DEFINITION OF AN AUTOMATED VEHICLE WITH AUTONOMOUS FAIL-SAFE REACTION BEHAVIOR TO CAPTURE AND DEORBIT ENVISAT

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ABSTRACT

e.Deorbit is a compelling mission concept that aims to address the most pressing debris challenge for Europe: the post-life disposal of ESA's environmental satellite ENVISAT, which has the highest catastrophic risk-impact of any European spacecraft. This mission is unique in its operational complexity and challenges, and calls for a high fidelity system.

With ESA as the customer, an Airbus DS-led industrial team has developed the system definition to the intermediate System Requirements Review (SRR). The developed concept foresees the Chaser as a constrained automated vehicle with autonomous fail-safe monitoring and reaction behaviour functions. All activities required to approach, synchronise, capture and fix the Target can be performed automatically onboard, with corresponding autonomous monitoring functions. The autonomous monitoring functions are capable of taking onboard decisions if constraint violations are detected to abort the operations and to escape the surrounding of the Target without creating debris. The major results of this Phase B1 study on mission context, mission analysis, safety, system properties, system architectures and capture techniques are reported.

1 INTRODUCTION

1.1 The space debris problem

According to ESA [1] [2], today's space debris environment poses a hazard to the safety of operational spacecraft in space and of people and property on Earth. As of November 2015, more than 5100 launches had placed some 7200 satellites into orbit, of which about 4100 remained in space. Only a small fraction - about 1100 - are still operational today. These are accompanied by almost 2000 spent orbital rocket bodies and a large number of fragmentation debris, caused by the break-up of more than 200 objects, as well as mission related objects. This large amount of space hardware has a total mass of more than 8000 tonnes.

Since 2005, some IADC (Inter-Agency Space Debris Coordination Committee) members have been assessing, under a variety of space debris mitigation scenarios [3], the stability of the LEO space object population and the need to use active debris removal (ADR) to stabilize the future LEO environment. ASI, ESA, ISRO, JAXA, NASA, and UKSA [4] employed their own environment evolution models under a common set of initial conditions and assumptions,

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reaching very similar results. The study confirmed that the current LEO object population will grow even in a scenario with full compliance with existing national and international space debris mitigation guidelines. To stabilize the LEO environment, first of all, mitigation measures need to be applied to the required level, but also additional measures, in particular the active removal of the more massive non-functional spacecraft and launch vehicle stages, should be considered and implemented in a cost-effective manner [5].

1.2 The e.Deorbit study with ENVISAT

During the e.Deorbit ADR studies carried out by ESA, ENVISAT was used as the 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. By targeting ENVISAT, the e.Deorbit mission will remove the largest mass that ESA owns in orbit.

Another reason for studying ENVISAT removal is the complex capture. This is caused by the tumbling motion of ENVISAT, that forces the e.Deorbit Chaser to synchronize its attitude with that of the debris in case of a capture with a robot arm. Furthermore, the solar panel is locked in an unfavorable position, partially blocking the access to one of the strongest and stiffest external points on ENVISAT: its launcher adapter ring (LAR).

The combination of its large mass, complicated capture access, and high collision risk with debris in its current orbit, makes ENVISAT the perfect though ambitious Target for the first ever ADR mission, providing an opportunity for European industry to show case their technological capability to a global audience.

1.3 The e.Deorbit system definition

In the frame of the ESA e.Deorbit Phase B1 study led by Airbus DS with their partners QinetiQ Space nv, DLR-RM, SENER Sp. z o. o., GMVIS SKYSOFT S.A., GMV Innovating Solutions Sp. z o.o. and MacDonald, Dettwiler and Associates Inc., the e.Deorbit mission and the Chaser system were defined for the intermediate System Requirements Review (SRR) based on the analysis of

- the mission context and stakeholders,
- the mission phases and deorbiting,
- the mission risks and hazards,
- the risks mitigations,
- the system properties like capabilities, behaviour and physical characteristics,
- the required autonomy levels,
- the main architectures like functional, communications, GNC, physical, operational and safety
- the Chaser design with the platform and the payload (arm, gripper, clamp, visual-based navigation)
- the budgets (mass, delta-V, propellant, power, energy, data link, RF link, pointing accuracy),
- the technology development, the verification logic and the costing, and
- the definition of the system and architecture requirements.

This paper will present the main results obtained during the Phase B1 study in these different topics and endorsed by ESA at the intermediate System Requirements Review (SRR).

2 E.DEORBIT MISSION CONTEXT

2.1 Mission objective

The e.Deorbit mission objective as stated by ESA is to "Remove a single large ESA-owned Space Debris from the LEO protected zone", the single large ESA-owned Space Debris being ENVISAT.

2.2 Overall mission context

The mission consists of a Chaser (system-of-interest) that is launched by a medium launcher (Vega-C), performs a rendezvous with the Target (ENVISAT), captures it (establish a firm connection) and removes the Target by deorbiting from the LEO protected zone. The rendezvous and capture operations are performed in a LEO environment and are supervised from ground.

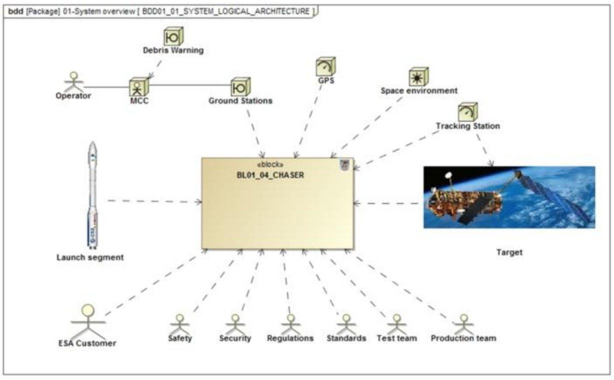


Figure 1. Mission context

The following analysis of the mission context includes the definition of the system-of-interest and the main stakeholders and their relationships.

2.3 System-of-interest

The system-of-interest subject to the definition activities in the e.Deorbit study is the Chaser. The Chaser is a versatile vehicle with different configurations activated according to the mission phase. It starts as a standard satellite to perform orbit rising to the ENVISAT orbit. It continues as an autonomous vehicle to navigate to the close vicinity of the Target. It deploys automatically robotic capture mechanisms to attach itself to the Target with ground supervision. It changes to a new Stack vehicle when firmly connected to the Target for operating the re-entry.

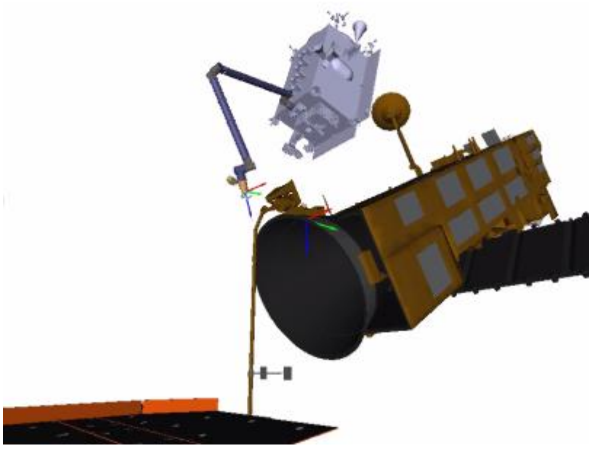


Figure 2. Chaser as system-of-interest

2.4 Launcher

The nominal launcher selected by ESA for this mission is the upgrade of the Vega launcher, named Vega-C. For the sake of the study the reference launch mass was 1573 kg for a 300km circular injection orbit, but a higher performance is expected (the final Vega-C performances are still under investigation).

