EXECUTIVE SUMMARY

DETUMBLING

ESA Contract No. 4000113022/ 14/NL/MV

Prepared by: Pedro Arroz (GMV), Fernando Gandía (GMV)

Approved by: Fernando Gandía

Authorized by: Fernando Gandía

Code:	GMV-DETUMBLING-ESUM
Version:	1.0
Date:	2017/09/04
Internal code:	GMV 24102/17 V1/17

GMV
Isaac Newton, 11; PTM Tres Cantos; Madrid 28760
Tel. +34 918072100; Fax. +34 918072199
www.gmv.com

DOCUMENT STATUS SHEET

Version	Date	Pages	Changes
1.0	2017/09/04	50	First version

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

1. INTRODUCTION

1.1. PURPOSE

This document is issued in the frame of WP 4200: Study Conclusions, roadmaps and future plans. It contains a summary of all relevant outputs from main project technical tasks.

1.2. SCOPE

This document contains a summary of relevant outputs from all project tasks (from TASK 1 to TASK 4).

1.3. DEFINITIONS AND ACRONYMS

1.3.1. DEFINITIONS

Common definitions used in this document are included in the following table:

Table 1-1: Definitions

Term	Definition
GNC	Guidance, Navigation and Control. Functions in charge of targeted orbit and attitude computation, attitude and orbit determination, attitude and orbit control. GNC versus AOCS: the term AOCS is commonly used when the orbit guidance is not performed on board. GNC is commonly used for the on-board segment, when the satellite position is controlled in closed loop.
GNC mode	State of the GNC for which a dedicated set of equipment and algorithms is used to fulfil the operational objectives and requirements
Validation	The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers.
Verification	The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process. Contrast with validation.

1.3.2. ACRONYMS

Acronyms used in this document and needing a definition are included in the following table:

Table 1-2: Acronyms

Acronym	Definition
AD	Applicable Document
ADR	Active Debris Removal
AOCS	Attitude and Orbit Control System
CAM	Collision Avoidance Manoeuvre
COM	Centre of Mass
CPU	Central Processing Unit
DI	Dynamic Inversion
DOF	Degrees of Freedom
ESA	European Space Agency
FDIR	Fault Detection Isolation and Recovery
FES	Functional Engineering Simulator
FG	Geometric Frame
FI	Inertial Frame
FMC	Forced motion control
FMCC	Forced Motion Control of Composite
GEO	Geostationary Earth Orbit
GNC	Guidance Navigation and Control
GNCDE	GNC Development Environment
HW	Hardware

Acronym	Definition
IMU	Inertial Measurement Unit
LEO	Low Earth Orbit
LFT	Linear Fractional Transformation
LIDAR	Laser Imaging Detection and Ranging
LQG	Linear Quadratic Gaussian
LQR	Linear Quadratic Regulator
LVLH	Local Vertical Local Horizontal
MB	Multi-Body
MCI	Mass, COM and Inertia
MEO	Medium Earth Orbit
MIB	Minimum Impulse Bit
MIMO	Multiple Input Multiple Output
MLI	Multi Layer Insulation
MPC	Model Predictive Control
MVM	Mission and Vehicle Management
OB	OnBoard
PID	Proportional, Integral, Derivative
POD	Precise Orbit Determination
QFT	Quantitative Feedback Theory
RD	Reference Document
RP	Robust Performance
RS	Robust Stability
RVD	RendezVous and Docking
S/C	Spacecraft
SLR	Scanner Laser Ranging
SMC	Sliding Mode Control
SSO	Sun Synchronous Orbit
SSV	Structured Singular Value
SW	Software
TBC	To Be Confirmed
TBD	To Be Defined
TITOP	Two Input Two Output Port
TN	Technical Note
TRL	Technology Readiness Level

2. REFERENCES

2.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.X]:

Table 2-1: Applicable Documents

Ref.	Title	Code	Date
[AD.1]	Investigation of Active Detumbling Solutions for Debris Removal. Detailed Proposal	GMV 11834/14 V1/14	26th September 2014
[AD.2]	Investigation of Active Detumbling Solutions for Debris Removal. Statement of Work	TEC-ECN-SOW-20140415	21st April 2014

2.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, amplify or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.X]:

