SATELLITE LASER RANGING FOR ATTITUDE DETERMINATION AND DESIGN FOR REMOVAL TO ENABLE ACTIVE DEBRIS REMOVAL OF FUTURE SPACE DEBRIS

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ABSTRACT

Active Debris Removal (ADR) is necessary for sustainable orbital environment. To ensure ADR is possible for any kind of mission, satellites need to be prepared to be removed. Thus, Design for Removal (D4R) technologies must be developed, standardised, space-qualified, and implemented. The objective of this paper is to provide an overview of the D4R technologies that were developed with the support of the ESA Clean Space initiative.

One of these D4R technologies needed for ADR is the Laser retroreflector (LRR), which consists of a corner cube retroreflector (CCR) with a housing. If a satellite fails and thus becomes a new space debris, satellite laser ranging (SLR) observation technique of those corner cubes can be used to determine the space debris attitude before launching a servicer. Therefore, it is possible to know if the servicer could capture this new debris and save money if not by avoiding an unnecessary launch.

1 INTRODUCTION

A spacecraft failure in orbit can have catastrophic consequences on the orbital environment as well as for the safety of operational space assets. Policies and regulations on Space Debris Mitigation are evolving, and in particular ESA's Zero Debris initiative [1] aims at ensuring a remediation action in case a spacecraft fails to deorbit itself. However, Space Debris Removal is a challenging and risky task if there are no aids for capturing the object. In other words, if satellites are not prepared to be removed each D4R solution would be different and entail higher costs and risks (e.g. of in-orbit collision). Developing standardized interfaces would ease the removal by an external servicer and decrease associated costs. Therefore, future satellites need to be prepared to be removed in case of failure. This has highlighted the lack of standardized and widely accepted interfaces for removal, which are fundamental to ensure that ADR operations are carried out in a safe manner.

Indeed, ADR is not a straightforward operation, especially in cases where the targeted satellite to be removed is to some extent un-cooperative. This is the case of a failure in orbit or a collision, among others. In the last decade, ESA has been actively funding several research activities through, among others, the Clean Space initiative, to develop technologies for approaching, grasping, and removing spacecraft on orbit. These technologies developed, which are a possible D4R solution for LEO missions, include:

1. Mechanical capture interface to support capture and manoeuvring by an external servicer
2. Laser Retroreflectors to support the attitude determination from ground
3. 2D markers to support rendezvous from 50 m to 5 m
4. 3D marker to support the final metres of rendezvous and the visual servoing of the capture system
5. Passive detumbling solutions (short-circuiting of the magnetorquers) in case of loss of control of the satellite

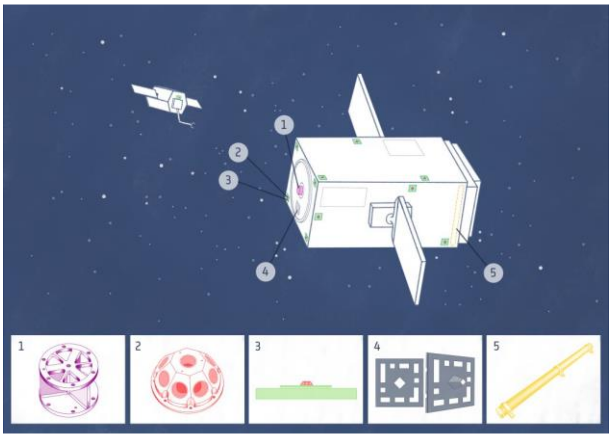

Figure 1. Representation of the D4R technologies developed by ESA research activities

These technologies development needs to be accompanied by a validation and verification at system level. In addition to these interfaces, the Agency has also developed an Interface Requirements Document (IRD) [2] to gather the interface requirements with the host system and is developing capture payload systems to verify the functionality of these interfaces. Also, all these features are developed to withstand and keep full functionality during long term (more than 12 years).

The Agency is taking a proactive and innovative

Proc. 2nd NEO and Debris Detection Conference, Darmstadt, Germany, 24-26 January 2023, published by the ESA Space Safety Programme Office Ed. T. Flohrer, R. Moissl, F. Schmitz (http://conference.sdo.esoc.esa.int, February 2023)

approach by preparing the future Copernicus Expansion satellites (Earth Observation missions) for a possible removal as part of the End-of-Life management. The interfaces are being developed and matured, so that in the future they can be reliably adopted by other missions.

