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Pico-Satellite Platforms as Effective Sensors for In-Situ Asteroid Characterization

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In the study of Near Earth Objects (NEO), it is crucial to advance our current modelling capabilities of Potentially Hazardous Asteroids and imminent impactors, especially smaller size ones. This would allow for more accurate and more timely prediction of their effects and, ultimately, for a more effective protection of our planet. This objective can be achieved by enabling key technologies that can be utilised in support to missions to NEOs, in particular for in-situ validation of theoretical models of their properties. The design requirements for these technologies are derived from the modelling needs of the target body (asteroid dynamics, surface characteristics, topography, temperature in various locations) in terms of modelling capabilities, parameters to be measured for model validation, required measurement accuracy and resolution.

One of the in-situ characterization technologies currently under investigation at Delft University of Technology is the so-called “Smart-Net”, which makes use of the PocketQube satellite platform developed by the Space Systems Engineering group. PocketQubes are cube-shaped platform based on 50 mm^3 units with a mass of less than 250 g each. Delft University of Technology has embarked in the design and development of this class of picosatellites in order to further advance its research on satellite miniaturization: a PocketQube, by definition, has 8 times less volume when compared to a CubeSat. Potentially, deep space and interplanetary missions can gain even more advantage from the use of large networks of these very small satellites, by reducing costs, improving redundancy and assure high scientific return through their use in big numbers.

In the innovative Smart-Net, a number of PocketQube devices, equipped with a full suite of sensors and radio beacons, are used to sense the surface of an asteroid, measure its temperatures in various locations and its dynamics and rotational speed, while directly transmitting the gathered scientific information to the Earth. These PocketQube units represent the nodes of a net that can fully wrap and cover the entire surface of a small asteroid up to a few meters in size, with the net wires representing at the same time an antenna for direct communication from the PocketQubes to the Earth or a mother spacecraft. The PocketQube units are also equipped with hooks, to increase the chances for anchoring a body with very low gravity field. This paper presents the preliminary design of the Smart-Net and the expected challenges for its development and in-situ validation in an actual space mission.

I. INTRODUCTION

The development of technologies for the characterization, observation and modelling of low gravity field asteroids is one of the current hot topics in the space field. The future goal of these instruments is to enable in-situ validation of ground-based models, developed for small and medium sized asteroids. One of these in-situ validation opportunities is based on an existing mission currently in the roadmap of the European Space Agency (ESA): Hera, as part of the international Asteroid Impact and Deflection Assessment (AIDA) mission [1]. Hera is the first planetary defence mission intended to validate an asteroid deflection procedure by means of a “kinetic impactor”.

The mission (Figure 1) aims at characterising the binary near-Earth Asteroid Didymos using a mothership equipped with various instruments including two CubeSat spacecraft. An impact spacecraft, DART (Double Asteroid Redirection Test), developed by NASA, will impact the secondary asteroid of the Didymos binary system. The ESA spacecraft is expected to contribute to the evaluation of changes in geophysical and dynamical properties after the impact. Hera is designed based on the previous lessons learned from its ESA predecessor, Asteroid Impact Mission (AIM) and targets the re-use of several pre-designed technologies.

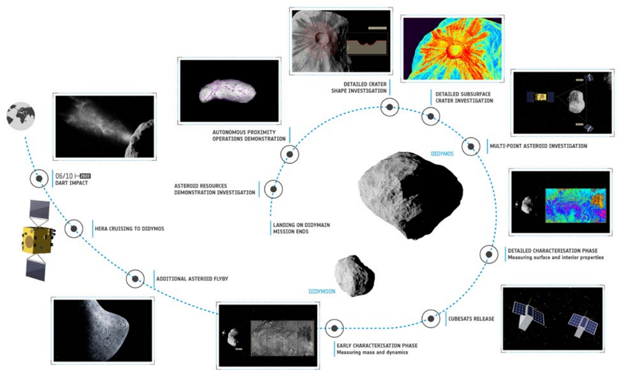

Fig. 1 – Mission description of Hera (photo credit: ESA).