The backup launcher for the e.Deorbit mission is Soyuz which has a significantly higher capability in terms of volume and mass. So, if the Chaser is compliant with Vega-C, it will be automatically compliant with Soyuz in this respect.

2.5 ENVISAT

Whilst the approach to the e.Deorbit system is one of versatility and adaptability to the state of ENVISAT during development and on-orbit operations, it is important that a strong effort continues on the Target analysis, with a focus on the following aspects:

- The ENVISAT rotational dynamics: the synchronisation to which is a key driver for the mission. These will be characterised in an on-ground campaign prior to launch and also on-orbit during the Target Characterisation Phase. For the purpose of the study a worst case rate of 5deg/s in all axes is assumed.
- The non-passivation: especially in the case of impact on the capture and stabilisation dynamics and the capability of the system (especially joints and closed-loop stabilisation control) to account for this. Some potential consequences may be partly characterisable on-orbit, such as in the case where a non-natural rotational dynamic motion of ENVISAT is observed during the Target Characterisation Phase, indicating on-board AOCS actuator activity. However, not all will be apparent by observation, such as battery residual charge. In the case of the latter, the Chaser must be designed to cope with worst-case scenarios for these events.
- The interface parameters: worst-case relative charging between the Chaser and the Target, structural dimensions and strength for confirmance of the gripper and clamping mechanisms and thermal transient and equilibrium behaviour.

Therefore, a design of the Chaser is required that is able to deal with this kind of uncertainties in the Target status.

2.6 Mission Control Centre

The Chaser spacecraft is an automated system with extended supervision functions. All activities required to approach, synchronise, capture and fix the Target can be performed automatically onboard, with the corresponding supervision functions. The ground supervision functions are intended to provide independent ground supervision and to check the Chaser status health at the control points, which reduces the risk of these activities. Therefore, the ground segment (data links, ground supervision application) shall be designed to minimise data latency, allow a high bandwidth and maximise operator representation of the onboard configuration from multiple sources. All operations and trajectories are verified on-ground prior to their onboard execution.

Another aspect is the teleoperations support for the clamp operations. The operator shall have the ability to prepare a list of telecommands which are then sent to the robot for execution. This is an interactive control of the robot from ground. This does not go as far as telepresence, which is not foreseen in the baseline.

The ground supervision is composed of different functions. The following functions are currently foreseen:

- Supervision of the ‘relative’ GNC subsystem, mainly during all phases where relative navigation is used, with a clear focus on the synchronised flight phase,
- Supervision of the robotic subsystem, during the actual capture of the Target, and
- Supervision of the clamp subsystem, during the

final fixation to the Target.

These capabilities are real-time, therefore requiring a continuous up/down-link to the spacecraft during the time-critical phases. Only very short gaps in the link are allowed. The current assumption is to allow maximum time gaps of 7 seconds (which correspond to a time-to-collision after Chaser engine cut-off during capture). High-rate communications capabilities during critical manoeuvres and capture phases shall be achieved with the support of the ESTRACK ground station network.

2.7 Mission phases

The mission phases during the in-orbit operation of the Chaser are depicted on the following picture and summarized in the table below.

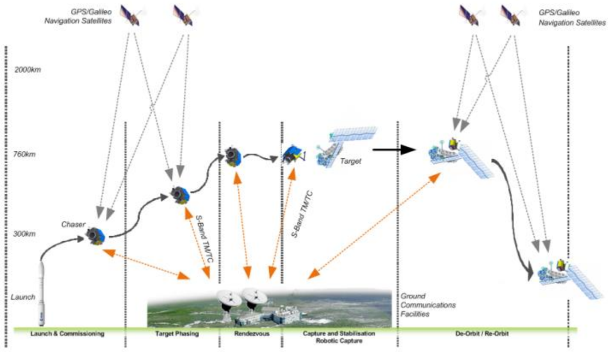


Figure 3. Mission concept

Mission Phase and Description	**Duration**
Launch and Early Operations Phase and Platform Commissioning (LEOP) LEOP starts with launcher lift-off and finishes when the Commissioning phase is ready to be undertaken. On the injection orbit only the platform commissioning is performed.	1 week
Orbit Transfer and Phasing Phase The system performs the transfer of the Chaser from the launch orbit to the orbit of the Target object, carrying out a phasing with the Target object.	10 days
Rendezvous The Chaser performs a rendezvous with the Target object from the Entry Gate (8km behind the target) to the Parking Hold Point (100m behind the target).	4 days
Target characterisation The Chaser shall perform an inspection of the Target and evaluate the structural integrity, attitude dynamics and CoM position. The Rendezvous and Capture shall be performed on battery, so previously the Chaser will charge its batteries.	12h + ground assessment
Synchronized Flight Chaser synchronises its motion with ENVISAT's rotation.	20 min
Target Capture The Chaser performs a forced translation in order to reduce the relative motion between Chaser and Target to levels which are adequate to initiate the capture operations. The Chaser then performs a final approach to the Capture Point (LAR in workspace of robot arm). Capture operations are then conducted, and upon confirmation by the system of successful capture of the Target, the rigidisation is performed. Upon confirmation by the system of successful rigidisation, the Capture Phase is completed.	5 min
Target Stabilisation The Chaser performs the detumbling of the Stack until the attitude envelope required for starting the stack orbit transfer burns has been acquired.	10 min
Coupled Flight Slewing to power optimal attitude for battery charging	3 h
Target Fixation This is the phase when the Chaser is mounted on the ENVISAT LAR with the robotic arm. The trimming phase is to assure that the thrust vector is well aligned on the Stack centre of mass.	6 min + recharge time + SA boom fixation time
Stack Orbit Transfer Once the Stack has acquired a suitable configuration and attitude, the transfer to a disposal orbit is undertaken.	24 hours for orbit determination and recharge time
Disposal Phase Final burn is programmed, the burn attitude is acquired and the burn is executed. As the amount of propellant could be not negligible at the end of the mission, the Chaser is passivated.	2 h

Table 1. Mission phase description

3 CONSTRAINED AUTOMATED VEHICLE WITH AUTONOMOUS FAIL-SAFE REACTION BEHAVIOUR

The Chaser shall have properties that allow both safe and cost efficient operations. The automation level onboard the Chaser should be high to allow cost efficient operations. The operations should also be constrained and combined with onboard monitoring to increase the safety. For such a complex system like e.Deorbit with high safety requirements, the safety properties should be considered right from the beginning in the design process to make sure that the functional architecture and the control structure can effectively implement the system safety that can avoid to the maximum extend the occurrence of accidents leading to debris generation.

3.1 Safety-guided design [6]

Most of the time, hazard analysis is done after the major design decisions have been made. Safety-guided design can be used in a proactive way during the system design by defining accident prevention as a control problem rather than a "prevent failures" problem.

