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HERA vision based GNC and autonomy

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Abstract
The Asteroid Impact and Deflection Assessment mission (AIDA) is a joint mission between ESA and NASA to demonstrate the kinetic impactor technique for planetary defence. A NASA spacecraft, DART, will impact the moon of the Didymos asteroid binary system and the HERA spacecraft, from ESA, will get closer to investigate what was the effect of such impact. The HERA mission is based on the extensive work done by the Agency and European industry between 2011 and 2016 in the frame of the Asteroid Impact Mission (AIM). In order to be able to detect the slightest change to the system and better understand the effect of the impact, close proximity operations are baselined in the mission timeline. Both AIM and HERA missions share the vision of a highly autonomous system, which is necessary to allow such close proximity operations. As it is the first time that a binary asteroid system will be studied from such a short distance, it is also important to remark the value of the scientific return of the mission. In order to guarantee a high level of autonomy, the first step is to give to the Spacecraft enough on-board information to estimate its position with respect to the asteroids and, based on that estimation, to act accordingly following a preloaded sequence of commands or objectives. To achieve this requirement, a vision based GNC has been designed, which includes image processing algorithms and a navigation filter capable of processing the visual information and to get the desired estimation. The HERA GNC baseline presented here will not only use a visual camera but also several other payloads, involving data fusion with a hyperspectral/thermal camera and a laser altimeter (PALT). These additional instruments will be able to increase the robustness of the strategy: the hyperspectral/thermal imager will be able to see where the AFC is limited by shadows and phase angle issues; PALT will be able to give observability on the radial direction, which is poorly estimated in a vision based GNC (especially if the low gravity environment does not allow stable orbits and hyperbolic arcs are preferred for safety reasons).
HERA close proximity operations have been investigated and the design will be consolidated by the end of Phase B1. A specific distance of 8 km is identified from a GNC driving factor. If the Spacecraft will be outside the 8km sphere centred in the main asteroid, the AFC will give a full visibility of the body and centroiding techniques can be used for the state estimation. For closer fly-bys the entire camera FoV will be covered by the asteroid and a feature tracking technique is baselined to maintain the relative state estimation. Image Processing and navigation functions have been designed taking into account this factor and a detailed designed showed its feasibility taking into account ground segment operations and pushing the validation of the on-board algorithms up to TRL 5/6 with Hardware-In-the-Loop tests.
This paper will include the consolidated strategies of the vision based GNC designed for the HERA mission, together with the test campaign results. Additionally, the required future developments will be addressed.

1. Introduction

The scientific and technical principles of the kinetic impactor concept are well established by theory and models, with ESA and Europe playing a leading role through numerical modelling developed in the frame of hypervelocity impacts and evolutionary simulation of the solar system. Nevertheless, so far no full scale test has ever been conducted at the necessary energy levels and, therefore, the effectiveness of the method to modify the dynamics of an object is purely

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theoretical: previous missions (such as NASA's Deep Impact and LCROSS) were not designed to measure the dynamic effect in the trajectory of the target body. By contrast, HERA will be designed to be an effective element of a deflection test proof of concept, which would collect the scientific and technical data needed to confirm the impact effects. These, together with the physical characterization for the target body, will enable for the first time the full characterization of the so-called "ß-factor" which describes the momentum transfer efficiency and the role the ejecta momentum might play. With HERA, we will be able to:

- Investigate an asteroid deflection test for the first time ever.
- Visit for the first time an asteroid of the size representative of a potential threat (i.e. 140m diameter).
- Analyse in detail the impact crater from DART and validate numerical impact models
- Measure the momentum transfer from a kinetic impactor on an asteroid and disentangle the linear momentum from changes in other dynamical effects.
- Validate scaling laws.
- Technology demonstration, such as the autonomous GNC that has to be developed in order to get closer to the target body, to obtain high resolution data and to maximize science return.

To achieve its mission objectives, HERA will nominally be launched on-board a Soyuz within a 21-days launch window opening in October 2024. For the purpose of mission feasibility analysis, launcher trajectories and performance with Soyuz 2.1b-Fregat MT from Baikonur/Vostochny is assumed. Following the injection into a direct escape trajectory and commissioning phase, a deep-space manoeuvre is foreseen. The rendezvous phase last about one month, based on a strategy similar to Rosetta.

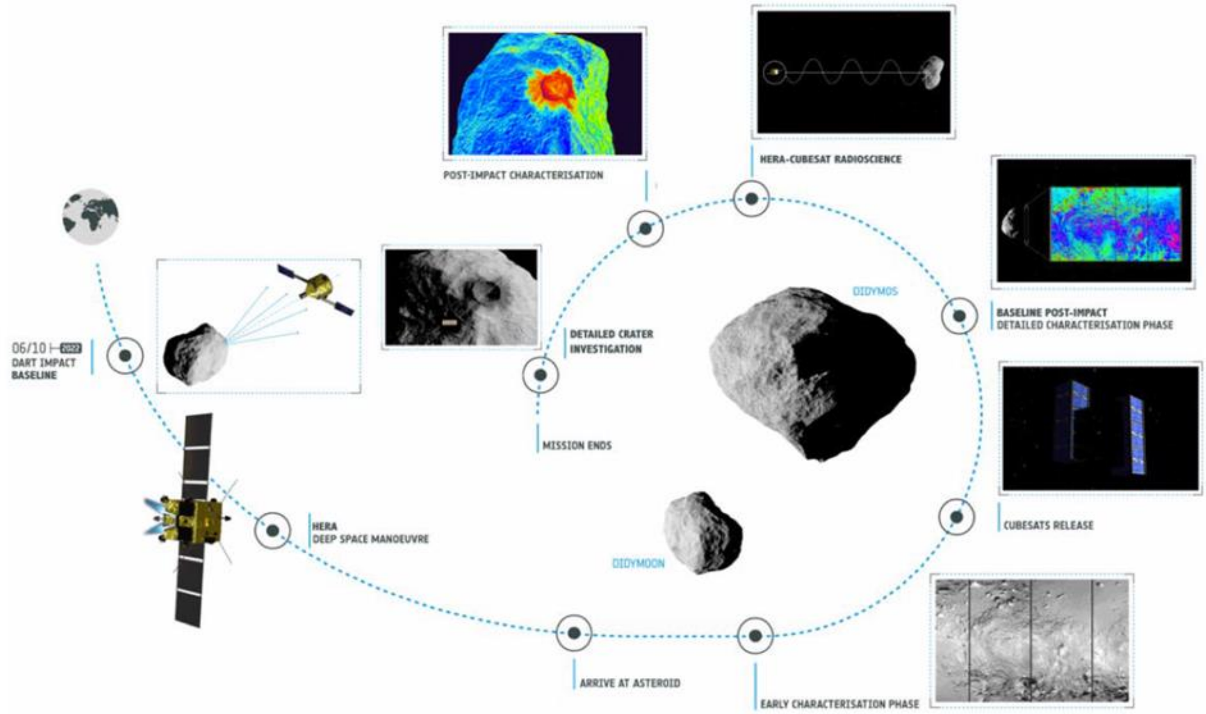

Figure 1: HERA Mission phases

The main objective of the paper is to describe the HERA vision based GNC. Starting from the autonomy justification with ground based navigation considerations, the paper will go through the design of the GNC and the Image Processing algorithms necessary for the on-board estimation. During HERA phase B1 an extensive validation campaigned has also been performed, from Model-In-the-Loop tests in Matlab/Simulink, passing through autocoding and Processor-In-the-Loop tests up to Hardware-In-the-Loop using the qualification model of the AFC (Asteroid Framing Camera).