One of Hera's high level objectives consists of validating the kinetic impactor technique through DART in order to enable its applicability to other future targets. Additionally, the general aim is to contribute to planetary defence by using cost-effective platforms such as CubeSats for highly important scientific purposes. Hera will be the first mission in: performing precise measurements of asteroid deflection, visiting and characterizing a binary asteroid, measure body cratering, use deep-space CubeSats for asteroid missions.

Another well-known historical mission is Rosetta [2]. The mission consisted of an orbiter and a lander (Philae) that aimed at a detailed in-situ study of a comet (67P/Churyumov-Gerasimenko). The mission concluded as expected with a controlled impact on the comet surface. Rosetta was the first mission orbiting a comet and landing on it, with valuable findings on the composition of the comet and the origin of its typical shape, proving that the comet was formed by the collision of two independent bodies.

Hayabusa represents another success among asteroid missions, through its attempt to bring a sample return from asteroid 25143 Itokawa. The mission also had as an objective the detailed study of spin state, shape, topography, density, composition and history of the asteroid. Its successor, Hayabusa 2, is a currently ongoing mission launched in 2014 which has recently performed a rendezvous with the Ryugu asteroid and will perform another sample return like its predecessor mission [3]. Another relevant ongoing mission is OSIRIS-REx from NASA, launched in 2016, which has as its main goal the return of a sample from the asteroid 101955 Bennu.

II. STATE OF THE ART OF PICO PLATFORMS

As first showcased, pico-satellite platforms represent a cube-shaped platform of 50 mm^3 with a mass of no more than 250 g per unit, called in literature PocketQubes. The design and development of this class of pico-satellites contributes to further advance research in satellite miniaturization. This platform has 8 times less volume when compared to a CubeSat.

The new platform is seen as a great opportunity for innovation and offers great research challenges in the miniaturization field. At the beginning, a consolidated standard for the PocketQube was lacking, which offered a significant amount of design freedom that was harnessed despite the small volume available. The main difference between the CubeSat and the PocketQube is highlighted in the structure and ejection logic. Unlike CubeSats, which are deployed along their four edges, the PocketQube uses a sliding backplate in order to be ejected from the deployer [4]. Low gravity asteroid bodies represent a challenge for landing and operating with passive probes and small satellites are even more prone to bouncing back from the asteroid at greater velocity than the one for escape. Therefore, using PocketQubes to perform in-situ measurements of a NEO (Near Earth Object) can work only if a device that can attach itself to the body is designed. Because of this, Delft University of Technology is developing the idea of a Smart-Net equipped with PocketQubes acting like sensors, which would wrap around the asteroid in order to perform measurements, as further described in section IV.

One of the most typical applications for capturing nets in space is represented by space debris removal. The term "space debris" usually refers to inactive objects with high velocity relative to Earth (in the order of 8 km/s), which represent a collision risk for active spacecraft and therefore additional costs and demands in design of technologies needed in order to ensure the safety of autonomous spacecraft in Earth Orbit [5]. In a recent research conducted at Delft University of Technology [6-9], contact dynamics has been researched using the penalty and impulse method, and the deployment and contact dynamics models have been validated through a parabolic flight experiment. During the research, several debris removal methods were studied, concluding that the net capturing method has clear advantages as opposed to docking/undocking, gecko adhesive or harpoon ones. Using a net allows for larger distance between the chaser and the target to such extent that the close rendezvous operations are limited and docking operations are not required. The net increases also the compatibility in size and shape of the objects to be caught, is more flexible, light weighted and therefore cost-efficient, presenting less risks of creating more space debris in case of failure. The research also investigated the deployment dynamic characteristics of net folded in an “inwards-folding scheme” pattern. Based on the modelling and analysis of the folding pattern, it was concluded that higher bullet mass shooting angles and more flexible net material contribute to larger net area. The simulations also showed that the net material does not have a large influence on deployment time and travelling distance; higher initial bullet velocity and larger shooting angle lead to a shorter effective period, which contributes to a higher risk of failure and less reliability of the capture. Finally, the simulations concluded that for free tumbling targets the net is able to capture and encircle the target without pushing it away, while tumbling CubeSats can be successfully captured when their tumbling rate is smaller than ~86 deg/s [6-9].

