ADVANCING ESA's VISION FOR SUSTAINALE SPACE OPERATIONS: DESIGN FOR REMOVAL AND IN-ORBIT SERVICING INITIATIVES

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ABSTRACT

With the growing challenge posed by orbital debris, the European Space Agency (ESA) is leading efforts to ensure the safe and sustainable operation of space missions through its Clean Space and Space Safety programs. Central to these efforts are the development and standardization of Design for Removal (D4R) technologies and encouraging the implementation of several In-Orbit Servicing (IOS) and Active Debris Removal (ADR) activities, essential components of ESA's vision for a future space circular economy. This paper provides an overview of the D4R and ADRIOS technologies developed with support from ESA's Clean Space office.

Keywords: design for removal; In-Orbit Servicing; space debris mitigation.

1 INTRODUCTION

ESA has supported the development of D4R technologies for Low Earth Orbit missions, including mechanical capture interfaces, navigation markers, laser retroreflectors for attitude determination from ground, and detumbling solutions. These technologies are being integrated by European spacecraft manufacturers, notably within the Copernicus Sentinel Expansion missions. To further this progress, ESA has released a dedicated D4R Interface Requirements Document and is supporting the development of capture payload systems to ensure long-term interface compatibility. While the technologies presented here represent significant strides, further optimization and adaptation for diverse satellite configurations and different orbital environments (also beyond LEO) remain essential.

In parallel, ESA's IOS activities are advancing the agency's strategic objectives for sustainable orbital operations. The ADRIOS project is a cornerstone initiative paving the way for debris removal and servicing missions. Near-term missions such as ClearSpace-1 and ELSA-M target the capture and removal of orbital debris by 2026. ESA is also conducting studies for future missions, including CAT-IOD for debris removal demonstration using standardised rendezvous and docking interfaces and e.Inspector for close-proximity space debris inspection.

Looking towards 2030, ESA aims to facilitate commercial IOS activities with missions like RISE and ENCORE, offering in-orbit life extension services for commercial satellite operators in Geostationary orbit. The In-Space Proof of Concepts (InSPoC) initiative aims to demonstrate in-space transportation and refuelling services. By 2050 and beyond, ESA envisions enabling a space circular economy encompassing in-orbit manufacturing, assembly, and recycling.

Design for Removal Initiative

1.1 Background

Spacecraft failures pose a significant risk in Earth's orbit by contributing to the growing issue of space debris. The population of operational space objects and space debris is constantly growing, partially due to the unprecedented growth in the use of Earth orbits in recent years. Tackling the trend of a deteriorating space environment around Earth demands a proactive approach if we are to control the hazards associated with space debris [1]. As depicted in Figure 1, current projections indicate that even if launches were to cease immediately, the amount of space debris in Earth's orbits would continue to grow. This persistent increase and the associated risks necessitate the implementation of measures for the active removal and disposal of malfunctioning or end-of-life spacecraft. It is imperative to address the existing debris, rather than relying solely on passive decay, especially for objects that do not comply with space debris mitigation guidelines and requirements. One main aspect of requirements from ESA and other organizations is ensuring that spacecraft in low Earth orbit (LEO) have an orbit lifetime of less than five years from the end-of-life epoch. This requirement helps reduce the risk of collisions with other space objects and ensures the spacecraft's timely removal from critical orbital regions. Not all spacecraft are disposed of withing 5 years, however, necessitating Active Debris Removal (ADR) services to remove spacecraft that cannot perform self-disposal. As such, spacecraft should be designed to be easily approached, inspected, and captured by servicers.

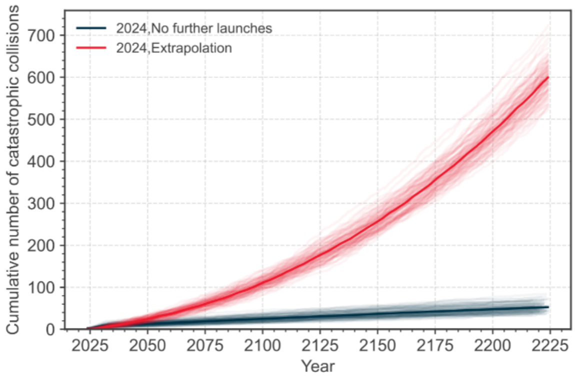

Figure 1: Extrapolation of cumulative number of catastrophic collisions in LEO for different scenarios

2 Key D4R Technologies

The successful execution of Removal missions relies on various technologies that facilitate capture, navigation, attitude reconstruction from ground and detumbling of satellites at the end of their operational lives. Some examples of these key technologies include the Mechanical Interface for Capture at End-of-Life (MICE), Markers for Navigation Support (MSN), Laser Retroreflectors, and Passive Detumbling mechanisms. This section provides an overview of these technologies [2].