Protection against component failure accidents is well understood in engineering with the use of redundancy and overdesign (safety margins) to protect against component failures. These standard design techniques provide little or no protection against component interaction accidents in a complex system. The added complexity of redundancy designs can even increase the occurrence of these accidents.

After the hazards and system-level safety requirements and constraints have been identified, the safety-guided design starts:

1. Try to eliminate the hazards from the conceptual design
2. If any of the hazards cannot be eliminated, then identify the potential for their control at system level.
3. Create a system control structure and assign responsibilities for enforcing safety constraints.
4. Refine the constraints and design in parallel:
   a. Identify potential hazardous control actions by each of system components that would violate system design constraints. Restate the identified hazard control actions as component design constraints.
   b. Determine what factors could lead to a violation of the safety constraints.
   c. Augment the basic design to eliminate or control potentially unsafe control actions and behaviours.
   d. Iterate over the process on the new augmented design and continue to refine the design until all hazardous scenarios are eliminated, mitigated or controlled.

The highest precedence is to eliminate the hazard. If the hazard cannot be eliminated, then its likelihood of occurrence should be reduced, the likelihood of it leading to an accident should be reduced and, at the lowest precedence, the design should reduce the potential damage incurred. The higher the precedence level, the more effective and less costly will be the safety design effort.

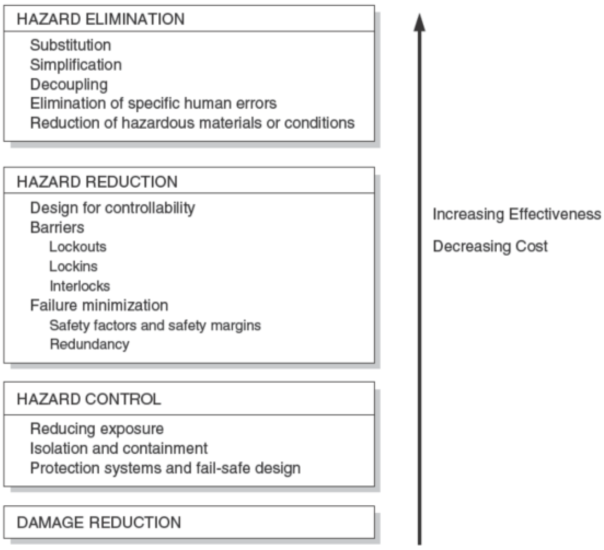


Figure 4. Basic system safety design precedence

The system approach treats safety as an emergent property that arises when the system components interact within an environment. Emergent properties like safety are controlled or enforced by a set of constraints related to the behaviour of the system components. Accidents results from interactions among components that violate these constraints (or from a lack of appropriate constraints on the interactions). Component interaction accidents, as well as component failure accidents, can be explained using these concepts.

In this framework, understanding why an accident occurred requires determining why the control was ineffective. Preventing future accidents requires shifting from a focus on preventing failures to the broader goal of designing and implementing controls that will enforce the necessary constraints. Three basic constructs underlie the proposed method: safety constraints, hierarchical safety control structure and process models.

3.2 Elimination of hazards

The e.Deorbit mission and especially the rendezvous and capture rely on well-known conditions:

- The environment is known: Orbit, dynamic, light conditions. Due to the ENVISAT tumbling the direction to the sun of the Chaser is not constant but deterministic and predictable, after the Target characterization.
- The Target behaviour is known with high accuracy, when the Chaser is in front of the Target and the Target characterisation has been performed.
- The object geometries are known: the Chaser with its appendices like the arm is fully known. The ENVISAT Target is known and the status will be updated once the Chaser is in orbit. Nevertheless, uncertainties on the ENVISAT

status exist, as describe previously.

- The trajectories are known, i.e. the relative pose between Chaser and Target is known after the Target characterization. All trajectories from the launch to the capture point are prepared and verified on ground. Even if some trajectories are generated onboard, they shall be first validated on ground prior to their execution. The determination of the movement of the gripper can also be seen as a form of navigation. In this case too, all the trajectories of the gripper are defined in advanced and are validated on ground in simulation w.r.t. collision, arm configuration and reachability of Target points.
- The system modes are known: The order of operations to approach and capture the Target is fully defined and deterministic.
- The communication to ground is predictable, including the potential communication blockages due to interferences with the Target.

All these knowns shall be integrated in the system design to eliminate the corresponding hazards. For instance, there is actually no need for onboard mission planning. Uncertainties can be resolved in time flexible hold points at safe distance. Like in factory automation, the activity program (in e.Deorbit for rendezvous and capture) is given by the operator and must be followed by the machine. Along the program, the Chaser onboard processing shall adapt its behaviour to small variations due to the environment uncertainties and the Target behaviour. The Chaser is just performing mission execution of a program which is constrained by trajectories and relative poses known in advance at each time step. This is the automation part. One advantage of an automated system is the possible deterministic verification of the single functions which operate in predefined conditions and the known transitions between the system modes.

3.3 Control approach of safety constraints

For the hazards that cannot be eliminated, the system architecture needs to implement functions which guarantee a safe reaction of the Chaser in failure cases. The safety control functions can be defined at following levels:

- Onboard monitoring: The Chaser shall be able to permanently check its system health status and dynamical state (relative pose to Target, speed, rate, internal status) w.r.t. the reference program active for the mission phase. In case of violation of the program constraints the Chaser has to interrupt or abort the current operations. This can mean to stop an approach manoeuvre, to retreat the robot arm or to perform a CAM (Collision Avoidance Manoeuvre). The reaction in failure case is also part of the program. One important part of the system verification will be therefore to automatically test the failure conditions and the Chaser reaction to the maximum extend. The escape trajectories for the platform (CAM) and the robot arm (retreat) are generated onboard at each cycle based on the object geometries and the current relative pose.
- Ground monitoring: At check points, before the Chaser enters a new mission phase, the system shall be checked on ground. At Parking Hold Point the platform navigation data with the LIDAR are checked (the onboard system has no reference data to judge whether the computed Target pose is correct) by an operator. This typically is a plausibility/consistency check rather than a performance check. After the positive ground check, the operator sends a GO command to the Chaser to release the next mission phase, which is then executed automatically onboard and monitored onboard based on the constraints defined for this mission phase. The operator needs to see what the Chaser sees and measures to understand the Chaser dynamic state. Additionally, the operator independently assesses the remote situation with the raw sensor data camera and LIDAR, augmented by visualisation and simulation.
- The CAM delta-V's and the robot arm retreat trajectory are generated onboard. The CAM delta-V calculation is deterministic and is therefore performed fully onboard. The robot arm retreat trajectory is interpolated between pre-planned trajectories in joint space which have been generated on ground. This mechanism is to assure that the Chaser will react properly in a contingency case. The CAM and robot arm retreat are triggered and executed on-board without ground interaction if a contingency case is detected.
- Failure corrections on ground: Without in-orbit validation and qualification of the system during the first flight, it is expected that some failures may occur during onboard initialisation procedures. This concerns mainly the initialisation of the image processing for the navigation of the platform (visual based navigation) and the robot arm (visual servoing). Some consistency checks shall be done onboard with the expected pose, but real accurate reference data are not available for such uncooperative Targets. In such cases, it shall be possible with operator interaction on ground to correct the onboard visual navigation data and to send back this information to the

Chaser to start the tracking with the correct initial object pose.