III. REMOTE OR IN-SITU MEASUREMENTS

The NEO population comprises asteroids and dormant or extinct comets. NEOs have orbits stable for periods much smaller than the age of the solar system and about 10 million years after they come to the near-Earth space, they meet their doom by being destroyed near the sun [10], being ejected of the solar system, or impacting a planet. The NEO population must thus be replenished. Modelling NEOs and the main belt asteroid orbits enabled us to understand the regions from where NEOs come from in order to keep their population stable [10, 11]. NEO source regions are essentially the different sections of the asteroid main belt and to less extent the reservoir of the Jupiter family comets. After decades of astronomical observations, the orbit, size, rotational state, shape, and composition distribution of NEOs are relatively well know down to sizes as small as 100 m ([12, 13]). The orbits of NEOs are determined from imaging observations of the surveys devoted to find these bodies. The known NEO population is mostly related to larger objects, since smaller NEOs (less than 10 m) are much more difficult to detect and therefore represent a great interest to the study field of planetary protection.

The scientific interests for NEOs stems in the possibility to study very small asteroids (size << 1 km), as they come close to Earth and can be investigated compared to main belt asteroids of equivalent sizes that are far away and often below the detection limit of telescopes. The study of their nature and materials allows us to investigate the conditions and the process that 4500 million years ago formed the planets but also inform us about the stage of the evolution of the solar system such as impacts and collisional process.

A particularly interesting subcategory of NEO are the Potentially Hazardous Asteroids (PHA). These bodies represent potential hazard for the Earth through impacts that can cause regional damages. An asteroid is considered PHA based on its orbit (minimum orbit intersection distance less than 0.05 AU) and intrinsic brightness (absolute magnitude less bright than 22). Given the absolute magnitude and the albedo, it is possible to estimate the PHA size: for example, for an average albedo of 15% and an absolute magnitude of 22, the object would have approximately 140 m diameter. In this respect, the study of Near Earth Objects is part of the so-called Space Situational Awareness (SSA), which started as part of a program proposed by the European Space Agency as an initiative to support independent space access and utilization of precise information regarding the space environment. The idea is to avoid as much as possible potential hazards in orbit or on ground stations by producing relevant data in 3 different segments: Space Weather, Near Earth Objects and Space Surveillance and Tracking. NEOs hit indeed the Earth constantly: these objects are mostly small and burn up when they enter planetary atmospheres, but a smaller number of larger objects occasionally pass through the atmosphere and create an impact crater. Crater-forming impacts, although rare on Earth, can have local or global catastrophic consequences. Airbursts caused by the disruption of larger meteoroids (>10 m) in the atmosphere are more common but can also be extremely hazardous if they occur in a populated area, as in the case of the unpredicted Chelyabinsk event [14]. There is still significant uncertainty, however, on the origin, impact rate and characteristics of this class of NEOs, which are typically too small to be directly tracked by telescopes. Most of our knowledge on the meteoroid environment is based on observations of terrestrial "meteors" [15], but in-situ measurements have been lately considered fundamental for a better understanding and characterization of asteroids due to the diversity of these bodies.

So far, science and engineering has relied on very few analysed cases which are too little to be able to characterize the entire population. The composing materials of such bodies is very important in terms of its strength, thermos-mechanical properties and their response to impacts. This assessment is mostly performed from ground-based observations. The mentioned missions from section I are contributing to validating these observations in order to overcome the limitations of the current techniques, which represent a short-coming in our scientific knowledge of small NEOs so far.