Table 2-2: Reference Documents

Ref.	Title	Code	Date
[RD.1]	TN1. Identification of Classes of Tumbling Objects and Survey of Detumbling Strategies	GMV 21198/15 V2/15	5th May 2015
[RD.2]	TN2. Trade-Off Analysis of De-Tumbling Techniques and Baseline Selection	GMV 22656/15 V2/15	22nd March 2015
[RD.3]	TN3. System Requirements Document	GMV 22842/15 V2/15	17th November 2015
[RD.4]	TN4. GNC Requirements Document	GMV 22801/15 V2/15	11st March 2015
[RD.5]	TN5. Chaser GNC System Robustness Analysis and Design	GMV 22836/16 V3/16	2016/09/03
[RD.6]	TN6. Chaser GNC Implementation, Verification and Validation	GMV 23188/17 V3/17	2017/07/05
[RD.7]	TN7. Chaser GNC Design Boundaries and further Applicability to Other Systems	GMV 22645/17 V1/17	2017/07/10
[RD.8]	TN8. Technology Roadmaps for De-tumbling Techniques Maturation	GMV 22644/17 V1/17	2017/07/11
[RD.9]	TN9. Recommendations for future Spacecraft Chaser Design	GMV 22709/17 V1/17	2017/07/10
[RD.10]	Committee on Space Debris, 1995, Orbital Debris: A Technical Assessment, National Academies Press	-	1995
[RD.11]	Kaplan, M. H., Bradley Boone, B., Brown, R., Criss, T. B., Tunstel, E. W., 2010, Engineering Issues for All Major Modes of In Situ Space Debris Capture, AIAA SPACE 2010 Conference & Exposition 30 August - 2 September 2010, Anaheim, California	-	2010
[RD.12]	Levin, E., Pearson, J., Carroll, J., "Wholesale Debris Removal From LEO," Acta Astronautica, v. 73, pp. 100-108,. April-May 2012.	-	April-May 2012
[RD.13]	Isakowitz, S. J., Hopkins, J. B., Hopkins Jr., J. P., 1999, International Reference Guide to Space Launch Systems, AIAA	-	1999
[RD.14]	Liou , J. C., "A Parametric Study On Using Active Debris Removal For LEO Environment Remediation", 61st International Astronautical Congress, Prague, Czech Republic, Paper IAC-10.A6.2.5, September 2010).	-	September 2010
[RD.15]	Peterson, G. E., 2012, "Target Identification and Delta-V Sizing for Active Debris Removal and Improved Tracking Campaigns," Proceedings of the 23rd International Symposium on Spaceflight Dynamics,Pasadena, California, October 29 - November 2 2012. Paper No. ISSFD23-CRSD2-5	-	November 2012

Ref.	Title	Code	Date
[RD.16]	Wertz, J. R. (Ed.). (1978). Spacecraft attitude determination and control (Vol. 73). Springer.	-	1978
[RD.17]	Fehse, W., 2003, Automated Rendezvous and Docking of Spacecraft, 1st ed., Cambridge Univ. Press, Cambridge, England, U.K.	-	2003
[RD.18]	Caubet, A., Biggs, J. 2013, "Design of an Attitude Stabilization Electromagnetic Module for Detumbling Uncooperative Targets," Aerospace Conference, 2014 IEEE, 10.1109/AERO.2014.6836325	-	2013
[RD.19]	Nishida, S., Kawamoto, S., 2011, Capturing a Space Debris by Space Robot	-	2011
[RD. 20]	B. Bastida Virgili, S. Lemmens, H. Krag, Investigation on Envisat attitude motion, e.Deorbit Workshop.	-	06/05/2014
[RD. 21]	Kucharski, D., Kirchner, G., Koidl, F., Fan, C., Carman, R., Moore, C., Feng, Q., 2014, "Attitude and Spin Period of Space Debris Envisat Measured by Satellite Laser Ranging", IEEE Transactions on Geoscience and Remote Sensing, Vol. 52, Issue 12, pp. 7651 – 7657.	-	DOI 10.1109/TGRS.2014. 2316138
[RD. 22]	Ortiz Gómez, N., Walker, S., 2014, "Earth's Gravity Gradient and Eddy Currents Effects on the Rotational Dynamics of Space Debris Objects: Envisat Case Study," Advances in Space Research, 1-15. (doi:10.1016/j.asr.2014.12.031).	-	2014
[RD. 23]	D. Alazard, J. Perez, T. Loquen, C. Cumer, *Two-input two-output port model for mechanical systems*. In 53rd AIAA Aerospace Sciences Meeting, Kissimmee, United States.		2015/01/05

3. INTRODUCTION

Due to the intensive activities in the space during the last half century, the population of man-made space objects is playing an increasingly relevant role in the space environment. Today more than 6000 satellites are orbiting around the Earth but only 900 are operational and the problem is not going to an end: almost 1200 new satellites are expected to be launched in the next 8 years (Euroconsult forecast). Of this population of man-made space objects approximately 6% are operational spacecraft, 22% are non-functional spacecraft, 17% are rocket upper stages, 13% are mission-related debris, and 42% are fragments from (mostly) explosions or collisions [RD.10].

Table 3-1 provides a classification of the major types of debris and their characteristics. Currently, the removal of small debris objects is not practical. A commonly proposed strategy consists of mitigation on one hand and removal of the largest objects on the other, which would remove the largest sources of potential new small debris.

