/estec/

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

DOCUMENT

e.deorbit Implementation Plan

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1 INTRODUCTION

Decades of launches have left Earth surrounded by a halo of space junk: more than 17 000 trackable objects larger than a coffee cup, which threaten working missions with catastrophic collision. Even a 1 cm nut could hit with the force of a hand grenade.

The only way to control the debris population across key low orbits is to remove large items such as derelict satellites and launcher upper stages. Such uncontrolled multi-tonne items are not only collision risks but also time bombs: they risk exploding due to leftover fuel or partially charged batteries heated up by orbital sunlight. There is also a risk that these objects are hit by smaller pieces of debris already in orbit, such a collision may result in a catastrophic break-up. The resulting debris clouds would make these vital orbits much more hazardous and expensive to use, and follow-on collisions may eventually trigger a chain reaction of break-ups.

Since 2005 some Inter Agency Debris Committee (IADC) members have been assessing the stability of the LEO space object population. Studies confirmed that compliance with existing space debris mitigation measures will not be sufficient to prevent the continuous growth of the LEO object population. It concluded that in order to stabilize the LEO environment, the most effective way is to remove the large non-functional spacecraft and launch vehicles from orbit. Without doing so, the space debris environment in the future will see the exponential growth of the debris population, known as the Kessler effect, which would make some orbits unsable. The term used to remove a large object in orbit is termed an Active Debris Removal mission (ADR).

The efficiency in reducing the risk to future mission posed by space debris by performing Active Debris Removal (ADR) is increased when applied to objects with high mass, high collision probabilities, at high altitudes, and applied early enough so as to prevent the further degradation of the environment.

e.deorbit will be the first ADR mission ever conducted, which provides a real opportunity for European industry to be at the forefront of development for the technologies required for such a challenging mission.

The first technical challenge the mission will face is to capture a massive, drifting object left in an uncertain state, which may well be tumbling rapidly. Sophisticated imaging sensors and advanced autonomous control will be essential, first to assess its condition and then approach it.

Making rendezvous and then steady stationkeeping with the target is hard enough but then comes the really difficult part: how to secure it safely ahead of steering the combined satellite and chaser spacecraft down for a controlled burn-up in the atmosphere.

Several capture mechanisms are being studied in parallel in order to minimise the mission risk. Throw-nets have the advantage of scalability – a large enough net can capture anything, no matter its size and attitude. A robotic arm with a gripper has the capabilitiy to capture launch adapter rings or other apendages on spacecraft. In order to transfer the high loads developed from the deorbit thrusts, clamping mechanisms are being considered.

This being the first active debris removal mission, e.deorbit is a very challenging and risky mission, therefore ESA is assessing the possibility of an In-Orbit Demonstration (IOD) mission to demonstrate some of the ADR functions. Several options are being studied, the most representative and ambitious is is the CAPTARE mission which will start its Phase A activities beginning of 2016.

1.1 Activity Support

The activities presented within this document are supported from a number of different sources. The following table is applicable to all technical roadmaps within this document unless otherwise stated on the individual roadmap, and demonstrates through which means the technologies may be implemented:

Activity is conducted internally within ESA	Internal activity
General Studies Programme (GSP)/ Technology Research Programme (TRP)	GSP/TRP
General Support Technology Programme (GSTP)	GSTP
Support method for this study has not yet been determined.	TBD

Table 1 Funding Method

1.2 Activity Status

To support each of the roadmaps, there is an associated activities list presented, along with the status of each activity at the release of this document. The status definitions are presented below:

Proposed	Under consideration within ESA and delegation officially informed (e.g. GSTP compendium)
Planned	Activity has been presented to the relevant board to look for support (e.g. to the IPC for GSTP support)
Approved	Support has been granted. (e.g. Delegation has provided formal approval and ITT phase can begin)
On-going	The successful ITT has been selected and the activity has been kicked-off
Finalised	The final results have been presented and the activity has been closed

2 E.DEORBIT SYSTEMS APPROACH

The goal of e.deorbit is to start the development and demonstration of the key technologies required for ADR through capture and controlled atmospheric re-entry of an uncooperative target orbiting in the LEO protected region. The technology developments shall be streamlined with a system oriented approach. This will place European industry at the forefront in the worldwide active removal efforts, providing a competitive advantage for the industry involved.

The e.deorbit mission objective is to perform active debris removal on an uncooperative ESA-owned debris object (large satellite or upper stage) with a heavy mass in an orbit of 800 - 1000km near polar region.

The e.deorbit Concurrent Design Facility (CDF) study carried out in 2012 consisted of a multi-discplinary team where the scope of the study was to assess the feasibility of a mission to perform the controlled de-orbiting and re-entry of Envisat, using technologies previously identified in other studies such as tentacles, robotic arm and a net. A system level conceptual design of the spacecraft was produced and different mission scenarios were traded-off. Following an assessment of the programmatics, risks and cost aspects, technology roadmaps were consolidated for the key technologies.

Following the e.deorbit CDF study in 2012, three separate system study approaches were taken:

1. Service-Oriented Approach to Active Debris Removal
2. Using the Vega Upper Stage (AVUM) as a Platform
3. e.deorbit Phase A

During all ADR studies carried out by ESA, ENVISAT was used as debris target. This selection was based on several criteria. ENVISAT is one of the few ESA-owned space debris in the densely populated near-polar region in the 600-800 km altitude band. It is also the debris object with the highest collision risk of all ESA objects. Its heavy mass (8 tonnes) and large size makes it representative of the many heavy space debris objects such as the many Zenit 2 SL-16 stages.

Another reason for studying ENVISAT removal is the complex capture. This is caused by the tumbling motion of ENVISAT, that either forces e.deorbit to synchronize its attitude with that of the debris in case of a capture with a robot arm, or to de-tumble a heavy object with a flexible link. Furthermore the solar panel is locked in a difficult position, partially blocking access to one of the strongest and stiffest external points on ENVISAT: its launcher adapter interface.

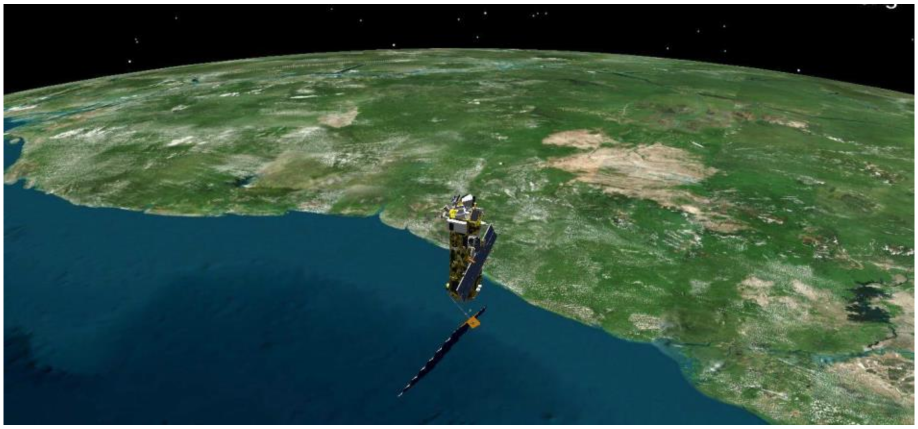


Figure 2-1 Envisat as a Study Case for Phase B1

Removing ENVISAT is removing the largest mass that ESA owns in orbit. The combination of its large mass, complicated capture access and high collision risk, makes ENVISAT the perfect study case , although an ambitious one, for the e.deorbit system studies.

2.1 Service Oriented Approach

Three contracts were awarded to identify the feasibility of setting up ADR as a service by defining a business model for the implementation of an ADR mission, with the involvement of:

1. Kayser-Threde, OHB System, Polimi
2. Airbus Defense and Space (Formerly Astrium) and DLR
3. SSTL, Aviospace and Deimos

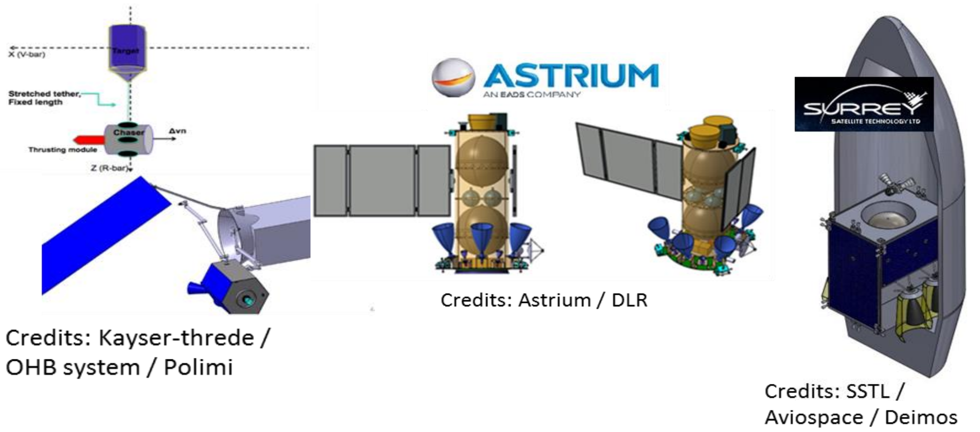


Figure 2-2 Service Oriented Approach System Options

Three contracts were placed in 2012 on a possible ‘Service oriented approach to the procurement and development of an active debris removal mission’ with the aim to:

- Analyse if industry was ready to take the risk to carry out this mission as a service and be paid after successfully achieving it;
- Analyse if a market exists for debris removal missions.

From a programmatic side, these studies highlithed that the technology gap to achieve such a mission is still very high. They also identified that insurances will only partly cover the mission since there is no historical data on the technology. Another outcome was that ESA may need to hold liability since industry is not ready to take over the liabilities of a launching state.

2.2 Using the VEGA Upper Stage (AVUM) as a Platform

As a follow on action from the e.deorbit CDF study, an industrial pre-phase A contract was placed with ELV S.p.A. to investigate the potential of utilising the upper stage of a VEGA launcher (AVUM) for ADR. The design looked into the potential advantages of using the existing hardware on AVUM such as the thruster and propulsion subsystem, as the CDF study team had noted that the propulsion and GNC subsystems for an ADR mission account for approximately 45% of the total cost of the mission.

ELV separated the design of ADR with AVUM into three separate components. This can be seen in Figure 2-3.

1. AVUM Standard: This is the AVUM module which is normally used in the VEGA launch.
2. AVUM PRE (Propulsion Runtime Extension): This component was designed to provide the extra ΔV required for the mission, for both far range rendezvous and the deorbit phase.
3. AVUM Proximity Module: Contains the capture mechanism along with the dedicated avionics and sensors with its own GNC.

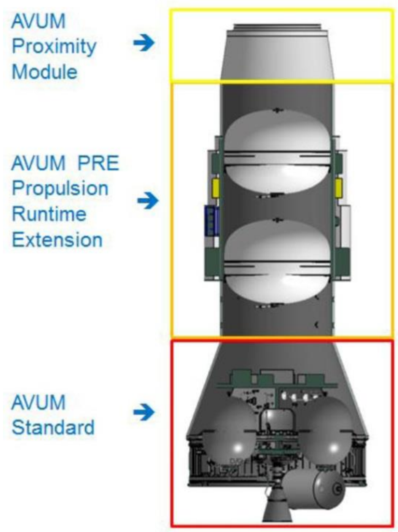


Figure 2-3 AVUM Design Layout for ADR (Credits: ELV)

The ELV design implemented a robotic arm and clamping mechanism, both of which would both grasp the Launch Adapter Ring (LAR) of Envisat.