2.1.1 Mechanical Interface for Capture at End-of-Life (MICE)

MICE is a passive metallic interface mounted on a target spacecraft's structure, designed to allow physical capture with a gripper before the spacecraft is permanently rigidized against the removal vehicle. The primary function of MICE is to enable capture of satellites, ensuring a repeatable operation under various conditions.

Key requirements for MICE include:

- The interface must support the capture forces and moments.
- It must allow capture before contact, ensuring that the gripper does not exceed a diameter of 250 mm, with relative misalignments of up to +/- 20 mm and +/- 3 degrees.
- The height of the interface should not exceed 50 mm and must avoid coatings to ensure reliability during operation.

MICE is currently at a high level of maturity (TRL 8). The interface has recently been launched into LEO aboard LUR-1 and is being integrated in the upcoming Copernicus Expansion Missions. Future developments include MICE-lite, a lighter and cost-effective version designed specifically for smaller satellites (as opposed to the current design which is sized towards larger satellite systems).

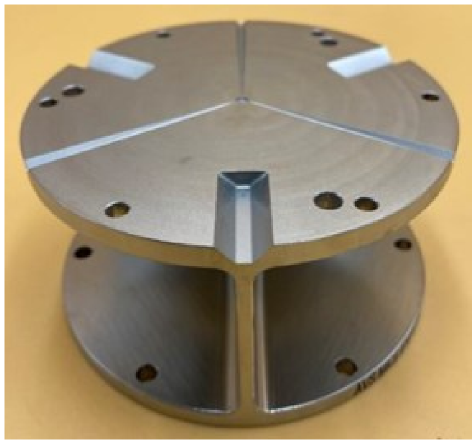

Figure 2. Mechanical Interface for Capture at End-of-Life (MICE)

2.1.2 Markers to Support Navigation (MSN) and Laser Retroreflectors (LRR)

The accurate and reliable navigation of the servicing spacecraft during rendezvous and capture is facilitated by the use of navigation markers. These include both 2D and 3D markers, which both play a crucial role in aiding pose and attitude determination:

2D Navigation Markers are equipped with laser retroreflectors (LRRs) and support both ground-tracking and close-range navigation. These markers provide essential data on the spacecraft's attitude, distance, and velocity from distances of 50 meters down to 5 meters. Built-in LRRs allow ground-based attitude determination through laser ranging, ensuring accurate pose estimation.

3D Navigation Markers are used in the final phase of the capture, supporting pose and attitude determination from 5 meters to direct contact. These markers provide the necessary spatial references helping the servicing spacecraft maintain an accurate approach as it nears the target.

The key requirements for these navigation aids are their ability to operate in changing lighting conditions and provide clear contrast against the satellite's surface. Furthermore, distinct patterns on the markers ensure the correct identification of the target's orientation, with at least four markers placed on five faces of the satellite for optimal attitude estimation.
The Markers are at high level of maturity (TRL8) and are being integrated in the upcoming Copernicus Expansion Missions. The 2D markers have recently been launched aboard LUR-1.

Future developments include a second generation of Markers to Support Navigation, with improved optomechanical configuration and the development of phosphorescent painting to use only the visual spectrum.

Additionally, future optimizations in 2D and 3D marker design are being developed to suit smaller satellites, with improved performance in capturing pose and attitude data at closer distances. As these markers are currently designed for larger spacecraft, advancements will focus on making them lighter and more compact while maintaining their efficacy in navigation and capture operations.

