Design for Removal (D4R) technologies to ease the removal of future LEO platforms

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1 INTRODUCTION

The rising concern of space debris has driven guidelines to limit and reduce their creation in the future. One of the key requirements lies in the removal of space objects from protected regions within 25 years following the end of their operational life (EoL). Orbits below 2000km altitude are of particular concern, as they remain a favoured region for many types of space missions, it is getting increasingly easy to access them for a growing number of space-fairing nations, and they will soon welcome several mega-constellations.

Complying with the Space Debris Mitigation (SDM) guidelines is constraining due to the harsh environment to which the spacecraft is exposed for potentially more than a decade during its operational lifetime. Despite the high reliability required to comply with the guidelines, the risk that satellites fail before performing re-entry manoeuvres remains. Space-fairing nations must therefore also be prepared for this contingency, and adapt their platforms to be manually removed should these events happen.

Indeed, Active Debris Removal is not a straightforward operation, especially in cases where the targeted satellites to be removed are to some extent un-cooperative. For this purpose, ESA, through the Clean Space Office, has supervised a series of activities, "Design for Removal", aiming to ease the capture of its future LEO platforms in case of failure.

Supported by previous e.Inspector and e.Deorbit studies, as well as other numerous close proximity operation (CPO) related activities, ESA has identified key technologies which could efficiently help the navigation of a chaser meant to perform Active Debris Removal and On-Orbit Servicing in the future. Among the current on-going activities, ESA has undertaken the design, manufacture and tests of:

- infrared and phosphorescent markers to help the chaser's navigation in the visual and/or infrared spectrum;
- fully passive, robust, and highly reliable RF (radio-frequency) tags, supporting pose and range estimation;
- a combined system with a grasping mechanism on a chaser, coupled with a passive interface on future LEO platforms to be captured;
- and magnetorquers that can be autonomously, as well as manually from ground if needed, short-circuited at the end of life of the satellite, to efficiently and passively reduce tumbling rate and, thus, ease its removal by a chaser.

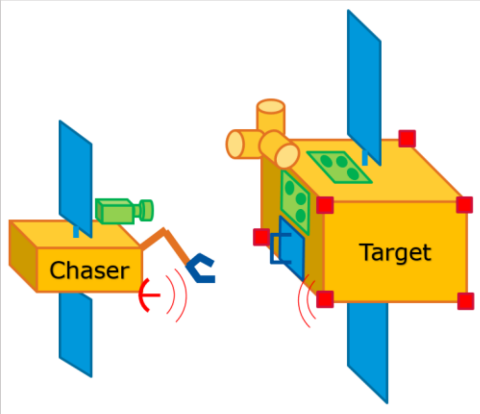
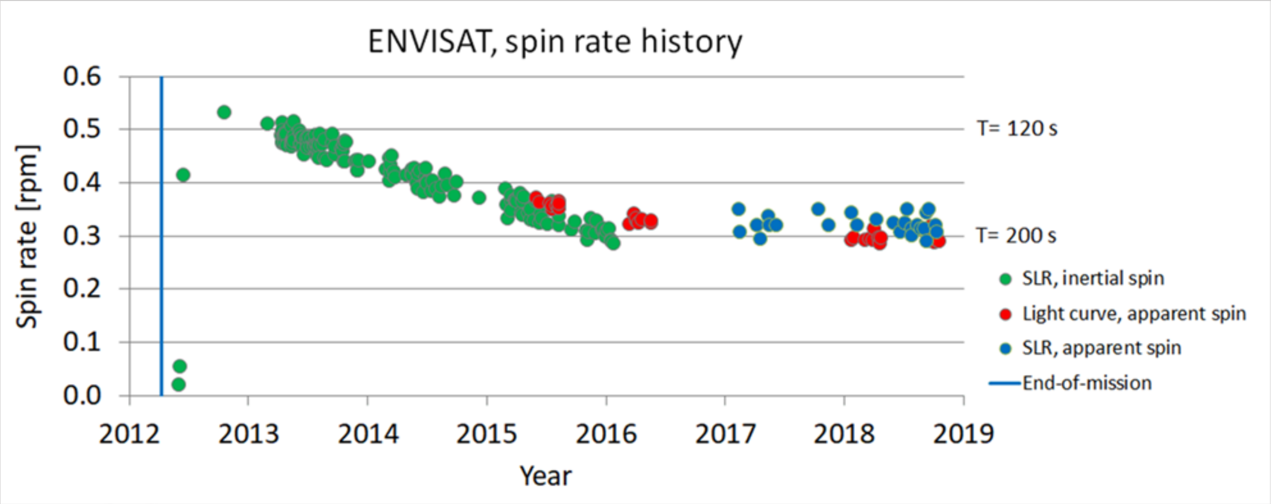


Fig. 1. Sketch representing current D4R technologies under development, with infrared/visual markers (green), RF tags (red), grasping mechanism (blue) and magnetorquers (yellow)

2 PASSIVE DETUMBLING AT EOL: SHORT-CIRCUIT MAGNETORQUER (PATENT PENDING EP 19182205)

When it comes to capturing a defunct satellite, its tumbling is a twofold problem:

- phenomena coming into play are complex and sometime unknown, resulting in a high prediction uncertainty;
- and catching a tumbling satellite is always harder to achieve.