2. HERA Mission Analysis and Ground Based Navigation results

During HERA Phase B1 a detailed mission analysis has been performed in order to design a mission capable of achieving the challenging objectives described in the previous section. The interplanetary trajectories have been designed by ESOC, while the Approach Phase (rendezvous with the asteroid) has been designed by industry considering heritage from Rosetta.

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2.1 HERA close proximity operations

The most challenging mission phases are the so called close proximity operations, divided in the following main phases:

- **Early Characterization Phase (ECP)**
  This phase takes place at a distance beyond the gravitational sphere of influence and only as soon as optical remote sensing instruments will be operable (currently estimated in 30 km) with the objective of conducting a physical and dynamical characterization of Didymos (notably: size and shape by imaging, and dynamical characterization -including orbital and rotation periods- by imaging).

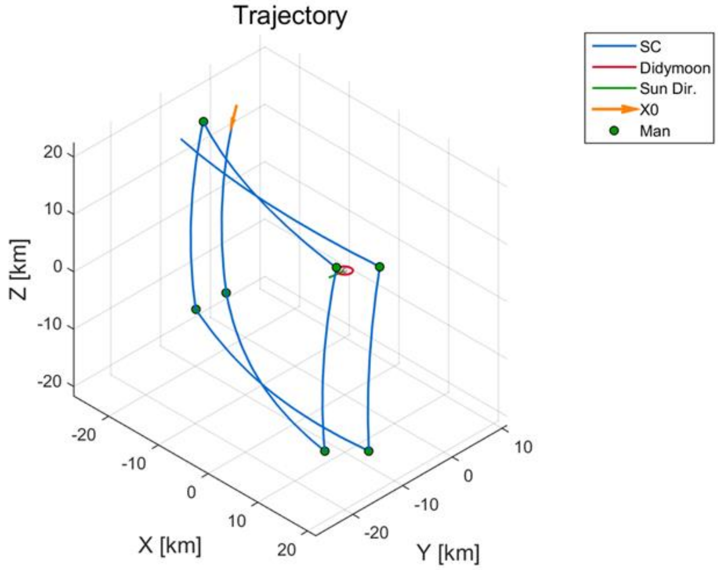

Figure 2: HERA ECP

- **Detailed Characterization Phase 1 (DCP1)**
  It involves a closer proximity operations at about 10 km from the system barycentre, still beyond the gravitational influence of the asteroid, but enabling the accurate characterisation of Didymoon’s mass (by determining the ¨wobble¨ period of Didymain around the system barycentre) and density in the combination with size measurements, medium-resolution imaging and the operation of the Planetary Altimeter (PALT).

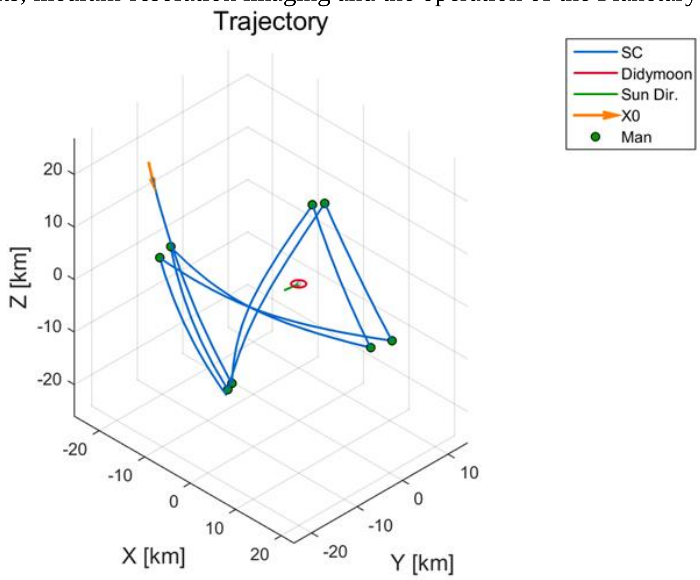

Figure 3: HERA DCP1

- **Payload Deployment Phase (PDP)**
  During this phase the CubeSat(s) are released and commissioned until they reach fully operational capabilities.

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- **Detailed Characterisation Phase 2 (DCP2)**
  Equivalent to DCP1 but involves also operations of the CubeSat(s).
- **Detailed Characterisation Phase 3 (DCP3)**
  HERA will progressively approach Didymoon to fully characterize DART´s impact. Approach is assumed to up to go below 10 km for full payload operation. Higher resolution images of the crater will be taken with close flyby trajectories down to 2 km distance. This phase also involves higher-risk autonomy demonstration experiment close to the surface.

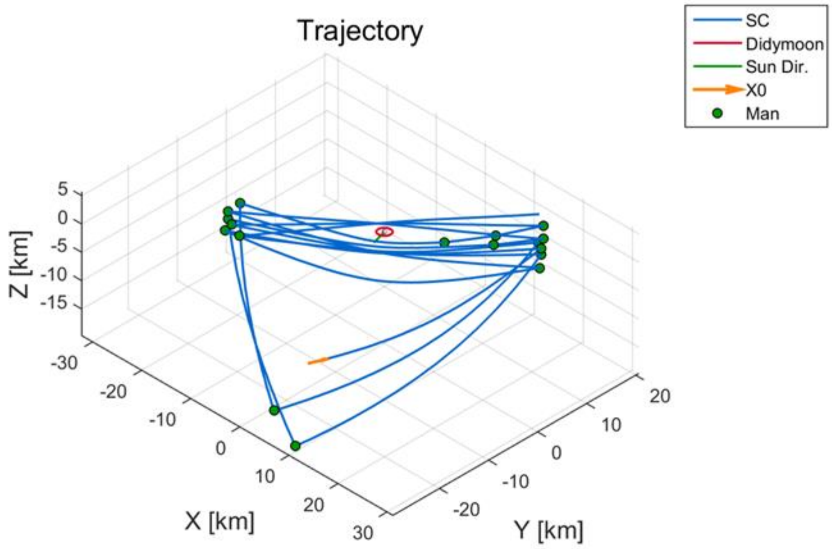

Figure 4: HERA DCP3

- **End of life Phase (ELP)**
  Following the nominal mission of the spacecraft, it will disposed by landing on the surface of "Didymain". Alternatively, the spacecraft operations will be handed over to private operators.

2.2 Ground based Navigation results

The trajectories designed by the mission analysis allowed to achieve mission objectives, respect spacecraft safety (the spacecraft is always in collision-free hyperbolic arcs) and it has been demonstrated by a ground based navigation analysis that they are feasible from operations point of view.