IV. ADVANTAGES OF IN-SITU DISTRIBUTED MEASUREMENTS

In-situ measurements are the most effective way for validating asteroid characterization from ground-based observations, however this type of validation is naturally limited by the amount and variety of NEO as compared to the number of expected missions to be able to cover all types of population. A Smart-Net can contribute to the validation of such data. The overall objective of the Smart-Net research currently performed at Delft University of Technology, as further described in section V, is to develop a net of sensors capable of wrapping the full surface of the target NEOs and take distributed measurements, with resolution in the order of 1 m or better, of surface properties and phenomena such as surface temperature distribution, seismic waves (frequency of 5 Hz or higher), magnetic field (300 nT or higher), topography (through Doppler ranging or similar methods), rotation rate. This type of device can be used for small NEOs but, if slightly modified, it can also work for larger objects. Additionally, the net wires can be designed to act as an antenna for direct communication of the scientific data to a mothership and/or the Earth, ensuring a minimum data rate for direct downlink to the Earth of at least 0.5 kbit/s (extendable to a maximum of 50 kbit/s for NEOs having closest approach with the Earth).

V. TECHNOLOGY DESIGN AND VALIDATION CHALLENGES

The most important element of the Smart-Net is represented by the PocketQube sensors, which can be designed based on the sub-systems and components of the Delfi-PQ satellite currently available in the research portfolio of Delft University of Technology.

Fig. 2 – Example of a microspine gripper [16].

As previously mentioned, PocketQubes represent cube-shaped platforms based on 50 mm^3 units with a maximum mass of 250 g per unit. Their outer structure is typically made out of PCB (Printed Circuit Boards) in order to simplify the mechanical design and reduce the costs. PocketQubes (one unit each) are used in this particular application as "sensors" to map the surface of the asteroid and measure its properties in a distributed manner in various locations. The PocketQube sensors are bound together by a net which not only represents a mechanical structure, but will also be the physical antenna for communications to the Earth or the mothership. The net will be adapted with hooks, conceptually similar to the microspine grippers presented in previous research (see Figure 2), aiming at a better grabbing of the surface, particularly important given the low gravity field of the small NEOs that will be considered for this study. Depending on the size of the selected target, the intention is to capture and wrap the entire asteroid, with PocketQube sensors at a distance from each other in the range of 0.5-2 m depending on the actual expected size of the target NEO. The technology can however also be adapted to the case of larger NEOs (~100 m or more) by ensuring better gripping capabilities with the use of more hooks and accepting only partial asteroid surface coverage. As an example, for a small NEO target with external surface in the order of 100 m^2, a sensor distance of 1 m translates into a requirement for a total of approximately 100 PocketQube sensors in the net. Depending on the shape of the asteroid and the approach velocity, it is possible that the asteroid wrapping is not uniform or the PocketQube sensors end up in areas that do not face the Sun. This risk can be mitigated by adding buzzers within each PocketQube, calibrated with the expected gravity field magnitude. In case the placement of a specific PocketQube on the asteroid is not ideal, its buzzer can be actuated to allow for slight position adjustments.

Sensors and instrumentation accommodated in each single PocketQube unit include: temperature sensors (with direct contact or close proximity to the asteroid surface); accelerometers (sensitivity in the order of 0.001*g*) and seismic sensors (with expected measurable frequency of 5 Hz or higher, and expected sensitivity in the order of 0.1*g*); magnetometers (in case any magnetic field is present), with an expected resolution in the order of 300 nT. Additional sensors, such as radios for communication of the PocketQube sensors to each other, can be optionally used for characterizing the topography/tomography of the NEO through Doppler ranging or similar methods. These radios can also be used to determine the exact position of all PocketQube sensors on the NEO surface after landing, through ranging with the mothership combined with optical images taken by the mothership camera and using the NEO rotation and consequent visibility of different sensors to discriminate between the various PocketQubes.

Additionally, in order to assure sufficient power is provided, silicon solar cells are used on the outer structure of the PocketQube sensors. A single junction silicon solar cell can produce a maximum open-circuit voltage of approximately 0.5-0.6 V and a maximum efficiency in the order of 20%. Given the size and expected illumination conditions of the PocketQubes, an average power generation in the order of 0.3 W per unit is expected, when the target NEO is at a distance in the order of 0.9-1.1 AU from the Sun. Moreover, these cells are considered extremely economical which make them an asset for space applications. Such cells can have sufficiently good performance in low light conditions, especially for monocrystalline silicon solar cells which makes them suitable for application in asteroid missions. They are also sufficiently robust to limit the risk of cell fracturing during deployment and landing, which can be further mitigated through redundancy. Depending on the available volume, it is also preferable to equip the PocketQube sensors with batteries (an example is shown in Figure 3), in order to allow for power autonomy to take continuous measurements during eclipse periods.