- Tele-operation: All operations can be performed automatically onboard, from the proximity navigation to the grappling, to the stabilisation, to the clamping and finally the deorbiting. To continue the mission in case of malfunction of the robotic subsystem, the system shall be able to command manually the robot arm from ground in a tele-operation mode. In tele-operation mode the operator prepares increments of the robot movement sent to the onboard robot control system for execution. The increments are repeated until the desired position of the gripper is reached. The tele-operation therefore does not put high requirements on the communications to ground as low bandwidth and high latency are acceptable and the jitter does not matter (tele-operation should not be confused with tele-presence, which is a close-loop direct control of the robot arm from ground with force feedback).
- Ground mission preparation and validation: In the selected approach, the nominal operations and trajectories are prepared on ground to the maximum extend. Trajectories generated onboard like between the Rendezvous Entry Gate and the Safe Hold Point (spiral approach nevertheless not critical as passive safe), and the CAM and arm retreat trajectories shall be monitored and verified continuously on ground. All trajectories shall be verified w.r.t. collisions, configuration and reachability. Basically, the logical approach for the platform navigation and arm / gripper navigation is identical regarding the generation and validation process.

3.4 Constrained automated vehicle

The consequence of the selected safety approach is that the proposed concept will not lead to an autonomous Chaser, as during the operations, there are no onboard decisions on the planning of the nominal operations, but only decisions to abort the operations based on defined constraints. The Chaser disposes of onboard program execution and monitoring and not of onboard autonomy for nominal operations.

The main motivation is to increase the system safety and reliability to the required level by eliminating hazards while discarding full autonomy in the system, and focusing on control with ground mission preparation and onboard monitoring. An operation can only take place if all the conditions are fulfilled at the start of this operation. For each operational phase, limits are defined with margins. The limits are the constraints on the system for each type of operation.

The selected concept to achieve a high mission safety combined with a high automation level and ground supervision relies therefore on a "Constrained Automated Vehicle with Autonomous fail-safe Monitoring and Reaction Behaviour". This means that

1. the Chaser can only execute automatically onboard mission timelines prepared and verified on ground, applying small corrections based on onboard sensor data to adapt its behaviour to changes in the environment and Target dynamic not modelled in detail in the simulators. The Chaser has no onboard mission planning. This guarantees full control on the Chaser behaviour and also on its verification.
2. the Chaser has an independent onboard monitoring chain to observe its own behaviour with sensors independent from the nominal chain and compare the states to predefined safety constraints. In case of constraint violation, the FDIR takes the foreseen actions like a CAM.

4 MAIN SYSTEM PROPERTIES REQUIRED TO CAPTURE ENVISAT

The main properties necessary for the Chaser to safely capture and deorbit ENVISAT are derived from the analysis of the mission context, system-of-interest, mission phases, mission characteristics, risks and safety. The system architectures presented in chapter 5 have been selected for generating these required properties.

4.1 Chaser capabilities

The core capabilities of the Chaser needed to implement the mission rendezvous and capture activities are:

- Station keeping at Rendezvous entry gate (GNC)
- Approach the Target in homing and close range (GNC)
- Capture the Target (GNC + Robotic)
- Stabilize the Target (GNC)
- Attach the Chaser to the Target (GNC + Robotic)
- Control the attitude of the stack (GNC)
- Monitor onboard the approach and capture for safety
- Support bus functions to sustain the operations

The more general capabilities w.r.t. hardware and software delivering the previously defined core capabilities are following:

- The hardware has to survive the launch and to deliver the functions in the space environment of the different mission modes.
- The software controls the functional chains of

the Chaser in the different mission modes for allowing an automatic and safe behaviour.

- Hardware and software are delivering performances in terms of Chaser position, attitude, velocity, rate, accuracy, and communications, power, thermal control.
- Hardware and software are monitoring the Chaser health status and safety constraints to detect failures and react automatically to assure a fail-safe behaviour, i.e. to avoid collision with the Target and the generation of debris.
- The software manages the mission by selecting the prepared and validated mission program according to the mission mode and interacting with the operators as planned (for example wait for GO command at the hold points).

The identified top-level Chaser capabilities for the e.Deorbit mission are represented on the diagram below.

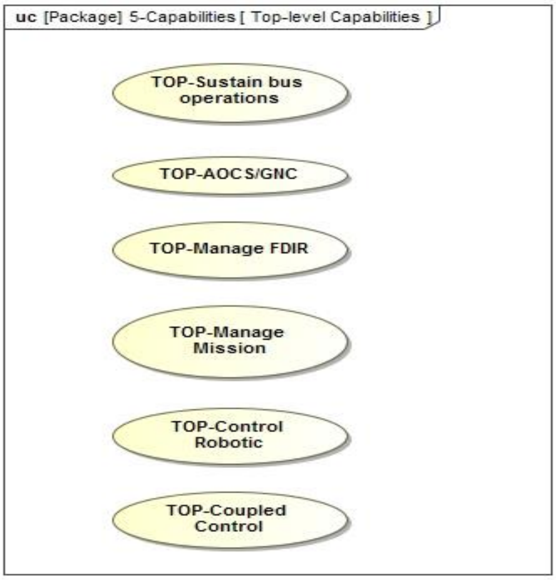


Figure 5. Top-level Chaser capabilities for the e.Deorbit mission

4.2 Chaser behaviour

The Chaser behaviour is characterized by mission phases, Chaser states and Chaser modes as defined in [7].

The system behaviour is defined first with the overall system states: in-validation, in-transport, in-prelaunch, in-launch, in-operation, in-disposal. Then, for each system state, the mission phases are defined. The activity diagram below shows the mission phases for the Chaser system state "in-operation".

Next, the Chaser modes are defined, i.e. which capabilities are used in conjunction with which mission phase. Typically, a mission phase is using specific capabilities of the Chaser and therefore a specific Chaser mode, whereas different mission phases can use the same Chaser mode.

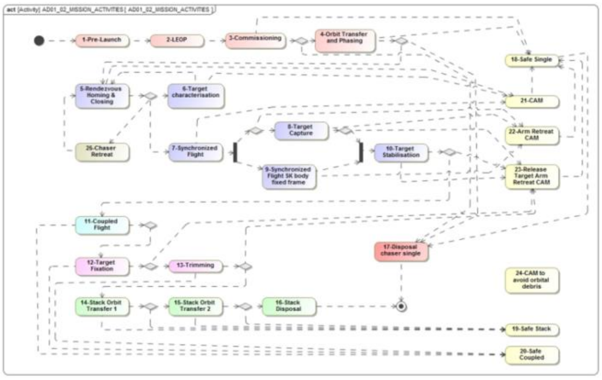


Figure 6. Mission phases for the Chaser system state "in-operation"

The Chaser modes are described as a state machine. The Chaser modes are also a strong mean to define and control the assembly, test and verification activities. The state machine diagram below shows the capture sub-modes including the transitions between the modes.