The on-going preparation of satellites for removal is not only seen as a need to guarantee the sustainability of the orbital environment in the short term, but also as a steppingstone towards a much more efficient, safer and environmentally friendly, management of the assets in orbit. In fact, if a satellite is unable to control its attitude at the end of its lifetime or due to a failure, it may begin to spin due to external or internal torques acting on the spacecraft. With the help of the satellite laser ranging (SLR) observation technique conclusions about the attitude of such rotating satellites can be drawn. For this, CCRs are mounted in the target satellite, so it is possible to know before launching the servicer if it could capture this new debris which is spinning at the determined spin rate or save money if not by avoiding an unnecessary launch.

The goal of this paper is to provide an overview of all the work performed at ESA in the topics of D4R in the last few years and to show how standardization and demonstration of these interfaces will allow for a safer orbital environment for future missions. Lessons learnt and knowledge gaps that could be addressed in the future will be pointed out. Indeed, the technologies presented are not the unique solutions for D4R. Also, they could be further optimised, and further work is needed to adapt them for small satellites and/or other orbital environments (MEO/GEO).

2 DETUMBLING SOLUTION

A solution could be to embed passive capabilities that would allow the spacecraft's tumbling rate to be dampened, once triggered. This point is important: the capability should allow nominal operation, but then turn on automatically as soon as a critical failure is detected.

For this reason, the Clean Space team have been investigating a technology to enable the 'short-circuiting' of magnetorquers at end of life.

When magnetorquers are short circuited, they form a closed electrical circuit. This closed circuit is surrounded by Earth's magnetic field, and because of the satellite's tumbling motion, the magnetic field in the satellite's rotational frame is actually time varying.

From Faraday's law of induction, eddy currents are therefore generated within the magnetorquer's wires which, from Lenz's law, implies the creation of an electromotive force opposing the motion.

In such a case, the motion is the satellite's tumbling and the short-circuited magnetorquers would produce a torque that helps damp this tumbling rate. The rotational kinetic energy is dissipated through Joule effect inside the magnetorquer.

Short-circuited magnetorquers use the most basic laws of electromagnetism to brake an uncooperative satellite and make its capture by a chaser vehicle much more feasible.

Figure 2. Magnetorquer. Credits: Zarm

3 LASER RETROREFLECTORS TO SUPPORT ATTITUDE DETERMINATION FROM GROUND

Even if the magnetorquers are successfully triggered into action when the spacecraft fails, today there exists no direct way to know if they managed to damp the angular rate to an acceptable value for capture (since there is no contact with the satellite). Therefore, the spacecraft's attitude must be tracked remotely from ground.

LRRs can be used to determine the attitude of the spacecraft from ground using SLR technique. A LRR consists of a corner cube retroreflector (CCR) with a housing.

A CCR or trihedral optical prism, is an optical structure that consists of three adjacent, mutually-orthogonal plane-reflecting surfaces which form the corner of a cube. CCRs are designed to reflect light back in precisely the same direction it came from to provide independent measurements of the satellite's position.

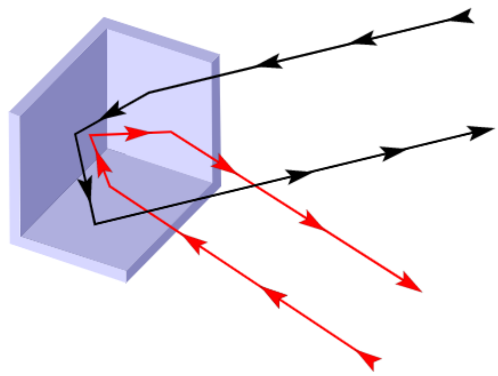

Figure 3. Working principle of a corner cube retroreflector (CCR).

According to past experience, it is possible to model the attitude of small tumbling satellites in LEO using several ‘corner cubes’ distributed on a satellite’s faces [3]. This physical positioning must be known in advance, and the positioning of the LRR should create different patterns on each face of the spacecraft.

