IAC-18,A6,5,x43644

ELSA-D: AN IN-ORBIT END-OF-LIFE DEMONSTRATION MISSION

Chris Blackerby[1], Akira Okamoto, Kohei Fujimoto, Nobu Okada

ASTROSCALE Japan Inc.

Jason L. Forshaw[2,*], John Auburn

ASTROSCALE UK Ltd.

ABSTRACT

Emerging plans for low Earth orbit (LEO)-based constellations featuring large numbers of satellites mean in the near future, space populations could significantly increase. Systematic spacecraft end-of-life (EOL) management strategies assuring post-mission disposal (PMD) are required to maintain utility of all LEO assets.

This paper will provide an overview of the ELSA-d EOL mission, Astroscale's first semi-cooperative spacecraft retrieval technology and capability demonstration mission, due for launch in 2020. ELSA-d consists of two spacecraft – a chaser and a target. The chaser is equipped with proximity rendezvous technologies and a magnetic capture mechanism, whereas the target has a docking plate (DP) which enables it to be captured.

Each phase of the main concept of operations (CONOPS) will be discussed and how these would align with future servicing missions. Demonstrations include: target search, target inspection, target rendezvous, both non-tumbling and tumbling capture. The preliminary satellite design will also be discussed with an outline of the core rendezvous, short and long-range navigation, and capture technologies behind the mission.

Keywords: active debris removal, end-of-life, in-orbit servicing, proximity rendezvous, tumbling capture, magnetic capture

I. INTRODUCTION

ELSA-D, which stands for End of Life Services by Astroscale (-demonstration), is an in-orbit demonstration (IOD) for key end-of-life technology and capabilities of future debris removal missions. In Astroscale (AS), end-of-life (EOL) and active debris removal (ADR) have the following distinction: EOL is concerned with removal of future entities that are launched with a docking plate (DP) for semi-cooperative removal, whilst ADR is concerned with removal of existing entities in space that do not have a DP and are fully non-cooperative. ELSA-d, due for launch in early 2020, consists of two spacecraft, a chaser (∼160 kg) and a target (∼20 kg), launched stacked together. The chaser is equipped with proximity rendezvous technologies and a magnetic capture mechanism, whereas the target has a DP which enables it to be captured. With the chaser repeatedly releasing and capturing the target, a series of demonstrations can be undertaken including: target search, target inspection, target rendezvous, and both non-tumbling and tumbling capture. ELSA-d is operated from the UK at the National In-orbit Servicing Control Centre Facility, developed by AS as a key part of the ground segment.

I.1. Literature

The field of debris removal and satellite servicing is rapidly growing with a number of comprehensive studies or IOD missions, both past and future, to test core technologies.

Regarding government-funded projects, ESA has produced a range of CleanSpace roadmaps, two of which focus on (a) space debris mitigation and (b) technologies for space debris remediation. A main part of these roadmaps is e.Deorbit, a programme spanning a host of phase studies examining removing a large ESA-owned object from space [1, 2]. This initiative started with ESA's service orientated ADR (SOADR) Phase 0 study involving the analysis of a mission that could remove very heavy debris from orbit, examining both the technical challenges and the business aspects of multiple ADR missions [3, 4]. Progressing on, ESA has also now completed Phase A (feasibility) and Phase B1 (PDR) studies [5, 6], with several more mature designs available. The French space agency, CNES, is also involved in debris removal and has funded studies such as OTV which traded-off different ADR mission scenarios [7]. DLR's (German space agency) DEOS (Deutsche Orbital Servicing Mission) went as far in design as PDR level and aimed to rendezvous with a non-cooperative and tumbling spacecraft

*Corresponding Author. Tel.: +44 (0)1235 39 5359
Email address: j.forshaw@astroscale.com
URL: www.astroscale.com
[1]Chief Operating Officer (COO)
[2]European R&D Manager

by means of a robotic manipulator system accommodated on a servicing satellite [8].

Although recently there have been advances in relative space navigation, the complex application of fully uncooperative rendezvous and capture for tumbling debris has not yet been attempted. The Autonomous Transfer Vehicle (ATV) was one of the first times a spacecraft initiated and commenced a docking manoeuvre in space in a fully autonomous mode [9]. The Engineering Test Satellite VII 'KIKU-7' (ETS-VII) by JAXA in 1997 was one of the first missions to demonstrate robotic rendezvous using chaser and target satellites [10]. The AoLong-1 (ADRV) 'Roaming Dragon' satellite was also recently launched by CNSA (China National Space Administration) in 2016 in order to test target capture with a robotic arm. Most recently, JAXA's HTV-6 vehicle, which launched in early 2017, unsuccessfully attempted to deploy an electrodynamic tether under the Kounotori Integrated Tether Experiment (KITE) [11].