Credits:
ESA Activity "Debris Attitude Motion Measurements and Modelling" (Project 40000112447).
Daniel Kucharski, Research Fellow, Space Environment Research Centre, Canberra, Australia
Visiting Researcher, the University of Texas, ICES, Computational Astronautics Group, Austin, USA

Fig. 2. Example of observations (light curves and Satellite Laser Ranging) of ENVISAT satellite tumbling behaviour since its EoL

Having a passive system on board future satellites that would slow their rotation down once they became defunct would greatly increase probability of success of future debris removal missions, or of any CPO (close proximity operations) in general.

One possibility studied by ESA was to adapt the design of magnetorquers, which are already being used during the nominal mission of the satellite, and add a short-circuit system autonomously triggered at the EoL.

Indeed, considering a rotating satellite within the influence of the Earth's magnetic field:

- a time-dependent magnetic field is created inside the magnetorquer;
- the magnetic flux variation produces an electromotive force at the magnetorquer terminals;
- if a load or short-circuit is applied to its terminals, an induced current is generated on the coil wire;
- when the magnetorquer has a magnetic moment (in this case produced by the induced current) a torque is generated.

The dissipation of rotational kinetic energy is slowly achieved through Joule effect within the magnetorquers' wires and contributes to slowing down the satellite. The work performed by ESA and its industrial partners has been to estimate the performance of such technology and adapt the design (number of coils, diameter, length, material, etc.) in order to improve the damping while limiting the impact on the platform.

Simulations were carried from 400km up to 2000km with Sentinel-like satellites, between 800kg and 4000kg. They were borne out by laboratory testing as well, as shown in Fig. 4.

First, results obtained confirmed what was expected, that is, altitude and inclination greatly influence the damping capacity of this technology. Indeed, high altitudes and low inclinations result in lower intensity of the Earth's magnetic field. Besides, the closer to equatorial orbit, the less magnetic flux variation, resulting in weaker induced current and slower detumbling. The influence of those parameters can be seen for Sentinel-5P in Table 1.

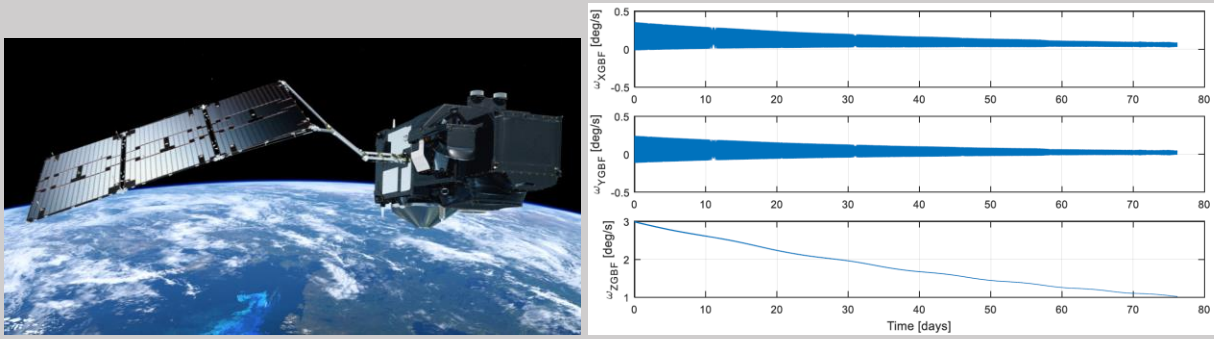


Fig. 3. Example of simulations carried for Sentinel3-like satellite, starting at 3°/s with a 12 A.m^2 magnetic dipole