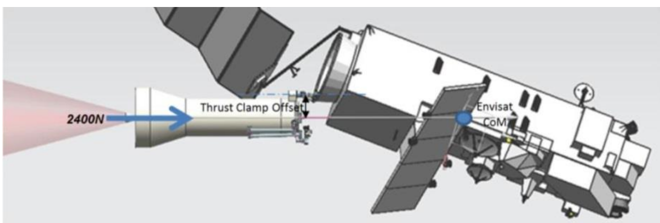


Figure 2-4 AVUR for ADR in Stack Configuration (Credits: ELV)

The motivation behind the utilisation of ADR with AVUM was to save costs, however following a review by ESA of this study, there were concerns over the requalification efforts required which may prove to be significant and potentially could overlap with the launcher qualification testing. It was concluded that the cost benefit with the reuse of AVUM would be minimal, with a risk of additional costs to keep Vega certified.

2.3 e.deorbit Phase A

In 2014, three contracts were awarded to ADS, OHB and TAS to conduct a Phase A for e.deorbit. The Phase A consisted of three mission scenarios;

1. Capture and deorbit using a rigid link;
2. Capture and deorbit using a flexible link such as a harpoon or net;
3. Using either capture mechanisms but to reorbit the space debris outside of the Protected Region[1], above 2000 km.

Phase A Technical Solutions:

	Rigid Deorbit	Flexible Deorbit	Reorbit
ADS	Robotic arm and clamping mechanism on the Hold Down Release Mechanism (HDRM) of Envisat	Net	Robotic arm and gripper
OHB	Robotic arm and clamping mechanism on the sides of Envisat to hold the chaser on the top face	Net	Robotic arm and clamping mechanism
TAS	Robotic arm and clamping mechanism on the Launch Adapter Ring (LAR) of Envisat	Harpoon	Robotic arm and clamping mechanism

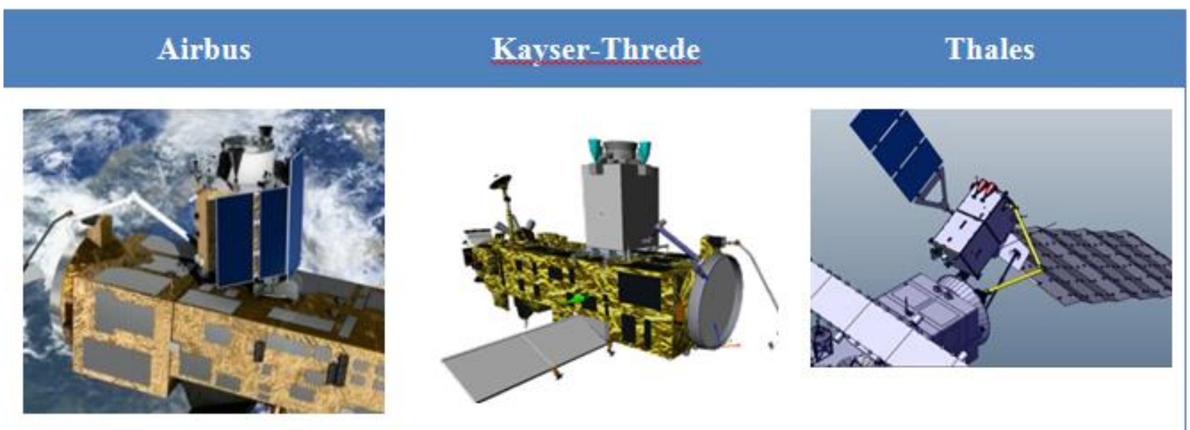


Figure 2-5 e.deorbit Phase A - Robotic Capture Concept

[1] The Protected Regions are defined by the IADC, where in Low Earth Orbit this is between 200 and 2000km.

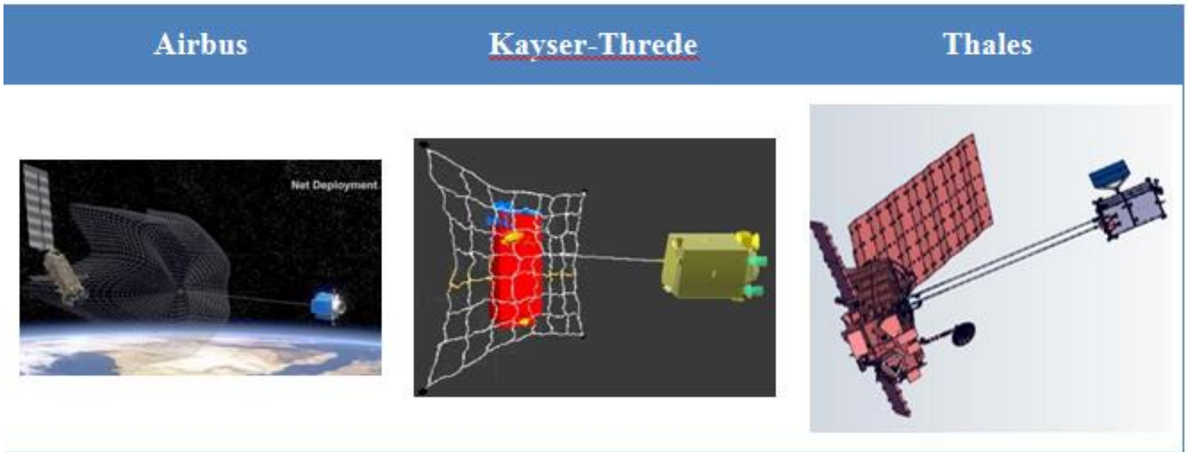


Figure 2-6 Flexible Capture Concept

Following the Preliminary Requirements Review (PRR) board, three CCN's were awarded, one to each of the Phase A contractors to study in a bit more detail the capture mechanisms selected, but also to import all requirements into SysML in a bid to identify gaps/overlaps in the mission and system requirements, to update technology development plans, and to further improve the design of the capture or clamping mechanisms.

2.4 e.deorbit Phase B1

The e.deorbit Phase B1 kicked off in September 2015 with 2 parallel contracts, one with Airbus Defense and Space and the other with OHB. The Phase B1 tasks implement the normal mission design tasks for a Phase B1, but have been built around the mitigation of 5 main risks that were identified in Phase A:

1. Risk of debris generation
2. Risk of unsuccessful capture
3. Risk of collision between chaser and target spacecraft
4. Risk of casualty on ground
5. Risk of schedule slipage

The Systems Requirements Review (SRR) for e.deorbit will take place in mid-2016.

2.5 e.deorbit In-Orbit Demonstration (IOD)

In December 2014 a Memorandum of Understanding was signed between ESA and DLR on an Joint Mission for an IOD for ADR. DLR had been working for a number of years on an In-Orbit Servicing mission known as DEOS, which has many synergies with an ADR mission in terms of rendezvous and capture.

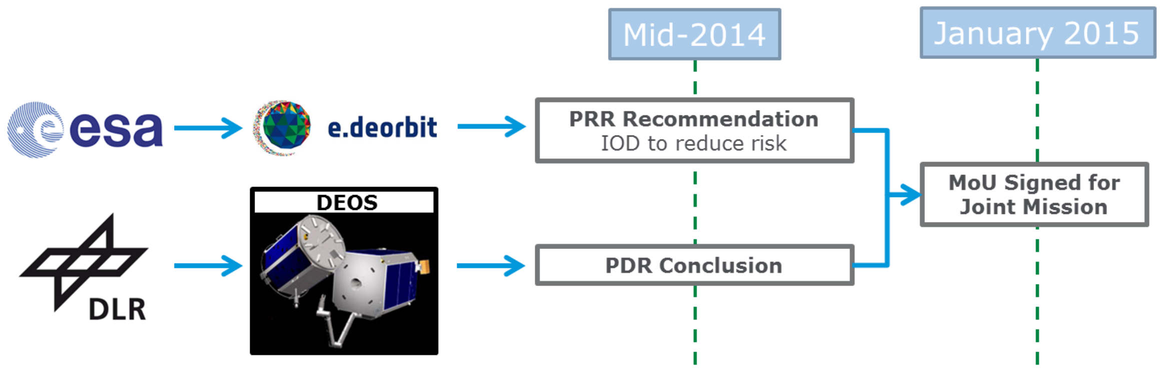


Figure 2-7 MoU Between ESA and DLR for an ADR IOD

The characteristics of the Joint Mission according to the Memorandum of Understanding are the following:

- ESA will place two Phase A contracts which will look into the feasibility of the Mission and System Impacts
- DLR will place a contract on the Robotic Service Module
- There will be a 50/50 cost split with a cost cap of 200 m€.
- The design will implement a robotic arm.
- Launch by 2020 to ensure it is inline with the e.deorbit programmatic schedule.

The feasibility of an IOD will be determined in this initial Phase A which will begin in March 2015, with the PRR will take place in late 2016.

2.6 e.deorbit System Studies Overview

This is all displayed below in Figure 2-8, providing an overview of all system level activities regarding ADR in ESA. There are three separate roadmaps for the different categories of technology developed provide over the next three sections of this document.

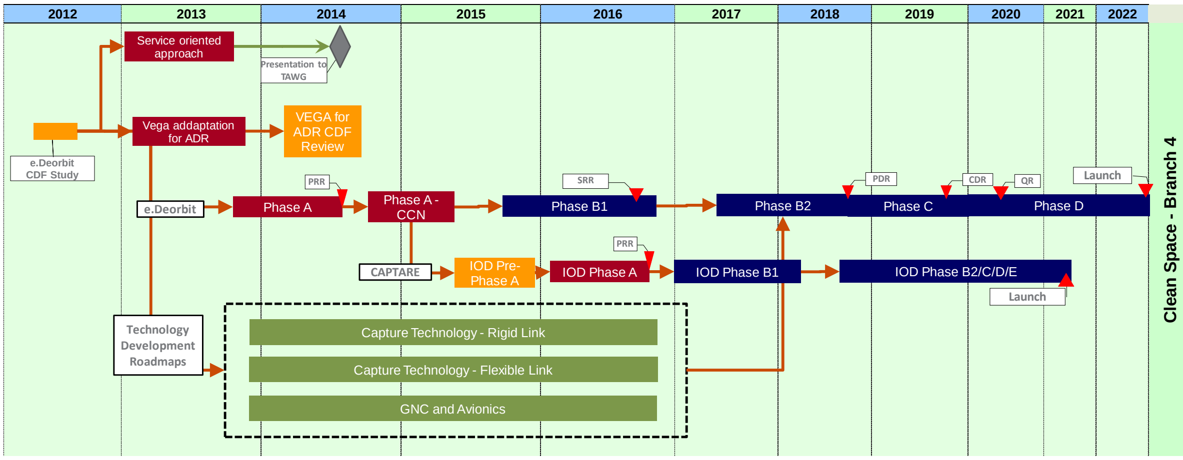


Figure 2-8 e.deorbit Roadmap - System Studies

Activities	Funding Prog.	Total Budget	Time-frame	Status
e.Deorbit CDF study (ESA internal)	GSP*	-	2012	Finalised
Service Oriented Approach (3 parallel contracts)	GSP	€900,000	2013	Finalised
System design Phase A (3 parallel contracts) + CCNs	GSP	€2,250,000	2013	Finalised
Vega upper-stage addaptation for ADR -Phase 0	GSP	€150,000	2013	Finalised
Phase B1 of an Active Debris Removal mission (2 parallel contracts)	GSTP	€1,600,000	2015	On-going
IOD Pre-Phase A (ESA internal)	GSP*	-	2015	Finalised
Captare phase A (2 parallel contracts)	GSP	€1,300,000	2016	Approved