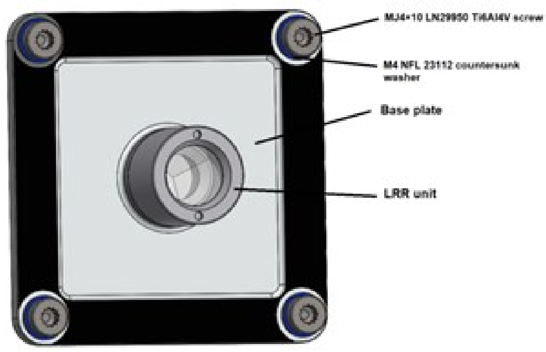

Figure 3. 2D Marker to Support Navigation (MSN)

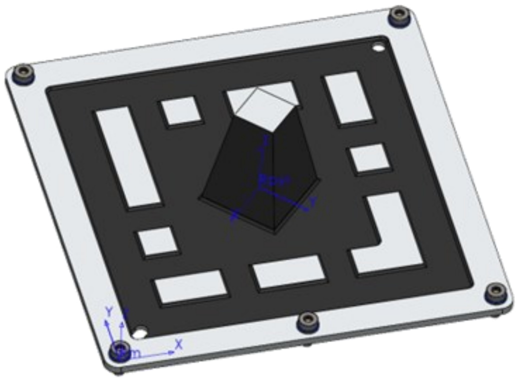

Figure 2: 3D Marker to Support Navigation (MSN)

2.1.2.1 Laser Retroreflector-Based Attitude Determination System (RADS)

For uncooperative satellites, especially those that may be tumbling or spinning, attitude determination prior to the launch of a servicer is critical. The **Retroreflector-based Attitude Determination System (RADS)** leverages laser retroreflectors embedded in 2D markers to enhance ground-based attitude reconstruction.

This system helps measure the spin rate and spin axis of the satellite before capture, which is essential for planning the removal operation. The use of distinct configurations of retroreflectors across several faces of the spacecraft ensures that its position and orientation can be accurately determined from ground.

2.1.3 Detumbling Mechanisms

One of the key challenges during ADR missions is managing the unpredictable and uncontrollable tumbling motion of target satellites. Technologies aimed at stabilizing this motion include dedicated passive magnetic detumbling devices and short-circuited magnetorquers. Both utilize the interaction with Earth's magnetic field as a method to dissipate kinetic energy from the satellite tumbling motion and damp the angular rates. When a rotating satellite in LEO interacts with a time-dependent magnetic field, an electromotive force is generated, resulting in induced currents within the magnetorquer coil. This generates a magnetic moment and torque that gradually dissipates the satellite's rotational kinetic energy through the Joule effect. The system is capable of damping residual rates from up to 3 degrees per second down to 0.75 degrees per second within 12 months [4].The TRL is currently 7.

Figure 3: Magnetorquer short-circuit test

3 Technology Implementation

Embedding interfaces for removal services reduces the risk and cost associated with removing satellites in case of failure. This chapter provides an overview of the missions already implementing ESA D4R technologies:
Some future Copernicus Expansion missions (next generation Sentinel Satellites for Earth Observation) have adopted the D4R IRD that ESA has developed. These are the first spacecraft that have fully committed to the Agency`s proactive and innovative approach by preparing 2 tons class Spacecraft for a possible removal as part of End-of-Life management. Most notably the CHIME, CO2M, CRISTAL and LSTM projects are in the process of integrating the D4R interfaces onto their spacecraft.

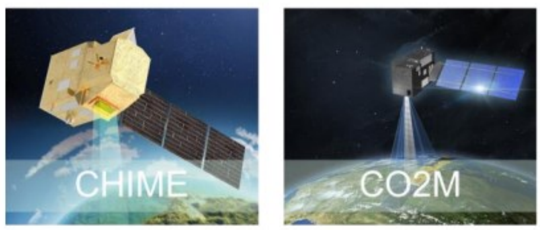

Figure 4: Copernicus Expansion missions embarking ESA's D4R standard removal interfaces

These Spacecraft are equipped with the following D4R technologies:

- MICE on LAR plane
- 3D marker on LAR plane
- 2D markers with retroreflectors on five faces
- Detumbling (short-circuited magnetorquers)

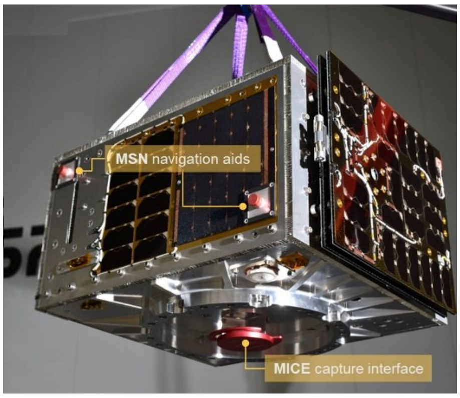

Figure 5: LUR-1 during integration with MICE and 2D MSN

The *LUR-1 spacecraft* is a microsatellite platform (mass 57 kg) developed by AVS for an in-orbit technology demonstration mission. Although by itself compliant with the space debris mitigation requirements, the spacecraft offers a target of opportunity for future IOD of capture interfaces.