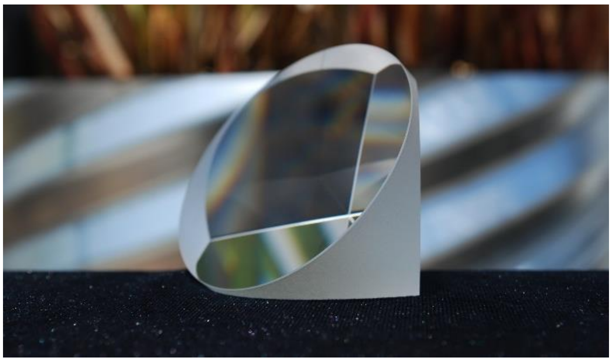

Figure 4. Example of a corner cube retroreflector. Credits: Precision Optical [4]

Once the spacecraft is in orbit, a ground station transmits a laser beam, which reflects from the LRRs. The reflected signal includes information on the observed face such that, after interpretation, the spin rate and the spin axis of the target can be characterized.

If a failure occurs, a removal mission can be launched if the data given by the LRRs meets the tumbling requirements for capture. Then, the dead satellite would be a known, viable target for removal.

3.1 REQUIREMENTS RELATED TO LRRs

As mentioned before, to enable ADR not only the D4R technologies shall be developed, but also their implementation at system level shall be defined. Indeed, this implementation can impact other subsystems, so it shall be considered when designing the mission. The Interface Requirement Document [2] developed by the Agency through different research activities gathers these interface requirements.

Some examples of requirements related to the ground tracking aids (LRRs) included in that IRD are the following:

- Four LRRs shall be included per face, except in one face that can have zero LRRs. The recommendation is to include 3 LRRs per face as a minimum to have at least two baseline distances in each face, increasing the accuracy of the attitude determination.
- Unique pattern of the LRRs in each face is needed for unequivocal identification of each face. This will help the attitude estimator converging faster and removing ambiguities.
- 1 meter distance as a minimum between LRRs is required, with the general recommendation of maximising the distance between LRRs to increase accuracy on attitude determination.
- Angular clearance of at least 30 deg in the deployed configuration of the Spacecraft. This is needed for the proper characterization of the attitude from ground.

4 2D MARKER

The 2D markers will support rendezvous, with signature on visual and infrared wavelength, that can be used to improve pose and attitude determination from 50 m down to 5 m distance between the spacecraft and the servicer. To be able to perform ground-based attitude determination a LRR is built into the centre of the marker, allowing to combine both functionalities in one equipment.

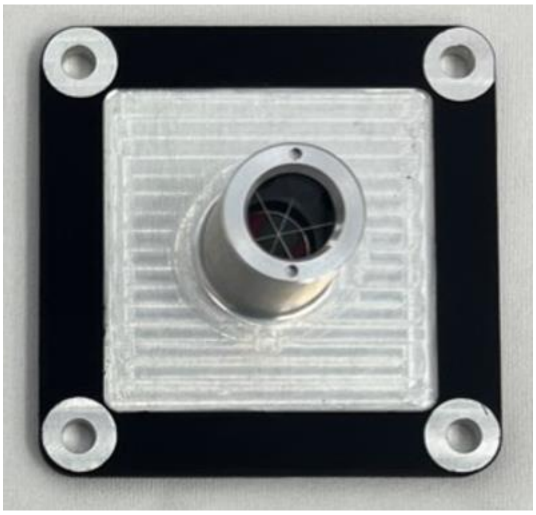

Figure 5. 2D marker with LRR as central element. Credits: Admatis [5]

Detectability of the markers is ensured by the high contrast in optical and thermal infrared against MLI, solar panel and different types of radiator coatings. Within the markers, coatings are chosen and applied to have different thermo-optical properties, and the special spatial geometry support the visual based navigation processes.

The pattern of these on each face has to be unique so that it is possible to identify the face and therefore reconstruct the attitude of the target. As the LRR is the central element of these 2D markers, the patterns are the same for LRRs and markers.

However, when the chaser gets closer to the target, there is a point from which the chaser’s cameras won’t be able to observe the full target anymore because of field of view limitations. When this point is reached, relative navigation can’t rely on the 2D markers anymore. That is why the target should also embed a different type of marker.

5 3D MARKER

One 3D marker is needed, which has to be located on the target face to be captured by the chaser. It is identifiable in the visible wavelength to support precise pose and attitude determination for the last phase of the capture, from 5 m down to 0 m distance between the spacecraft and the servicer.