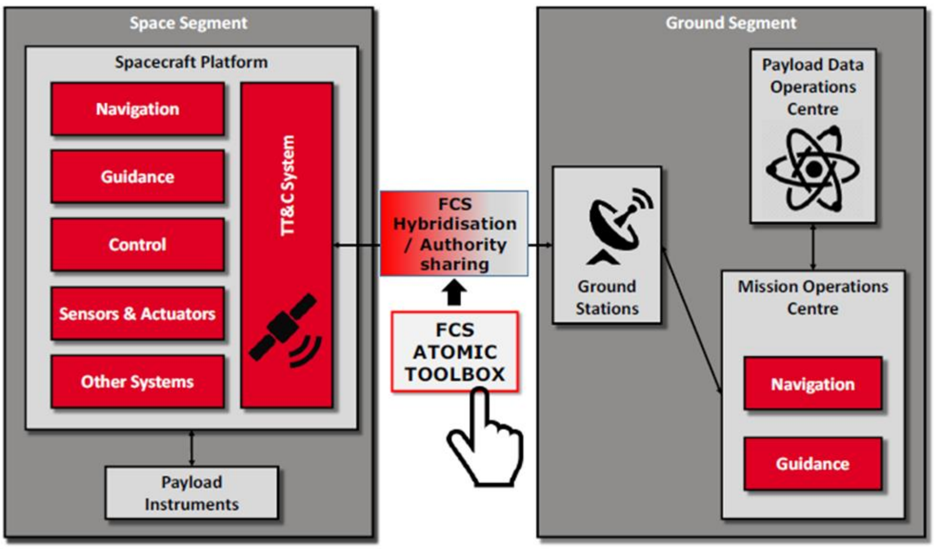

Figure 5: FCS-ATOMIC tool

The FCS-ATOMIC tool described in Figure 5 has been developed by GMV in collaboration with ESOC and it has been used to perform the ground based navigation analysis of the close proximity operations of HERA.

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ECP

The ground based navigation analysis showed that in ECP the estimation of the relative state between the spacecraft and the asteroids (vision based but by ground with the same technique adopted in ROSETTA) is good enough to navigate the spacecraft safely.

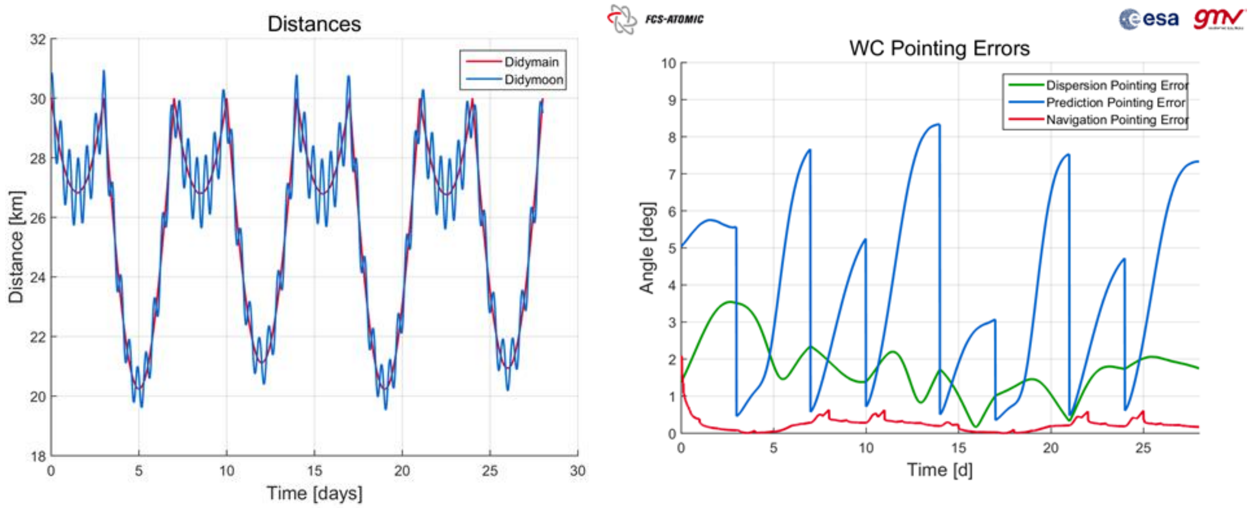

Figure 6: ECP ground based navigation analysis (distance and pointing performance)

The nominal distance of the order of 30 km prevent from having any collision risk and the slow relative velocity between the spacecraft and the asteroids does not require any fast autonomous reaction. The pointing error from the state prediction can become higher than the 5.5 degree FoV of the camera (in blue it can be seen the 3-sigma value), but this happens only towards the end of the arc and if images are required in that phase a simple scanning procedure can be implemented.

DCP1-2

The ground based navigation analysis showed that in DCP the estimation of the spacecraft state is still good enough to navigate safely.

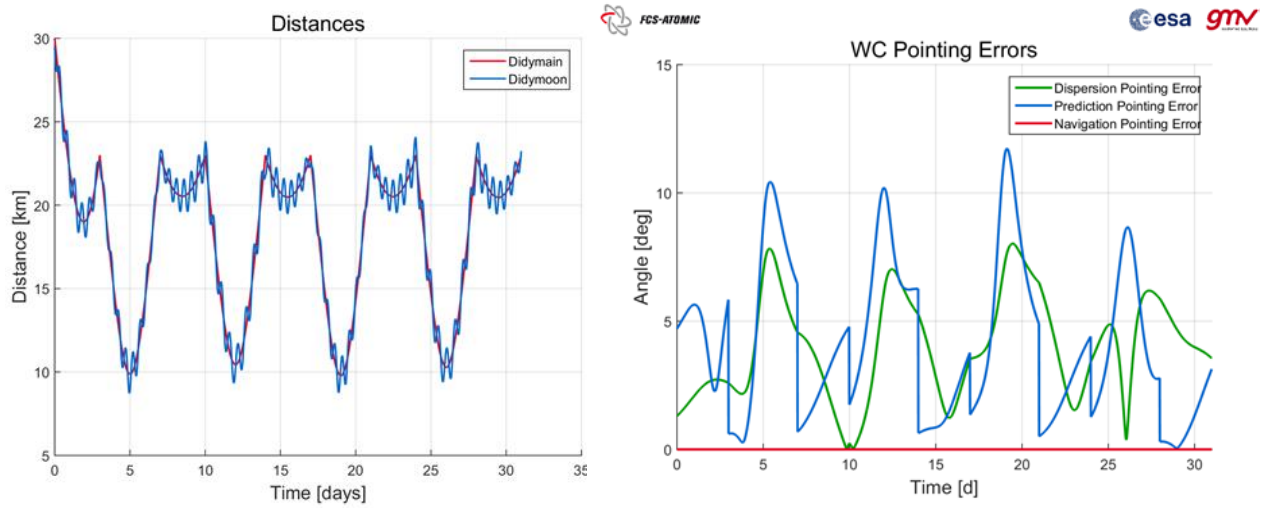

Figure 7: DCP ground based navigation analysis (distance and pointing performance)

The nominal distance of the order of 10 to 20 km prevent from having any collision risk also thanks to the improved system dynamic parameters estimated during the ECP. The pointing error is higher than ECP and might lead to the loss of the asteroid from the FoV for a significant part of the arc. The scanning procedure can still be implemented and it is possible to navigate this phase with ground based authority as for ECP. Still, this is the moment where a low level of autonomy can help and the semi-autonomous attitude guidance (SAG) GNC mode has been designed in order to guarantee that the asteroid never gets out of the FoV. This GNC mode will allow an on-board correction of the primary pointing towards the target.