LUR-1 can maintain a three-axis stabilized attitude aligning the LAR with the negative V-Bar axis for the cooperative scenario or it can simulate an uncontrolled tumbling in BBQ mode for the uncooperative scenario.
Considering the constraints of a compact satellite platform, it has been equipped with the following D4R technologies:

- MICE on LAR plane
- 6x 2D markers with retroreflectors on four spacecraft faces

3.1 Standardization and Interface Requirements

Standardization has become increasingly important to ensure the safety, sustainability, and efficiency of space operations [3]. There is a need for standardization to reduce space debris and facilitate the safe removal of defunct satellites ,and standardization ensures that the various components, systems, and services required can work together seamlessly. It reduces the chances of mission failure and minimizes the generation of space debris. Compatible interfaces allow different removal vehicles to interact with multiple satellite designs, making the capture and removal process more efficient. This reduces the need for custom designs and extensive testing, thereby decreasing development time and costs.
ESA, together with European industry, has developed the D4R Interface Requirements Document (IRD). The goal is to prepare LEO satellites under development with standardized interfaces for possible future removal missions.Within the scope of standardization and requirements for D4R, it is necessary to differentiate between two cases:

1. Uncooperative Removal: This is the case when the satellite is or becomes non-operational, either completely or in terms of attitude control, and is tumbling in space.
2. Cooperative Removal: In this scenario, the satellite is operational but unable to perform the end-of-life functions required to remove it from orbit.

Due to the different loads experienced during controlled and uncontrolled re-entry, the requirements for D4R are also differentiated between these two cases. Controlled Re-entry involves high loads during de-orbiting whereas an Uncontrolled Re-entry involves much lower loads. While the capture itself must satisfy the requirements and standards, the operational approach of such servicing missions must also be facilitated. For this purpose, 2D and 3D Navigation Aids play a crucial role in supporting the rendezvous and capture phases. These aids, including laser retro-reflectors (LRRs) and visual markers, help improve pose and attitude determination from distances of 50 meters down to direct contact.
Further work is needed to adapt these requirements to other orbital environments, such as Medium Earth Orbit (MEO) and Geostationary Earth Orbit (GEO).

4 ADRIOS

The European Space Agency's (ESA) Active Debris Removal/In-Orbit Servicing (ADRIOS) initiative is a pivotal component of its Space Safety Programme, focusing on mitigating space debris and promoting sustainable space operations.
Several cornerstone missions are under preparation as part of the ADRIOS programme. Following an overview of some of these missions [7]

4.1 ClearSpace-1 mission

The ClearSpace-1 mission aims to demonstrate the feasibility of active debris removal and set the stage for future in-orbit servicing activities.

The mission intends to capture and deorbit an ESA-owned satellite left in LEO orbit. This object will be an uncooperative target, making it ideal for demonstrating debris removal technologies.

ClearSpace-1 will showcase critical technologies such as advanced guidance, navigation, and control systems, as well as vision-based artificial intelligence. These technologies enable the chaser spacecraft to autonomously approach and capture the target using robotic arms.

Post-launch, the chaser spacecraft will undergo commissioning in a lower orbit before ascending to rendezvous with the target. Upon successful capture, the combined system will be deorbited to ensure a controlled atmospheric re-entry, thereby removing the debris.

By contracting the ClearSpace-1 mission as a service from the Swiss startup ClearSpace SA, ESA is fostering the development of a commercial market for in-orbit servicing and debris removal. This approach not only addresses the immediate challenge of space debris but also stimulates the growth of a sustainable space economy.

4.2 RISE mission

Developed in collaboration with D-Orbit, the RISE mission aims to demonstrate the ability to dock with geostationary satellites, perform necessary manoeuvres, and subsequently release them. This mission seeks to validate technologies essential for extending the operational life of satellites and reducing space debris.

The RISE mission will utilize D-Orbit's GEA platform which will be a new development. The mission will focus on life extension services for operational telecommunications satellites, marking a significant step toward sustainable and efficient space operations.