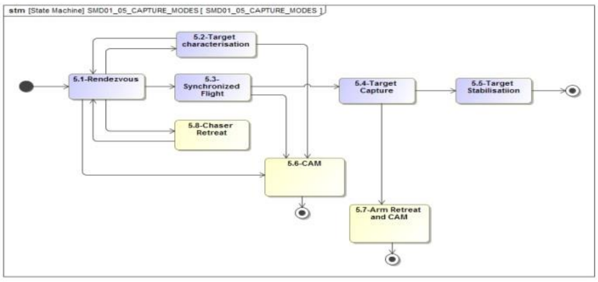


Figure 7. Capture sub-modes embedded in the Chaser mode state machine

It should be noticed that the e.Deorbit mission is characterized by a vehicle which takes 3 totally different configurations according to the operations to be performed in the different mission phases:

1. Standard satellite in absolute navigation mode: After launch separation and commissioning, the Chaser performs an orbit transfer to the ENVISAT orbit and an absolute navigation to 8km behind the Target. In these phases, except the commissioning, the payload (GNC and robotic) is deactivated and the Chaser operates as a normal space vehicle reaching its operational orbit.
2. Autonomous robot with relative navigation and capture capabilities: From 8 km to the capture point and after the stabilisation, the fixation of the Chaser to the ENVISAT LAR, the Chaser is a robot. It is capable of navigating automatically to the tumbling Target, capturing automatically the Target and stabilising it. Then, with robotic arm means it positions the

clamp on the Target LAR for establishing the required firm connection.

3. Stack as new space vehicle: As soon as the Chaser is firmly attached to the Target, a new space vehicle has been assembled in orbit which should not separate again for the remaining of the mission. It can perform automatically with ground support the orbit transfer and the disposal.

Finally, the observable and measureable Operational, Dynamic and Physical States are defined. The Operational States are stored in the Chaser vehicle database which indicates the equipment duty cycles for power and data. The Dynamic States are mainly provided by the GNC architecture generating the GNC states according to the flight phase (e.g. absolute navigation, relative navigation, coupled-control with Chaser platform and robot arm, Stack stabilisation, Stack deorbiting). The Physical States on the Chaser configurations are as well defined in the Chaser vehicle database.

The full behaviour of the Chaser has been described in SysML state machines and activity diagrams which can be as well simulated to validate the system behaviour definition [8] and [9].

4.3 Autonomy levels

The Chaser in its various modes covers indeed all ECSS autonomy levels according to ECSS-E-ST-70-11C:

- E1 - Mission execution ground control; limited on-board capability for safety issues: Covered by the tele-operation during clamping.
- E2 - Execution of pre-planned, ground defined, mission operations on-board: Covered by all nominal mission phases where all operation timelines are prepared and verified on ground prior to onboard execution.
- E3 - Execution of adaptive mission operations on-board: Covered by the onboard definition and execution of CAMs and arm retreats.
- E4 - Execution of goal-oriented mission operations on-board: Covered by the onboard autonomous decision when to apply a mission abort to avoid a collision (Goal-oriented mission re-planning).

4.4 Physical properties

As typical for satellites, the main physical properties are on the mass and the volume. Based on the study results, the targeted mass sharing is as follows:

- Targeted Chaser wet mass: 1573 kg for a 300km circular injection orbit, coming from the currently known Vega-C launcher performances (the launcher mass may be increased in the next release of the Vega-C performances).
- Targeted total propellant mass: 798 kg including all ECSS margins on the different mission phases.
- Targeted Chaser dry mass: 775 kg including 20% system margin.

The maximum Chaser volume of 2216mm in diameter and 3180mm in height is given by the Vega-C fairing.

Constraints on the material properties of the Chaser are related to the Space debris mitigation requirements [5]. Main impacted equipment like the tanks and the batteries are COTS equipment compatible with these requirements.

The accelerations to be applied on the Chaser to implement the selected rendezvous trajectories are other physical properties to be considered. According to the results of the GNC analyses, a max acceleration of 0,037 m/s^2 is required in each direction during rendezvous and capture.

4.5 Chaser / Arm dynamic properties

The major challenges in the close range navigation are the motion synchronisation between Chaser and Target and the coupled control during capture employing the robotic arm. During the coupled control phase, the Chaser performs station keeping at the so-called Capture Point which is a point relative to the Target in the Target body frame. Due to ENVISAT's tumbling motion the Chaser has to follow a trajectory which is determined by the angular rate and by the moments of inertia of the Target. The Chaser has basically to compensate the centrifugal forces along this trajectory. Furthermore, it has to compensate the forces and torques from the robot arm acting at the arm base.

The robot arm has to position the end-effector at the launch adapter ring while compensating the station keeping errors of the chaser platform. The end-effector trajectory has to respect several constraints:

- The launch adapter ring must remain in view of the end-effector camera throughout the complete manoeuver, which implies an inequality constraint on the orientation of the robot end-effector.
- The robot joints shall not exceed position and velocity limits. This also guarantees that robot singularities are avoided.
- The end-effector velocity shall not exceed image processing requirements.
- Collision avoidance between the robot and the Target, and between itself and the Chaser.

The contact forces between end-effector and Target shall be limited in order to avoid significant transfer of energy, bouncing and impulse to the Target. Therefore, the positioning of the end-effector is performed in impedance control mode.

The overall performance of the coupled control in terms of station keeping performance for the chaser and positioning performance of the end-effector was demonstrated in Monte Carlo simulations. The GNC performances required for the e.Deorbit mission are detailed in [10].

4.6 Operations

The mission is very complex from an operational point of view. Where a typical LEO mission is mainly focused on operations with a clear repetitive character, the e.Deorbit mission is very sequential, with new and complex activities following each other at a high pace. Especially the synchronised flight, Target capture and Target stabilisation phase are critical. The onboard system shall be capable of performing all required activities automatically including sophisticated FDIR. The on-ground system shall perform real-time ground supervision based on the raw and processed onboard data.

The required longest period with continuous contact is currently estimated to 19m10s, in which no gaps over 7 seconds are allowed for the ground supervision functions.

During critical mission phases (synchronized flight, Target capture, Target stabilization and Target fixation phase phases), the onboard activities are fully automatic, but ground has the authorization to abort the activity, which in most cases will result in a CAM. These ground supervision functions are required to be able to detect when the operations go out of the nominally planned boundaries. A dedicated set of flight rules (similar to ATV docking flight rules) shall be available to the operations team to ensure clear identification of situations in which ground can interfere and what action to trigger.

4.7 System safety

Safety is defined as the absence of accidents, where an accident is an event involving an unplanned and unacceptable loss. To increase safety, the focus should be on eliminating or preventing hazards, not only eliminating failures. Making all the components highly reliable will not necessarily make the system safe. Safety represents a system property not a component property and must be controlled at system level, not the component level.

As developed in chapter 3, the selected concept to achieve a high mission safety combined with a high automation level and ground supervision relies on a "Constrained Automated Vehicle with Autonomous fail-safe Monitoring and Reaction Behaviour".

5 MAIN SYSTEM ARCHITECTURES AND PERFORMANCES

The system properties identified in the previous section need to be translated in coherent architectures capable to provide these properties [11]. The major architectures of the e.Deorbit system summarized in this section have the goal to provide a Chaser as a constrained automated vehicle with autonomous fail-safe monitoring and reaction behaviour functions.