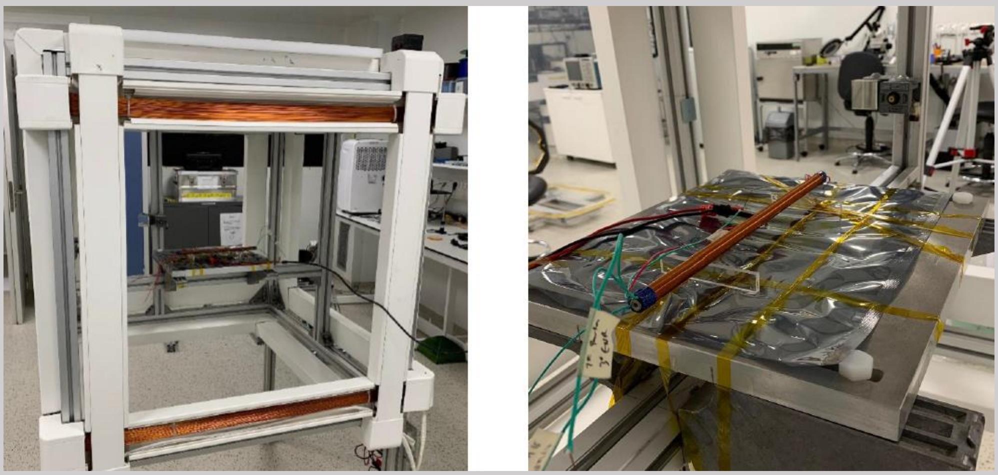


Fig. 4. Measurements of induced torque created by a short-circuit magnetorquer

Table 1. Months necessary to detumble from 3°/s down to 0.5°/s Sentinel-5P

Sentinel-5P	i = 0°	i = 90°
h = 400 km	7.2	1.7
h = 1600 km	11.7	4.7

Secondly, it backed up the potential of this technology for a fully passive, robust and little impact way to detumble a defunct satellite in a short time. For a typical Sentinel-3-like satellite (presented in Fig. 3.), detumbling from 3°/s down to 0.5°/s can be achieved within 5 months.

The triggering system has also been investigated to ensure a high reliability, avoiding involuntary triggering and keeping a little overall impact for the existing platforms.

This technology has limitations, as it is particularly efficient in LEO at high inclinations and the generated torque can only be perpendicular to the Earth's magnetic field. However, this still encompasses most of today's and future's Earth observation missions, which makes this system particularly relevant.

3 EASING RELATIVE NAVIGATION DURING CPO

Another critical part during CPO is the relative navigation with respect to the target. Indeed, a non-cooperative target is not able to provide by itself critical information for the navigation of the chaser such as relative distance and attitude. One can choose to visualize the target with an infrared or visual camera and match it with a pre-loaded

3D model of the satellite in order to estimate its distance and pose. LIDARs are also powerful sensors to get an accurate estimation of those parameters. However, they require heavy processing capacity and electrical supply.

A couple of technologies have been investigated to simplify CPOs, two of them are presented herein.

3.1 Infrared/visual markers

One approach chosen was to design markers to be visible in visual and infrared (IR) spectrum, and match their visualization with distance and orientation. Compared to model-matching an entire satellite, this technic requires less processing capacity and does not rely on knowing every detail of the target's design (making this method robust to break-up of the satellite or uncertainty on the shape of the target).

In order to make this technology usable in any illumination condition, it is designed to be seen properly in infrared (improving contrast by studying the best combination for cover and reflector materials) and visual (phosphorescent paints have been investigated to glow sufficiently during eclipse).

Hereunder in Fig. 5. are shown the 2 models used for experiments, separately for IR and visual spectrum visualization. Tests have been performed at ESA (Fig. 6.) and industry premises, simulating an approach of a chaser towards the target from 100m down to 2m.

Fig. 5. Marker made out of MLI (Multi-Layer Insulation) to be visualized in IR (left) and phosphorescent paint with marker's pattern (right) to be visualized in visual spectrum during eclipse (both 400x400mm markers)

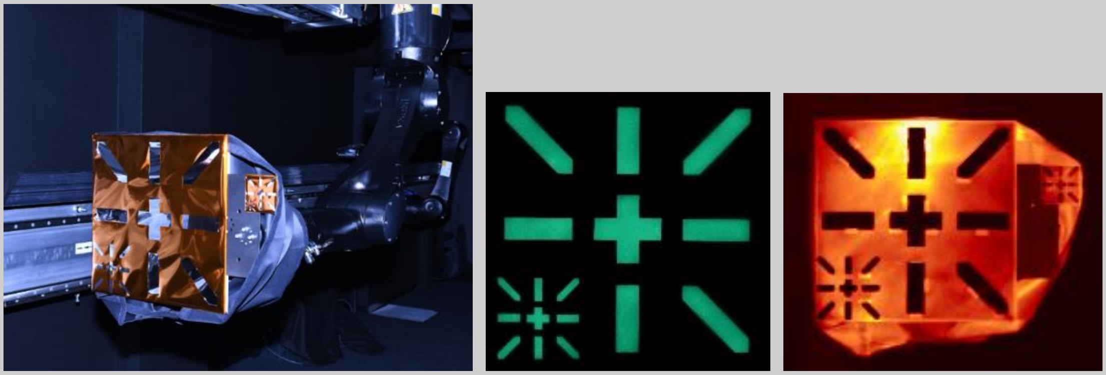


Fig. 6. Marker embedded on robotic arm, simulating the approach of the chaser and the tumbling of the target (left), example of pictures taken with phosphorescent paint during simulated eclipse (middle) and IR marker (right)

To this date, the performances of such system in order to estimate relative distance and pose estimation still need to be estimated. Among other results, the afterglow of the phosphorescent paint has been analysed, showing a promising application at different distances and orientations, as shown in Fig. 7. and Table 2.