Table 2 e.deorbit Activities- System Studies

3 TECHNOLOGY DEVELOPMENT

3.1 Capture Mechanisms Overview

Out of all the mechanisms studied to capture non-cooperative targets during the e.deorbit CDF study in 2012, the most promising ones identified were: throw-net, enclosing tentacles, harpoon and robotic arms. Clean Space initiated technology development for these capture mechanisms in parallel to the system studies so as to limit the associated programmatic risk, with the aims of raising the TRL of the mechanisms up to TRL 5 or 6:

- **Robotic arms**: Consisting of booms, joints to achieve 6 DOF with breaks capable of withstanding the forces following capture during synchronisation, and implementing an end-effector, or gripper, capable of grasping the Launch Adapter Ring (LAR). However under further evaluation during the Phase A it was identified that some form of a clamping mechanism is required in order to transfer the loads produced from the disposal burns.
- **Nets**: Appear to have a very large applicability to debris, because of the associated scalability and low sensitivity to the target attitude. A thorough programme for characterisation, development and testing of throw-net systems is therefore proposed.
- **Tentacles**: A clamping mechanism for which the development can build upon heritage from current berthing and docking mechanisms. It provides the ability to capture different targets, as it can be easily adapted to capture the launch adapter ring of a satellite. This mechanism requires more accurate rendezvous manoeuvres but simplifies the operations after capture.
- **Harpoons**: Rather insensitive to the target attitude and shape and do not require very close proximity operations.

3.1.1 *Robotic Arm/Clamping Mechanism*

Four of the most promising robotic technologies identified have been assessed in dedicated technology development activities:

1. Clamping Mechanism (Tentacles Option from CDF study)
2. Robotic gripper
3. Robotic arm
4. Clamping Mechanism (Simplified mechanism to attach to the launch adapter ring of Envisat)

3.1.1.1 Assessment of a Clamping Based Capture Mechanism (Tentacles)

Following the e.deorbit CDF study a TRP activity called "Assessment of a Clamping Based Capture Mechanism" was run with OHB System and SENER, which was concluded in late 2014. The objective of the activity was to define a low cost concept for a tentacles based capture mechanism for ADR. Based on multi-body simulations, a baseline concept was defined, from which external loads appearing during the capture process were derived. Finite element analyses was then used to size the mechanism components, before finally technology gaps and future recommendations were made.

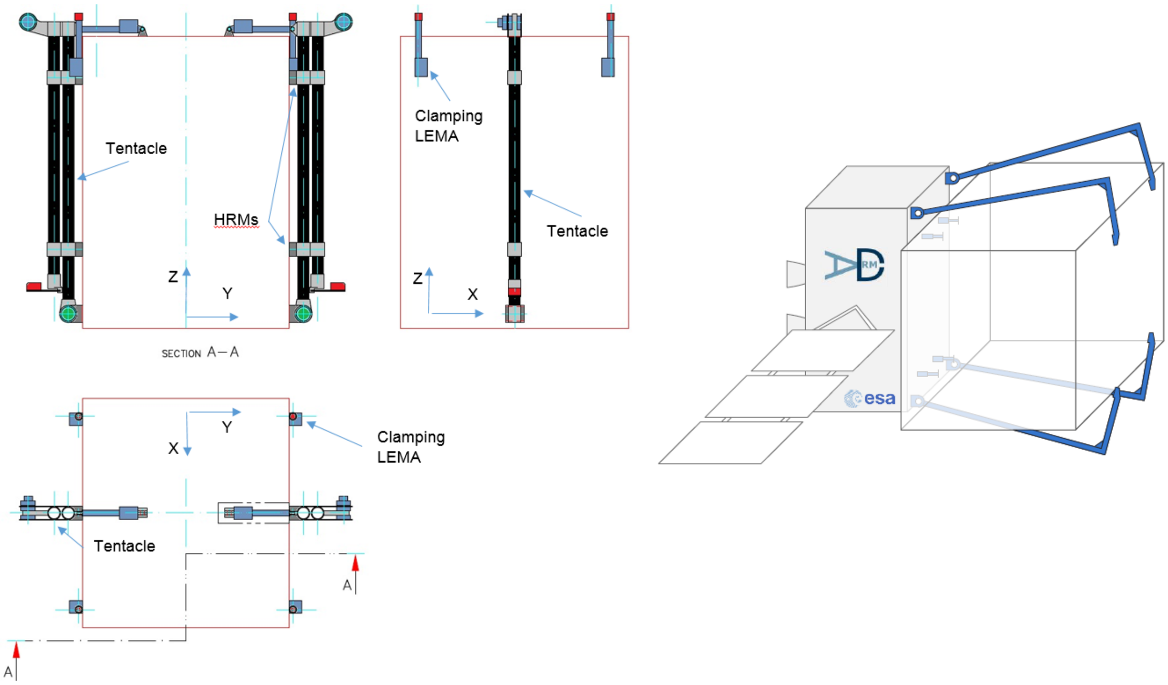


Figure 3-1 Tentacle Based Clamping Mechanism (Credits: OHB System and SENER)

Envisat was the target satellite selected for the study as it was expected to be a conservative case due to its size. It was estimated that the applicability of such design to smaller satellites would only require minor modifications.

During the Phase A of e.deorbit a number of capture concepts were studied by ADS, TAS and OHB (formerly Kayser-Threde), where the conclusion was that following the capture via robotic arm and gripper, a clamping mechanism would be needed that is capable of transferring the loads produced when performing the disposal burns.

Due to system trade-offs the tentacles based clamping mechanism was not selected for further analysis. This was based on the assumption that it would be complex to repeat the capture attempt for a second time if the first one failed due to the reopening of the long tentacles whilst avoiding collision with appendages on the target. The reliability of this technology was also questioned from a system perspective due to the minimal offset in the chaser allowed in the attitude approach up to capture.

3.1.1.2 Clamping Mechanism from Phase A

On the other hand there was no consensus from the three contractors during the Phase A regarding the type of clamping mechanism, nor the location on Envisat to clamp. The options identified during the Phase A can be seen in Figure 2-5 , which is shown in the image below where the following clamping mechanisms were identified:

- Airbus: Clamping mechanism to attach to four of the hold down release mechanisms (HDRMs) on Envisat which were originally for the solar arrays. Hence the loads generated during the disposal burns will pass through the HDRM's into Envisat.
- Kayser-Threde selected a clamping mechanism that can grasp the sides of Envisat to keep the chaser in a seated configuration while the main loads were transferred through the clamping mechanism arms into the main Envisat body, distributing the loads over a large surface.
- Thales together with MDA selected a clamping mechanism that would grip the LAR of Envisat. A finite element analysis was conducted to size the clamping mechanism to ensure that no plastic deformation would be generated in the LAR as a result of the loads produced from the disposal burns. This clamping mechanism also had a single degree of freedom which meant that the thrust vector could be aligned with the CoG of the stack configuration to minimise the propellant loss.

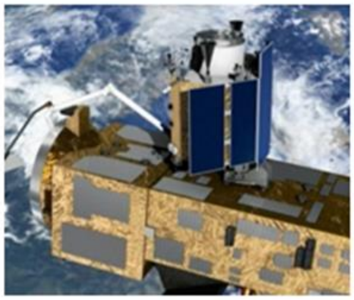
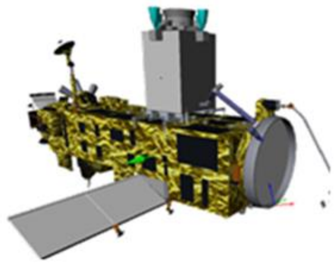
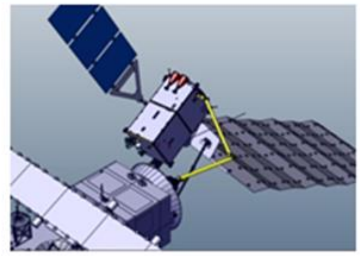
Airbus	Kayser-Threde	Thales
		

Figure 3-2 Clamping Mechanisms from phase A

Towards the end of the Phase B1, taking system level requirements into account there will be a dedicated TRP to further develop a clamping mechanism for ADR, specifically focusing on a clamping mechanism to grasp the Launch Adaper ring for ADR. This activity will be implemented in 2016 and is titled “Pre-Development of the a Clamping Mechanism”. The potential goals of this activity are:

- To produce a preliminary detailed mechanical design
- Conduct a finite elements analysis to size the clamping mechanism
- Develop a functional breadboard of the clamping mechanism
- Perform function tests and Q-S load testing on the breadboard

For more information on this upcoming activity please see Section 4.2.

This may be followed up by another activity, to raise the TRL sufficiently so that it can be integrated into e.deorbit.

3.1.1.3 Gripper Design

All three contractors in the Phase A identified the Launch Adapter Ring (LAR) of Envisat to be the location where the robotic arm would grasp using a robotic gripper. Such a grasp location has a clear advantage over any other area point, as the LAR can withstand large forces and are common on many satellites, so a gripper design to grasp a LAR could be reused on another mission with little or no redesign necessary.

In 2015 an activity was initiated with the Industrial Research Institute for Automation and Measurements in Poland (PIAP) and Thales Alenia Space in France called “Active Debris Removal Demonstration in Laboratory Condition Experiment (ADRexp). This activity aimed to develop and verify in laboratory conditions an andaptive anthropomorphic gripper for ADR by raising the TRL to 3.

Towards the end of the Phase B1, taking system level requirements into account there will be a dedicated TRP to further develop a gripper for ADR, specifically focusing on a gripper to grasp the Launch Adapter Ring (LAR) of Envisat. This activity is known as “Pre-Development of a LAR Gripper”.

The potential goals the Pre-Development of LAR Gripper are:

1. Analysis the capture operation and identification of system requirements and design constraints from the system studies (see Section 2)
2. Develop a concept design and evaluation different options, performing a trade off to define the best design.
3. Assess the kinematics and define the geometry of capture mechanism
4. Define the sensors and control system design
5. Perform structural/loads analysis
6. Breadboard development and demonstration tests

For more information on this upcoming activity please see Section 4.3.

This may be followed up by another activity, to raise the TRL sufficiently so that it can be integrated into e.deorbit.

