# DESIGN AND DEVELOPMENT PLAN OF A TENTACLES BASED CLAMPING MECHANISM FOR ACTIVE DEBRIS REMOVAL
# 13TH SYMPOSIUM ON ADVANCED SPACE TECHNOLOGIES IN ROBOTICS AND AUTOMATION

Jan-Christian Meyer [(1)], Marc Scheper [(1)], Javier Vazquez Mato [(2)], Ronan Le Letty [(3)]

[(1)] OHB System AG, Universitätsallee 27-29, 28359 Bremen, Germany, jan-christian.meyer@ohb.de
[(2)] SENER Ingeneria y Sistemas S.A., Spain, , javier.vazquezm@sener.es
[(3)] ESTEC ESA, Noordwijk, The Netherlands, ronan.leletty@esa.int

## ABSTRACT

Space-debris around Earth is becoming a more and more significant threat to the proper functioning of our satellites in orbit. The active removal of five large debris objects per year from low Earth orbit (LEO) seems to become mandatory for the near future to stabilize the debris population there. Case studies of potential targets led to the conclusion that after its failure in April 2012 the ESA-owned ENVISAT is the target of the highest interest due to its high mass of approximately eight tons and its orbit (800km/98°) in one of the most densely populated regions with a high orbital lifetime. The de-orbiting of the non-operational ENVISAT was investigated within the ESA-funded phase A system study called “e.Deorbit”. Capturing of a non-cooperative satellite like ENVISAT is one major challenge of such a mission. As one of the most promising options the “assessment and simulation of a tentacles based capture mechanism for ADR” is performed. This activity works towards the design of a clamping mechanism concept to capture the debris and ensure a stiff link between the chaser and the target during the de-orbiting phase. This clamping mechanism follows a “capture before contact strategy”.

The baseline concept is constituted by two tentacles for target capture, and four linear actuators for target clamping and preload. Each tentacle consists of a double boom allocated at the chaser satellite’s middle plane. The clamping and preload function is provided by four linear actuators located at the corners of the chaser’s top panel.

The preliminary design is supported by a multi-body simulation of the capturing operation. The paper will show the design of the clamping mechanism as well as the results of the multi-body simulation of the mechanism operations. The operational and functional designs have also been developed and will be presented. Furthermore, the programmatic aspects of developing the mechanism are laid out. This includes both system and technology developments as well as a verification tests plan.

## 1. Nomenclature

| | |
|---|---|
| ADR | Active Debris Removal |
| ADRM | Active Debris Removal Mechanism |
| AOCS | Attitude and Orbit Control Subsystem |
| CoM | Centre of Mass |
| CTM | Collapsible Tube Mast |
| HDRA | Harmonic Drive Rotary Actuator |
| HDRM | Hold-Down and Release Mechanism |
| IBDM | International Berthing and Docking Mechanism |
| LEMA | Linear Electro-Magnetic Actuator |
| LEO | Low Earth Orbit |
| LLA | Long Linear Actuator |
| MBS | Multi-Body Simulation |
| PDR | Preliminary Design Review |
| TC | Telecommand |

## 2. Introduction

The work presented in this paper aims at defining a concept for a tentacles based capture mechanism for active debris removal. After an initial survey of existing technology and components in the field of mechanisms for space applications, a baseline concept is defined based on a set of requirements. These requirements have been derived from mission objectives and spacecraft interface constraints. Likewise, the design of the mechanism poses constraints on the design of the hosting spacecraft. This bidirectional interaction demands on the one hand a close collaboration between the teams working on the mechanism and on the satellite; on the other hand it allows for an optimised implementation of the mission requirements.

## 3. Background

Space agencies and satellite operators have acknowledged the threat of in-orbit collisions between active satellites and uncontrolled, man-made objects known as space debris [1]. In satellite missions planned or launched today it is common practice to account for the post-mission disposal of the satellite outside of the most frequently used orbital regions, called LEO- and GEO-protected region [2].

Historically, this has not always been the case, which is why the number of objects in Earth orbit is currently very high. Recent models estimate about 29,000 objects with a size larger than 10 cm [3]. A collision with such an object would not only most likely lead to the loss of the spacecraft, but would in addition create a cloud of new debris [4]. Simulations of the future development of the debris population indicate that an active removal of five to ten large objects per year is required in order to stabilize the situation in LEO [5][6].