One of the core missions to test debris removal technologies is RemoveDebris, launched in 2018, that aims to test a net, harpoon, vision-based navigation and a dragsail in space - useful payload technologies for future missions [12, 13]. Flight results are expected later in 2018.

Upcoming smaller platforms to tackle debris removal include CleanSpace One by EPFL, which aims to use microsatellites with a grabber to demonstrate capture [14]. Airbus DS is working on a vehicle known as 'The Cycler' for mega-constellation applications [15]. With regards to larger platforms, as mentioned previously, ESA's e.Deorbit (or surrounding CleanSpace activities) will likely result in a mission to remove a larger ESA-owned object. Some future missions are proposed to perform in-flight repair or refueling, such as SSL's RSGS mission for GEO and Restore-L for LEO, both targeting the 2020 to 2021 timeframe. ESS is also targeting GEO servicing with their 'space drone' docking system for demonstration in 2020.

It is believed that the ELSA-d mission will be an important step towards fully operational EOL and ADR missions by maturing technologies and capabilities necessary for future services. In particular, the ELSA-d mission will not just space-prove future payload technologies, but will also go through almost the full series of CONOPS expected in a full servicing mission with a demonstration target. The ELSA-d mission also demonstrates capabilities including: integrated ground segment to space segment interaction, rendezvous and docking in a safe and autonomous manner, and demonstration of capture of a tumbling target. For former ELSA-d information see [16, 17].

I.2. Paper Structure

Section II focuses on an overview of the whole mission. Section III examines the mission CONOPS. Section IV examines the key innovations including technologies and capabilties. Section V examines the ground segment. Finally, Section VI concludes the paper and outlines key contributions to the field.

II. MISSION OVERVIEW

The ELSA-d mission is an in-orbit demonstration that aims to test several capabilities and technologies needed for future services. The chaser and target can be seen in Figure 1, showing renditions for both docked and undocked configurations. For the ELSA-d mission, the target, for convenience and mass-minimisation, is smaller relative to the chaser than a future EOL or ADR mission. The target is also commandable, ensuring demonstrations can be tested in a simplified manner earlier in the mission. For example, before tumbling capture is attempted, the easier case of non-tumbling capture is attempted which requires the target to hold a set attitude. Because the target is launched with the chaser, the CONOPS can be designed such that the complexity and risk increments gradually. This compares to a full service where the non-trivial task of finding the target would be among the first mission actions.

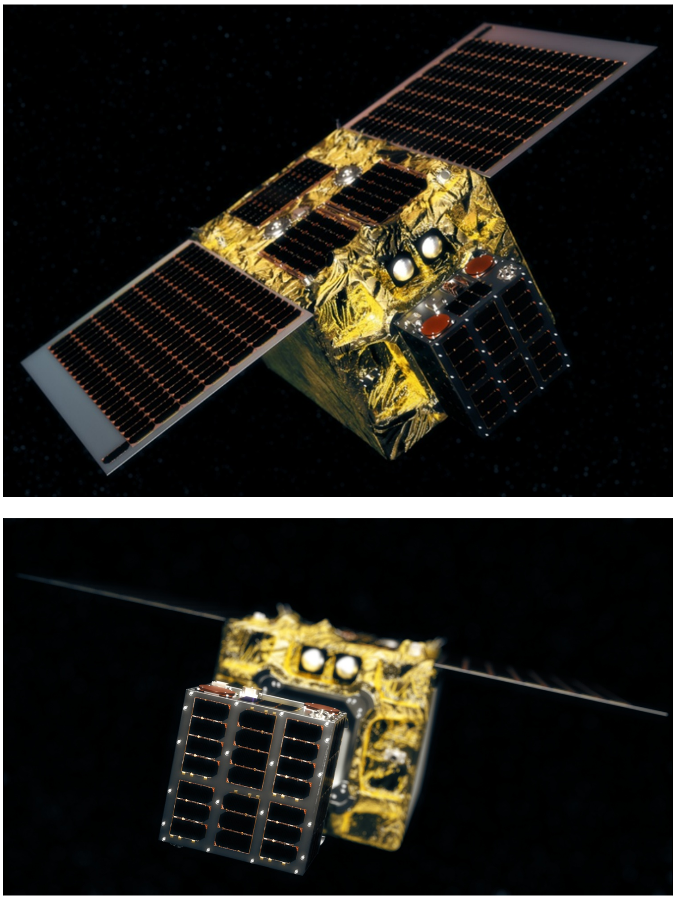

Fig. 1: **ELSA-d: Chaser and Target.** Top: chaser with attached target. Bottom: target at front (detached) with chaser in the background.