3.1.1.4 Robotic Arm / Clamping Mechanism Roadmap

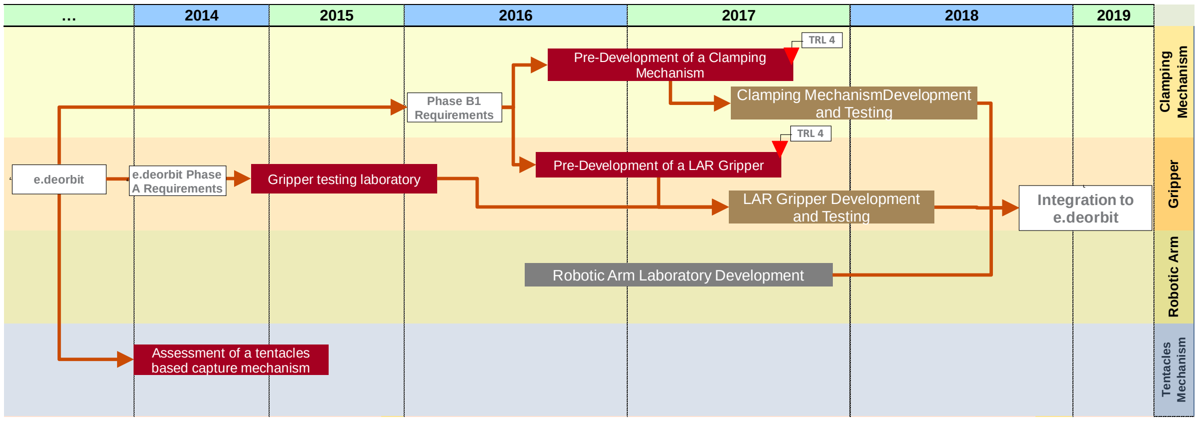


Figure 3-3 e.deorbit Roadmap – Rigid Capture Mechanism

Activities	Funding Prog.	Total Budget	Time-frame	Status
Assessment of a clamping based capture mechanism	TRP	€150,000	2013	Finalised
Pre-development of a clamping mechanism	TRP	€350,000	2017	Planned
Active Debris Removal demonstration in laboratory condition experiment	ish Industry Initiat	€200,000	2014	On-going
Pre-development of LAR Gripper	TRP	€300,000	2017	Planned

Table 3 e.deorbit Activities – Rigid Capture Mechanism

3.1.2 Flexible Capture Mechanism

During the initial e.deorbit CDF study in 2012, two promising forms of flexible capture mechanisms were identified, a net option and a harpoon option. Both of these options utilise tether technology which provides the only connection between the chaser and target after capture.

Presented below is an initial indication as to some of the questions that were raised regarding the feasibility of such technologies:

1. For the harpoon:
    - The velocity at which to impact the target
    - The type of barbs in order to ensure the force during the disposal burns can be distributed to the target without breaking it
    - How to ensure no debris is generated
2. For the net:
    - The type of material
    - Size of the mesh
    - Type of braiding method
3. For the Tether
    - Type of material,
    - Temperature profile of the tether during the disposal burns
    - How to unwind the tether once it is fired

Outlined hereafter is an overview of how the understanding of these issues have evolved, with completed and planned future activities for technology developments in these areas.

3.1.2.1 Harpoon Option

The harpoon option is being studied by Airbus under a TRP called “Harpoon Characterisation, Breadboarding and Testing for ADR”. The aim of this activity is to bread-board and test the harpoon concept with the application of a real ADR mission in mind so as to raise the TRL of both the harpoon itself and the ejection mechanism.

Harpoons intrinsically rely on 3 physical actions that are a concern for the conduct of a safe and clean grasping operation:

- High energy impact on the debris;
- Piercing of structural elements of the debris;
- Pulling of debris from a single point.

The activity envisages to address all of these through a programme of modelling, analysis and experimentation, followed by successful breadboarding of hardware.

Programme of work:

1. Elaborate detailed system requirements for the harpoon system with a focus on the system being able to capture generally a range of uncooperative targets without generating additional debris, and specifically, Envisat.
2. Development of a mathematical model of the harpoon-target interaction, accounting for all the various design parameters and environmental parameters affecting the system.
3. Design of a test-campaign for harpooning a large and representative selection of debris types and materials. The test campaign may include low-friction and/or droptower or parabolic flight testing.
4. Development of harpoon breadboards, ejector breadboards, testing rigs and all supporting equipment.
5. Carry out the test campaign.
6. Derive requirements on the mission scenarios in which harpoon capture is suitable.

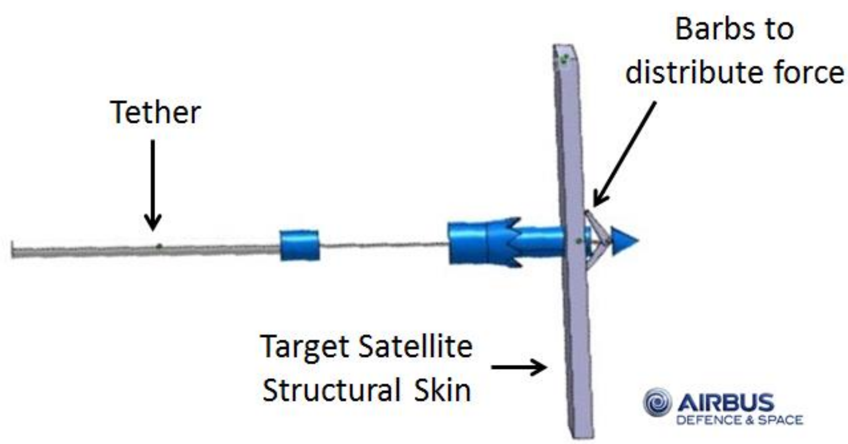


Figure 3-4 Harpoon Design by Airbus DS

This activity is expected to be completed in 2016.

3.1.2.2 Net Option

In 2013 two parallel contracts were initiated called "Net Parametric Characterisation and Parabolic Test", one contract with GMV and the other with SKA Polska. The main objective of this activity was to produce a validated simulator that can be used to design and test the net system in conditions not easily replicated in an experiment such as a full size net to capture Envisat. Following this the simulator was to be validated through parabolic flights to simulate 0 g. The main goals were to:

1. Develop a mathematical model of the net and the interdependence of the various system design parameters (e.g. cable dynamic parameters, knot type, mesh size, size of flying masses, closing mechanism), and environmental parameters (e.g. distance of throw, speed of throw).
2. Realise a parametric simulator of the capture operation.
3. Identify materials and assembly technology for the net.
4. Design a parabolic flight test campaign, related test equipment and measurement instrumentation/techniques. The campaign shall envisage different test items/test so that all parameters can be investigated with at least 2 data points.
5. Procure/manufacture integrate and validate test equipment on ground.
6. Perform a mathematically rigorous validation of the simulator and model against the test results.

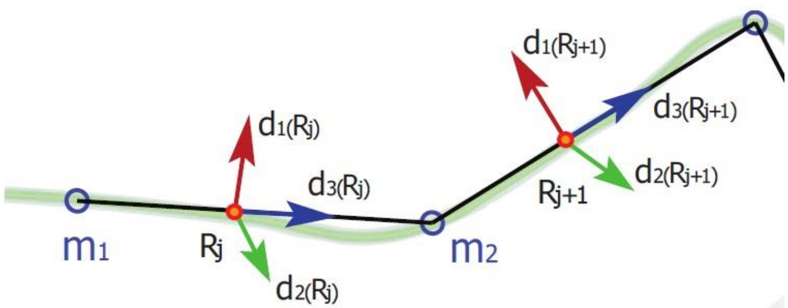


Figure 3-5 Cosserat rods Theory Used for Net Simulation by SKA Polska

Parabolic flights by both consortia were carried out in 2015, a recording of the parabolic flight tests conducted and are available online:

GMV
https://www.youtube.com/watch?v=exIR9qSrJqA

SKA Polska
https://www.youtube.com/watch?v=mx9Fb5sixBU

Having developed the net to approximately TRL 4, a GSTP activity will commence in 2016 regarding the End-to-End testing of the entire net subsystem in order to achieve TRL 7 by testing the full system in a sounding rocket campaign. This will include the development and testing in a relevant environment of the following components:

1. Net
2. Net closing mechanism
3. Tether
4. Spool
5. Net Ejector

More details on this activity can be seen in Section 4.1.

3.1.2.3 Tether Technology

There are three major tasks in developing a tether for ADR:

1. Design of the tether itself including material, stowage, deployment, together with dynamic and finite element analysis.
2. The potential degradation in performance of the tether during the disposal burns due to the thermal effects from the propulsion subsystem.
3. The controllability of the stack configuration (post-capture) as there will be two objects of different masses connected via a single cable, and due to the different masses, large torques will be induced during the disposal burns.

3.1.2.3.1 Design of the Tether

The design of tether has been initially studied in the system studies and technology developments for the net and harpoon. Additionally the mathematical and physical components underpinning a mechanically tethered spacecraft undergoing a high-thrust deorbiting burn was studied in detail in the GSP activity entitled "BOdies UNder Connected Elastic Dynamics (BOUNCED)". These initial investigations are being continued with a technology development, performed under TRP, entitled "Elastic Tether Design and Dynamic Testing" that kicked off in 2015. The activity will raise the TRL of both a stiff and also an elastic tether, in order to:

- Investigate and trade-off of different material and weave combinations;
- Design and manufacture of one or two sample tethers;
- Extensive testing of the sample tether(s) (environmental testing and dynamic and static properties)

It is expected that with time the material will slowly degrade and hence further evaluation and studies may be required to characterise and test the material properties after long term storage.

3.1.2.3.2 Thermal Degradation of Tether

It is planned to run an activity to characterise the impact a plume has on a tether in a vacuum. This will be done through testing and then implemented within the simulation models to see what impact this has on the performance of the tether. Currently under development is the development of a testing facility to perform such an experiment. Following this activity, there will be a follow up GSTP for the experiment to test the thermal degradation a plume induces onto a tether called "Hot Gas Plume Characterisation in a Vacuum", for more information please refer to Section 4.10.

3.1.2.3.3 Tether dynamics

An activity called Bodies Under Connected Elastic Dynamics (BOUNCED) developed a theoretical basis for the modelling the dynamics of an elastic tethered system. This activity was a GSP activity which was completed in 2015 by a consortium lead by Belstead Research Limited. The objectives of this activity were to:

- Provide a grounded theoretical basis for the modelling the dynamics of an elastic tethered ADR system;
- Perform a parametric study to determine potential advantages and disadvantages of elastic tethers;
- Assess potential resonances of the elastic system with spacecraft dynamics;
- Identify the potential collision risk between the target and chaser;
- Determine the early interaction with the atmosphere.

Following the development of the models for an elastic tethered system, by exploring the behaviour of such systems a number of key points were highlighted. One example is that the risk of collision is extremely low, and can effectively be designed out by using a stiffer or longer tether.

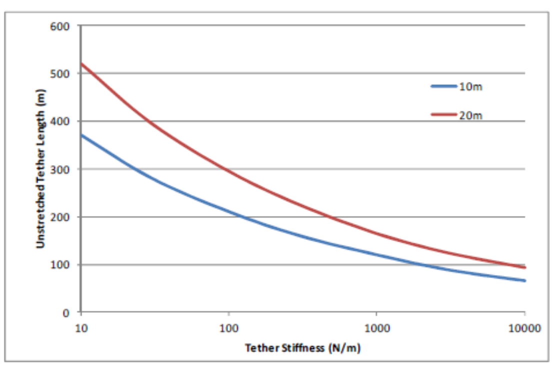


Figure 3-6 Required Tether Length to Avoid Collision [Belstead Research Limited]

Nevertheless the controllability of the tether is directly related to the inputs provided by the GNC sensors, hence a number of activities are described in Section 3.2 that address this issue such as the TRP activity "Advanced GNC for Active Debris Removal"(AGADiR), and the upcoming GSTP activity "GNC design and performance validation for active debris removal with FLEXIBLE capture".