5.1 Functional architecture

The process of the functional decomposition is started from the capabilities identified in section 4.1. The Chaser top-level functions derived from the capabilities are shared between the platform and the payload.

- The platform functions
  - BL01_01_SUSTAIN_BUS_OPERATIONS
  - BL01_02_PERFORM_ GNC_BUS
  - BL01_03_PERFORM_PLATFORM_FDIR
  - BL01_04_MANAGE_MISSION

manage the platform bus from LEOP to the end of the absolute navigation at the Entry Gate and during the disposal and re-entry mission phases. These are the mission phases where GNC-BUS for orbit and attitude control without GNC-RVC (RendezVous and Capture) is active, either for the Chaser alone or in the Stack configuration after fixation.

- The payload functions:
  - BL01_05_PERFORM_GNC_RVC
  - BL01_06_CONTROL_ROBOTIC
  - BL01_07_PERFORM_PAYLOAD_FDIR

manage the relative navigation phases from the Entry Gate to the Capture Point, the capture phase with the robot arm and the gripper where coupled-control is active, the stabilisation and the fixation.

From these top-level functions the sub-levels functions are further defined together with the ports and connectors between the functional blocks at the same level. This decomposition allows the definition of the functional interfaces up to the Chaser level as depicted on the diagram below.

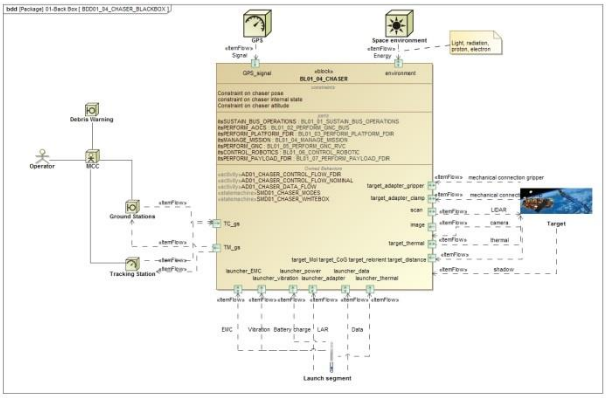


Figure 8. Identification of the system interfaces from the functional decomposition

5.2 Communications architecture

To meet the requirements of this mission, an S-band communication system has been selected [12]. For near-Earth missions, the default frequency band for spacecraft operation is the S-band but due to its popularity, bandwidth restrictions are in force in this band. However, at 5 Mbit/s the requirements for telemetry downlink do not necessarily push towards X-band when using filtered OQPSK modulation, for example. Staying in S-band guarantees the re-use of a lot of the existing flight hardware and support from a maximum amount of ground stations. S-band therefore remains the preferred option for both uplink and downlink.

5.3 GNC architecture

The Chaser is equipped with AOCS sensors, thrusters for attitude control and orbit control, rendezvous sensors, the robotic payload including a clamping system. The AOCS sensors comprise IMU, star tracker, sun sensor and GPS. The rendezvous phase requires narrow angle camera, wide angle camera and LIDAR. The narrow angle camera is also used as inspection camera. The robotic payload consists of the robotic arm, the gripper, the clamping mechanisms and the payload computer. The clamping system is required to rigidly attach the Chaser to the launch adapter ring of the Target. It has a trimming device allowing the alignment of the main engine thrust vector with the stack CoG. The GNC functions are shared between GNC-BUS and GNC-RVC. The GNC-BUS contains the standard satellite AOCS functions as needed outside the Rendezvous and Capture phase whereas the GNC-RVC takes over the entire satellite during Rendezvous, Capture and Stabilisation.

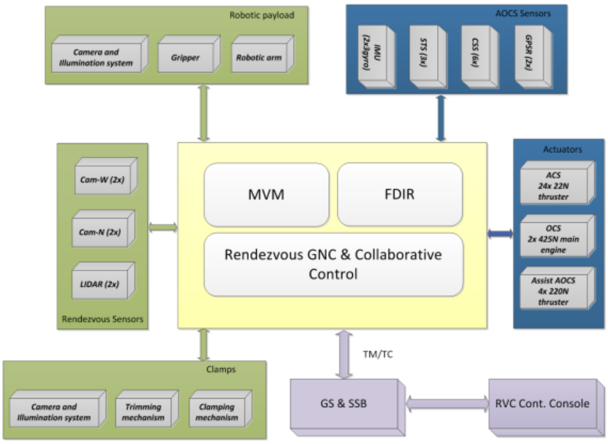


Figure 9. GNC architecture

The central part of the diagram summarises the functions required on board. The payload management function (MVM) is controlling the guidance, navigation and control modes. It also enables and disables sensors and actuators as needed according to the current mission phase and system mode.

5.4 Physical architecture

The Chaser design configuration is mainly driven by the launch mass requirement. The configuration is made as compact as possible and uses a minimal amount of panels to fit inside the launcher fairing and aims for a low mass. The panel configuration is chosen such to have an optimum load path from the payload panel, via the sandwich panels to the launcher interface.

The general layout of the e.Deorbit Chaser configuration is:

- Compact overall design for accommodation inside launcher fairing aiming for low mass
- Optimum load path via sandwich panels to the launcher interface (1194mm, standard clampband)
- Unit accommodation on the inside of sandwich panels in between the propellant tanks
- Upper and lower platform area used for propellant system accommodation
    - 2x 425N Main Engines
    - 4x 220N Assist Thruster in the edges of lower platform
    - 24x 20N Attitude Control Thruster in the edges of upper and lower platform
    - Propellant equipment mainly on the lower platform
- Robotic arm on the –X side of the structure box
- GNC Sensors mounted on top panel:
    - Two LIDARs
    - Two wide angle cameras and two narrow angle cameras
- Clamping mechanism for attachment of the

Chaser on top of ENVISAT.
- Configuration closed by one body mounted solar array panel on sun facing side and MLI / radiator tent on opposite side.
- Two S-Band antennas and two GPS antennas.
- All platform electronic units are located on the +/-Y panels in the same compartment as the propellant tanks. The accommodation of the platform subsystems is mainly driven by thermal optimisation.
- Electronic units close to the tanks in order to use their heat for warming up the propellant (less additional heater power required).
- Electronic units mounted to side panels (+/-Y panels) since the +X panel is too hot (directly behind the solar panel).
- Batteries are at cold side of the spacecraft (-X panel, anti-sun side).