4.3 CAT mission

CAT Mission (Capture Payload Bay In-Orbit Demonstration) mission is designed to demonstrate technologies for capturing and removing inactive satellites. It focuses on implementing standardized coupling interfaces and navigation aids to facilitate the safe and efficient removal of defunct satellites from orbit.

The mission will involve a chaser spacecraft equipped with a standardized interface, known as MICE, to dock with target satellites. Navigation aids will assist in precise rendezvous and capture operations, enhancing the effectiveness of active debris removal efforts.

These missions, alongside ClearSpace-1, underscore ESA's commitment to advancing technologies for active debris removal and in-orbit servicing, thereby contributing to the long-term sustainability of space activities.

4.4 Circular Economy studies

As part of the Zero Debris Approach for Space for a sustainable and safe space environment by 2050, ESA is encouraging the implementation of a ‘circular economy’ in space that ensures long-term orbital sustainability through an ecosystem of in-orbit servicing, in-orbit assembly, in-orbit manufacturing, and eventually in-orbit recycling.

The implementation of a Space Circular Economy could play an important role in guaranteeing the sustainability of the orbits, maximising the usage of space assets (reduction of costs) and protecting the Earth’s environment by limiting the exploitation of raw materials on-ground and lowering the number of satellites launches and re-entries. [7]

Following this approach, ESA has been working with four companies since September to design pioneering mission concepts for the space circular economy. The four companies involved are Astroscale, Astroscale, Kinetik, and Thales Alenia Space.

Astroscale are working to develop an In-orbit Refurbishment and Upgrading Service. Their proposed mission will develop capabilities to refurbish and upgrade satellites, moving away from the current single-use culture in space. Astroscale will focus on both the technological and commercial feasibility of the project with inputs from In-Space Missions.

Growbotics are preparing the foundations of circular on-orbit economy through a commercial refurbishment mission of a spacecraft in GEO. Along with their industrial partners 3Keel and Thales Alenia Space UK, they will decide between competing mission concepts and build the business case for their selected mission, as well as identifying how design for refurbishment will change the design of satellites in the future.

Kinetik aim to revolutionize the manufacturing and assembly processes giant or complex structures in orbit, such as giant solar sails, solar farms, antennas or reflectors. By using robotic fabrication technologies, their mission aims to simplify and expedite the assembly of space infrastructure as well as reducing the time, labour, and risks associated with traditional assembly methods.

Thales Alenia Space's mission has the main objective of enabling an orbital recycling capability, both by identifying the materials and methods for on-orbit recycling as well as determining the impacts of a 'design for circularity' initiative in the broader space ecosystem. They will also propose a preliminary design for a Recycling Space Plant system with inputs from the PROMES laboratory of CNRS.

Based on the outcomes of these activities, ESA will proceed with a request for funding at the next Council Ministerial, to perform a more detailed investigation of several selected concepts, with Phase A/B1 studies and technology development activities.

4.5 Other

Other missions and studies are also in the pipeline of the ADRIOS programme, such as the ENCORE mission (GEO life extension mission) with ClearSpace Luxembourg and the ERASE active debris removal mission, with a collaboration between ESA and EUMETSAT, to investigate the removal service for METOP satellites. [6]

Within ESA but under different programmes, more initiatives are under study, such as the InSPoC (In-Space Proof of Concept) activities and the ELSA-M (Sunrise program) debris removal mission.

Other initiatives in the frame of IOS are also funded by EC (e.g. EROSS IOD) or outside Europe (e.g. ADRAS-J by JAXA) [5].

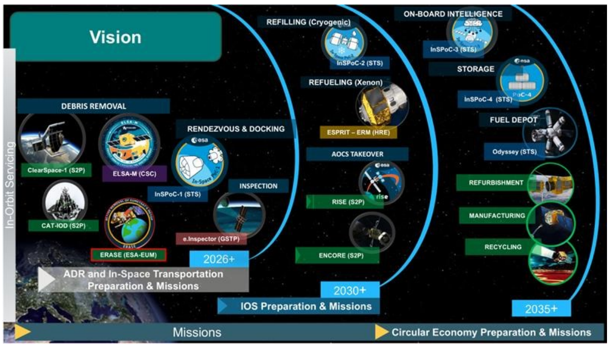

Figure 8: ESA IOS Vision

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