Another planned activity planned will be to identify a potential test experiment to be conducted on the ISS in order to validate some of the control algorithms, more information on this activity is available in Section 4.4.

3.1.2.4 Flexible Link Activity Summary

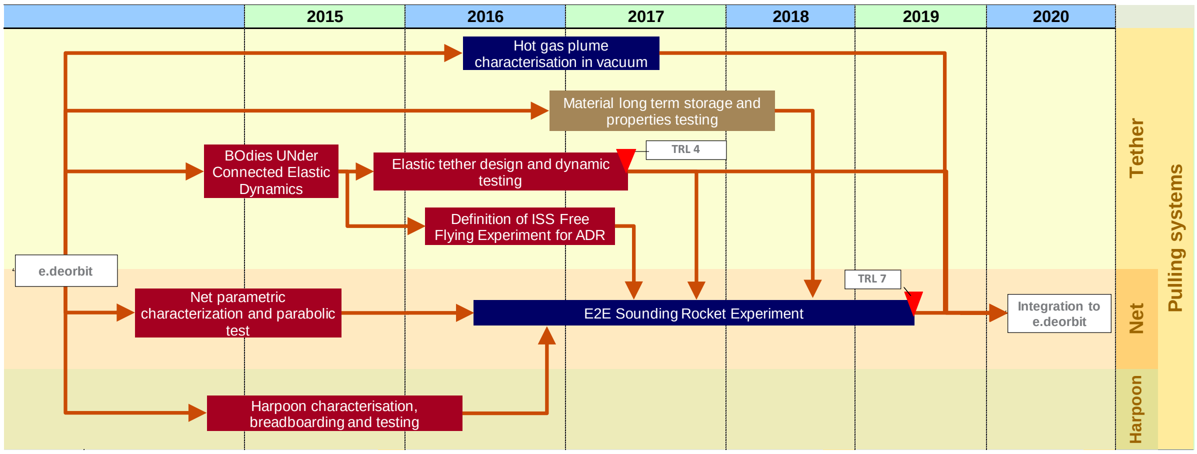


Figure 3-7 e.deorbit Roadmap – Flexible Capture Mechanism

Activities	Funding Prog.	Total Budget	Status
Hot gas plume characterisation in vacuum	GSTP	€500,000	Draft
BOdies UNder Connected Elastic Dynamics (BOUNCED)	GSP	€120,000	Finalised
Elastic tether design and dynamic testing	TRP	€300,000	On-going
Definition of ISS free flying experience for ADR	TAS	€50,000	Approved
Net parametric characterization and parabolic test (2 contracts)	TRP	€695,000	On-going
Sounding rocket test and end to end validation for capture of space debris	GSTP	€3,000,000	Draft
Harpoon characterisation, breadboarding and testing for ADR	GSTP	€700,000	On-going

Table 4 e.deorbit Activities – Flexible Capture Mechanism

3.2 GNC Sensing Suite and Advanced GNC Techniques

The sensing suite for ADR requires dedicated hardware together with the associated algorithms in order to both determine the attitude and range of the target and to also assist in close proximity operations and synchronised motion between two objects.

The proposed development plan will bring the required GNC technologies for ADR up to TRL 5 or 6 prior to integration to e.deorbit. This approach includes the development, testing and validation of hardware, control algorithms and the avionics required for an ADR mission.

3.2.1 Control/Algorithm Development

3.2.1.1 Flexible Link

Advanced GNC Algorithms for Active Debris Removal (AGADiR) was a TRP activity conducted by Airbus Defense and Space which addressed a number of key drivers for deorbiting two satellites connected by a tether. By identifying a baseline for a potential GNC architecture a dynamics analysis was performed, following this collision risk was assessed, then the potential for winding was estimated and finally stability issues with the architecture were addressed by carrying out a number of simulations with varying characteristics. AGADiR produced a number of key findings for e.deorbit:

1. To prevent winding, and hence the risk of collision from such, the system needs to prevent slackness in the tether.
2. In order to reduce the fuel budget for the control, the system needs to prevent sensor noise by improving the performance of the GNC sensor suite, or reducing the length of the tether.
3. In order to achieve the minimal target-chaser distance, the system needs to rapidly dissipate the tether elastic energy during post-burn by increasing the tether stiffness and length, or provide a ramp down thrust capability to the apogee engine in the thrust direction.
4. To reduce the debris footprint uncertainty, the system needs to provide as much tangential ΔV as possible, by improving the apogee engine calibration uncertainity, improving the orbit determination or by improving the GNC performance.

A number of conclusions from this activity were similar to the conclusions drawn from the activity BOUNCED mentioned previously in section 3.1.2.

To improve our knowledge in this area, and raise the TRL of such a system, the aim is run a GSTP activity called “GNC design and performance validation for ADR with flexible capture”. This activity will build upon the models developed in AGADiR and BOUNCED by including hardware in the loop (HIL) testing in order to validate and verify the control algorithms previously developed. Please see section 4.6 for more information.

3.2.1.2 Rigid Link

In 2014 an activity began called “Rendezvous, capture, detumbling and de-robiting of an uncooperative target using clamping mechanisms”, known as CLGADR. The objective of this activity was to develop a simulator composed of a number of different models such as actuator performance, sensor performance, chaser environment, target environment, target and chaser kynamatics and dynamics, attitude determination, intertial state determination to name but a few. Using this Model-in-the-Loop (MIL) approach, and e.deorbit (“Tentacles” clamping mechanism option from Section 3.1.1.1) as reference active debris removal scenario, conduct simulations to determine the robustness of the control in terms of oscillations due to sloshing, post-capture detumbling capability, control forces required along with others. Validation tests were then performed and finally an initial FDIR was implemented. This activity will finish by mid-2016.

In order to raise the TRL of these control algorithms, a GSTP activity is planned for 2016 called “GNC Design and Performance Validation for ADR with Rigid Capture”. This activity will look to consolidate the guidance and control systemfor the capture and de-orbit phase of an ADR mission using a robotic arm and clamping mechanism in line with what is being used in the Phase B1.

3.2.1.3 Image Processing

The ongoing activity “Image Recognition and Processing for Navigation” has the objective to design, develop and verify the necessary capabilities in Image Recognition and Processing (IRP) for position, and angular motion detection on uncooperative targets in an Active Debris Removal (ADR) scenario.

The activity will analyse the data fusion of different sensors including visual camera, Thermal Infrared camera, and 3D imaging LIDAR. In addition, optical flow will also be produced and used in the navigation filter. This is followed by prototyping of the software algorithms corresponding to the different navigation options. This includes the preprocessing of the 2D and 3D data to perform the necessary corrections required by the sensing mechanism, as well as detection of the target object and generation of compound data, e.g. average range, LOS and bounding box of the 3D point cloud.

The visual and Infrared cameras and 3D Imaging LIDAR are key elements in ADR scenarios as they allow to acquire a 3D point cloud of the target object with high accuracy and thereby enable 3D image processing algorithms, e.g. for pose estimation of the target object. With the step from cooperative targets to non-cooperative targets, the amount of data to be processed by visual and IR camera or a

LIDAR is increasing significantly, and hence this imposes requirements and design constraints on the processing units.

3.2.2 Collaborative Control (COMRADE)

One issue that has been highlighted a number of times during ADR system studies, is how the GNC and robotics systems work, whether each of the systems take the 'lead' during a specific mission phase, or if there is a single collaborative controller interfacing directly with the GNC and robotic systems simultaneously.

The first option, with two independent control systems is considered to be a robust approach provided that the number of system modes and states remain reasonable, and as some off the shelf equipment (COTS) may be used, there may be lower development and testing costs. However this may not be able to handle the large relative rates between vehicles, in particular during the Capture Phase when both GNC and robotics are active it will be challenging to define exactly how all mode transitions occur, as a result it will be likely that some form of supervised autonomy needs to be implemented.

The second approach considers a single collaborative controller that interfaces directly with both systems. Here the controller has direct access to the raw data from the GNC and robotic sensors and actuators in order to control both systems and take into account directly the influence of one system on the other. This type of technology can handle higher drift rates between the targets and can support higher levels of autonomy in the chaser spacecraft. However it is currently considered low TRL for space applications and will require expertise in both GNC and robotics to develop, considering both of these attributes the development and testing costs are expected to be higher than for the separate controllers option.

In order to raise the TRL a TRP activity in 2016 will be run called "Control and Management of Robotics for Active Debris Removal" (COMRADE). The activity shall comprise the control and management of the spacecraft in combination with the control and management of a robot arm used to grasp, stabilise and hold the target with the aim perform the controlled de-orbit. Please see Section 4.8 for more information on this upcoming activity.

3.2.3 GNC Hardware Development

For the e.deorbit mission a number of different sensors are needed to gather the various information required, such as:

1. Target attitude dynamics and pose estimation
2. Relative position
3. Target pointing navigation
4. Inspection of the target to assess structural integrity
5. Relative navigation with a target
6. Capability to conduct measurements during eclipses

Two specific pieces of hardware will be developed for the e.deorbit GNC subsystem one being a LIDAR and the other a Multi-spectral Camera (Visual and Infrared). Other sensors such as a far range camera or a dedicated infrared camera may be utilised but currently no technology development is foreseen for these.

3.2.3.1 LIDAR

The LIDAR is proposed in order to achieve pose estimation and range of the target from the chaser. It will be used heavily during the Inspection Phase of the target and during the Rendezvous and Capture of the target. However due to the mass and volume constraints, a new development for a miniturised LIDAR is required. An upcoming GSTP activity will look into the design, manufacture and test of a Miniaturized Imaging LIDAR System (MILS) of an elegant breadboard targeting the rendezvous & docking operation between two spacecrafts. The MILS elegant breadboard shall implement novel technologies, like for example CMOS detector arrays, in order to achieve a high level of compactness and low risk (preferably a flash-type LIDAR system without moving parts) while reducing substantially the mass and power consumption, when compared with traditional Imaging LIDAR systems. For more information on this upcoming activity please see section 4.7.

3.2.3.2 Multi-spectral Camera

A multi-spectral camera can be used in parallel to a LIDAR in order to provide inorbit validation of the pose estimation independent of the illumincation condititions.

In 2014 ESA started a TRP study called “Multi-Spectral Sensing for Relative Navigation” (MSRN) which focused on the design of a multi-spectral camera that can be used for navigation purposes in a wide variety of scenarios. This activity focused on increasing the accuracy and robustness of normal multi-spectral cameras.

To build upon this knowledge, a GSTP activity is planned to breadboard and test such a multi-spectral camera, the title of this activity is “Breadboard of a Multi-Spetral Camera for Relative Navigation”. The aim will be to develop the camera and perform initial validation and verification tests in order to achieve TRL 4. More information on this activity is available in Section 4.9.

3.2.4 Investigation of De-tumbling Solutions

Unlike cooperative rendezvous, where the attitude of the target is controlled or stable by design, uncooperative targets can have any rotational state. Any envisaged capture technique (throw-nets, robotic arm, and tentacles) has a natural physical limit in the angular momentum it can absorb.

This on-going activity with GMV is first looking into defining the different tumbling cases for potential ADR targets. Following this a reference capture technology is selected and then finally a potential GNC system design is defined for the chaser based on a number of different elements. This activity is expected to finish by mid-2016.