The key features of the mission are summarised in Table 1. The core constituents of the mission include a rendezvous (RDV) and docking suite and a magnetic capture system. Other elements include classical bus elements, such as power, propulsion, communications and processing.

Table 1: **ELSA-d Mission Features**. [†]sensor handling unit [‡]target separation mechanism [§]target activation unit

Chaser	Structure	~ 0.6×1.0 *m*, ~160 *kg*
	GNC (command)	GNC OBC, GNC SHU[†]
	GNC (sensing)	star trackers, gyros, magnetometers, sun-sensors, accelerometers, GPS
	GNC (actuation)	reaction wheels (pyramid), magneto-torquers
	GNC (RDV)	night cameras, day cameras, laser ranging device, radiometric ranging device, illuminator
	Capture	magnetic capture system
	Comms	S-band, X-band
	Power	deployable solar array, PCDU system, flight battery
	Propulsion	green propellant chemical propulsion system, 8 thrusters
	C&DH	BUS OBCs, CAN bridge, spacewire router
	Other	retro-reflector, TSM[‡], TAU[§]
Target	Satellite	~20 *kg* satellite containing OBC, EPS, S-band COM, AOCS
	Docking plate	DP mounted on target
	Other	retro-reflector, witness camera, illuminator

II.1. Key Commercial and Mission Factors

There were a range of key design factors for the ELSA-d mission. Being in an immature commercial and legal market, ELSA-d is a market leader in this domain. AS attempts to engage in discussions with multiple parties to develop doctrine, standards, and regulation critical to active debris removal. For more information on Astroscale's efforts in regulation and policy see [18].

- AS is in discussions with the UK Space Agency (the mission licensing agency) to ensure a licensable chaser design.
- AS is in preliminary discussions with UK insurance providers to understand future insurance standards in in-orbit servicing (IOS).
- AS is part of various standardisation and policy-development committees to ensure lessons learned are fed into future doctrine and that ELSA-d and future missions are in alignment with the future direction of policy.
- AS interfaces with legal structures to ensure future design for legal compliance, including entities such as IADC and UNCOPUS.

A key design factor in ELSA-d is mission safety. These aspects encompass all areas across the mission development, including:

- Safety evacuations and passively safe trajectories (passive / active aborts, predefined evacuation point, protected safety ellipse insertion)
- Collision avoidance manoeuvres (CAMs)
- Ground segment and operator oversight (including manual experimental abort)
- Protected critical mission functions (including reversion to higher levels of hardware and software authority)
- Safety critical computing (including multi-level FDIR, mostly fail-safe and some fail-operational)
- Architectural redundancy (some units are semi-hot redundant, some cold redundant)
- High-fidelity ground-based simulation (full on-ground simulation of all operational sequences before execution)

III. CONOPS

The mission CONOPS are shown in Figure 2 and are divided into 7 phases as follows. Between demonstration phases, when the chaser and target are docked, they can enter a routine phase which is power and thermal safe. The phases are designed to generally increase in complexity ensuring less risky demonstrations are attempted first.

Phase 1 to 2: Launch and Commissioning

The chaser and target are launched together into the operational orbit of roughly 550 *km*. The chaser undergoes commissioning, testing interfaces with the ground segment, ensuring subsystems (where possible) are calibrated, and resulting in a system ready to start the demonstrations. The target is activated using the target activation unit (TAU) and undergoes the majority of its commissioning prior to separation.