The 3D marker requires an active illumination source and a visual camera on the chaser. The protrusion of the 3D marker, coupled with a painted pattern, gives different images depending on the relative position of the chaser.

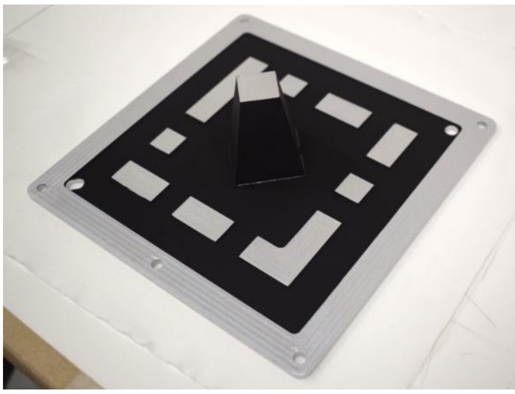

Figure 6. 3D marker. Credits: Admatis [5]

6 MECHANICAL CAPTURE INTERFACE

Once the stand-off distance has become small enough, the capture can start. This is a critical phase of the mission, and it is even more challenging when the target satellite is unprepared for removal. Indeed, it is hard to determine a specific portion of the dead satellite that can be safely grabbed and that can sustain the capture loads. This is also extremely difficult because the chaser has to deal with appendages – like solar panels — that can restrict the potential capture areas.

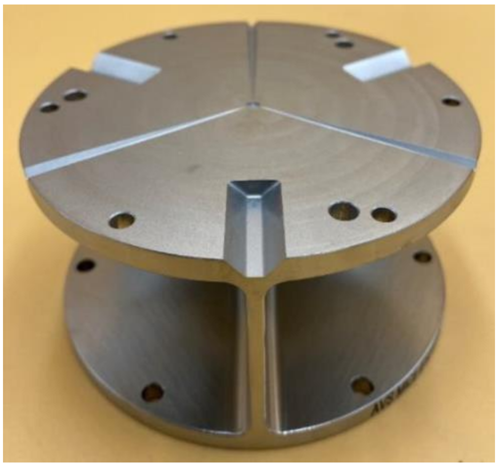

Figure 7. Mechanical capture interface MICE. Credits: GMV

To assist in the capture phase, ESA has been carrying out a study to develop a mechanical interface. It is a single piece made of stainless steel about 10 cm wide and 5 cm high. It is designed to support the capture loads and also to enable a gripper (also to be developed) to grasp this interface. In that respect, a 'keep-out' zone must be enforced on the target side to allow this future gripper to operate.

7 CONCLUSIONS

Design for Removal is an important part of ESA's Zero Debris initiative. Satellites need to be prepared for removal to ease the removal by an external servicer and decrease associated costs. This is more challenging when a satellite is unable to control its attitude at the end of its lifetime or due to a failure, as it becomes a space debris and it may begin to spin due to external or internal torques acting on the spacecraft.

SLR is proposed to be used to determine the attitude of the spinning object in orbit, which has already embarked corner cubes retroreflectors to ease this process. This way, it is possible to know if the servicer could capture this new debris and save money if not by avoiding an unnecessary launch. However, further work is needed in this topic, especially regarding the development of a proper attitude estimator and its validation through a real case testing.

The same applies to all the described technologies: this first generation of D4R technologies shall be demonstrated in orbit to validate its performance. The Agency is taking a proactive and innovative approach by preparing the future Copernicus Expansion satellites (Earth Observation missions) for a possible removal as part of the End-of-Life management. Thus, the technologies will be on board of the six Earth Observation missions and the satellites will be removed by a chaser in case of a failure. In that case, in orbit demonstration will be achieved for the D4R technologies presented. The aim is that in the future the technologies can be reliably adopted by other missions.

In the meantime, the development and demonstration of the correspondent capture payload (chaser) is on-going.

Future steps are the adaptation of these technologies for small platforms and also for other orbital environments, as the detumbling solution presented in this paper is not valid for GEO/MEO satellites.

In conclusion, European standard interfaces for D4R applicable to all platform classes and in all orbital environments are needed, together with the corresponding requirements derived from their implementation at system level. Standardization of these interfaces is needed to reduce risks and costs of ADR, allowing for a safer orbital environment for future missions.

8 REFERENCES

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