. However, the uncertainty in spacecraft position determination between the subsequent navigation passes that are used in ground-based navigation may grow to such an extent that pre-defined attitude guidance profiles are no longer sufficiently synchronised with the spacecraft position to keep Didymos in the navigation camera FOV. To counter this potential issue a semi-autonomous attitude guidance has been developed. This algorithm applies a delta quaternion to the reference attitude profile uploaded by ground in order to correct the camera pointing to the asteroid. To maintain some degree of predictability of the spacecraft attitude, this technique has been designed to constrain the deviation from the ground-generated attitude profile: the delta quaternion can be limited by thresholds which depend on the ground-predicted navigation dispersion; in case these thresholds are exceeded or any failure occurs, the ground-based reference attitude profile is used.

2.4. MASCOT-2 release phase

MASCOT-2 is a shoebox-sized lander, provided by DLR, which will carry in-situ measurements on the surface of Didymoon. It has no means of controlling its descent trajectory once released from AIM, therefore successful landing depends on the accuracy of the ballistic deployment by AIM. MASCOT-2 is equipped with a hopping mechanism that can be used to relocate it after landing in case it comes at rest in an unsuitable location, typically for power generation or communication reasons. Because of this, the target area for MASCOT-2 landing is relatively wide (an equatorial region limited by a latitude band of ±60 deg), while localisation after landing is required. In fact, in support to localisation, the capability of AIM to provide radio ranging and optical observations of MASCOT-2 during its descent are defined as goals.

The gravity environment of the Didymos system is one of the major challenges for the MASCOT-2 release and landing phase. Indeed, landing on Didymoon implies being subject to a 3-body dynamics (see Fig. 3) where the escape velocity relevant for landing is to be interpreted as escape through the L1 and L2 necks, which are equal to approximately 4.2 cm/s and 4.6 cm/s, respectively.

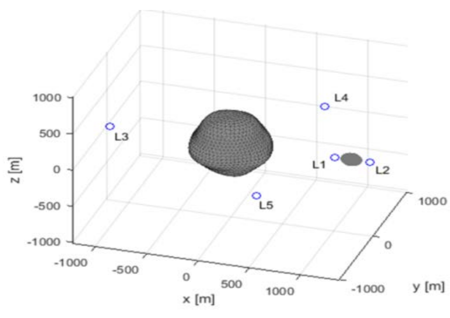

Fig. 3. Lagrangian points in the Didymos system

Also for the MASCOT-2 release problem, the operational experience from the Rosetta mission provided useful lessons learned. Indeed, based on the experience of the Philae lander release, the following guidelines are considered for the MASCOT-2 release by AIM:

- The release of the lander shall not put the orbiter at risk: the deployment trajectory to be flown by AIM must be passively safe (i.e. collision-free even in case a manoeuvre is missed)
- Continuous availability of images for optical navigation shall be ensured (this implies restrictions on the Sun/asteroid/spacecraft angle)
- The number of manoeuvres to be autonomously executed shall be limited (to avoid accumulation of uncertainties in the trajectory)

All above considerations have been used to formulate the objectives relevant for the AIM descent trajectory towards Didymoon. The (somehow competing) objectives are the following:

- Minimise landing velocity by inserting MASCOT-2 in a low energy trajectory in the 3-body dynamics (through or close to the L2 neck).
- Minimise flight time while ensuring robustness to deployment position and velocity errors due to navigation and deployment mechanism (this limits the minimum velocity that can be achieved)
- Ensure good observation conditions of Didymain during the first part of the descent (low enough phase angle)
- Ensure good observation conditions of Didymoon before MASCOT-2 deployment (low enough phase angle, avoid occultation by Didymain and eclipses)
- Achieve MASCOT-2 landing immediately after eclipse with good phase angle (to ensure MASCOT-2 observability during bouncing, then power generation)
- Ensure that the angle between the release velocity and Didymoon surface is smaller than the navigation camera FOV (to allow taking images of MASCOT-2 and surface of Didymoon during descent)

An example of a feasible trajectory designed according to the objectives above is shown in Fig. 4 and Fig. 5.