Phase 3: Capture without Tumbling

A target separation mechanism (TSM) holds the target and chaser together during launch and phase 3 is the first time the target is separated; once separated, the magnetic capture system is used to repeatedly capture and release the target, so the TSM is no longer in use. The majority of the target commissioning has already been undertaken, so any remaining commissioning is performed. The chaser has the ability to position itself at set distances behind the target, which are defined as specific holding points (these include for example Point A and Point B, 10 *m* and 5 *m* behind the target, respectively). At Points A and B, the chaser performs a navigation check-out and calibration using its rendezvous sensors. This is the first time these sensors can be tested in space, since they can't be tested whilst the target is docked. Finally, the target is commanded to hold a set attitude

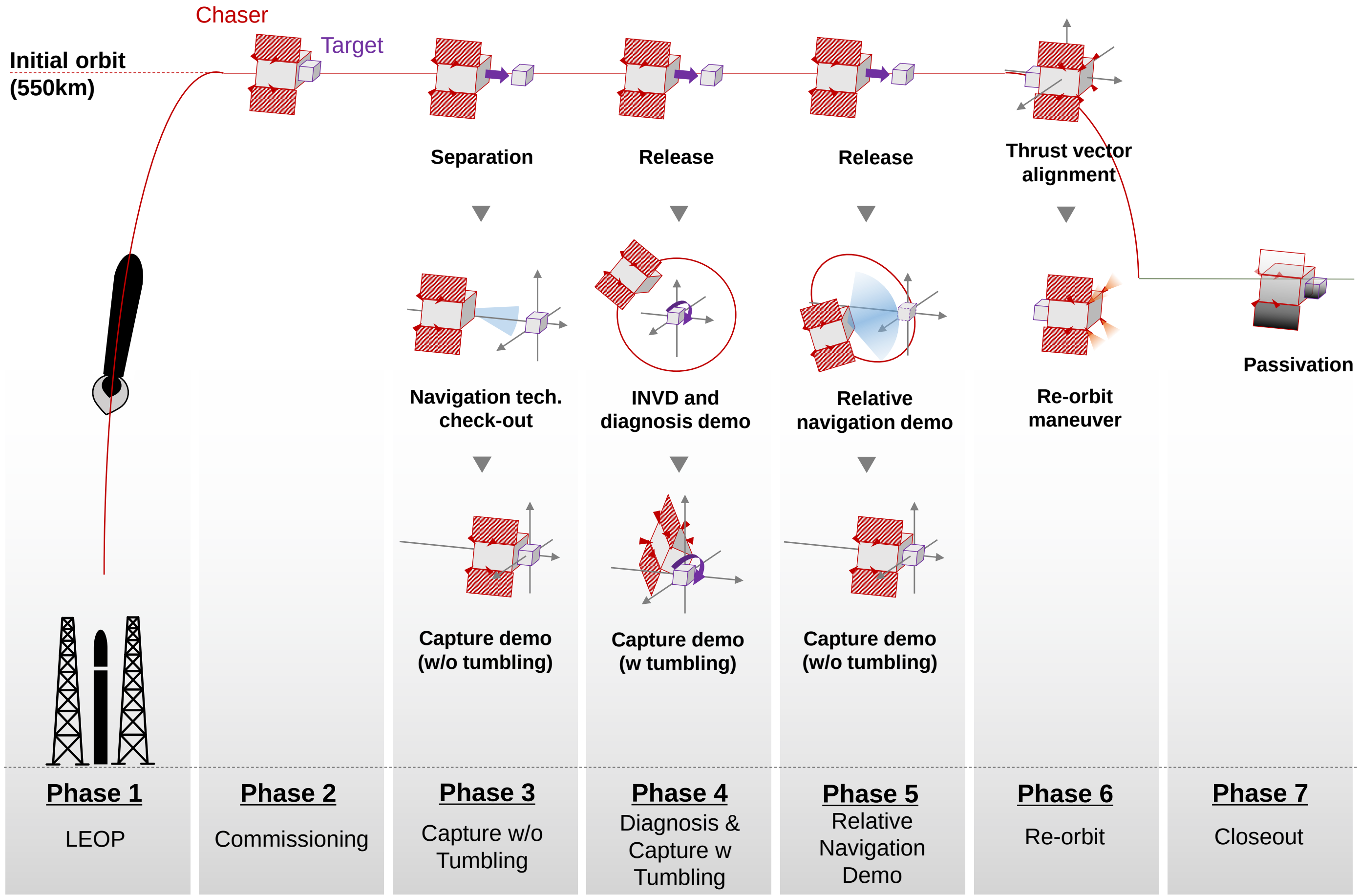

Fig. 2: **ELSA-d CONOPS.** This figure shows the mission CONOPS through 7 mission phases, progressing from launch and commissioning (phase 1 to 2), initial non-tumbling capture (phase 3), tumbling capture (phase 4), target search demonstration (phase 5), to final re-orbiting and passivation (phase 6 to 7).

and the chaser goes in for capture utilising the docking plate on the target for guidance. There are several sub-phases of the final capture including target acquisition and tracking, and velocity, position and roll synchronisation, but these are easier in the non-tumbling case than the tumbling phase 4 case.