DCP3

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This phase consists on a first part of trajectories that are similar to the ones of DCP1-2 but with a closer approach of the order of 6 km and a second part, called "*close fly-by*" where the spacecraft will perform re-targeting manoeuvre in order to progressively reduce the pericenter (down to 2 km from primary and 900m from secondary body).
For the close fly-by, the huge dispersion that can be of the order of few km when the spacecraft is controlled manually from ground is not compatible with the challenging relative distance that are baselined in order to achieve mission objectives. For this reason, an autonomous GNC mode has been designed: the ATCM (Autonomous Translational Control Manoeuvres), which will allow for autonomous trajectory correction manoeuvres.

3. HERA GNC Subsystem

The HERA GNC subsystem has been designed in order to implement the on-board functionalities necessary to navigate the spacecraft both manually and autonomously. As shown in the previous section, a certain level of autonomy is necessary in order to get close enough to the asteroids, achieving all mission objectives. The table below shows the incremental autonomy level increase from E2 (Execution of pre-planned, ground-defined, mission operations on-board) to E3 (Execution of adaptive mission operations on-board):

Mission Phase	Autonomy level	GNC units
LEOP	E2	ADCS units only
Interplanetary	E2	ADCS units only
ECP	E2 + SAG rehearsal	ADCS units + AFC
DCP1	E3 (SAG only)	ADCS units + AFC
PDP	E3 (SAG only)	ADCS units + AFC
DCP2	E3 (SAG only)	ADCS units + AFC
DCP3	E3 (SAG only)	ADCS units + AFC
DCP3 – close flyby	E3 (ATCM)	ADCS units + AFC + Altimeter
ELP	E3	ADCS units + AFC + Altimeter

Table 1: Autonomy level

3.1 GNC modes

The GNC subsystem major groups of functions are the ADCS (Attitude Determination and Control Subsystem) and the ODCS (Orbit Determination and Control Subsystem). The GNC modes are shown in Figure 8.

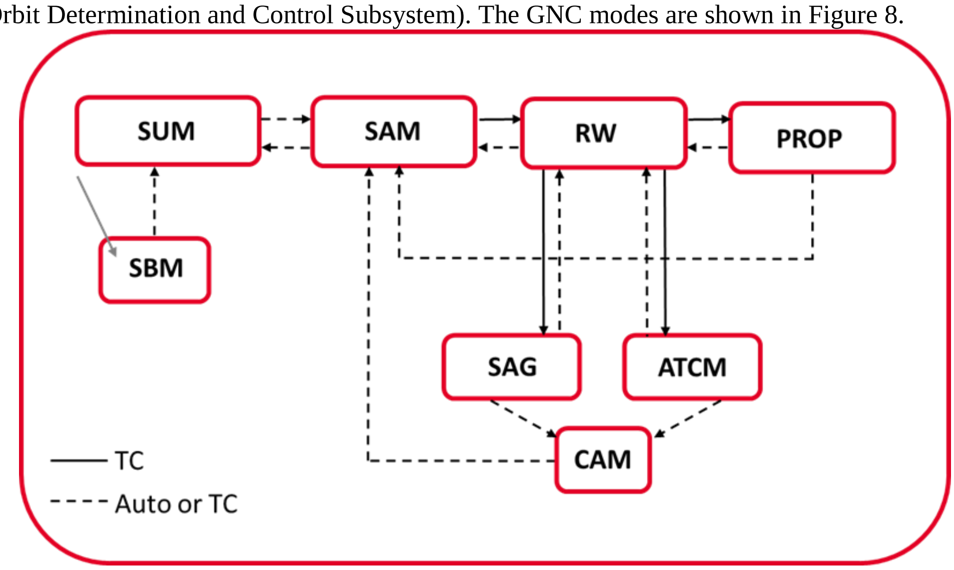

Figure 8: GNC modes

The GNC modes have been iterated during the phase B1 and the current baseline description is give below:

- SBM (Stand-by GNC mode):
  The GNC MVM enters this mode during S/C verification, before launch, when all the GNC has to stand-by
- SUM (Survival GNC mode):
  The GNC MVM enters this mode at the boot of the system (including LEOP) and every time the S/C mode is set to Survival (the SC cannot be 3-axis stabilized)

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- SAM (Safe GNC mode):
  The GNC MVM enters this mode every time the SC mode goes to Safe.
- RW (Operational Reaction wheels attitude based mode):
  The GNC MVM stays in this mode most of the mission life time.
- PROP (GNC Propulsion mode):
  The GNC MVM enters this mode both when the SC mode is set to Operations and an RCS manoeuvre is planned by the ground station, and when SC mode is set to Propulsion for main engine manoeuvre execution.
- SAG (Semi-autonomous Attitude Guidance mode):
  This is part of the experimental modes/technology demonstrations that will allow the SC to achieve distances of the order of 10 km with respect to Didymos.
- ATCM (Autonomous Translational Control Manoeuvres):
  This is part of the experimental modes/technology demonstrations that will allow the SC to achieve distances smaller than 2 km with respect to Didymos.
- CAM (Collision Avoidance Mode):
  The GNC MVM enters this mode when the SC mode is set to CAM (a collision risk has been detected and the SC perform a Collision Avoidance Manoeuvre)

The ADCS algorithms are standard and common to other mission, so the focus will be on the ODCS algorithms and on the vision based GNC used both in SAG and ATCM mode in order to improve pointing towards the target and to perform autonomous re-targeting manoeuvre.

3.2 Vision Based GNC algorithms

The challenging part of the GNC subsystem for interplanetary mission is the navigation. The solution proposed in this paper is called vision based and it uses information retrieved by the images taken on-board in order to estimate the relative state of the spacecraft with respect to the target. The GNC is based only on images taken by the AFC, but it can perform data-fusion (as shown in Figure 9) with thermal images and an altimeter. Thermal images allow to have a solution which is not dependent from phase angle and illumination conditions, very useful for scenarios that goes beyond the terminator line. The Altimeter gives a very important information on the radial axis (perpendicular to the camera) that suffers of low observability due to the nature of the vision based solution.