3.2.5 Avionics

Due to all the inputs from robotics and GNC, high demands are placed in the processor requirements for such a mission. A GSP known as High Performance Avionic Solutions for Advanced and Complex GNC Systems (HIPNOS) activity is looking into the feasibility of using off the shelf components in order to cope with very demanding autonomous closed loop controlled for an ADR mission scenario. A proof of concept and preliminary design of the proposed avionics architecture shall be developed and possible design solutions shall be investigated targeting an architecture compatible for a e.deorbit mission.

Following HIPNOS there may be further activities under GSTP looking into fault-tolerant, high-performance COTS based hardware for achieving the above functions.

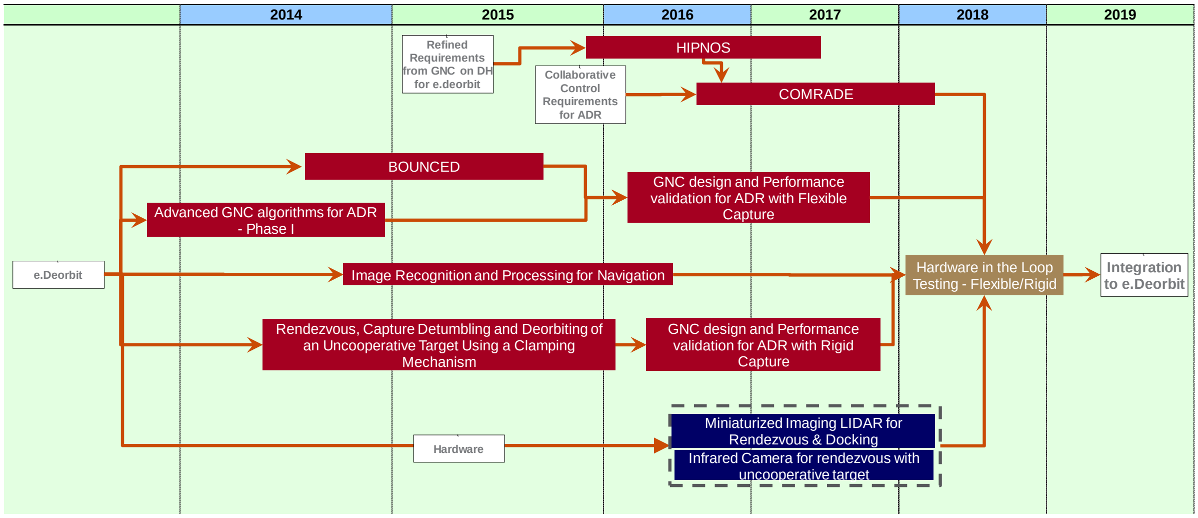


Figure 3-8 Clean Space Roadmap Branch 4 – GNC & Avionics

Activities	Funding Prog.	Total Budget	Status
Multispectral Sensing for Relative Navigation	TRP	€350,000	On-going
Multispectral Camera breadBoard for rendezvous with non-cooperative target	GSTP	€800,000	Evaluation
Compact Imaging LIDAR system for Rendezvous and Docking Operations between Spacecraft	GSTP	€500,000	Evaluation
Image Recognition and Processing for Navigation	GSTP	€600,000	On-going
Advanced GNC algorithms for ADR - Phase I	TRP	€200,000	**Finalised**
Rendezvous, capture, detumbling and de-orbiting of an uncooperative target using clamping mechanism	TRP	€240,000	On-going
GNC design and performance validation for active debris removal with rigid capture	GSTP	€350,000	Evaluation
GNC design and performance validation for active debris removal with flexible capture	GSTP	€250,000	Evaluation
COntrol and Management of Robotic for Active DEbris removal (COMRADE)	TRP	€1,000,000	Planned
High Performance Avionics Solutions for Advanced and Complex GNC Systems	GSP	€150,000	Approved

Table 5 Clean Space Activities Branch 4 – GNC & Avionics

3.3 Debris Attitude Motion Measurements and Modelling

Today, there is little knowledge on the attitude state of decommissioned objects. However, this is an essential element for the preparation of a removal mission, since the selection of the appropriate capture method strongly depends on the attitude motion of the target.

An on-going GSTP study with Fraunhofer Institute, HTG, IWF and Asotronomical Institute University of Bern is looking into collaborating measurements of attitude motion by optical, laser and radar techniques. To do so, the various methods will analyse the attiude motion of defunct satellites in LEO and quantify the influence of debris impacts on the attitude motion. This activity is known as “Attitude Motion Measurements and Modelling”.

4 UPCOMING ACTIVITY DESCRIPTIONS

In this section information is provided on upcoming activities by Clean Space which are expected to got to tender in 2014. This is intended as a guideline only, as the final scope of some activites may change slightly depending on the support for an individual activity.

A description of the following activities are presented hereafter:

1. **Sounding Rocket Test and End to End Validation for Capture of Space Debris with Throw Nets**
2. **Pre-Development of a Clamping Mechanism**
3. **Pre-Development of a LAR (Launch Adapter Ring) Gripper**
4. **Definition of ISS Free Flying Experiment for ADR**
5. **GNC Design and Performance Validation for ADR with Rigid Capture**
6. **GNC Design and Performance Validation for ADR with Flexible Capture**
7. **Compact Imaging LIDAR System for Rendezvous and Docking Operations between Spacecraft**
8. **Control and Management of Robotics for ADR (COMRADE)**
9. **Breadboard of a Multi-Spectral Camera for Relative Navigation**
10. **Hot Gas Plume Characterisation in a Vacuum**

4.1 Sounding Rocket Test and End to End Validation for Capture of Space Debris with Throw Nets

Funding Type	GSTP
Funding Amount	3,000 k€
Duration (Months)	30
Deliverables	Engineering Model and Sounding Rocket Experiment
Currrent TRL: 4	Final TRL: 7

OBJECTIVES

The objective of this activity is to build on a number of recent technology developments to perform the maturation, integration and final verification of the net system for debris capture so that it is ready for inclusion in an Active Debris Removal mission.

To achieve this a sounding rocket campaign shall be carried out for end-end validation of the space debris net.

DESCRIPTION

This activity will have three technical and contractual phases.

Phase A: Development of Engineering Models (TRL 5). This phase will get its inputs from current activities for tether development, net development, and rely heavily on high-fidelity simulation tools currently verified in the frame of a TRP activity to consolidate and develop full-scale engineering models of all parts of the net capture system. The main components are

- Net
- Net closing mechanism
- Tether
- Spool
- Net ejector

A detailed test-plan shall be developed for the next phase. The sounding rocket experiment and the sounding rocket platform design shall be completed. Detailed simulations of the sounding rocket campaign shall be undertaken with validated simulators.

Phase B: Development of Qualification Model (TRL 6)

The second phase of the activity will bridge the system from TRL5 to TRL6 through a carefully designed series of environmental and mechanical tests. The sounding rocket platform shall undergo Manufacture Assembly and Integration as well as appropriate environmental and mechanical tests.

Phase C: Sounding Rocket Experiment (TRL 7)
The payload shall be integrated with the sounding rocket and the sounding rocket experiment performed. The experiment shall be fully instrumented, and high speed cameras will record the development with the aim for a full 3D reconstruction of all phases of the net deployment and closure.

4.2 Pre-Development of a Clamping Mechanism

Funding Type	TRP
Funding Amount	350 k€
Duration (Months)	12
Deliverables	Breadboard
Currrent TRL: 2 Final TRL: 4	

OBJECTIVES

To design and test a breadboard of a clamping mechanism that can be used to attach a chaser spacecraft to an interface on a target spacecraft in order to achieve a structurally rigid connection required for the deorbit burns of the e.deorbit Active Debris Removal (ADR) mission.

DESCRIPTION

The e.deorbit CDF study and consequent Phase A studies identified the clamping mechanism as a necessary part of the space debris removal mission. On the basis of the results of a previous TRP on a capturing/clamping mechanism, and the results from the Phase A of e.deorbit, the new capture method is to use a robotic arm for capture, and a clamping mechanism only for the high torques resulting from the deorbit burns.

The target spacecraft is in the initial phase captured by the chaser's robotic arm in order to establish a mechanical link between the two bodies. The robotic arm is, however, not sufficiently strong and stiff to be only relied on for the final deorbit manoeuvre where large forces have to be transferred between the two bodies. The clamping mechanism which will be located on the chaser spacecraft will clamp to a defined interface on the target. After clamping, the mechanism shall provide structural link between the two spacecrafts in order to enable a controllable deorbit burn manoeuvre.

Preliminary requirements:
The mechanism shall tolerate some uncertainties w.r.t. to the position and condition of the interface on the target. The mechanism shall allow several clamping attempts to increase the robustness of the clamping operations. The mechanism shall also remain clamped after being powered off.

For controllability reasons it is necessary that the thrust of the deorbit burn engine is transferred through an axis on which both the target and chaser centers of gravity are located. The mechanism shall therefore also provide at least one degree of freedom in order to compensate for any residual misalignment of centers of gravity of the two bodies.

4.3 Pre-Development of a LAR (Launch Adapter Ring) Gripper

Funding Type	TRP
Funding Amount	300 k€
Duration (Months)	12
Deliverables	Breadboard
Currrent TRL: 2 Final TRL: 4	

OBJECTIVES

Design and prototype/demonstrate a robotic end-effector gripper that can be used to capture the Launch Adaptor Ring (LAR) of uncooperative satellites during a debris removal mission. The gripper shall implement a 2 phase capture sequence:

1. Soft capture phase where the gripper encloses the LAR such that the satellite cannot escape as a result of contact forces;
2. Rigidization phase where the gripper securely captures LAR in a deterministic state that allows the interface to handle manoeuvring, stabilisation, and orbital loads .

The gripper shall include various sensors needed to monitor the capture operation and the state of the LAR within the mechanism.

Description

The d.deorbit CDF study identified the robotic gripper mechanism as a key area of technology development. The gripper, which is attached to the tip of the robotic arm, plays a important role in the satellite capture operation as it provides the mechanical and structural interface between the servicer/chaser vehicle and the target satellite during the critical capture and stabilisation operations. Due to the potentially unknown state of the target satellite, the capture operation must be able to handle both cooperative satellites (i.e those in a known state and attitude), and tumbling uncooperative satellites. This translates to a wide range of relative motion rates between the gripper and the LAR at the start of the capture operation. The gripper design must accommodate these relative motion rates while ensuring that the capture operation is reliably completed in timely fashion and without causing the target satellite to tumble out of the capture envelope of the gripper and potentially causing damage to either or both vehicles.

In order to ensure safe capture of the target satellite and reduce the possibility of pushing it out of the capture envelope the capture operation shall be done in two phases:
1. Soft capture phase where the gripper encloses the LAR, ;
2. Rigidization phase where the gripper securely captures LAR in a deterministic state.
The kinematic design of gripper contact geometry and motion profile of the contact surfaces must ensure that both phases are done in quick enough time to minimise the window of exposure to risks during the critical capture phase of the mission, while at the same time forcing the LAR into alignment with the gripper and reaching a deterministic rigidified state that will permit the interface between the LAR and the gripper to

accommodate external loading events (such as manoeuvring the target, detumbling if required, and possibly de-orbit burns)

In order to fulfil the requirements listed above, the gripper must also include a set of sensors that positively detect the state of the LAR and the gripper (e.g. ready for capture, soft capture, rigidized, capture failed). The reported states of the sensors shall be reported to the gripper control software, which uses the information to transition between the various capture modes.