Phase 4: Capture with Tumbling

This phase is the more dynamically complex version of phase 3. The phase also contains two sub-demonstrations - INVD and Diagnosis. INVD (inertial navigation validation demostration) tests the full rendezvous sensor suite. Diagnosis is a fly-around performed to visually inspect the target. Diagnosis simulates a full service, where images of the target are taken and downloaded to the ground for operator inspection before capture. After these two demonstrations, tumbling capture is performed. The target is commanded to follow a natural motion tumbling attitude profile. The chaser performs the sub-phases of final capture listed in phase 3. Part of the capture involves taking images of the tumbling target which are downloaded to ground and post-processed to extract target attitude. There, the FDS (flight dynamics system) in the ground segment calculates a trajectory to move and orient the chaser with the target such that the chaser is always facing the target DP. The trajectory is uploaded and executed to align the chaser and target, whereby settling is then used for final alignment before capture.

Phase 5: Relative Navigation Demonstration

This phase is a critical one in testing target search capabilities. The chaser separates and thrusts away from the target until its sensors lose the target at long range. The chaser moves into a safety ellipse, simulating first approach to an uncooperative target as in a full service mission. In a full mission, a combination of sensor data, including GPS and ground tracking, is used for the FDS to calculate a trajectory to insert the chaser on to a rendezvous trajectory with the target. In the ELSA-d mission, the FDS is still used but the demonstration is performed off-line. The chaser comes within a medium range of the target, eventually performing an absolute to relative navigation handover to transfer to relative navigation technologies and to make the final approach and non-tumbling capture.

Phase 6 to 7: Re-orbit and Passivation

In the final phase, the chaser performs a re-orbit manoeuvre to reduce the target altitude. This simulates the final de-orbit in a full mission. At a lower altitude, the craft is passivated. Both chaser and target proceed to an uncontrolled de-orbit burning up on re-entry. The mission at all times maintains 25 year debris mitigation compliance, as the initial demonstration altitude is only 550 *km*. The full duration of the mission is expected to last up to 6 months, including non-demonstration (routine) phase periods.

Additional Demonstrations

In phase 3, as part of a safety test, a manual safety abort can be performed by the operator prior to capture to test an active abort scenario, which the chaser will perform if any fault conditions are identified during final rendezvous stages.

Subject to fuel availability, entire phases can be repeated. For example, phase 3 could be attempted twice to develop greater experience.

The mission CONOPS is designed in a fluid manner that give operators the final decision in spacecraft operations, and making up-to-date decisions about undertaking demonstrations based on satellite health and performance.

IV. CAPABILITIES AND TECHNOLOGIES

IV.1. Overview of Key Innovations

The following are key innovative capabilities in the ELSA-d mission.

1. **End-to-end rendezvous solution including far-range and short-range approaches**
   Rendezvous and docking in space is among the most complicated technical challenges. To date, only manual-docking or some limited autonomous docking (with many constraints) has ever been attempted in space (e.g. ATV, Orbital Express, ETS-7, Dragon). ELSA-d utilises an integrated suite of technology for rendezvous and capture including both hardware (processing, sensing and control) and software (guidance and navigation algorithms, control laws), enabling these complicated scenarios to be undertaken in space efficiently and safely.

2. **Search for targets and approach with absolute to relative navigation hand-over**
   Searching for and discovering an object in space is a complex technical challenge. ELSA-d's search is performed by using absolute navigation (ground-based radar or optical methodologies plus the chaser's GPS system) to get within a knowledge boundary. On first acquisition of the target, relative navigation is switched to in an absolute to relative navigation handover phase. Final approach is achieved using relative navigation.

3. **Fly-around inspections of target with operator assessment**
   A fly-around (diagnosis) stage enables an operator to visually examine the chaser before final approach. This may be useful if communications with the target have been lost.

4. **Docking plate to enable semi-cooperative removal**
   The DP is a core part of ELSA-d's rendezvous suite, providing a point of contact on the target for a magnetic capture system, and also provides an optically controlled surface for GNC. The DP turns the capture into a semi-cooperative case, compared to the more complicated uncooperative case.

