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The HERA GNC subsystem, the State of the Art Autonomy for Planetary Exploration

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Extended Abstract—

HERA is a planetary defence mission currently being developed by the European Space Agency. Its main aims are to fully characterize the Didymos binary asteroid and to measure in-depth detail the aftereffect of the successful impact of NASA's DART (Double Asteroid Redirection Test) mission. Together with ground telescope observations, it will produce the most accurate knowledge possible from the first demonstration of an asteroid deflection technology. Thanks to the international collaboration of NASA and ESA and to the work of scientists and researchers that share their findings, the synergies between HERA and DART are enhanced and the scientific return is maximized.

The HERA GNC (Guidance, Navigation and Control) Subsystem under development by GMV, is one of the most challenging subsystems of the HERA mission, as it implements state of the art autonomous vision-based technologies that will allow spacecraft operations very close to a binary asteroid. The GNC of HERA has been designed to operate the spacecraft without ground intervention to allow fast operations that would not be possible otherwise. In the first part of the mission, the autonomy will be limited to the spacecraft attitude in order not to lose the target from the field of view of the HERA payloads. As the knowledge on the Didymos system becomes more precise, the spacecraft will fly closer trajectories to the asteroids. As the distance decreases, the pointing errors (associated to the trajectory prediction) increase, making increasingly difficult to ensure the proper pointing of the payloads to the asteroids. Towards the end of the nominal operations, there will be an experimental phase where the GNC will become fully autonomous and will compute and execute autonomous maneuvers. The autonomy will allow to safely reduce the minimum distance to the asteroids, permitting to image the Dimorphos crater produced by the impact of the DART spacecraft and also incrementing the resolution of the data about the system.

The design of the GNC includes the whole cycle of navigation guidance and control for both attitude and translational states. The GNC is organized into two main blocks, the high priority block where the functions related to the attitude guidance, determination and control are managed, together with the actuation manager function and the ephemeris computation block; and the low priority block where the orbit determination, translational guidance, and translational control are executed. The GNC Mode Manager, part of the High Priority block, is the key function that controls and select the execution of the different algorithms. This selection is based on predefined GNC modes of operation that are tailored to the different phases of the mission, including contingency modes to operate in case of an anomaly is detected. In total, there are nine GNC modes, which are tailored with minor modifications to create different sub-modes. The default mode is the stand-by mode (SBM), where no functions of the GNC are active and the GNC is just waiting the units to be ready to enter survival mode. The survival mode permits, by means of the Reaction Control Thrusters (RCT), the sun sensors and the gyroscopes, to reduce the angular momentum of the SC and to achieve a controlled angular state. Afterwards, it also allows to acquire the sun direction and keep the spacecraft pointing towards the Sun while maintaining the angular rate of the spacecraft within a selected range. Once the spacecraft is in steady state, the transition to the safe mode can be done. The safe mode requires the star trackers to be active to permit absolute attitude state estimations and thus, providing the possibility to acquire any desired attitude profile uploaded by the ground operators. Nominally, the safe attitude

profile corresponds to pointing the high gain antenna of the spacecraft towards the Earth to communicate efficiently with the ground stations. There are two sub-modes within the safe mode, the first one is dedicated to the acquisition of the uplinked profile and the other one is oriented towards maintaining the pointing. When the desired profile is achieved, the operators will switch to the propulsion mode to command the spin-up of the reaction wheels that allows the transition towards the nominal modes of operation. The propulsion mode is designed for the following purposes, the spin-up of the reaction wheels and for commanding maneuvers using both the orbital control thrusters (OCTs) and the RCTs. The maneuvers can either be ground-based or autonomously computed. After spinning up the reaction wheels, the GNC can make the transition to the next mode. For most of the mission lifetime, the spacecraft will stay in the Reaction Wheel mode. This mode allows to acquire the desired uplinked attitude profile by means of actuating the reaction wheels. The angular momentum of each wheel is monitored to switch t Wheels Off-loading mode if necessary. The Wheels Off-loading mode permits to remove the residual angular momentum of the wheels that is accumulated due to the presence of external torques acting on the spacecraft such as the solar radiation pressure. During this mode, the desired attitude is maintained by actuating the reaction wheels, while a train of pulses is provided by the RCTs in order to desaturate the wheels via the reaction of the control loop to attitude errors. For the autonomous phases, the Auto-m and Exp-m modes make use of the image processing algorithms together with the planetary altimeter to reconstruct the spacecraft state. The information coming from the different measurements is fed to an Extended Kalman Filter (EKF) that considers the dynamical environment and the uncertainties in its modelling together with the uncertainties in the measurements modelling. Thus, EKF outputs the whole state vector of the spacecraft (position and velocity). The state vector is later used within the attitude guidance and translational guidance modules to autonomously operate the spacecraft. The attitude guidance module generates attitude profiles that points autonomously the spacecraft camera towards the selected asteroid based on the estimated position. The translational guidance module computes autonomous maneuvers based on the estimated state that serves as input to the Fixed Time of Arrival algorithm, which allows to correct a pre-planned nominal maneuver by means of linearization. The estimated deviations of the spacecraft state with respect to the nominal trajectory are considered to compute the final maneuver that will make spacecraft to arrive at the desired point at a specific epoch. Finally, in case a risk of collision with the asteroids is detected, a special mode of recovery called CAM-GNC has been designed to execute a pre-planned contingency maneuver to avoid any risk of collision.

Together with these two blocks, GMV has also designed the Image processing block, in charge of translating the optical images coming from the Asteroid Framing Camera into usable measurements for orbit determination. This block includes a general preprocessing routine of the image, two algorithms to determine the centroid of each asteroid and another algorithm of increased complexity that allows to track features on any of bodies. The first centroiding algorithm attempts to find the maximum correlation with a Lambertian sphere within the image. This algorithm has been selected to be used over Didymos for two main reasons, the shape is closed to a sphere and the algorithm does not degrade when Dimorphos appears in the image. For Dimorphos, the algorithm is based on simply computing the binary center-of-brightness of the image. The complexity of this algorithm arises from the fact that Didymos must be previously removed from the image to avoid counting illuminated pixels that do not belong to the Dimorphos body. The feature tracking algorithm is designed to operate when the distance to the asteroids causes their angular size to become greater than the field of view of the navigation camera. For the three algorithms, a routine to correct for the geometrical distortion of the camera is included. The geometrical distortion of the camera together with its orientation related to the star-trakers are calibrated in flight prior to the beginning of the proximity operations. The image processing algorithms are implemented in the on-board computer and also in the Image processing Unit (an FPGA based unit, also manufactured by GMV).

Along the execution of these blocks, FDIR (Failure Detection, Isolation and Recovery) routines monitor the proper functioning of the algorithms, having the capability of inhibiting the execution of certain blocks or even triggering the request of autonomous Collision Avoidance Maneuvers with the asteroids based on the Collision Risk Estimator calculations. The FDIR is structured in four levels. The first one is responsible for monitoring the GNC units, looking for anomalies in their behavior and raising alarms when they are detected. The second level is oriented to monitor the proper functioning of the GNC algorithms such as the navigation filter. The third level monitors the collision risk at trajectory level and the fourth level is oriented towards the implementation of recovery actions and is responsible for triggering CAM maneuvers.

The HERA GNC subsystem is also composed by a set of GNC units, procured by GMV: gyros used in hot redundancy, sun sensors, reaction wheels and star trackers.