The work required for this activity includes the analysis and design of the gripper system including the capture mechanism, control electronics, and sensor package. A breadboard model of the gripper system shall also be built and used to demonstrate the successful capture of a LAR at various relative motion rates and misalignments.

4.4 Definition of ISS Free Flying Experiment for ADR

Funding Type	GSP
Funding Amount	50 k€
Duration (Months)	12
Deliverables	Test Report
Currrent TRL: 2	Final TRL: 4

OBJECTIVES

The objective is to define a free flying ISS experiment, to test GNC algorithms that control two spheres or cubes connected to each other by a tether, simulating de-orbit phase of a debris captured by the e.deorbit mission using a net.

Description

Today's space debris environment poses a safety hazard to operational spacecraft, as well as a hazard to safety of persons and property in cases of uncontrolled re-entry events. Since 2012, ESA's e.deorbit mission, which objective is to capture and remove a large space debris from orbit – therefore placing European industry in the forefront position on anticipated future active debris removal (ADR) markets –, is being developed through system level activities complemented by a comprehensive technology maturation programme.

As part of the e.deorbit technology developments for space debris rendezvous, capture and re-entry, an experiment using free flying spheres inside the ISS is investigated. The spheres experiment is to test GNC algorithms that control two spheres connected to each other by a tether, simulating the de-orbit phase of a debris captured by the e.deorbit mission using a net.

Task 1: Study the capabilities of free flying ISS experiments based on publications (e.g. http://ssl.mit.edu/spheres/spheresLibrary/projectDocumentation.html#), manuals, past experiments, constraints (e.g. limited space, short experiment duration) etc.

Task 2: Study the proposed e.deorbit post-capture phases (de-tumble and de-orbit) and requirements, as well as technology development results, and identify how a free flying spheres experiment could validate GNC control algorithms. Aspects as scalability of masses, moments of inertia, thrust levels, attitude rates, mass and size ratios of debris-to-e.deorbit, duration of burns, etc. should be taken into account. The simulation of drag at perigee, after several de-orbit burns which have lower the perigee to altitudes where drag plays a role, should be investigated to.

Task 3: Create a test requirements document, system implementation document, and test-plan. Determine what capabilities the free flyinging spheres need to have, and analyse suitability of the required capabilities with existing hardware such as MIT's SPHERES.

4.5 GNC Design and Performance Validation for ADR with Rigid Capture

Funding Type	GSTP
Funding Amount	300 k€
Duration (Months)	15
Deliverables	Report and Software
Currrent TRL: 3 Final TRL: 5	

OBJECTIVES

The objective of the activity is to improve and consolidate the design and performances of the Guidance, Navigation and Control (GNC) system of a chaser spacecraft that actively removes an uncooperative debris from orbit using a robotic arm and a clamping mechanism .This is one of the potential future methods of debris removal being considered by ESA's Active Debris Removal (ADR) mission, e.deorbit.

DESCRIPTION

In 2015 ESA led a TRP study (CLGARD) to design and validate a Guidance & Control (G&C) system for the capture and de-orbit phase of an Active Debris Removal mission using a robotic arm and a clamping mechanism. The multi-body dynamics of the chaser with a robotic arm before capture and of the composite (chaser and target mated with the clamping mechanism) were modelled in MATLAB/Simulink. The CLGARD study managed to develop the G&C of the chaser with the robotic arm for the capture phase (finishes immediately before contact) and the G&C for the composite SC (after clamping mechanism if rigidized). During a CCN there was a preliminary assessment of the FDIR system related to the GNC and an enhancement of the navigation models to improve its representativity.

Tasks description

This activity will work towards the consolidation of an advanced Guidance, Navigation and Control (GNC) concept for active debris removal using a robotic arm and a clamping mechanism. The activity will build from the results of CLGADR study and the phase B1 of e.deorbit. The activity will focus on 1) the improvement of high-fidelity dynamics and equipment modelling, in particular the robotic arm, the clamping mechanism and the SC flexible modes, including the transients during the capture, 2) design of the GNC system, with particular emphasis placed on synchronization motion of chaser with a tumbling target, the combined control of the chaser and robotic arm during capture and rigidization (including transients), detumbling and the deorbiting manoeuvre (two spacecraft coupled by a clamping mechanism), and the demonstration of global stability during these phases, and 3) design the FDIR related to the GNC function including the Collision Avoidance Manoeuvres (CAM) during all mission phases. This activity concentrates on debris removal from circular low-Earth orbits, where ENVISAT is the reference target.

The activity will be broken down in tasks as follows:

Task 1: Consolidation of Requirements and Modelling.
This task shall analyse the results of the latest activities on dynamics and control of the combined chaser - robotic arm and of the composite chaser - clamping mechanism - debris (from CLGADR, 'GNC Simulation Tool for Active Debris Removal with a Robot Arm', and 'Image Recognition and Processing for Navigation (IRN)' studies). The previous analyses and the results from e.deorbit phase B1 shall be used to consolidate the mission scenario and to elaborate the GNC requirements for an Active Debris Removal system that is compliant with the scenario. This task shall consolidate the requirements of a high-fidelity Model-in-the-Loop (MIL) simulation Framework, that will permit testing of the GNC design (e.g. improved models of chaser with robotic arm, sensor models). A real-time PIL test bench shall be developed from the MIL simulator. The task shall create a validation plan, that demonstrates how all the GNC requirements shall be tested and validated using the MIL Framework and the RT PIL test bench.

Task 2: GNC Design and Development.
This task shall design and develop a GNC that satisfies the requirements of Task 1. The Guidance block shall include any feed-forward terms necessary to meet the requirements. The Navigation chain shall be able to provide the required estimates by the controller at the proper frequency, in particular chaser attitude in inertial frame, chaser COM state in inertial frame (or other reference frame required by the controller), target relative pose with respect to the chaser (the sensor suite will be defined from e.deorbit and IRN studies and the measurements model from sensor and image processing derived from IRN results). The robotic arm state shall be estimated (additional sensors in the arm shall be agreed with ESA). The Control block shall be based on modern Multiple-Input Multiple Output (MIMO) control techniques and considered combined control of chaser and robotic arm relative to a tumbling target. A MIL simulator shall be implemented and validated including models from previous activities, in particular CLGADR and 'GNC Simulation Tool for Active Debris Removal with a Robot Arm'

Task 3: GNC Validation and Verification.
This task shall run sufficient tests with the MIL framework to successfully demonstrate the GNC performance of the chaser. The Contractor shall run different tests to validate the GNC design under different robotic arm, clamping mechanism, sensor conditions and assumptions. The contractor shall perform analyses and tests to demonstrate that the switched system is globally stable. The tests shall demonstrate the safety of the capture phase (including the synchronization with a tumbling target according to e.deorbit requirements). A number of tests shall be executed in the PIL test bench to demonstrate the GNC performances in a representative flight processor.

Task 4: Conclusions and Recommendations
This shall summarise the output of this study, including any lessons learned during the course of this study. The Contractor shall also propose future activities to raise the TRL. This activity shall also update the GNC requirements from Task 1 based on the results of this activity and shall review any sensor characteristics and errors that lead to difficulties in

achieving a satisfactory GNC design, based on the results of this activity. The Contractor shall provide a preliminary set of requirements on the sensor suite, in order to feed back into future sensor design. Also the task shall review any robotic arm and clamping mechanism characteristics and uncertainties that lead to difficulties in achieving a satisfactory GNC design, based on the results of this activity. The Contractor shall provide a preliminary set of requirements on the robotic arm, in order to feed back into future robotic arm hardware design.

4.6 GNC Design and Performance Validation for ADR with Flexible Capture

Funding Type	GSTP
Funding Amount	300 k€
Duration (Months)	15
Deliverables	Report and Software
Currrent TRL: 3 Final TRL: 5	

OBJECTIVES

The objective of the activity is to improve and consolidate the design and performances of the Guidance, Navigation and Control (GNC) system of a chaser spacecraft that actively removes an uncooperative debris from orbit using an elastic tether which connects the chaser and the target object. This is one of the potential future methods of debris removal being considered by ESA's Active Debris Removal (ADR) mission, e.deorbit.

DESCRIPTION

In 2013 ESA led several studies assessing the controllability of two spacecraft connected via a tether. In particular, the study Multiple-body Dynamics Simulation Tool for Active Satellite Removal System Modelling (MUST) designed a library of building blocks that allows a control engineer to specify, design, and develop multi-body dynamics for flexible links (tethers) between two space vehicles in MATLAB/Simulink. The AGADIR study (TRP) managed to develop the GNC of a tether joining a target captured by a net and a chaser. Another study known as BOUNCED (Bodies Under Connected Elastic Dynamics) performed a preliminary analysis of the de-orbit burn an elastic tethered system.

Tasks description

This activity will work towards the consolidation of an advanced Guidance, Navigation and Control (GNC) concept for active debris removal assuming the use of an elastic tether. The activity will build from the results of the MUST, AGADIR and BOUNCED studies. The focus of the activity will be on 1) the improvement of high-fidelity dynamics and equipment modelling and 2) design of the GNC system, with particular emphasis placed on the control of the coupled system during the deorbit (two spacecraft coupled by a tether), and the demonstration of global stability during multiple fixed-magnitude deorbit burn ignitions and shut-downs. This activity concentrates on debris removal from circular low-Earth orbits, where ENVISAT is the reference target.

The activity will be broken down in tasks as follows:

Task 1: Consolidation of Requirements and Modelling.
This task shall analyse the results of the latest activities on dynamics and control of the chaser - elastic tether - debris (from MUST, BOUNCED, AGADiR and 'Image Recognition and Processing for Navigation (IRN)' studies). The previous analyses shall be used to consolidate the mission scenario (for instance tether stiffness and damping) and shall elaborate the GNC requirements for an Active Debris Removal system that is compliant with the scenario (e.g. tether pretension). This task shall consolidate the requirements of a high-fidelity Model-in-the-Loop (MIL) simulation Framework, that will permit testing of the GNC design (e.g. improved models of elastic tether, sensor models). A real-time PIL test bench shall be developed from the MIL simulator. The task shall create a validation plan, that demonstrates how all the GNC requirements shall be tested and validated using the MIL Framework and the RT PIL test bench.

Task 2: GNC Design and Development.
This task shall design and develop a GNC that satisfies the requirements of Task 1. The Guidance block shall include any feed-forward terms necessary to meet the requirements. The Navigation chain shall be able to provide the required estimates by the controller at the proper frequency, in particular chaser attitude in inertial frame, chaser COM state in inertial frame (or other reference frame required by the controller), target relative pose with respect to the chaser (the sensor suite will be defined from e.deorbit and IRN studies and the measurements model from sensor and image processing derived from IRN results). The Control block shall be based on modern Multiple-Input Multiple Output (MIMO) robust control techniques. A MIL simulator shall be implemented and validated including models from previous activities, in particular elastic tether from BOUNCED or MUST.

Task 3: GNC Validation and Verification.
This task shall run sufficient tests with the MIL framework to successfully demonstrate the GNC performance of the chaser. The Contractor shall run different tests to validate the GNC design under different tether and sensor conditions and assumptions. The contractor shall perform analyses and tests to demonstrate that the switched system is globally stable. The tests shall demonstrate the safety of the coupled chaser-target during the complete de-orbit phase (including the uncontrolled post-burn flight). A number of tests shall be executed in the PIL testbench to demonstrate the GNC performances in a representative flight processor.