5. **Magnetic capture of non-tumbling and tumbling targets**
   AS has developed an innovative magnetic capture technology for use in capture. The technology improves on the shortcomings of both tethered systems (tether dynamic issues, complexity / jamming of a reeling mechanism, difficulty in controlling target attitude) and robotic systems (degree of complexity, cost).

6. **Re-orbit, de-orbit and passivation capabilities**
   ELSA-d uses chemical propulsion to provide both re-orbiting and de-orbiting capability. A re-orbit to a lower altitude simulates immediate evacuation from the operating altitude, which is needed in future missions to quickly take a satellite out of harms way from other satellites in that orbit.

7. **Mission designed with safety evacuations and passively safe trajectories in mind**
   Mission safety is of paramount importance to ELSA-d to ensure there is no further debris generation in space. Safety is also a large part of having a licensable mission design. The mission's range of safety features includes (but is not limited to): collision avoidance manoeuvres (passive and active aborts), ability to move to an evacuation point, ability to enter a protected safety ellipse, and ground segment oversight during critical phases.

8. **Ground segment designed specifically for in-orbit servicing**
   Unlike a conventional ground segment, ELSA-d's ground segment is specifically designed with in-orbit servicing in mind. Features include the ability to chain and align ground station passes to service longer demonstration scenarios while providing operator-in-the-loop safety.

IV.2. Magnetic Capture System

ELSA-d's capture system enables magnetic capture of tumbling objects using a specialised capture mechanism. The system has a set of small concentric permanent magnets which are extended and retracted using a mechanism to allow connection with the docking plate on the target. Once it attaches to the docking plate, the capture system can also release when desired using an internal mechanism that slowly pushes the docking plate away. This enables repeated docking and undocking cycles.

IV.3. Docking Plate

The ELSA-d grappling interface is designed to be mounted on a target satellite and consists of a flat, disc-shaped docking plate

(DP) on top of a supporting stand-off structure. It provides distinctive functions that make a defunct satellite easier to identify, assess, approach, capture, and de-orbit, thus minimising future costs of removal. Specific characteristics of the Astroscale DP, shown in Figure 3, which facilitate navigation and capture include: optical markers for guidance and navigation in proximity operations, a flat reflective plane for precise distance and attitude measurement, and ferromagnetic material suitable for magnetic grappling concepts.

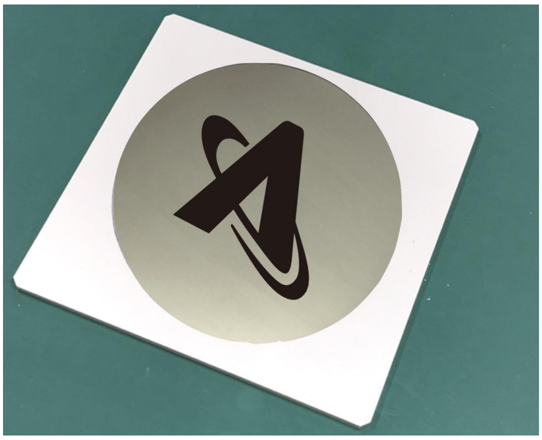

Fig. 3: **ELSA-d: Docking Plate (DP).** A prototype of the DP (optical markers not visible).

V. GROUND SEGMENT AND OPERATIONS

ELSA-d utilises the National In-orbit Servicing Ground Segment Facility hosted at the Satellite Applications Catapult (UK) and developed by AS (prime) with Catapult, RHEA, GMV, SciSys subcontracts. The facility has been developed as a multi-mission facility with a long-term view to provide capability for a variety of IOS missions.

V.1. Architecture

The control centre has, at its core, a Mission Control System for the chaser spacecraft and one for the target spacecraft. The centre interfaces to a number of external entities including Astroscale's own ground station in Totsuka (Japan), external ground stations for contact with the chaser and target, and a ground support centre in Tokyo. It is built in the virtualised environment of a CEMS cloud infrastructure. Satellite communications are based on CCSDS standards and a core suite of ESA software tools are part of the system. The main components are as follows:

1. **Mission Control System (MCS)**
   The MCS is responsible for controlling and monitoring the spacecraft. It is based on ESA MICONYS SCOS-2000 framework. The Mission Database (MIB) is considered a sub-component of the MCS. The MCS relies on the File Based Operations (FBO) approach which guarantees improved reliability on command sequences, bandwidth optimisation, file compression, and use of standard file formats.