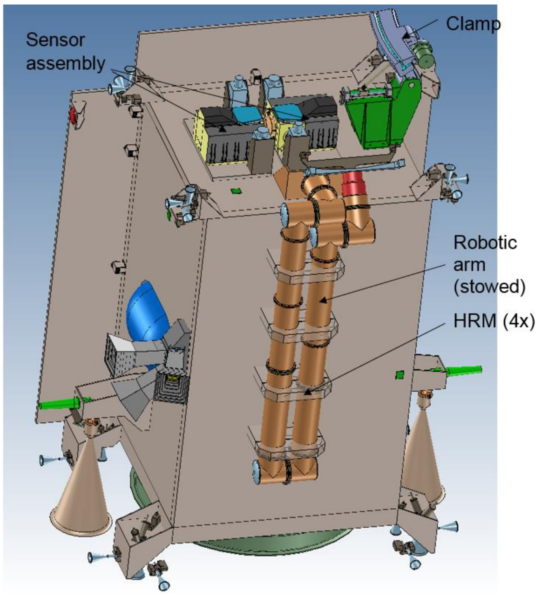


Figure 10. Accommodation of the payload on the chaser

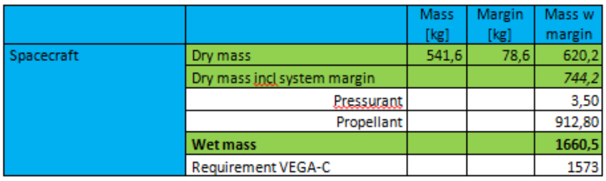
For the solar power generation, a fixed solar panel has been selected. The dimensions are maximised, taking into account the constraints from the launcher envelope and the position of ENVISAT in the clamped configuration. A fixed solar panel has advantages over a deployable solar panel in terms of reliability, dynamic disturbances during manoeuvres, testing and cost.

All payload units related to the capture of ENVISAT are located on the top panel: the robotic arm, the clamp and the visual navigation sensors (LIDAR and cameras). In stowed configuration, the robotic arm is attached to the –X panel using 4 Hold-down and Release Mechanisms (HDRM).

5.5 Chaser budgets

The main Chaser budgets are summarized in this section.

Mass budget



		Mass [kg]	Margin [kg]	Mass w margin
Spacecraft	Dry mass	541,6	78,6	620,2
	Dry mass incl system margin			*744,2*
	Pressurant			3,50
	Propellant			912,80
	Wet mass			**1660,5**
	Requirement VEGA-C			1573

Table 2. Mass budget

The wet mass including all margins is about 87,5kg above the known launch mass. It is however expected that the payload launch mass of Vega-C will be raised to a level compatible with the estimated Chaser wet mass.

Delta-V

A total delta-V for the mission has been estimated to 778 m/s. This corresponds to a total propellant mass of 912,8 kg.

Power budget

The power budget with margins for the power critical phases is

- Arm rigidization: 1287 W
- Coupled flight: 557 W
- Trimming of clamp: 568 W

Data Link budget

The data link budget with 20% margin is for the following mission phases:

- Synchronized flight: 2,824 Mbit/s
- Target capture and stabilisation: 4,052 Mbit/s
- Target fixation: 3,846 Mbit/s

RF Link budget

- Downlink high power, high bitrate – 5 Mbps: 5.4 dB margin
- Downlink low power, low bitrate – 128 ksps:11.3 dB
- Uplink – 64 ksps: 23.0 dB

GNC accuracy budget relative navigation during capture

- Relative attitude: 2 deg
- Relative angular rate: 0,5 deg/s
- Relative position: 0,05 m
- Relative velocity: 0,01 m/s

5.6 Operational architecture

The 3 key teams for this mission are: the Capture Supervision and Control team (GNC & Robotics & Clamp), the Flight Dynamic System (FDS) team and the Platform operations team. The baseline is to have an integrated approach, where these teams are all co-located within the same location and infrastructure. It is believed that this is vital for the operations of the mission, especially during the most critical mission phases (synchronized flight, target capture, target stabilization and target fixation phase).

Although very linked, requirements for the systems to perform platform operations on one side and the Capture Supervision and Control on the other side are quite different. Both systems are therefore seen separate, but with a high degree of interaction between the two. Both shall be under the control of the flight director.

5.7 Safety architecture

The industrial team is confident that an acceptable level of mission risks can be reached, if a combination of architectural decisions, as defined during the study, is implemented.

- The Chaser relies on a high constrained automated vehicle with autonomous fail-safe monitoring and reaction behaviour. All activities required to approach, synchronize, capture, stabilize, fix and deorbit the Target can be performed automatically onboard with the associated monitoring functions using independent sensors.
- The share between onboard and ground activities that allows the maximum of mission planning and validation on ground and ground means to recover interactively from onboard failures. Check points are defined at the main transitions between the Chaser modes for guaranteeing a complete Chaser check.
- Target's attitude and motion are fully characterized at the time of capture and system updated with last information
- Reliable simulation prediction
- Robust GNC performance for proximity operations
- Light independent sensors for Chaser and arm navigation
- Tank selected to limit the sloshing
- Automatic Chaser operations with timeline prepared and verified on-ground including definition of strong safety constraints
- Ground supervision and intervention in all critical phases and in particular during the capture with low latency (400ms).
- A communications architecture that can avoid during the duration of the grappling communication blockages.
- Passive safe Chaser trajectories wherever possible.

6 ROBOTIC-BASED CAPTURE TECHNIQUE

One core technology selected for the e.Deorbit mission is the robotic capture described in this section.

6.1 Robot arm

The chosen robot manipulator configuration is a 7-DoF arm kinematics of 4.2 meters with following values for the complete robot:

Link lengths [mm] = 256, 168, 1900, 168, 1730, 168, 350

This configuration allows the robot to grasp the Launch Adapter Ring of ENVISAT, bring to zero the relative velocity between the Chaser and the Target after capture and subsequently seat the Chaser above the LAR.

The 7 joints provide a redundant kinematics for positioning the end-effector, permitting null-space movements to avoid workspace limits, joint singularities and collisions during all robot operations. The DEOS joints are designed to operate at a maximum rotational speed of 10°/s and are position, as well as torque controllable.

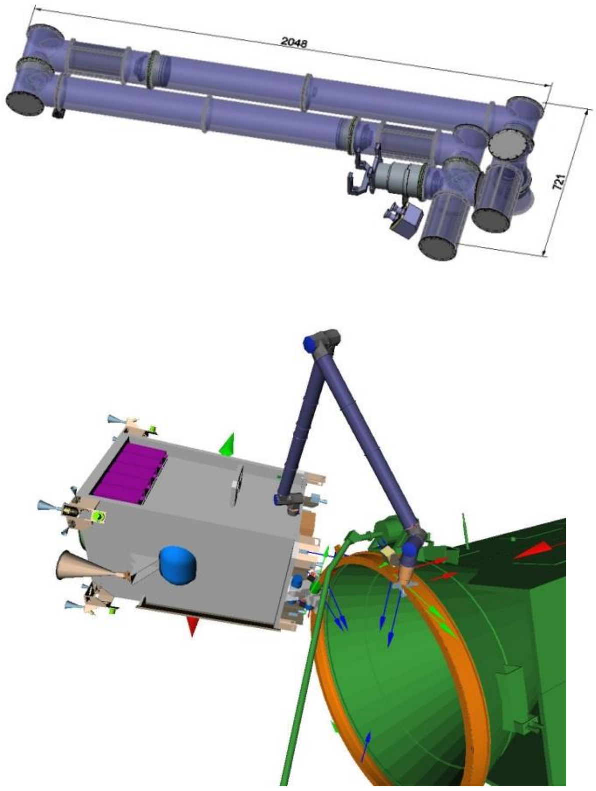


Figure 11. Robot arm configuration (top) and activation during fixation of the clamp after capture (bottom)

This implies that the robot can be controlled in position, impedance or force control modes, in accordance to the best choice for each given task. The design specifications for the joints maximum output torque define a repeated peak torque and a momentary peak torque, of 176 Nm and 314 Nm respectively.