The selection of an object to remove should consider its mass, its probability of collision with other objects and its orbital altitude [6]. One high priority target is ENVISAT, an uncontrolled, ESA-owned satellite of approximately eight metric tons in an orbit of about 800 km altitude and 98° inclination. Recently ESA has performed a phase A study called e.Deorbit. It aimed at identifying the most suitable concept for the capture and active removal of such a large debris object [7]. ENVISAT has been chosen as an exemplary target by the industrial partners.

One option investigated in e.Deorbit was the capture with a robotic arm and the creation of a stiff connection between the chaser spacecraft and the target by a clamping mechanism. While not part of the phase A system study, the work on the clamping mechanism presented in this paper was conducted in parallel and in close cooperation to it.

The presented design concept is therefore constrained by the satellite system design as well as the presence of a robotic arm performing the initial capture of the debris object.

## 4. Methodology

The activity is performed in the following steps that are further detailed in this chapter:

- Mechanism and operations requirements
- Trade-off and mechanism baseline selection
- Multi-body simulation
- Detailed mechanism design
- Programmatics

### 4.1. Mechanism and operations requirements

This task lays the groundwork for the follow-up study in conducting research on the state-of-the-art in mechanisms technology. The operational concept of the capturing process is defined. A close interaction between physical and operational design results in the set-up of major mechanism and operations requirements needed to define the mechanism baseline concept and to define the necessary inputs for the multi-body simulation.

### 4.2. Trade-off and mechanism baseline selection

The objective of this step is the selection and detailed description of a baseline concept for the capturing mechanism. A standard approach using weighted criteria as a metric for the trade-off is followed. The selected baseline concept will be elaborated in more detail in order to provide sufficient input for the ensuing multi-body simulation.

### 4.3. Multi-body simulation

This step has the objective of developing a multi-body simulation of the capturing operation. The simulation is established with a commercial, dedicated software tool and validated by experts in both space mechanisms and multi-body simulations. Based on a worst-case analysis the compliance of the baseline mechanism to the requirements is shown.

### 4.4. Detailed mechanism design

With the design verified through analysis a detailed description and justification is elaborated. This is accompanied by a refinement of the operational concept tailored to the selected baseline concept and assessed in the multi-body simulation.

### 4.5. Programmatics

The final task establishes the roadmap for the development of the required new technologies and the system maturity. Considering aspects from component- to system-level a timeframe for the expected development efforts is established. It is completed by an investigation and definition of a validation test plan.

## 5. Mechanism and operations requirements

Based on the objectives of the activity provided by ESA, a preliminary set of requirements for the mechanism has been established. They distinguish between the mechanism design and its operation.

### 5.1. Mechanism concept survey

The ADRM main functions considered are:

- Provide a stiff and compact stow configuration within the chaser dimensions to support the launch environment
- Deploy to “ready to capture” configuration allowing maximum capture range for the target dimensions, detection range, uncertainty box and capture time.
- Perform capture/release of the target with the speed required to accomplish the capture time, and with minimum contact to the target. This operation shall be reversible if needed.
- Perform tranquilization of the target by controlled contact forces, providing the required damping.
- Clamp the target with the required composite stiffness. This operation shall be reversible if needed, and the ADRM shall be able to release a clamped target.

To accomplish these functions different ADRM architectures have been developed based on the following well-known, existing and proven components:

- Booms
- Capture mechanisms
- Spring hinges, deployment dampers, latches and end stops
- Hold down and release mechanisms
- Rotary actuators
- Active damping linear actuators

Based on these components several mechanism architectures have been defined and preliminarily sized. They differ in the number and size of the tentacles, the concepts used for dampening the target's relative motion and the accommodation on the chaser spacecraft.