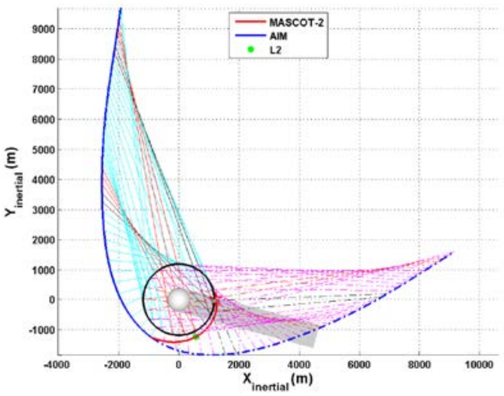

Fig. 4. Trajectories in inertial frame showing the line of sight from AIM to Didymoon (red: occultation by Didymain - black: eclipse – cyan: phase angle <90 deg – magenta: phase angle > 90 deg – solid lines: before release of MASCOT-2 – dashed lines: after release of MASCOT-2)

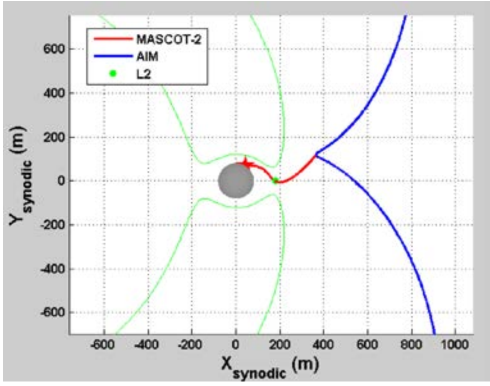

Fig. 5. AIM and MASCOT-2 trajectories in synodic frame

The epoch of the release is the free parameter that can be chosen to optimise the illumination conditions for optical navigation during the descent.

The success rate of the landing has been evaluated considering the total position and velocity dispersions due to navigation and to the deployment mechanism. Bouncing dynamics has been modelled and included in the simulation tool. Statics on the landing success have been obtained by Monte Carlo simulation campaign. An example of this type of assessments is shown in Fig. 6 and Fig. 7. As expected, MASCOT-2 will bounce several times before coming at rest, due to the extremely weak gravity of Didymoon. In the sample shown in Fig. 6 and Fig. 7, three trajectories do not come at rest on the surface and escape from Didymoon.

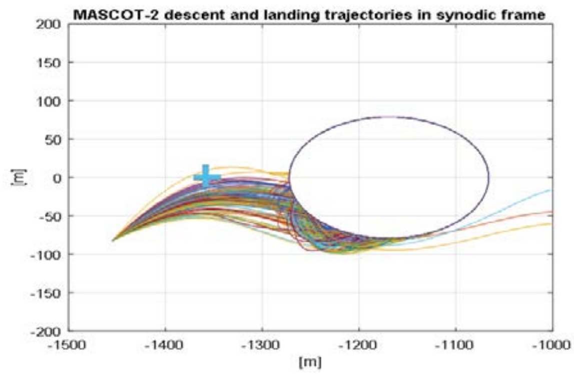

Fig. 6. Dispersion analysis of MASCOT-2 descent and landing trajectories in synodic frame

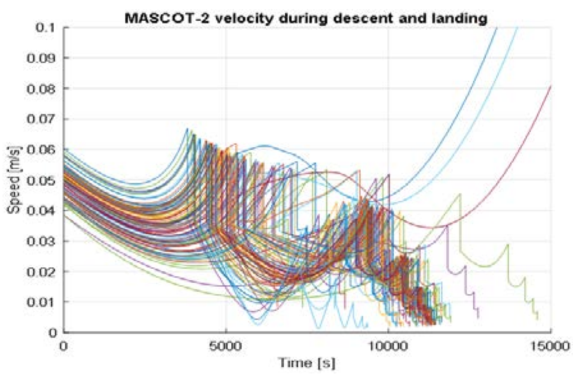

Fig. 7. Dispersion analysis of MASCOT-2 descent and landing velocity

2.5. Image processing algorithms for centroiding

Besides feature tracking algorithms, centroiding algorithms have been developed in the frame of AIM, for inclusion in technology demonstration experiments during ECP and DCP phases. During these phases, a dedicated image processing is needed to address the simultaneous presence of both Didymos and Didymoon in the navigation camera FOV, while centroiding of Didymos only is needed. This processing algorithm has been developed by GMV based on erosion and dilation techniques.

The overall process consists in performing a “binarisation” of the image (mathematically describing the image using only values of 0 and 1, where 0 is attributed to background pixels and 1 to bright pixels) and then applying erosion and dilation on the binarised image in order to eliminate the secondary asteroid from the image and to determine the centroid of the primary. Erosion methods are applied to eliminate the stars from the background and the secondary asteroid. This is done with the help of a structural element characterized by a shape and a safety factor, defined in order to encompasses the coarse radius of the secondary. The final result of the erosion process leads to an alteration of the original shape of the primary asteroid. Dilation techniques are employed in order to recover, as close to the original as possible, the shape of the target body (Didymain). Using the same structural element as the one used for erosion, the eroded parts from the primary asteroid are reconstructed. An illustration of the process is provided in Fig. 8.