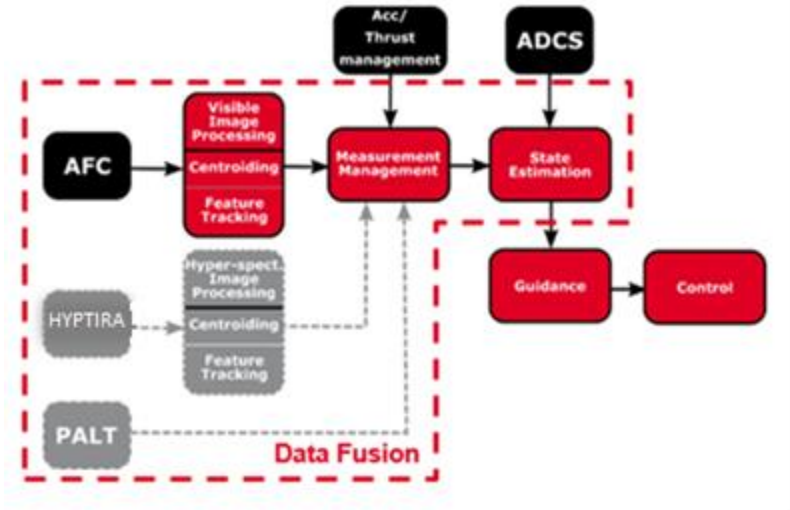

Figure 9: Vision based GNC and data fusion

The ODCS sub-modes are reported below and they are briefly described focusing on their functionality:

- **ODCS-MODE-1**: Centroid-based navigation for semi-autonomous attitude guidance. The mode shall be used during ECP and DCP phases, at distances from 30 to 8 km, when full asteroid can be seen in a single image frame. Navigation in this mode is based on centroid measurements obtained from AFC. The purpose of this mode is to enable (semi-)autonomous attitude guidance. Translation guidance is based on the ground computed manoeuvres.
- **ODCS-MODE-2**: Feature tracking navigation for low altitude fly-bys. This mode shall be used during low altitude fly-bys when asteroid is occupying entire FOV (below 8km). Features tracked in the AFC images are used as an input to the navigation filter to compute relative position with respect to the asteroid.

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- **ODCS-MODE-3**: Feature tracking with altimeter for very low altitude guidance. This mode shall be used during very low altitude fly-bys. In addition to feature tracking used in ODCS-MODE-2, the data fusion with the altimeter is performed. The guidance and control for execution of corrective manoeuvres can be implemented. The mode can be used both by navigating with respect to the primary or secondary.
- **ODCS-MODE-4**: Disposal/landing mode for a controlled descent and landing on Didymain. It is proposed to extend the ODCS-MODE-3 in such a way to enable soft landing on the asteroid.

4. Image Processing techniques

Two main techniques have been used for the HERA vision based system:
- Centroiding: the maximum correlation with a Lambertian sphere is an Image Processing (IP) algorithm used to determine the position of the asteroid in the FoV of AFC
- Feature tracking: relative navigation system which captures images from one on-board camera (AFC). The images are processed by an Image Processing (IP) algorithm that extracts significant points called features. The features are then compared with the features extracted in previous image in order to find their correspondence. This process allows determining the displacement of different relevant points selected between consecutive images.

Both techniques are necessary to the mission. The centroiding can be used for farther distances and does need a precise initialization. The Feature tracking is ideal for close proximity and gives better navigation performances but requires a precise initialization.

4.1 Centroiding

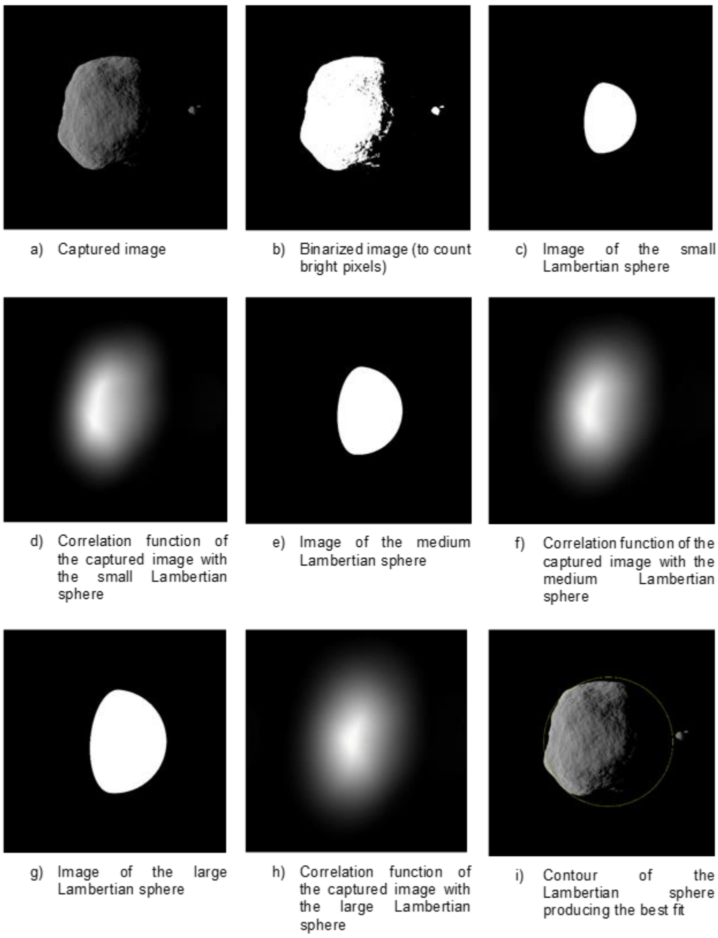

Figure 10: Centroiding – Convolution with the Lambertian sphere

This Image Processing follows the sequence:
- Counting of bright pixels in order to estimate a rough angular size of the primary.

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- Checking of several primary radii around the rough estimation of the angular size. For each radius:
  - Generation of the image of the Lambertian sphere that is defined by:
    - The given angular radius.
    - The viewing phase determined from Sun sensor measurements.
    - The sphere center at the image center.
  - Finding the normalized maximum correlation of the input image with the sphere image.
- Estimating the sphere radius that maximizes the normalized correlation between input a sphere images. For this radius:
  - Generate the image of the Lambertian sphere.
  - Find the optimal offset, i.e., the one that maximizes the normalized correlation between the input and the sphere images.
- The LOS estimation is given by the optimal offset.

4.2 Feature Tracking

The second algorithm used for vision-based navigation is using tracking of the distinctive features on the surface of the body. The selected image processing algorithm for HERA system is based on the KLT feature tracker. The algorithm was previously evaluated by GMV and tested in several landing scenarios, in studies of various missions to asteroids and to Phobos. The algorithm is sometimes referred to as the Kanade-Tomasi corner detector. It is based on the early work of Lucas and Kanade [1], was fully developed in SW by Tomasi and Kanade [2], and was explained in the paper by Shi and Tomasi [3]. GMV has developed its own HW implementation of the algorithm.
The process of selecting good features to track is closely related to selecting good features for more general recognition applications. Regions that contain high gradients in both directions and have high eigenvalues in the auto-correlation matrix (similarly to Harris detector), provide stable locations at which to find correspondences.
In subsequent frames, searching for locations where the corresponding patch has low squared difference often works well enough. However, if the images are undergoing brightness change, explicitly compensating for such variations or using normalized cross-correlation may be preferable. If the search range is large, it is also often more efficient to use a hierarchical search strategy, which uses matches in lower-resolution images to provide better initial guesses and hence speed up the search.
As shown in Figure 11, this IP algorithm has been tested both on the primary and the secondary body of this asteroid binary system.