## 5.2. Operational concept

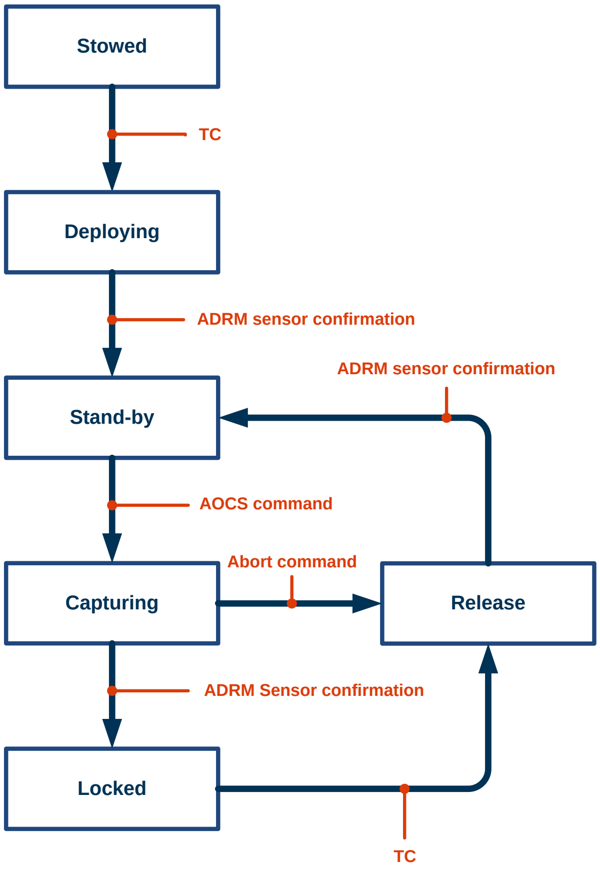


Fig. 1: Clamping mechanism state diagram

The clamping mechanism is operated in the context of an ADR mission. Initially it was intended to use the mechanism as a stand-alone capturing payload. During the course of the study this requirement was relaxed and the design of the clamping mechanism considers that the initial capture of the target is performed by a robotic arm.

The mechanism is controlled via commands coming either from ground control or from the on-board avionics of the hosting satellite. The commands initiate transitions between the mechanism states as shown in Fig. 1.

## 5.3. Target Definition

The clamping mechanism study was performed in parallel to the ESA phase A study called e.Deorbit which focusses on the capture and active, controlled de-orbit of ENVISAT. Consequently, the definition of the nominal target for the clamping mechanism study has been aligned with that of e.Deorbit.

Basic geometrical and kinematic parameters of the ENVISAT body as currently estimated are given in Table 1. The corresponding coordinate system is a target-fixed frame with the origin in the centre of the launcher interface ring, the x-axis perpendicular to the separation plane. The values for the body size are the ones relevant for the mechanism design

| Property | Value | Unit |
|---|---|---|
| body size in x | 10020 | mm |
| body size in y | 2750 | mm |
| body size in z | 1600 | mm |
| x_CoM | -3905 | mm |
| y_CoM | -9 | mm |
| z_CoM | 3 | mm |
| Mass | 7828 | kg |
| Ixx | 17023 | kg m² |
| Iyy | 124826 | kg m² |
| Izz | 129112 | kg m² |

Table 1: Target properties

## 5.4. Chaser definition

Properties of the chaser spacecraft are derived from the design in phase A of the e.Deorbit study. Relevant parameters are reported in Table 2.

| Property | Value | Unit |
|---|---|---|
| body size in x | 1450 | mm |
| body size in y | 1600 | mm |
| body size in z | 2200 | mm |
| Mass | 1435 | kg |
| Ixx | 892 | kg m² |
| Iyy | 837 | kg m² |
| Izz | 558 | kg m² |

Table 2: Chaser properties

## 6. Mechanism Baseline Selection

The selection of the baseline concept for the clamping mechanism is supported by a trade-off among a range of concepts.

### 6.1. Mechanism Options

A total of nine mechanism concepts were developed. It should be noted that not all concepts have been identified in parallel. Some are an evolution of others, designed by adapting certain aspects when it became clear that the initially proposed design had some drawbacks. The options considered were:

- A - Four two-boom tentacles
- B - Booms on a 4-link mechanism
- C - Four one-boom tentacles
- D - Collapsible tube mast tentacles
- E - 3-boom tentacles optimised for accommodation
- F - Linear stroke clamp
- G - Angled one-boom tentacles
- H - One-boom tentacle positioned by linear actuator
- I - One-boom tentacle positioned by rotary actuator

### 6.2. Trade-off results and baseline selection

Before the scores were assessed for the different options, any knockout criteria were looked at in order to avoid unnecessary design efforts.

For option D the performance criteria led to the exclusion from the detailed trade-off. The collapsible tube option D cannot perform the capture in the required period. Indeed, while all other mechanisms perform the capture within seconds or a couple of minutes, option D requires about eight minutes for capture. This is considered too long.