Furthermore, the joint design includes a brake to apply a maximum of 80 Nm.

6.2 Gripper

The Launch Adapter Ring Gripper will be used to establish the first contact between the Chaser satellite and ENVISAT via capturing the ENVISAT LAR. In doing so, it will bear the loads while the Chaser eliminates the residual rates between the two satellites and docks to ENVISAT for the de-orbit. To achieve these mission goals and remain compliant to the system and mission requirements, the LAR Gripper incorporates the following main features:

- A Grasping Mechanism to achieve a rigid connection to the LAR. The grasping mechanism is comprised of two jaw assemblies, a trigger mechanism, a drive assembly, and controller electronics.
- A Vision System formed of two sub-systems; a Situational Awareness Subsystem (consisting of an illumination source and a monochrome camera) to support the visual monitoring of the capture operation, and a Pose Estimation Subsystem (consisting of laser patter projectors, monochrome cameras, and optical filters) to enable the determination of the pose of the ENVISAT LAR.
- The Gripper Structure to which all sub-assemblies are attached, and which provides the mounting interface to the Chaser robotic arm.
- The Thermal Control, which is responsible for maintaining the gripper elements within their acceptable temperature ranges, and is comprised of multi-layer insulation, resistive heater elements, and thermostats.

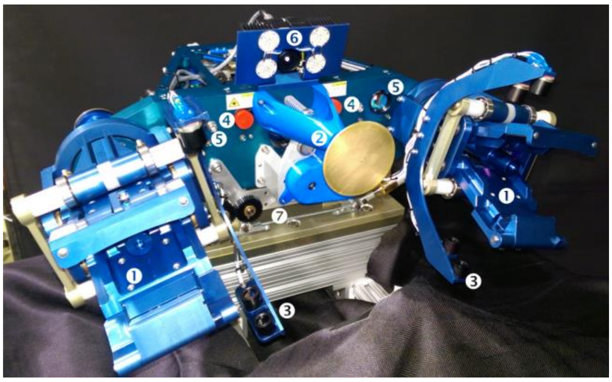


Figure 12. Overview of MDA's patented LAR Capture Tool

6.3 Clamping mechanisms

The Clamping mechanism provides a stiff interface link between the Chaser and ENVISAT. It is foreseen to carry a load of 1600N during de-orbit burns. ENVISAT's Launch Adapter Ring was selected as the default interface for the clamping mechanisms as it offers a clean interface.

The clamping mechanisms consist of the clamps with a locking mechanism (also referred as fixing or fixation mechanism). The Clamps assure self-alignment while closing as well as provide direct contact surfaces between the LAR and the mechanism. The main rotary actuator is composed of a motor with a two stage gearbox and an additional friction brake that is activated in power-off conditions. The locking mechanism, based on a system of linkages with an over-centred locked position, contributes to and maintains a proper locking and rigidisation of the clamps on the LAR. Furthermore, the alignment mechanism is used in order to perform trimming of the thrust vector with ENVISAT's CoG. Multiple sensors, including the stereo camera, rotary or linear position sensors for the actuators (or rotary joints), as well as adequate contact, proximity or force sensors were considered to form the mechanism's closed loop control system. Redundancy and reliability of the proposed clamping mechanism were central to the overall design.

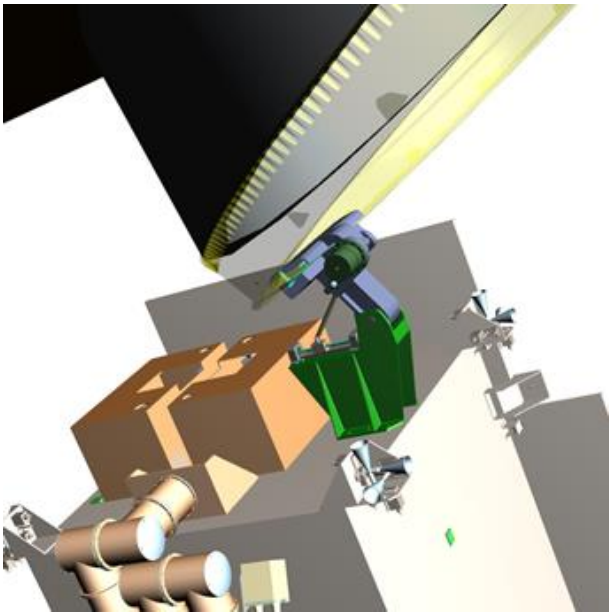


Figure 13. Overall view of the clamping mechanism as a stiff connection between the Chaser and the Target

7 INNOVATIVE SOLUTIONS

In the course of the study, innovative solutions were identified in the following domains:

- In-orbit characterization of the Target based on measurements from Chaser sensors
- Navigation to uncooperative Targets in all lighting conditions
- Synchronized flight with a tumbling Target
- Capture and stabilization of a tumbling Target

with a robot arm in compliant mode
- Gripper integrating fast soft capture and grasp rigidization, and light-independent sensor system for visual tracking
- Coupled-control between the Chaser platform and the robotics
- Full automatic robotic system with optional ground supervision
- Onboard monitoring concept for safe automatic operations
- Definition of a robust communications concept including onboard communications architecture and ground station selection
- Concept of operations with onboard and on-ground activity sharing
- Reuse of technologies for and from other on-orbit servicing missions like the spacetug
- Implementation of a MBSE process based on SysML and vehicle database

These innovative solutions could be first fully validated in the e.Deorbit mission, and then further deployed in on-orbit servicing missions like the Spacetug or exploration missions.

8 CONCLUSION

Central to the e.Deorbit mission is the rendezvous of a Chaser with a defunct satellite followed by its capture, stabilisation, fixation and disposal. An important part of the Chaser properties are related to safety for avoiding the generation of new debris due to potential collisions and also to mission efficiency.

The proposed approach to translate the Chaser properties to architectures for achieving a high mission safety, combined with a high automation level and ground supervision, is the concept of a "Constrained Automated Vehicle with Autonomous fail-safe Monitoring and Reaction Behaviour". Additionally, during the Airbus DS-led study it was shown that the architectures and technologies selected for the system comply with the required mission costs of 150M€ for the phases B2/C/D/E1.

Major achievements were made on the definition of the mission phases and activities, the architectures and their dependencies, the system limitations w.r.t. the Target tumbling rate, the required system performances, the safety approach, the autonomy concept and operations, the reuse approach for other OOS missions [13] and in general on the system definition to implement a safe active debris removal [11].

One limitation identified on the system performance is the worst case tumbling rate of 5deg/s of the Target. This pushes the propulsion and robot arm subsystem to the limit of their performance in the actual system configuration. As the ENVISAT tumbling rate is expected to decrease in the coming years, it is envisaged at ESA to relax the worst case tumbling rate to 3,5deg/s. New technologies with an actual TRL below 6, such as the visual based navigation (camera and image processing), robot joint, gripper, clamping mechanisms, monitoring software and payload computer, will also need further technology development, as planned by ESA for the next e.Deorbit maturation phase.

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