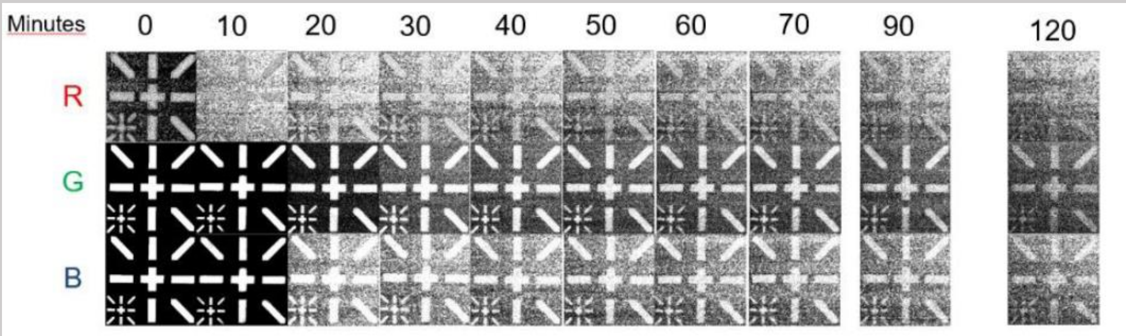
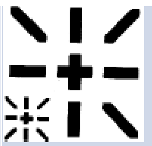
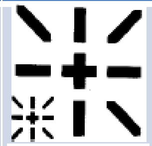
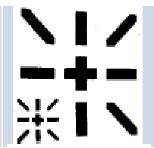
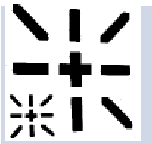
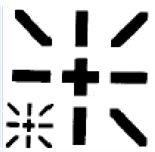
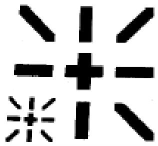
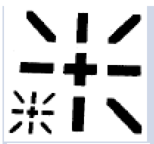
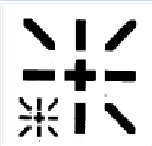
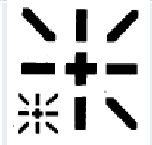
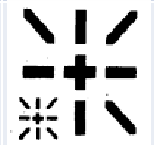
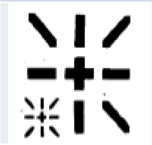
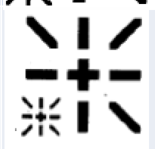
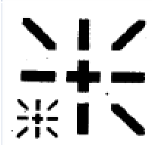
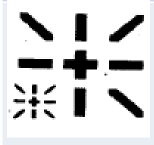
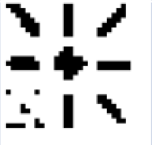
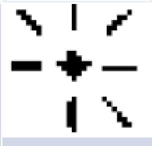
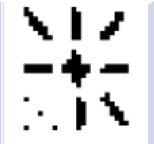
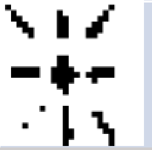
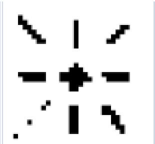
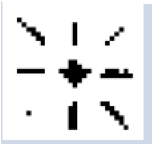
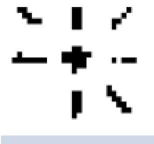


Fig. 7. Phosphorescent paint afterglow binary pictures in RGB (red-green-blue) channels, after 1h Sun exposure, with respect to time

Table 2. Binary images of the phosphorescent marker from various distances and angles

	X-0	X-15	X-30	X-45	Y-15	Y-30	Y-45
2m							
10m							
100m							

These preliminary tests showed promising results, enabling the distinction of the marker's pattern at least 2h after a 1h Sun exposure. The high resolution available for visual cameras allows a clear distinction of the pattern, even at far ranges (Table 2.).

Using visual spectrum cameras has the advantage of already having extensive flight heritage, higher resolution and a simpler system. The phosphorescent paint partially solves the issue of visualizing the marker during eclipses. However, the paint is still dependent on being illuminated at some point by the Sun and, most importantly, as for today it still needs to go through space-qualification tests.

IR visualisation is robust to illumination conditions, it uses MLIs which are space qualified and whose behaviour is well-known after long exposure to space environment. However, low-resolution, higher-complexity and little space heritage of IR cameras must also be taken into account.

ESA's way forward now includes space-qualification and aging tests for the phosphorescent paint selected, as well as an iteration on the marker's size and design, in order to take a maximum advantage of the technology's potential while keeping to a minimum its impact on the future LEO platforms.

3.2 Passive RF tags

ESA has also investigated a way to estimate relative distance and pose with respect to the chaser through RF tags. An antenna on board the chaser sends a signal to tags placed in different locations on the target, which responds with a modulated signal, analysed by the chaser's antennas and interpreting them to deduct relative pose and distance.