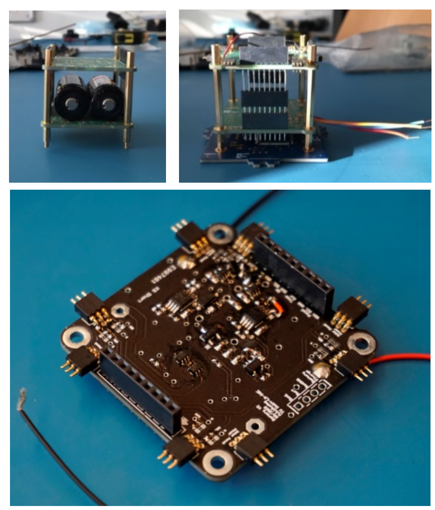

Fig. 3 – Battery board and Electric Power System of a typical PocketQube.

Each sensor is also equipped with an antenna board and a radio board (examples are shown in Figure 4) in order to provide communication among the sensors in the same net. Given the short distances involved, an alternative inter-communication method among the PocketQubes can be represented by the BlueTooth protocol; this alternative will be thoroughly evaluated during the design phase of the Smart-Net.

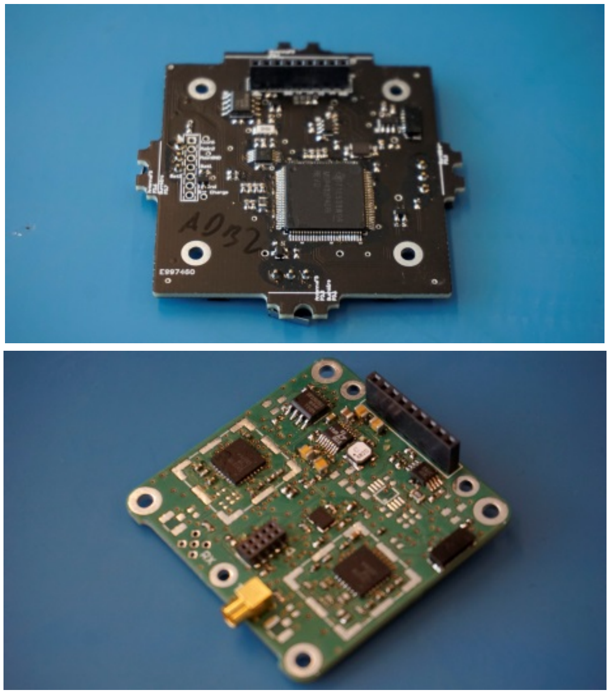

Fig. 4 – A typical PocketQube Antenna Board (top) and Radio Board (bottom).

The initial prototype testing of all functionalities of the PocketQube sensors is expected to be performed in the cleanroom facility of TU Delft through a FlatSat board (see the example in Figure 5). The purpose of the FlatSat is to check in a Hardware-in-the-Loop setting all electrical connections, communications between components and the overall systems before their final integration. The aim is to prove that all components are meeting their requirements by using the electronic workbench and end-to-end test communications between all boards.

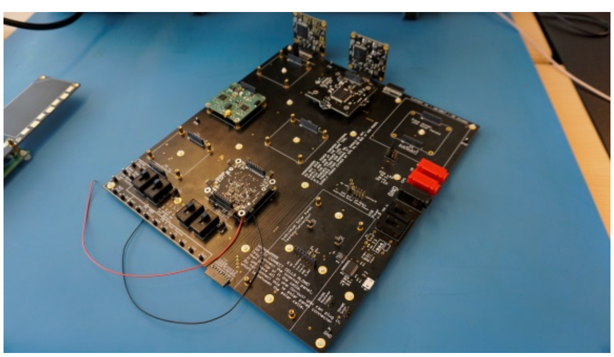

Fig. 5 - PocketQube FlatSat testing board.