Task 4: Conclusions and Recommendations
This shall summarise the output of this study, including any lessons learned during the course of this study. The Contractor shall also propose future activities to raise the TRL. This activity shall also update the GNC requirements from Task 1 based on the results of this activity and shall review any sensor characteristics and errors that lead to difficulties in achieving a satisfactory GNC design, based on the results of this activity. The Contractor shall provide a preliminary set of requirements on the sensor suite, in order to feed back into future sensor design. Also the task shall review any tether characteristics and uncertainties that lead to difficulties in achieving a satisfactory GNC design, based on the

results of this activity. The Contractor shall provide a preliminary set of requirements on the tether, in order to feed back into future tether hardware design.

4.7 Compact Imaging LIDAR System for Rendezvous and Docking Operations between Spacecraft

Funding Type	GSTP
Funding Amount	500 k€
Duration (Months)	16
Deliverables	Breadboard
Currrent TRL: 3 Final TRL: 4	

OBJECTIVES

Design, manufacture and test of a Miniaturized Imaging LIDAR System elegant breadboard targeting, initially, the identification of isolated space debris and later, with further development, for the rendezvous & docking operation between two spacecraft (such as the ones foreseen in the CleanSpace cross-cutting initiative and its e.deorbit mission). The breadboard shall implement novel technologies, for example high efficiency continuous wave (CW) laser sources, including novel detection algorithms and CMOS detector arrays in order to achieve a high level of compactness and low risk. Such a design will substantially reduce the mass and power consumption, when compared with conventional Imaging LIDAR systems. The test logic shall include the demonstration of the LIDAR elegant breadboard operation and performance in a representative scenario, with cooperative as well as uncooperative static targets.

The developed system should be sufficiently miniaturized such that, in a follow-on phase, a flight model can be accommodated on-board a CubeSat platform and tested in a future CubeSat in-orbit demonstration mission dedicated to close proximity operations (e.g. the CubeSat Active Debris Removal Experiment CADRE or CubeSat autonomous rendezvous and docking experiment).

DESCRIPTION

Imaging LIDARs (LIght Detection And Ranging) are considered a key enabling technology for future exploration missions and for space operations involving the rendezvous between two spacecraft in orbit (such as the ones foreseen in the CleanSpace cross-cutting initiative). These missions need to perform autonomous guidance and navigation operations that require the use of very accurate and high resolution distance measurement systems.

Typically the Imaging LIDAR is designed to acquire the target object from ranges between 5km to 3km, inside a defined field of view, and it is able to track the target down to less than 1m. An imaging LIDAR can be designed to operate with spacecraft with or without cooperative targets. In the case of acquiring and tracking objects without cooperative targets the challenge is to maintain the imaging LIDAR system mass and power consumption budgets within the acceptable levels for its use in a space-based platform, while maintaining the required operational range and accuracy performance. Highly

efficient Continuous Wave (CW) laser systems shall lead to very low power, low heat dissipation, EMI free sub-system elements. Novel CMOS detectors, with high resolution pixel arrays, can be implemented using for example advanced photon counting techniques.
The objective of the proposed activity is to design, test and manufacture an imaging LIDAR System elegant breadboard implementing novel technologies, and focusing on the with cooperative as well as uncooperative targets initially in a static case.
During this activity the following tasks shall be executed:

1. Design of a compact Imaging LIDAR System elegant breadboard with reduced mass and power consumption.
2. Manufacture the elegant breadboard
3. Test the elegant breadboard on static targets.

4.8 Control and Management of Robotics for ADR (COMRADE)

Funding Type	TRP
Funding Amount	1,000k€
Duration (Months)	24
Deliverables	Breadboard
Currrent TRL: 2 Final TRL: 4	

OBJECTIVES

The objective of the activity is to design, develop, and test the control system of a robotic spacecraft (i.e. a servicing spacecraft equipped with a manipulator) tasked to perform an Active Debris Removal mission up to TRL 4. The activity shall comprise the control and management of the spacecraft in combination with the control and management of a robot arm used to grasp, stabilise and hold the target with the aim perform the controlled de-orbit. The focus shall be in:

The increase of the compliance to the mission operational and technological constraints;

The achievement of high levels of Reliability Availability and Safety of the control software.

This activity shall eventually produce the mission vehicle management (MVM) software for the ADR mission validated and verified.

DESCRIPTION

The activity shall address the definition, design coding, verification and validation of the mission vehicle management (MVM) software for the ADR mission. The MVM shall be responsible for:

- the control of 1) the complete robotic spacecraft alone up to grasping, 2) the compound (i.e. robotic servicer + debris) in the following phases of ADR;
- Determine the selection and switching of control modes;
- Failure Detection, Isolation and Recovery (FDIR);
- operation anomaly detection;

The following tasks shall be performed:

- Consolidation of functional, operational, performance and environment requirements for the ADR mission taking into account the mission objectives and constraints;
- Definition of the control architecture, including sensor suite trade-off. This architecture shall also comprise the design of the use and operational modes;
- Detailed definition and analysis of the control algorithms;
- Implementation of a Model In the Loop (MIL) simulator with the complete control system architecture;
- Validation of the simulator and performance tests;

- Implementation of a Processor In the Loop (PIL) test bench consisting on the assembly of the modified MIL with a flight representative processing hardware;
- Verification and validation with the PIL with all sensors emulated or with representative model units procured for this testing;
- Implementation of two Hardware In the Loop (HIL) test benches consisting on the assembly of the PIL and a suitable robot arm on 1) air-bearing proximity testbed 2) dual-robot proximity testbed;
- Verification and validation with the HIL.

4.9 Breadboard of a Multi-Spectral Camera for Relative Navigation

Funding Type	GSTP
Funding Amount	800k€
Duration (Months)	15
Deliverables	Breadboard
Currrent TRL: 3	Final TRL: 4

OBJECTIVES

The objective of the activity is to breadboard a multi-spectral camera based on the preliminary design from a current TRP activity. The multi-spectral camera shall cover thermal infrared, near-infrared and visual spectral bands. The camera specifications shall be derived from the rendezvous with uncooperative targets. The breadboard shall reach TRL 4. The breadboard shall include the optical head, the proximity electronics and the Image Processing Board and algorithms.

DESCRIPTION

In 2014 ESA started a TRP study (Multi-Spectral Sensing for Relative Navigation MSRN) to design a multi-spectral camera that can be used for navigation purposes in a variety of scenarios. The main objective is to increase the accuracy and the robustness of the camera measurements. The activity focused on autonomous navigation systems for missions to uncooperative targets (e.g. active debris removal, asteroids, planetary landing). The navigation shall rely on passive cameras to cover all mission phases. A multi-spectral camera is needed to provide images under any illumination and environmental conditions.
In the case of e.deorbit continuous measurement of the relative states between the chaser and the tumbling target is required independently of the illumination conditions. That is important for safety reasons in the terminal approach to a tumbling target, to perform inspection for characterization of the rotational state of the target, for synchronization and capture.

Tasks description

This activity will work towards the design and manufacturing of a breadboard of a multi-spectral camera including the Image processing board. The design shall follow the results of the MSRN study and consolidate the specifications considering the 'Image Registration and Navigation' study. The activity will focus on 1) the manufacturing of the breadboard of a multi-spectral camera that can be used for the rendezvous and capture of e.deorbit mission and other missions requiring other relative navigation with uncooperative targets, 2) validation of the performances of the breadboard, optical head and image processing board, and 3) update a high-fidelity SW model, and a performance model for faster-than-real-time SW simulators (both models shall have the same interface than the breadboard).

The activity will be broken down in tasks as follows:
Task 1: Specifications and Preliminary Design Consolidation.
This task shall analyse the results of the latest activities on relative navigation for RDV with uncooperative targets (from previous MSRN and 'Image Registration and Navigation' studies). These previous analyses and the results from e.deorbit phase B1 shall be used to consolidate the mission scenario and the camera and image processing requirements for an Active Debris Removal system. The applicability to other missions with uncooperative targets (e.g. AIM) shall be analysed. A validation plan shall be prepared to verify the breadboard manufacturing and validate its performances. The validation plan shall include the SW models, namely, a high fidelity model with image generation and image processing, and a medium fidelity model without image generation but considering shape of the target, relative pose, and environment impact on the image processing output.

Task 2: Detailed Design.
The contractor shall design the multi-spectral camera that satisfies the requirements of Task 1. All the components of the breadboard shall be identified to provide the equivalent functional performances of the flight model. The image processing (IP) board and the IP algorithms shall be jointly optimized considering the mission requirements and the candidate alternative missions. The IP algorithms shall be implemented according to the selected HW/SW implementation. The design shall be validated in a MIL simulator from previous activities configured for e.deorbit mission scenario, including the high-fidelity model of the camera and a representative implementation of the IP algorithms (e.g. fixed-point).

Task 3: Procurement and Integration.
In this task the contractor will perform the procurement of the components of the camera including the required IP cores and SW licenses. The characterization of the components will be correlated with the SW models of the camera. The IP SW shall be embedded in the IP board. The EGSE shall be developed for the validation campaign. Integration tests shall be executed to demonstrate the readiness for breadboard validation.

Task 4: Breadboard Testing
The system tests are executed and analysed. The results are used to correlate the models (both high-fidelity and medium fidelity). The camera specifications are updated. In addition, in this task the contractor shall summarise the main findings, including any lessons learned during the course of this study. The Contractor shall also propose future activities to raise the TRL.

4.10 Hot Gas Plume Characterisation in a Vacuum

Funding Type	GSTP
Funding Amount	500 k€
Duration (Months)	15
Deliverables	Testing Study Report
Currrent TRL: 3	Final TRL: 4

OBJECTIVES

The objective of the present study is a detailed experimental characterisation of mono- and bi-propellant hot gas plumes in low density and near vacuum conditions.

DESCRIPTION

Existing data for low-Newton thrusters typically associated with low-density applications has been collected for cold gas thrusters, however, since in this case the plume is single species, the important features associated with multiple gas interactions in expanding rarefied plumes has not yet been measured (the expansion angle of low density gases exceeds that of high density gases). Current numerical tools such as DSMC (Direct Simulation Monte Carlo) urgently require validation if they are to be used to predict performance and mission requirements for ESA missions. Experimental characterisation of plumes is required for determination of:

- Contamination of solar panels, optical sensors etc. (satellite)
- Parasitic force and torque measurements (all satellite and craft)

ANNEX A ACRONYMS

Acronym	Definition
ADR	Active Debris Removal
CDF	Concurrent Design Facility
CoG	Centre of Gravity
ELV	European Launch Vehicle
GNC	Guidance Navigation and Control
HIL	Hardware in the Loop
IOD	In-Orbit Demonstration
HDRM	Hold Down Release Mechanism
LAR	Launch Adapter Ring
MIL	Model in the Loop
MVM	Mission Vehicle Management
PRR	Preliminary Requirements Review
SRR	System Requirements Review
TRL	Technology Readiness Level

ANNEX B PROCEDURE FOR ACTIVITY APPLICATIONS

Applications for activities being run by Clean Space can be made through ESA's Electronic Mail Invitation to Tender System (EMITS). This is located within the ESA's website at:

http://www.esa.int/About_Us/Industry/Industry_how_to_do_business/ESA_s_Invitation_to_Tender_System_EMITS

More information on activities can be found on the Clean Space website, or alternatively by contacting the Clean Space team at cleanspace@esa.int.