2. **Flight Dynamics System (FDS)**
   The FDS determines both the position and the orientation of satellites, and enables the planning and execution of required manoeuvres. It is responsible for LEOP calibrations, planning docking and orbit maintenance, conjunction avoidance manoeuvres with other resident space objects, de-orbiting and re-entry planning, and station-keeping operations. Classical functionalities, such as orbit and attitude determination, use advanced filtering techniques to fuse multiple measurements sources and absolute/relative navigation features. In addition, the FDS provides IOS specific functionalities such as diagnosis trajectory optimization, active abort manoeuvre reconstruction, safety orbit planning and capture trajectory optimisation. A 2D/3D visualisation tool is built-in to the FDS.

3. **Image Processing System (IPS)**
   The IPS is in charge of the estimation of the docking plate attitude information from a live stream of images taken by the chaser spacecraft. It includes advanced feature detection capabilities that allow the chaser to estimate the docking plate attitude information even when it is not directly visible.

4. **Mission Planning System (MPS)**
   The MPS is used to plan activities and use of resources (e.g. data budget). The MPS receives data from the FDS, the MIB, and the Mission Operations Preparation Tool (MOIS Preparation) to construct a coherent schedule, which can then be uplinked to the satellite, executed and verified by telemetry. The MPS is able to automatically negotiate passes with the ground stations providers based on the user needs. In addition to classical MPS functionalities, it automatically manages passes over ground stations in order to have (when possible) an uninterrupted stream of telemetry when switching from one ground station to the other.

5. **Automation System (MOIS)**
   The automation system is responsible for the automatic execution of schedules produced by the MPS and preparation system. It also provides validation and test harness components which can be used for testing before going operational, and a validator component which can be used alongside the MCS to validate that correct procedures are being executed.

6. **Ground Station Control System (GSCG)**
   The GSCG is based on the ESA SCOS2000 NIS component. It is used to interface the MCS and ground stations conforming to the CCSDS SLE standard.

7. **Simulator (SIM)**
   The simulator is implemented using the ESA SIMULUS Simulation framework. It provides an end-to-end simulation of both the chaser and target spacecraft. The simulator

includes a highly realistic chaser model that emulates the OBCs. This feature not only allows AS to run faster-than-real-time simulations but also to run on-board software in a plug-and-play fashion. The purpose of the simulator is testing and validation of operational procedures and databases, support the training of operators, and execution of simulation campaigns. Moreover, the simulator is used for testing and validating the on-board software in an operational environment.

V.2. Operations

The mission will be split into four main phases with respect to operations: LEOP, Commissioning, Critical Phases and non-Critical Phases. Docking and rendezvous will be performed during Critical Phases, and the mission will be continuously operated. Astroscale will be fully responsible for conducting all the operations for the chaser and target at the control centre in Harwell.

The control room has several operator desks; each desk includes a thin client for remotely connecting to the data centre. As all the MCC systems are running in a virtualised environment inside of the data centre, the positions and roles of the desks are flexible. The data centre will be replicated in two different locations in order to ensure the reliability of the MCC. In addition, every system will be composed of a primary and backup server, where data is replicated in near real-time across servers and data centre locations. The control centre and associated communication channels are designed with data encryption in mind.

VI. CONCLUSIONS

ELSA-d, which stands for End of Life Services by Astroscale (-demonstration), is an in-orbit demonstration (IOD) for key end-of-life technology and capabilities of future debris removal missions. ELSA-d, due for launch in early 2020, consists of two spacecraft, a chaser ($\sim$160 kg) and a target ($\sim$20 kg), launched stacked together.

This paper has examined key aspects of the mission, including the 7 phases proposed in the mission CONOPS that demonstrate the following capabilities: target search, target inspection, target rendezvous, and both non-tumbling and tumbling capture. The capabilities and technologies on the mission were explored such as the magnetic capture system and the Astroscale docking plate. Finally, an overview of aspects of the ground segment and operations was presented.

The ELSA-d mission is an important step towards fully operational EOL and ADR missions by maturing technologies and capabilities necessary for future services. In particular, the ELSA-d mission will not just space-prove future payload technologies but will also go through almost the full series of CONOPS expected in a full servicing mission with a demonstration target.

VI.1. Next Steps

ELSA-d is Astroscale's first IOD mission that is part of a roadmap of other IODs and capability developments for future EOL and ADR services. Presently, Astroscale is working with future customers and is in the early stages of developing a supply chain capable of enabling high volume production of chasers.