Fig. 8. Binarisation (left), erosion (centre), and dilation (right) for a sample navigation camera image of Didymos at 35 km (credits: GMV)

Following this process, the centroid is determined either by limb fitting or by correlation with a Lambertian sphere. In the first case, three pixels on the edge of the bright limb are used to define a circle which encompasses the asteroid: the centroid is identified as the centre of the encompassing circle. In the second case, the radius and offset from the centre of the image of a Lambertian sphere are defined which maximise correlation with the image: the offset defines the centroid.

2.6. Collision avoidance strategy

Capability of performing collision avoidance manoeuvres (CAM) is regarded as the ultimate spacecraft safety measure and is therefore included in the AIM baseline design. Objective of the CAM is to push AIM outside the sphere of influence of the Didymos system. This is readily obtained by achieving a radial post-CAM velocity of the appropriate magnitude. Given that the escape velocity is a function of the distance to Didymos, the minimum post-CAM velocity to be achieved to ensure no collision risk is also a function of the distance to Didymos.

An upper bound on the minimum post-CAM velocity that is needed can be obtained using a triangle inequality based on the concept illustrated in Fig. 9.

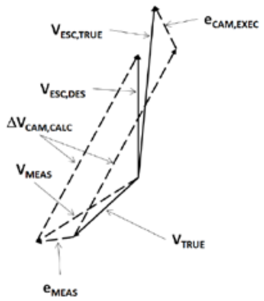

Fig. 9. Schematic of CAM triggering due to unexpected velocity

For a successful CAM, the true post-CAM velocity $V_{ESC,TRUE}$ must be larger than the desired post-CAM velocity $V_{ESC,DES}$. Considering the measurement error e_{MEAS} and the CAM execution error $e_{CAM,EXEC}$, the calculated CAM manoeuvre size $\Delta V_{CAM,CALC}$, is limited by the inequality shown in Eq. (1).

$$\Delta V_{CAM,CALC} \leq V_{TRUE} + V_{ESC,DES} + e_{MEAS} + e_{CAM,EXEC} \quad (1)$$

The triggering of the CAM is based on deviation of the spacecraft dynamical states (some measured by the navigation camera) from the expected behaviour and on selected system alarms.

For robustness reasons, the information on CAM magnitude and direction is pre-calculated on ground and loaded on look-up tables that can be accessed by the on-board FDIR system.

2.7. Data fusion

In parallel to the development of the relative navigation system based on a camera operating in the visible spectrum (baseline), possibility of fusing payload data with navigation camera data has been investigated, using data from an infrared instrument and/or data from an altimeter.

Concerning the former, the basic concept relies on exploiting multi-spectral sensing for relative navigation, whereby images in NIR or thermal infrared wavelengths are used together with images in the visible spectrum. Infrared images can aid navigation when illumination conditions are not suitable for vision-based navigation. In addition, navigation can be improved by use of infrared images in the asteroid approach phase, when distance to the asteroid is estimated based on angular size: in visible light, brightness alone does not correspond to asteroid size (due to albedo), while in infrared light, brightness corresponds to size. Dedicated experiments for the demonstration of these techniques have been included in the mission baseline.

Concerning the use of altimetry, this has an obvious advantage for navigation since it provides direct observability of the vertical distance to the surface, which is otherwise not present in pure optical navigation. Parametric studies of the navigation performance improvement brought about by different types of altimeters (lasers and radars) as a function of the altimeter accuracy and measurement frequency have been performed for all phases of close proximity operations (ECP, DCP, MASCOT-2 release phase).

2.8. GNC system rapid prototyping and verification

The design of the GNC system for AIM has been carried out using tools that allow a rapid prototyping and verification of the GNC system. Multiple verification levels are used, with increasing complexity and addressing different aspects of the system. At purely mathematical simulation level (model-in-the-loop – MIL), two simulators have been developed: a medium-fidelity simulator (which includes a performance model of camera and image processing functions) to support algorithm design and preliminary assessments and a high-fidelity simulator (which includes processing of realistic asteroid images synthetically generated using the PANGU tool,[9]) for design and verification of the image processing functions. Real time execution issues (processor-in-the-loop - PIL) and SW profiling have been addressed by testing auto-coded SW on a LEON-2 board. Finally, testing of the whole GNC system including the navigation camera hardware (hardware-in-the-loop - HIL) has been performed in two different test setups at GMV: an optical laboratory, where the navigation camera has been stimulated with realistic flight images, and a robotic laboratory (see Fig. 10) for dynamical testing using robotic arms and asteroid models with proper illumination conditions.