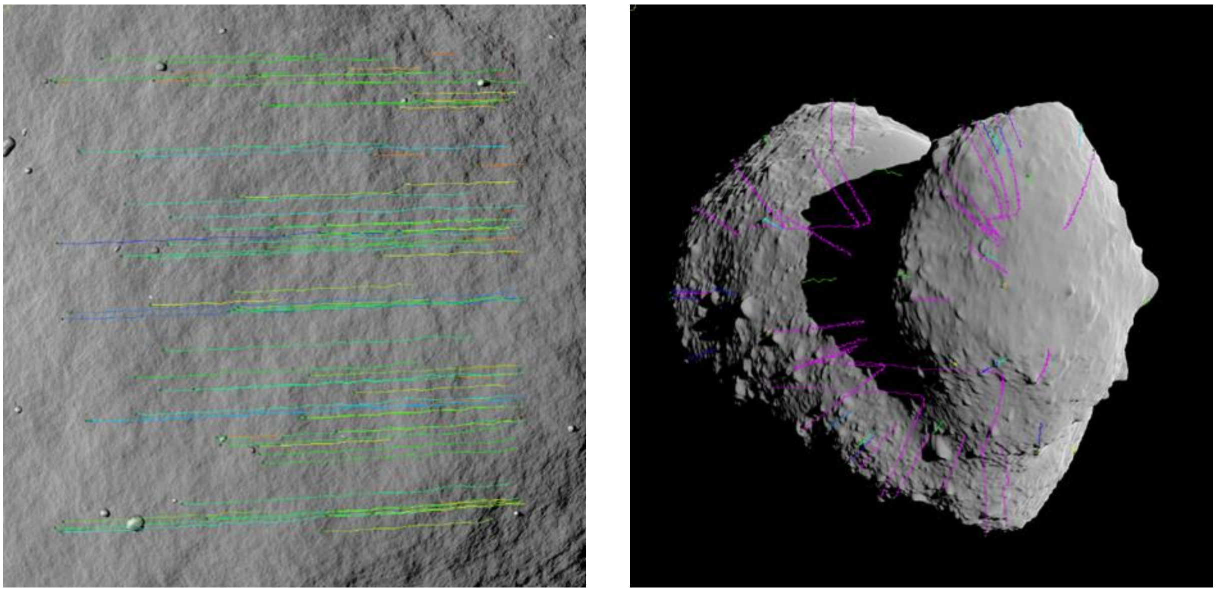

Figure 11: Feature Tracking – Feature tracks on surface of primary (left) and secondary (right)

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5. Incremental Validation and Results

The selected GNC design, development and verification strategy is based on autocoding of the GNC Matlab/Simulink models in order to generate ANSI C-code optimized for embedded systems. This development strategy is part of an integrated, coherent and incremental DDVV approach based on the chain:

FES/MIL ► Autocoding ► SIL ► PIL ► HIL

This auto coding chain can provide invaluable support during the Design and Development phases and possibility to test V&V requirements already at early and intermediate design phases, allowing fast design iterations and feedback and the possibility to correct design problems, thus minimizing the required effort. Furthermore, this approach will provide an additional flexibility in the GNC design and the associated iterations with the industrial team and the Agency. Detailed autocoding rules have been derived for HERA and distributed to the GMV consortium at the beginning of the activity, to guarantee a common coding approach, also compatible to the autocoding constraints.

It shall be noticed that with this approach the GNC (together with IP and FDIR) will be designed in Matlab/Simulink, using the Control Design and Simulation Environment (FES) and model driven software engineering. This Matlab/Simulink implementation will evolve in flight code using the autocoding tool chain. The autocoding development strategy consists in generating the GNC ASW C-code in a straightforward way, directly from the Simulink model of the GNC. Nevertheless, the compliance with ESA S/W development and quality standards shall be maintained; for this reason the specific impacts on the S/W development process related to autocoding use will be documented and justified.

The GNC DDVV will be based on the following steps:

- Analysis of scenario and derivation of GNC/AOCS Software Specification: The process of derivation follows the classical top down approach.
- Set-up of a Control Set-up and Simulation Environment (FES) with the use of reference models of the selected algorithms and solutions for the GNC system, allowing having an environment to define, analyse and maintain the S/W lifecycle. This represents the main conductive design supporting tool and verification at algorithm level (Model in the Loop, MIL) all along the activity. Together with the FES design environment, it is fundamental to define modelling rules/guidelines for compatibility with the autocoding tools.
- Autocoding of FES-validated GNC system: the GNC ASW C code is generated and the S/W V&V process is started. In this environment static and dynamic verification of the C-code functions can be performed using LDRA tool by embedding the generated C-code of the ASW functions in the FES simulator as s-functions (SIL). Unitary and Integration tests are realised.
- Preliminary GNC ASW validation environments: preliminary functional validation tests (main ASW requirements verification versus technical specifications) are performed in SIL environment, by integrating the produced ASW C-code in the FES simulator and test it in closed loop, in order to provide potential feedbacks on the design already at early stage.
- Validation and Verification in the HIL facility (HILF): the GNC ASW, integrated in the OBC (on-board computer), is then validated in the HILF, which includes the functional model of the OBC and the GNC SCOE, running in real time and closed loop environment. This facility is used for testing the correct integration of the GNC ASW and OBC in the on-board computer and real time conditions and verification of the GNC ASW requirements. It is possible to also include qualification/engineering models of on-board sensors in the closed loop, like the Asteroid Framing Camera (AFC). The camera would take pictures of the asteroid projected on a screen (optical lab) or of a mock-up of the asteroid (***platform-art***©). The HILF testing will be considered the last step in order to reach the GNC Software qualification status.

For HERA phase B1 HIL tests in the optical lab have been performed, together with HIL in the GMV robotic facility (***platform-art***©).

PIL tests have also been performed. The main purpose is to evaluate the computational cost of the implemented functions (GNC, FDIR and IP) so that the HW for the implementation can be selected.

5.1 Model-In-the-loop tests results

The first step of the incremental validation is the test in Matlab/Simulink. These tests are fast and it is easy and immediate to assess the feasibility of a strategy. Image processing and GNC algorithm have been tested separately with unitary tests and after integration as well in a close-loop structure.

During the study an assessment on the possible Hardware implementation of the IP algorithms have been performed and the result of the trade-off lead to the selection of an Image Processing Unit that will also be used to Control GNC Instruments and payload like the AFC. This unit has been called IP-ICU and will implement both the centroiding and the feature tracking IP.

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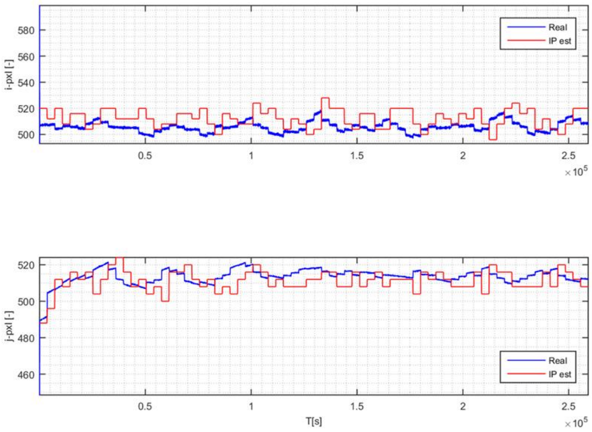

Figure 12: ECP – Centroiding performance

Figure 12 shows the centroiding IP results during ECP, where the autonomous translational navigation is not necessary, but can run off-line for on-flight validation. It is possible to notice that, almost independently from the illumination conditions, the IP solution follows Real World signal closely. The study demonstrated that the performance is good enough to respect the technological requirement summarize in the HERA MRD.