The other options are all assessed in each criterion and the weighted sum is calculated. The results are shown in Fig. 2. Details on the scoring in each category and criterion are omitted here as this would exceed the scope of this paper.

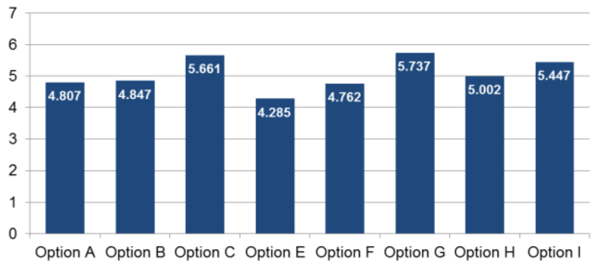


Fig. 2: Trade-off result – total score for each option. Option D has been excluded for not meeting performance requirements

It can clearly be seen that three options have a score of more than 5 points. As their scores are close together and their order is very sensitive to the scoring in the most important criteria they have been compared to each other to select the baseline concept.

They are option C, G and I. This is not surprising because option G is derived from option C. Moreover, option I is specifically designed to fit onto the e.Deorbit platform. The fact that option C requires a lateral accommodation of the chemical propulsion subsystem is a major drawback of this option. In option G this has been avoided by changing the tentacle design. Option I is also incorporating this advantage. However, uses only two tentacles, which leads to a significantly lower mechanism mass. In this case the same advantages apply as in option G with the addition of reducing even further the mechanism mass.

Consequently option I is chosen as the mechanism baseline concept.

## 7. Mechanism Design

This section presents the design of the clamping mechanism.

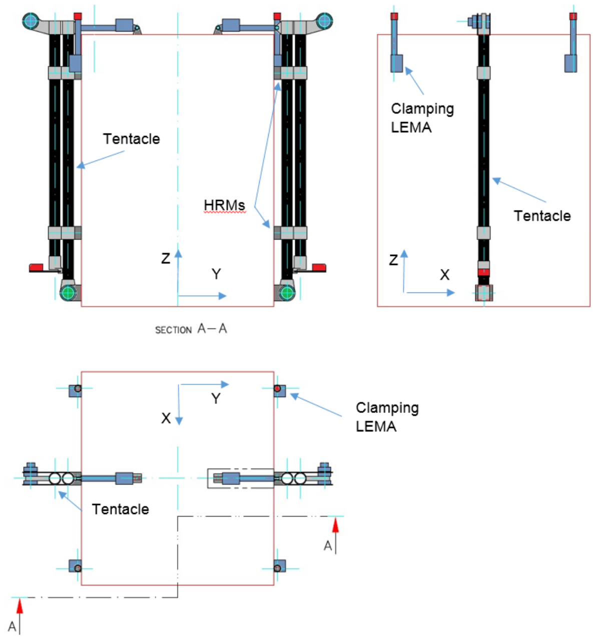


Fig. 3: Sketch of the stowed mechanism concept

The ADRM Baseline concept is constituted by two tentacles for target capture, and four linear actuators for target clamping and preload.

Each tentacle consists of a double boom allocated at the chaser's middle plane, on its +y-face and –y-face. The tentacles are stowed for launch, supported by two HDRMs as shown in Fig. 3.

The clamping and preload function is provided by four linear actuators located at the +z-corners of the chaser's +y-face and –y-face.

In a first approach each tentacle can be driven by a linear actuator located at the chaser's +z-face for position control of its first degree of freedom. With this configuration a certain adjustment in the relative position between chaser and target along the y-axis can be possible.

The tentacle's second boom is deployed by the HDRA placed at the double boom elbow, up to a ready for capture position.

Capture can be achieved by rotation of the second boom at constant angular velocity or a combination of rotation of the second boom and closing of the first boom aperture.

The clamped stiffness is based on the high contact stiffness of the LEMAs that is maintained in contact by the tentacles' tip leaf spring preloaded. The preload shall maintain the contact against the specified loads and has been estimated at about 800 N per tentacle.

### 7.1. Components

The components of the mechanism are presented in Fig. 4.