Fig. 10. Hardware-in-the-loop testing in robotic laboratory (image credits: GMV)

The tests on the robotic laboratory showed that the image processing is able to track features on a Didymos mock-up (see Fig. 11), even in presence of image defocusing.

7. Conclusion

This paper provides a survey of the challenges that must be faced in designing and verifying the GNC system for AIM. From the hardware point of view, the GNC equipment must be selected to be robust to the specific conditions of the Didymos environment (e.g. dust) and to be capable of providing adequate performance (in terms of navigation and ΔV manoeuvre execution accuracy). Autonomous vision-based navigation is an enabling technology to achieve successful MASCOT-2 landing on Didymoon. Trajectories, image processing algorithms, and navigation filters need to be optimised considering the constraints and requirements imposed by the use of vision-based navigation. Specific safety mechanisms, like collision avoidance manoeuvring capability, are mandatory to reduce the risk inherent in the mission. Finally, adequate verification methods must be employed, which allow covering several implementation issues and raise the technology readiness level (TRL).

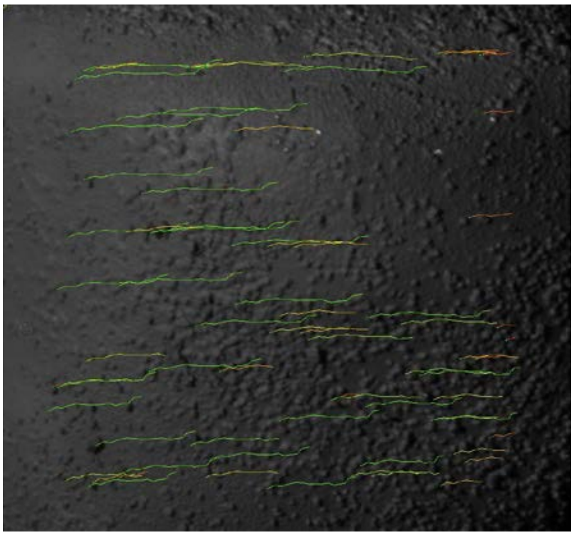

Fig. 11. Image captured by AIM navigation camera in the robotic laboratory with overlaid feature tracks (image credits: GMV)

References

1) Carnelli, I., Kueppers, M., Mellab, K., Pesquita, V., Gutierrez, B., Casasco, M., Gil Fernandez, J., Martino, P.: AIM: a Mission of Firsts in Deep-space, 31st ISTS, 2017-k-10, Matsuyama, Japan, 2017.
2) Gil Fernandez, J., Ortega, G., Casasco, M., Huertas, I., Dubois-Matra, O., Carnelli, I.: ESA GNC Technologies for Asteroid Characterization, Sample-Return, and Deflection Missions, 2016 IEEE Aerospace Conference, Big Sky, MT, USA, 2016.
3) Pardo de Santayana, R., Lauer, M.,: Optical Measurements for Rosetta Navigation near the Comet, 25th International Symposium on Space Flight Dynamics, Munich, Germany, October 2015.
4) Yu, Y., Michel, P., Schwartz, S., Naidu, S., Benner, L.: Ejecta Cloud from the AIDA Space Project Kinetic Impact on the Secondary of a Binary Asteroid: I. Mechanical Environment and Dynamical Model, *Icarus* **282** (2017), pp. 313-325.
5) Berrighi, G., Procopio, D., Star Sensors and Harsh Environment, Proceeding of the 5th International ESA Conference on Spacecraft Guidance, Navigation and Control Systems, Frascati, Italy, 22-25 October 2002, (ESA SP-516, February 2003).
6) Sierks, H., et al.: The Dawn Framing Camera, *Space Sci. Rev.* **163** (2011), pp. 263-327.
7) Gil Fernandez, J., di Domenico, M., Prieto, T., Dominguez, C., Suatoni, M., Mollinedo, L., Rowell, N., Huertas, I., Gherardi, D., Agnolon, D., Salehi, S., et al.: Autonomous GNC System For Marco-Polo Asteroid Sample Return Mission, 9th ESA Conference on Guidance, Navigation & Control Systems, Porto, Portugal, 2-6 June 2014.
8) Munoz, P., Budnik, F., Godard, B., Morley, T., Companys, V., Herfort, U., Casas, C.: Preparations and Strategy for Navigation During Rosetta Comet Phase, 23rd International Symposium on Space Flight Dynamics, Pasadena, California, October 2012.
9) Dubois-Matra, O., Parkes, S., Dunstan, M.: Testing and Validation of Planetary Vision-based Navigation Systems with PANGU, 21st International Symposium on Space Flight Dynamics, Toulouse, France, September 2009.