REFERENCES

[1] R. Biesbroek, A. Wolahan, Maturing the technology for ESA's e.Deorbit mission to remove a large, heavy space debris from low earth orbit, in: CNES 4th International Workshop on Space Debris Modelling and Remediation, Paris, France, 2016.

[2] L. Innocenti, Clean space - an overview, in: ESA Clean Space Industrial Days, ESTEC, Netherlands, 2016.

[3] C. Saunders, J. L. Forshaw, V. J. Lappas, A. Chiesa, B. Parreira, R. Biesbroek, Mission and systems design for the debris removal of massive satellites, in: 65th International Astronautical Congress, Toronto, Canada, 2014.

[4] C. Saunders, J. L. Forshaw, V. J. Lappas, D. Wade, D. Iron, R. Biesbroek, Business and economic considerations for service oriented active debris removal missions, in: 65th International Astronautical Congress, Toronto, Canada, 2014.

[5] S. Estable, Envisat removal by robotic capture means - results of the airbus ds led e.Deorbit Phase B1 ESA study, in: ESA Clean Space Industrial Days, ESTEC, Netherlands, 2016.

[6] M. Scheper, e.deorbit Phase B1 – System Overview (OHB), in: ESA Clean Space Industrial Days, ESTEC, Netherlands, 2016.

[7] A. Pisseloup, T. Salmon, C. Cougnet, M. Richard, ADR concepts from CNES funded study OTV, in: 64th International Astronautical Congress, Beijing, China, 2013.

[8] D. Reintsema, B. Sommer, T. Wolf, J. Theater, A. Radthke, W. Naumann, P. Rank, J. Sommer, DEOS - the in-flight technology demonstration of german's robotics approach to dispose malfunctioned satellites, in: ESA 11th Symposium on Advanced Space Technologies in Robotics and Automation, ESTEC, Netherlands, 2011.

[9] I. A. Sanchez, D. Paris, F. Allard, N. Frischauf, The navigation and communication systems for the Automated Transfer Vehicle, in: IEEE 49th Vehicular Technology Conference, Vol. 2, 1999, pp. 1187–1192. doi:10.1109/VETEC.1999.780535.

[10] K. Yoshida, ETS-VII Flight Experiments For Space Robot Dynamics and Control, Vol. 271, Experimental Robotics VII, Springer, 2001.

[11] S. Clark, Japanese Cargo Ship Ends Mission after Space Debris Experiment Flounders, spaceflightnow.com, 2017.

[12] J. L. Forshaw, G. Aglietti, T. Salmon, I. Retat, M. Roe, C. Burgess, T. Chabot, A. Pisseloup, A. Phipps, C. Bernal, F. Chaumette, A. Pollini, W. H. Steyn, Final payload test results for the RemoveDebris active debris removal mission, Acta Astronautica 138 (2017) 326 – 342. doi:10.1016/j.actaastro.2017.06.003.

[13] J. L. Forshaw, G. Aglietti, T. Salmon, I. Retat, C. Burgess, T. Chabot, A. Pisseloup, A. Phipps, C. Bernal, F. Chaumette, A. Pollini, W. H. Steyn, The RemoveDebris ADR mission: preparing for an international space station launch, in: ESA 7th European Conference on Space Debris, ESOC, Germany, 2017.

[14] B. Gorret, L. Métrailler, L. Moreau-Gentien, P.-A. Mäusli, A. Guignard, M. Richard, M. Lauria, Status of the development of the CleanSpace One capture system, in: CNES 4th International Workshop on Space Debris Modelling and Remediation, Paris, France, 2016.

[15] D. Alary, A. Grasso, C. Tourneur, C. Pruvost, The cycler: The affordable companion for post mission disposal in massive constellations, in: CNES 5th International Workshop on Space Debris Modelling and Remediation, Paris, France, 2018.

[16] M. Okada, A. Okamoto, K. Fujimoto, M. Ito, Maximizing post mission disposal of mega constellations satellites reaching end of operational lifetime, in: ESA 7th European Conference on Space Debris, ESOC, Germany, 2017.

[17] J. Forshaw, C. Blackerby, N. Okada, An overview of Astroscale and the ELSA-d mission, in: CNES 5th International Workshop on Space Debris Modelling and Remediation, Paris, France, 2018.

[18] C. Blackerby, N. Okada, A. Okamoto, E. Yamamoto, C. Weeden, J. Forshaw, J. Auburn, K. Rogers, Perspectives from a venture space company on regulatory frameworks for addressing space debris, in: 69th International Astronautical Congress, Bremen, Germany, 2018.