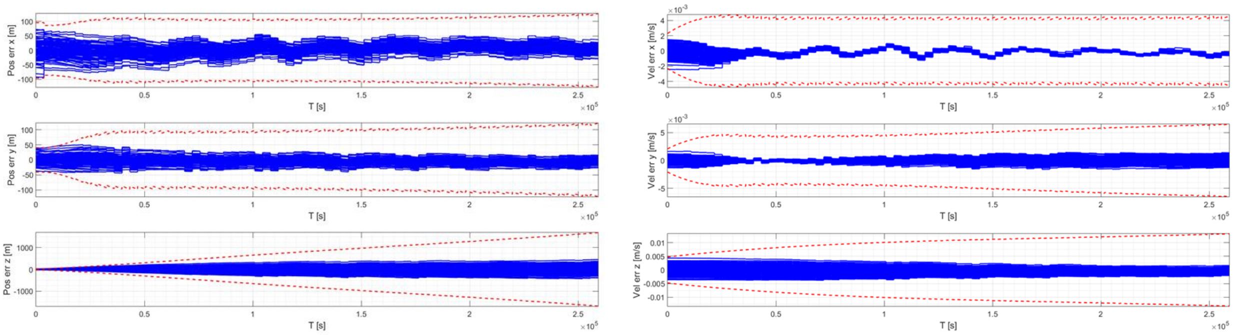

Figure 13: DCP1 - Monte Carlo campaign with position and velocity estimation

Figure 13 reports the autonomous navigation filter (Hybrid EKF-UKF) solution during the DCP1, where the centroiding IP is used. It is possible to notice the very good performance in the camera plane (X and Y axes) and the worse performance in the radial direction with an error of the order of hundreds of meters and a covariance 3-sigma that at the end of the hyperbolic arc can get up to 2 km (if the altimeter is used the radial direction precision is significantly improved). As for ECP, the performance has been demonstrated to be compliant with the requirement.

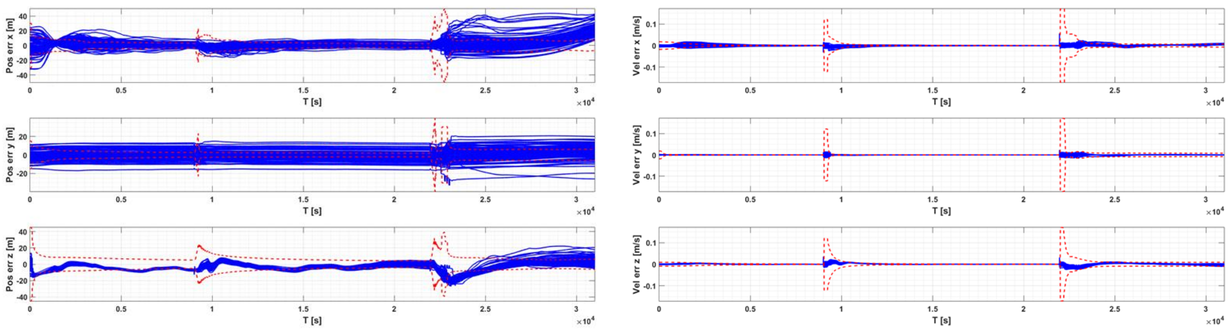

Figure 14: DCP3 close flyby - Monte Carlo campaign with position and velocity estimation

Figure 14 shows the results in the DCP3 close fly-by. For this phase, the data fusion with the altimeter is mandatory in order to guarantee the robustness of the navigation solution. This is clearly shown by the radial axis performance (Z axis) which is of the same order of magnitude of the one in X-Y axes. It is also interesting to observe the behaviour during the two autonomous manoeuvres, when the covariance increase due to the uncertainty of the manoeuvre execution error, but later converges again. Finally, after the second re-targeting manoeuvre, the target becomes the secondary body (Didymoon) and due to the poor illumination conditions it is possible to notice worse results then when navigating with respect to the primary body (Didymain). Nonetheless, no further manoeuvres are planned and the results are compliant with the requirements.

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5.2 Processor-In-the-loop tests results

After MIL testing, the autocoding of the algorithms has been performed and it has been demonstrated that the SIL and MIL results are numerically identical.

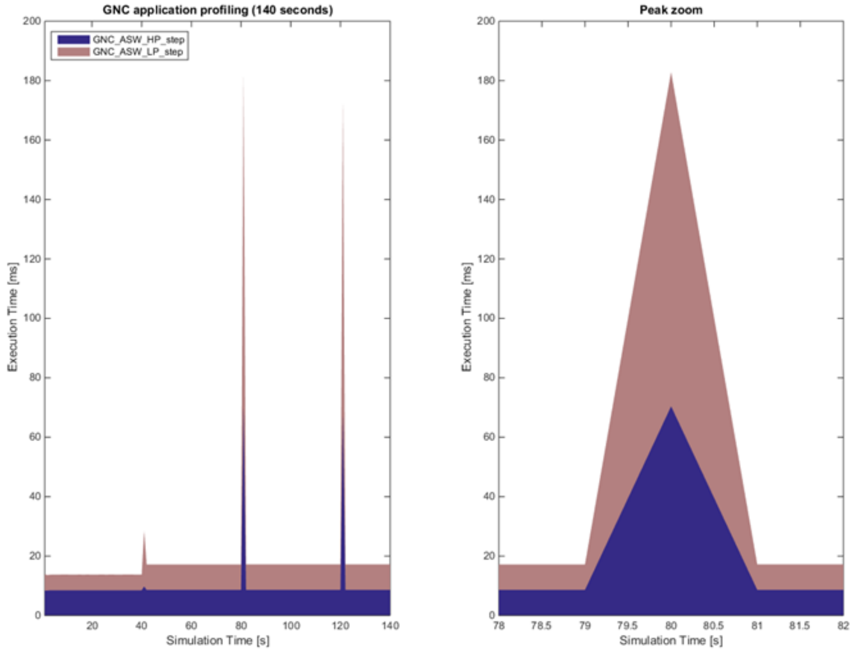

Figure 15: GNC application software profile

Figure 15 shows the profiling of the GNC functions performed thanks to the PIL tests for the close fly-by (autonomous navigation, based on feature tracking IP). They are divided between High priority (ADCS) and low priority (ODCS). It is possible to notice that there is a peak every time an image is processed. This is not due to the IP load (not part of the GNC ASW and implemented inside the IP-ICU) but to the pre-processing that is done to the tracked features and to the navigation filter updates with all the measurements. However, even during these peaks, the GNC ASW never exceeds the 20% of the OBC capabilities (GNC ASW run at 1Hz).

5.3 Hardware-In-the-loop tests results

In the frame of the HERA phase B1, Hardware-In-the-Loop tests have also been performed, both in the optical lab of GMV (see Figure 16) and the ***platform-art***©, robotic facility at GMV headquarters in Spain, Madrid (see Figure 17).