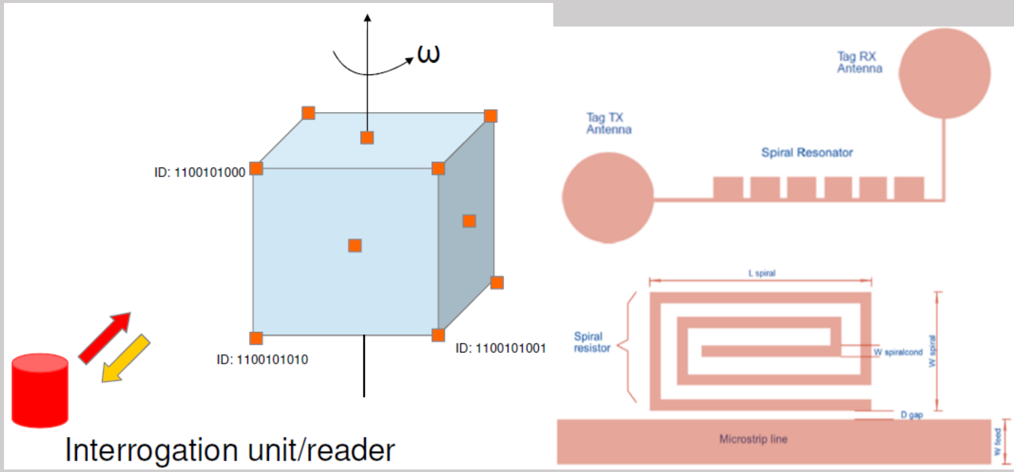


Fig. 8. Sketch representing a possible location for the tags on target (left), an example of design for the tags (top right) and resonator (bottom right)

The tags selected are chipless which make them robust, simple, reliable, cheap, fully passive, and with little impact for the platform.

From the chaser's point of view, a FMCW (Frequency-Modulated Continuous-Wave) radar is used at far ranges to measure distance and relative velocity. At closer range (~ 20m), it "interrogates" the tags and, from the signal received, deducts pose with 2 methods:

- By estimating the angle and distance of the tags through several Tx and Rx antennas (Fig. 9.);
- or mapping the tags' locations from the tags antenna directivity (Fig. 10.).

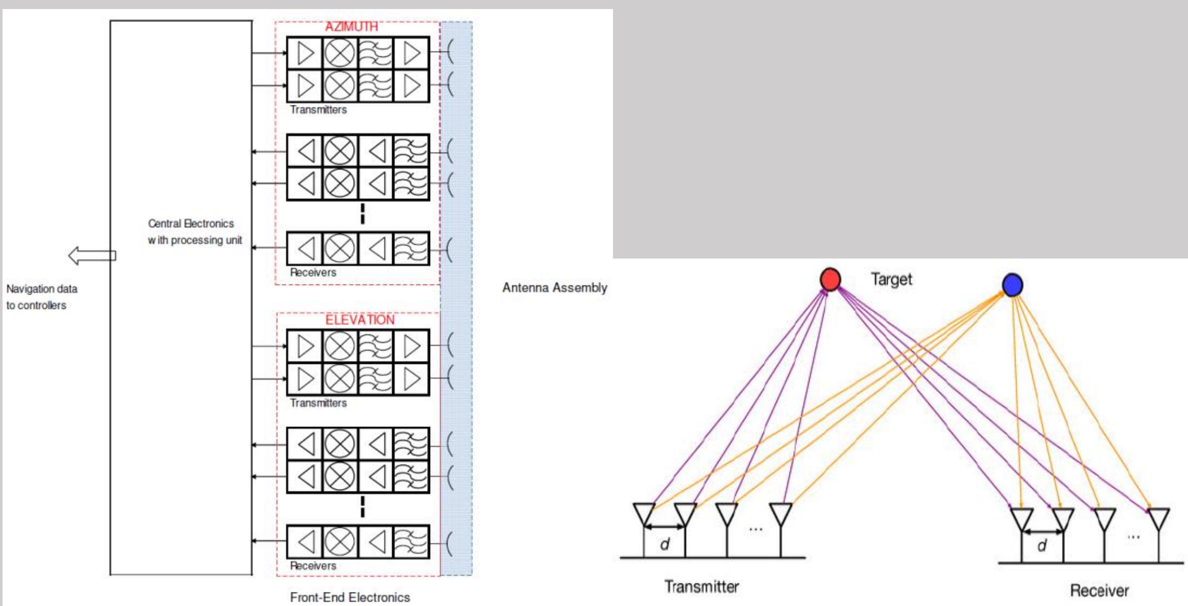


Fig. 9. Two sets of transmitters and receivers (one set for azimuth and one for elevation estimation)

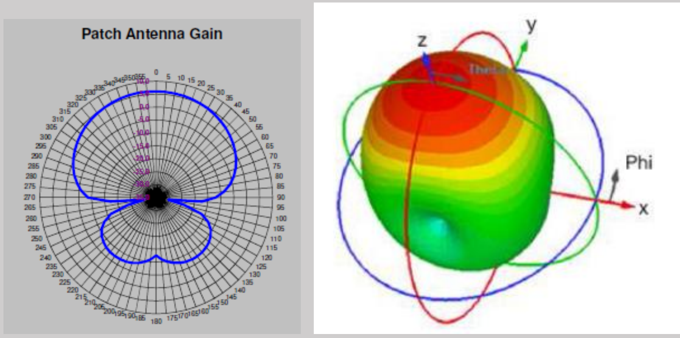


Fig. 10. Typical tag's radiation pattern

The preliminary design of the tags and antennas showed promising results, presented Table 3, which could be improved in the further stages for the development of this technology. Still, because of its limitations, this system could be used as a redundant system for pose estimation. Indeed, it has the great advantages of being simple and have limited impact for both the chaser and the platform, as summarised in Table 4.