The net connecting the PocketQube sensors is designed taking into account two separate but strictly interconnected aspects: the mechanical structure of the net and its innovative use as an antenna to allow for direct communication to the mothership or to the Earth. The net will therefore be manufactured using a combination of metallic and non-metallic wires, with the metallic wires expected to be used as antennas once deployed on the asteroid, with a net wire diameter in the range 1-5 mm and a total net diameter in the range 5-10 m (depending on the dimensions and shape of the selected target NEOs).

Unfortunately impedance matching cannot be known in advance (due to the randomness of the final distribution of the PocketQube sensors on the asteroid surface) and, in order to optimize the antenna transmission parameters, the system should be capable to adapt to a wide range of possible impedances. This approach is common in mobile phones which adapt to different hand/head positions, optimizing the antenna performances in real time. The limits of such an approach will be tested using a representative model of the asteroid, built with a comparable size and composition and used to deploy the net several times to have a statistical analysis of the possible impedances. The antenna is supposed to communicate directly with Earth during one of the fly-bys of the asteroid or to the mother spacecraft that deployed the net. Several assumptions need to be made at this early stage of the study on the available communications standards, effective antenna gain, ionosphere conditions, available power at each node to provide energy to the transmitter (expected to be only operated in bursts), landing conditions. Considering reasonable values for these assumed parameters, and in particular assuming communication to be performed in the S-band, a transmitter power of 0.1 W and a large ground antenna of 25 m diameter, a preliminary link budget study has been performed considering the Earth flyby of the small asteroid HB177, expected to reach a minimum distance to the Earth of around 80000 km in the next flyby in 2034. Results show a maximum downlink data rate of 1000 kbit/s at the minimum Earth distance, which reduces to 0.5 kbit/s at a distance of 4.5 million km from the Earth. These values are considered sufficient to guarantee complete feasibility of the proposed Smart-Net concept, both in terms of amount of transmittable scientific data and their transmissibility to the Earth.

VI. CONCLUSIONS AND FUTURE WORK

The Smart-Net technology presented in this paper is intended to contribute to planetary defence through gaining information on the visited NEOs. The outcomes from both science and technology activities of the current space and planetary exploration scenario aim at exploiting all possible opportunities for their actual use in asteroid missions and, ultimately, for using them as valuable tools for the defence of our planet. To this respect, a detailed study will be conducted on in-situ validation opportunities of the developed technology within future space missions. The overall ambition of this project is to contribute to the advancement of the modelling capabilities of NEO bodies through offering in-situ validation opportunities; enable the use of pico-satellite platforms for deep-space exploration; contribute to planetary defence through dedicated in-situ validation campaigns which will significantly improve the accuracy and capabilities of existing models of very small asteroids. This, in turn, will allow for a better knowledge of imminent impactors and eventual timely planning and execution of deflection actions, for which accurate knowledge of surface and sub-surface composition, topography, temperature variations, is crucial.

Miniaturization and standardization of spacecraft components for high-performance in deep-space applications using limited resources represent one of the most recognized global hot topics in space engineering. To this respect, PocketQubes can be considered the “miniaturization of miniaturization”. Their volume and other capabilities are more than sufficient for using them as landers for asteroids in the type of application described within this paper as the Smart-Net. The Smart-Net will represent a cost-effective set of distributed sensors that can be used to validate and enhance the current modelling capabilities of NEO characteristics, will establish direct communication with the Earth (provided through the net which will serve as antenna) and has the ability to reduce mission complexity by making the mission less dependent on the mothership or any other element of the space-segment.

Such technologies, will help at paving the way to cheaper, faster and more effective characterization of NEO bodies for the defence of our planet. Additionally, they have the potential and ambition to mark the ignition of a new era in the use of low-cost components for asteroid missions, with likelihood to contribute to near future missions focused on planetary defence.

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