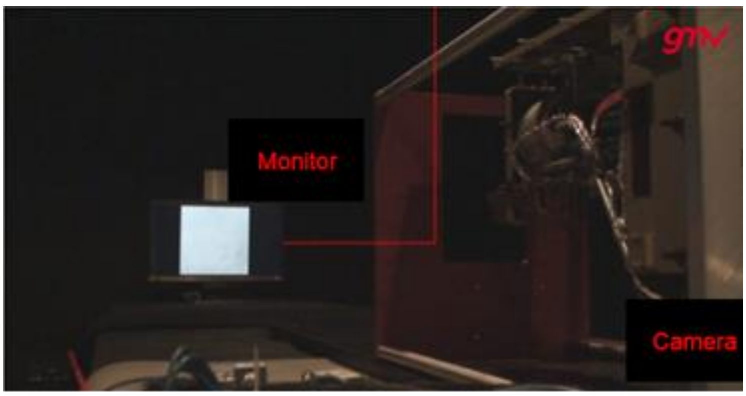

Figure 16: HIL-OPT Architecture and data flow

The optical lab consists into a dark room in which the camera (in this case the qualification model of the AFC, also the DAWN mission camera from Max Planck) is pointed towards a high resolution screen. This way it is possible to acquire images of the monitor that is projecting the result of an image generator (PANGU). The images are generated according to the results of the close loop GNC.

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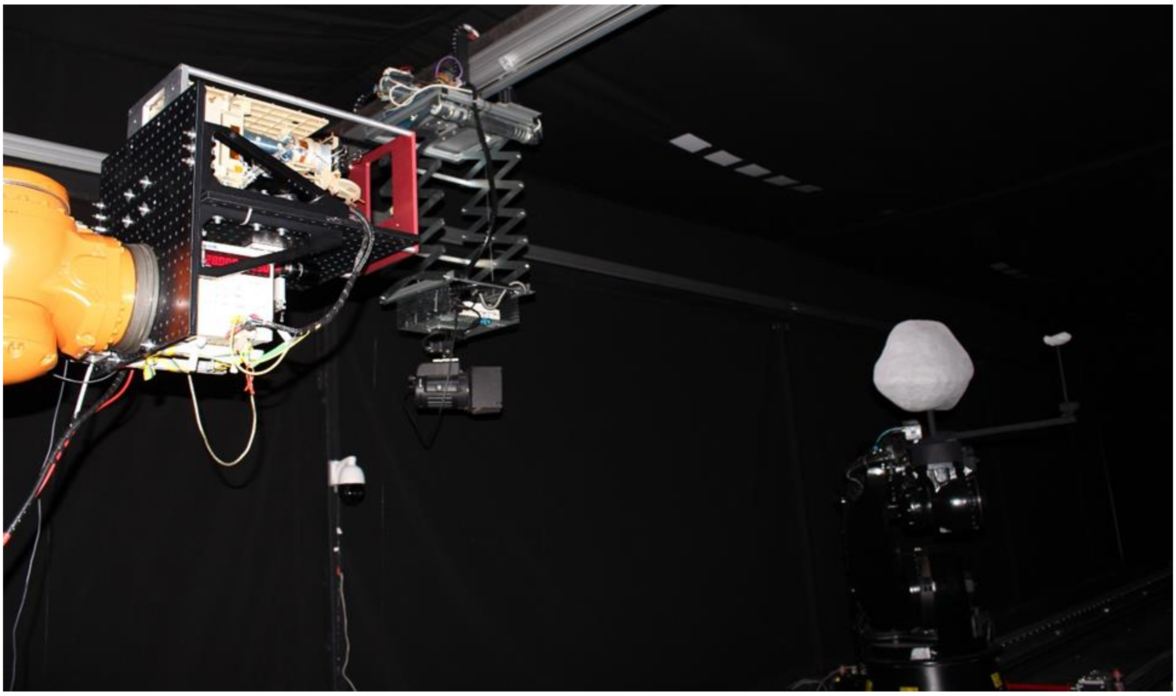

Figure 17: HIL-ROB Test set-up

The robotic test facility still includes the AFC, but there is no image generator (no synthetic images) and the mock-ups of the asteroids are used in space-like illumination conditions. Two KUKA robotic arms are used to recreate the relative dynamics between the camera/spacecraft and the binary asteroid system, then a Cartesian robot is used in order to control the illumination conditions.

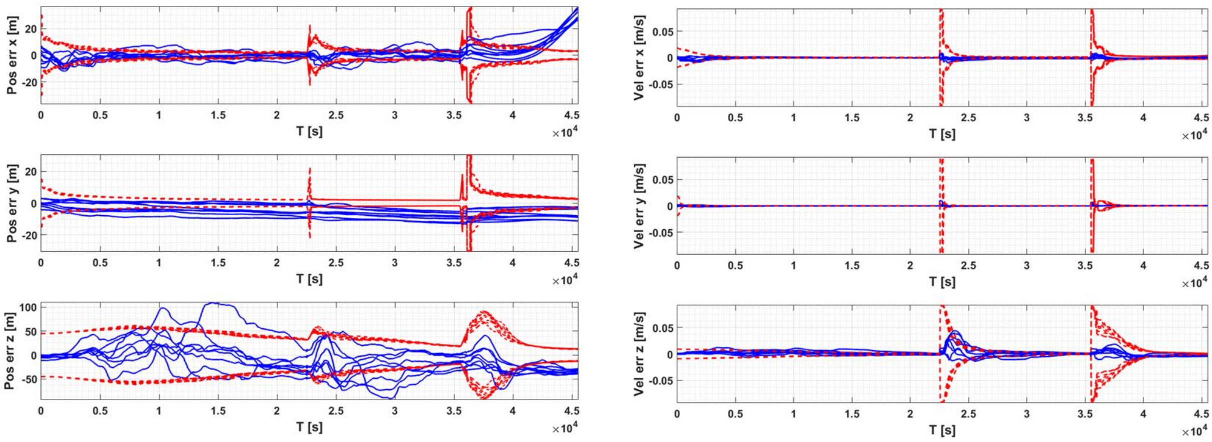

Figure 18: DCP3 close flyby - Monte Carlo campaign with position and velocity estimation

Figure 18 reports the results obtained in the HIL tests performed in the optical lab (the tests in the robotic lab are on-going at the moment of writing this paper). It is important to notice the correspondence of the results with the MIL ones, demonstrating that the GNC and IP implemented solution is robust to the errors introduced with a real camera in the loop.

6. Conclusions

The paper reported the autonomous GNC solution selected for the HERA mission, up to its design justification, development and testing as for Phase B1. An introduction on the Mission analysis has been given in order to demonstrate the drivers for the GNC subsystem. It was indeed clear, after the ground based navigation analysis, that the mission required semi-autonomous/autonomous techniques in order to achieve the challenging scientific and technological objectives. An overview on the GNC subsystem has been given, focusing on the Orbit Determination and Control System (ODCS), which is the part that brings most of the new technological development. The Image Processing algorithms are of primary importance in a vision based GNC, so they have been described, specifying in which phases they have to be used.

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Part of the validation results have also been reported in order to demonstrate the consistency of the selected solution, which has been proven to be robust considering performance and feasible from the implementation point of view. In the next mission phase there will be the chance to further consolidate the GNC, both in terms of Subsystem and of Application Software to be integrated in the On-Board Software. Furthermore, the extended operations phase can be exploited to test new technologies for interplanetary exploration.

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