Table 3. System performance summary

	Operating Mode					
	Rad_body	**Rad_tag**	**Map**	**Rad_tag + Map**	**Requirement**	**Remarks**
Accuracy performance						
Long range						
LoS	5 deg	-	-		6 deg (1)	Range 200 m ÷ 1500 m
Range	2%	-	-		10%	Range 200 m ÷ 1500 m
Short Range						
LoS	5 deg	5 deg (7)	-		3 deg (1)	Range 20 m ÷ 200 m
Range	2%	2%	-		5%	Range 20 m ÷ 200 m
Range	10 cm	10 cm			5%	Range < 20 m
Target orientation/Pose	-	7 deg (2) (3)	4 deg (4)	4 deg (5)	5 deg	Range < 20 m Applicable to each one of the two angles (azimuth and elevation)
Angle variation				1.8 deg/s (6) 0.18 deg/s	0.1 deg/s	Range < 20 m, 2 deg/s rotation speed 1s measurement time 10s measurement time

Table 4. Impact for the chaser (left) and for the target (right)

Parameter	**Requirement value**	**Unit**	**Remarks**
Antenna + Front-End			
Size (L x W x H)	300 x 300 x 20	mm^3	
Mass	1800	g	
Processing unit			Without DCDC converter
Size (L x W x H)	150 x 150 x 30	mm^3	
Mass	800	g	
Harness			
Mass	100	g	
Full System			
Mass	2700	g	
Power consumption	< 40	W	Total value
Reliability	TBD	FIT	Not critical, due to short lifetime of the mission (chaser)

Parameter	**Requirement value**	**Unit**	**Remarks**
Number of tags	14		
Number of bits for the tags	4	bit	
Frequency coding	TBD	GHz	Bandwidth
Size (L x W x H)	50 x 50 x 10	mm^3	
Mass	50	g	
Power consumption	No consumption		Passive component
Frequency of operation	24 GHz		
Accommodation constraints	TBD		
Lifetime	20	years	
Radiation	1M	Rad (Si)	
Reliability	TBD	FIT	Expected very high

4 DEBRIS CAPTURE

Different technologies are studied to capture debris. At ESA, a focus has been set on harpoons, nets and robotic arms (Fig. 11).