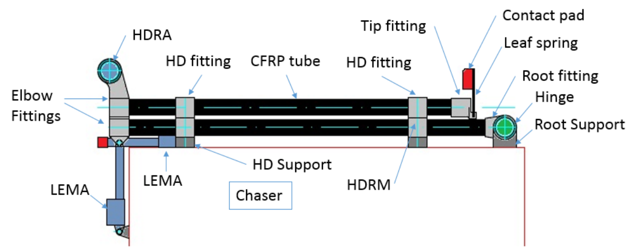


Fig. 4: Tentacle components

The tentacle is constituted by two CFRP booms with titanium or aluminium fittings.

The tentacle has a hinge at the first boom, allowing rotation between the root fitting and the root support. Additional hinges are required at both tips of the linear actuators of the tentacles.

The position control of the first degree of freedom of the tentacle can be made with a LEMA. This actuator allows a small deployment angle of the first boom and shall provide sufficient holding force to maintain the ADRM configuration under the de-orbit loads.

Each tentacle has a Harmonic Drive Rotary Actuator (HDRA) at its elbow. The HDRA is a full European, ITAR free product, developed by SENER in a co-funded program with ESA.

Each boom tip fitting can allocate a set of leaf springs to allow a flexible contact for preload control.

The clamping and preload system includes the necessary elements for closing the capture envelope up to the target dimensions and preload the target to maintain the composite stiffness required.

## 8. Programmatics

The required technology developments for the clamping mechanism are very little. In fact, only the linear actuator based on the IBDM LEMA has to be further developed in order to meet the clamping mechanism's requirements. This development can be started in parallel to the development and detailed definition of the mechanism itself. In this way, the overall development time is reduced to a range between two and three years until the product is qualified for use in a space application.

The proposed verification plan represents a suggestion. The final verification test plan, of course, depends on the system verification strategy.

The test philosophy is based on two ideas intended to combine high reliability with low effort. Wherever possible system level requirements should be flown down and tested on component level. Secondly, tests are preferred over other verification methods because of their comparatively high validity.

A detailed investigation into possible functional test scenarios has been made. A separation of deployment and capture tests is proposed. The capture tests will contain several tests simulating the uncertainty about target characteristics.

Finally, relevant test facilities have been identified and their characteristics highlighted. For the selection of one of them the requirements to the tests have to be specified and compared to the detailed capabilities of the different facilities.

## 9. Conclusion

A concept for the design of a tentacles based clamping mechanism has been created based on the results of a dedicated trade-off. The trade-off investigated a wide range of potential solutions and selected the one most suitable for the reference ADR mission planned by ESA and called e.Deorbit.

The baseline concept features two tentacles with two degrees of freedom each. This design was found to provide the best combination of high performance at low risk and low cost.

The design has been matured to a PDR level by defining the development and verification plan. The latter includes the model philosophy, definition of test procedures and identification of test facilities.

## 10. References


[1] ESA, *Space Debris Mitigation*, 21 January 2014, http://www.esa.int/Our_Activities/Space_Engineering/Clean_Space/Space_debris_mitigation, Accessed: September 2014

[2] ISO 24113:2011(E), *Space systems – Space debris mitigation requirements*, Second edition, Switzerland, 2011

[3] ESA, *How many space debris object are currently in orbit*, 25 July 2013, http://www.esa.int/Our_Activities/Space_Engineer

ing/Clean_Space/How_many_space_debris_objects_are_currently_in_orbit, Accessed: July 2014

[4] Klinkrad H., *Space Debris – Models and Risk Analysis,* Springer, Praxis Publishing, Chichester, UK, 2006

[5] Liou J., *An active debris removal parametric study for LEO environment remediation,* Advances in Space Research, 1 June 2011, 47(11), p. 1865–1876

[6] Wormnes K., Le Letty R., Summerer L., Schonenborg R., Dubois-Matra O., Luraschi E., Cropp A., KraG H., Delaval J., *ESA Technologies for Space Debris Remediation*, 6th European Conference on Space Debris, Darmstadt, Germany, 2013

[7] Biesbroek R., *Introduction to e.Deorbit*, e.Deorbit Symposium, Noordwijkerhout, The Netherlands, May 2014

[8] Urgoiti E., Hurtado E., Gabiola I., *Performances of Linear Electro Mechanic Actuators (EMA) for the International Berthing and Docking Mechanism (IBDM),* 13th European Space Mechanisms and Tribology Symposium. Vienna, September 2009, ESA SP-670