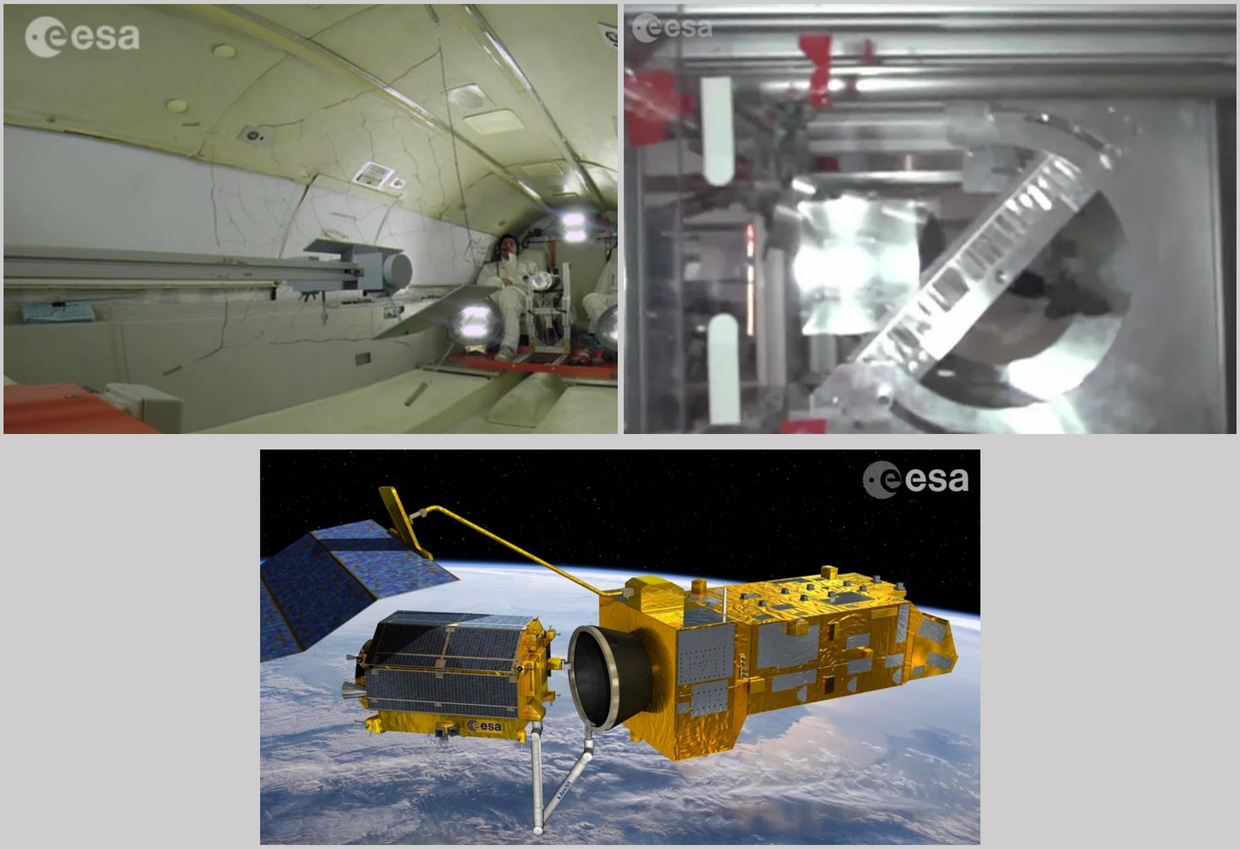


Fig. 11. Net (top left) and harpoon (top right) experiments to capture space debris, and representation of e.Deorbit mission aiming to capture Envisat satellite

The latter might be the most challenging technically, as it requires the chaser to be close enough to the target, to synchronise its motion, to capture it safely, and perform a deorbiting manoeuvre. Evidently, this is not a straightforward operation and could endanger both chaser and target satellites. With this in mind, ESA has developed a special set of technologies aiming to ease the capture of future defunct satellites in the frame of D4R activities, which comprise:

- A combination of an active interface (AIF) on the chaser and a passive interface (PIF) on the target;
- And a 3D-marker placed on the target, in order to improve relative navigation in close range.

4.1 Mechanical interfaces

One challenge for the capture is being able to find an area on the target which can support the capture load while being accessible to the chaser. To this extend, one approach is to “prepare” the target by adding a stiff passive interface (PIF) to be captured by the chaser’s gripper (AIF), in a location where one can ensure the chaser will perform safely the capture. Combinations of AIF and PIF studied by ESA and its industrial partners is presented Fig. 12. and Fig.13.

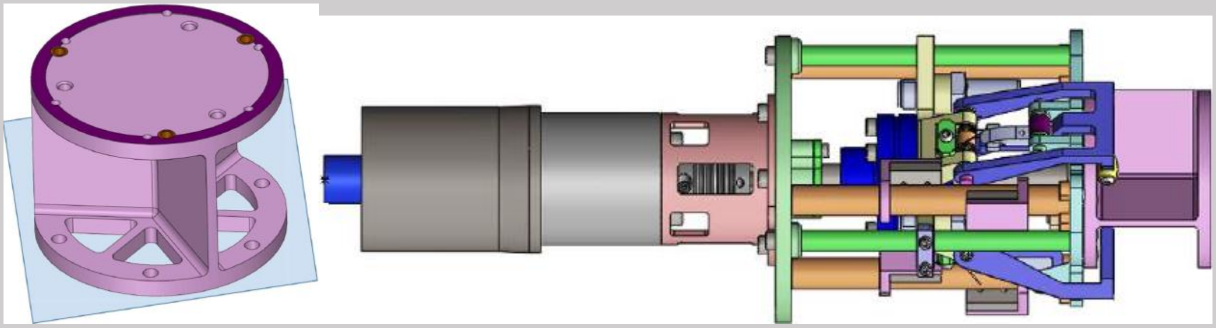


Fig. 12. One example of mechanical interfaces combination studied (credits: ESA/GMV/AVS), with PIF (left) and AIF having captured PIF (right)

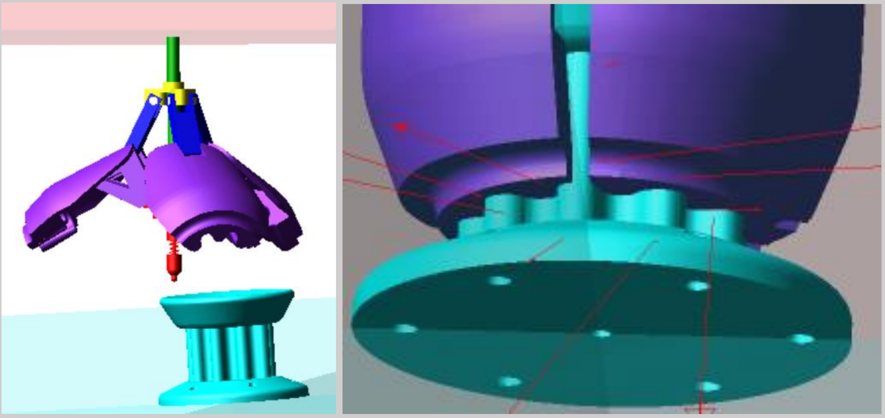


Fig. 12. Another example of mechanical interfaces combination studied (credits: ESA/NTUA/TAS-F), before capture (left) and in stack configuration (right)

4.2 Navigation aids

The successful capture of the target relies on an accurate relative navigation. It drives the sizing of the components and impacts both platforms. In order to improve the relative navigation on close range (< 5m), an additional 3D navigation aid will also be placed on future LEO satellites. One type of marker is presented Fig. 13.

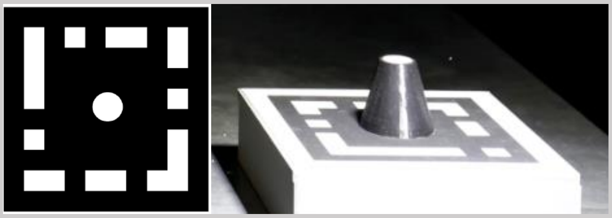


Fig. 14. Example of 3D navigation aids developed (credits: ESA/GMV/AVS), viewed from the top (left) and from the side during the laboratory tests (right)

4.3 Laboratory tests

Following the design, simulations, and manufacturing, open and closed-loop tests have been performed to evaluate the performance of the system developed. The test bench can be seen Fig. 13. The chosen configuration showed a 100% success rate in capturing the PIF with the AIF.

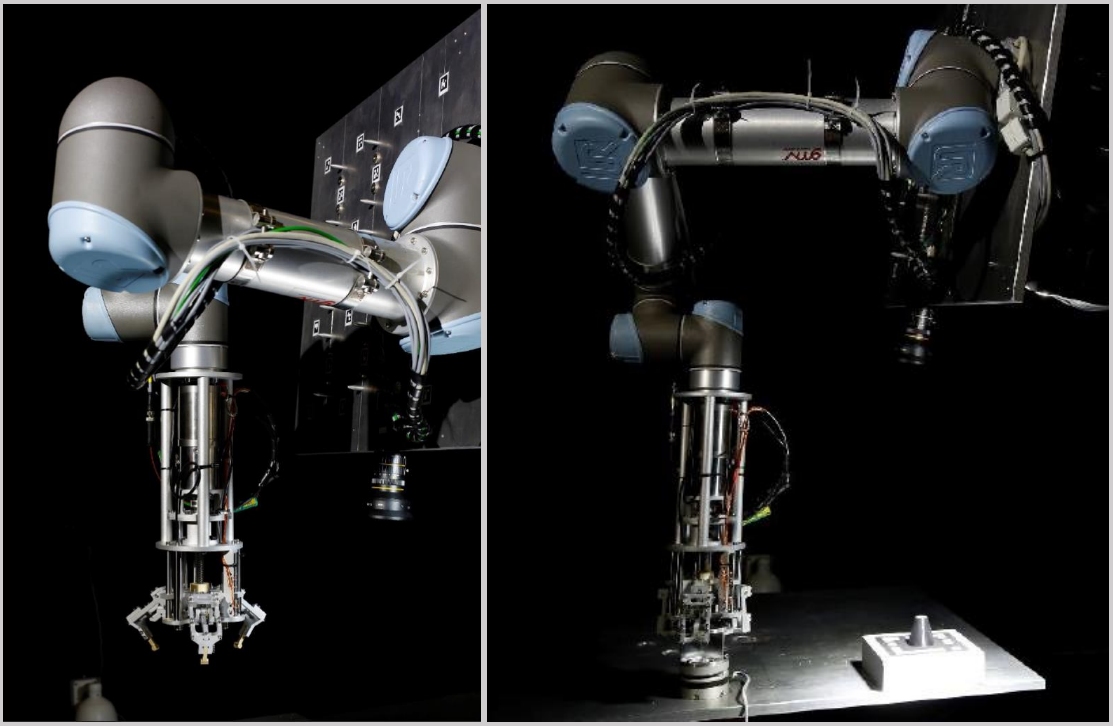


Fig. 15. Successful capture during closed-loop tests

With the success of these activities, ESA is now maturing these technologies, planning to embed them on board its future LEO satellites.

5 CONCLUSION

The Design for Removal technologies presented herein have shown great advantages for CPOs. Some technologies like the RF tags are in their early stages, while others like short-circuited magnetorquers are likely to be mature enough in a short period of time in order to be included in the design of the next generation of LEO satellites.

Developing technologies to ease CPOs is crucial and will represent a great asset in a near future. Not only will it help active debris removal missions, but it also paves the way to the so-called "servicing". Indeed, being able to interact with malfunctioning satellites (repairing, refuelling, re-orbiting, etc.) promotes sustainability in space, while enabling a whole new market for the space industry.

6 REFERENCES

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