Table 3-1: Debris classification (adapted from [RD.10], [RD.12])

Type	Characteristics	Hazard
Tiny	Not tracked, <1 cm	Shielding exists, damage to satellites may occur
Small	Not tracked, diameter 1 – 10 cm, 98% of lethal objects, ~400.000 objects in LEO	Too small to track and avoid, too heavy to shield against
Medium	Tracked, diameter >10 cm, <2 kg, 2% of lethal objects, ~24.000 objects in LEO, > 99% of mass (incl. large objects)	Avoidance manoeuvres performed most often for this category
Large	Tracked, >2 kg, <1% of lethal objects, > 99% of mass (incl. medium objects)	Primary source of new small debris, 99% of collision area and mass

The total mass of the population is estimated at 6300 tons. Figure 8-2 shows the distribution of debris in LEO. The highest concentration can be found at an inclination of 82-83° and around the sun-synchronous inclination. A large portion of the population at inclination 82-83° consists of objects launched from Plesetsk using the Cosmos-3M launch vehicle. The sun-synchronous orbit is of particularly high importance because of its usefulness for remote sensing and Earth observation purposes.

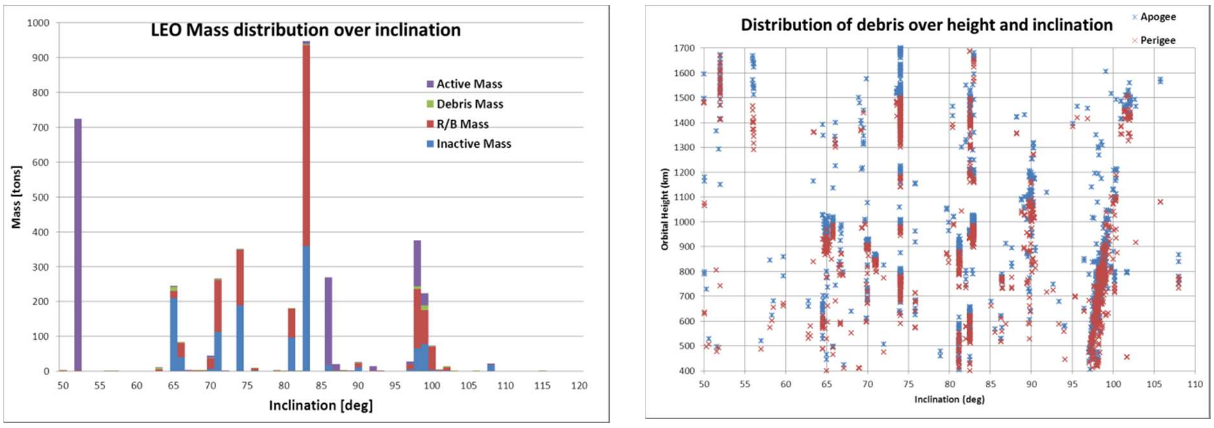


Figure 3-1: Debris distribution in LEO orbits

The debris database was filtered using two sets of criteria:

- European build, high mass, SSO, lifetime greater than 25 years.
- Many high mass, similar objects in similar orbits, lifetime greater than 25 years

Based on the first criterion, the following objects are identified:

- Envisat, ERS family, Spot family, MetOp-A (still operational, but at end of life and heavy)
- Rocket boosters:

– (Ariane 4) H-10, 1780 kg, 9 objects in SSO, 2 of which have a predicted lifetime < 25 years
– Cosmos-3M, 1420 kg, approximately 236 objects, 210 of which with predicted lifetime greater than 25 years

The rationale for selecting defunct European satellites as targets for removal missions is that design information (such as mass, inertia and shape) is more easily available. It is also expected that legal issues can be addressed more easily for European objects. Another selection criterion is to opt for objects of civilian build. It will likely be easier to obtain design information on the object and more importantly it will be easier to obtain permission to obtain and remove it. Rocket boosters are particularly interesting targets for debris removal missions because of their high similarity as a group. This means that a (possibly multi-object) debris removal mission can use a similar interface to handle the debris objects. It should also be noted that the 82-83° (where many of the Cosmos-3M upper stages can be found) orbit is inclination-paired with SSO [RD.12][RD.12], that is, the orbits precess in opposite direction and when the orbital planes meet, the debris meets head-on which increases the probability of collision. Removing rocket boosters and other large objects from the 82-83° inclination orbit helps to protect Sun-synchronous orbit. Characteristics of rocket boosters are available in [RD.13].

[RD.14] includes mass times collision probability as a debris selection criterion. This criterion seems very useful, although SSO and its inclination paired orbit of 82-83° should have a higher priority, because of the usefulness of SSO. The conclusions reached in [RD.14] are ultimately similar to the selection made here, that is to say, rocket bodies in the 82-83° inclination region and objects in SSO.

[RD.15] proposes yet another object selection criterion, namely the probability-severity criterion. This is the kinetic energy of the object times the collision probability. Figure 3-2 shows the collision probability-severity diagram from [RD.15]. Envisat is in the 8th place regarding the collision probability-severity criterion. The first seven places are rocket bodies, the majority of which are S/L 16 rocket bodies, or Zenit upper stages. COSMOS is S/L 8, which also occurs many times in the diagram. Based on these considerations, the COSMOS upper stage remains the preferred target for the class of rocket bodies, while Envisat remains the prime target for the class of defunct satellites. It should be noted that it may be interesting to include a smaller object as well; such objects may serve as targets for smaller scale trials of ADR and de-tumbling techniques.

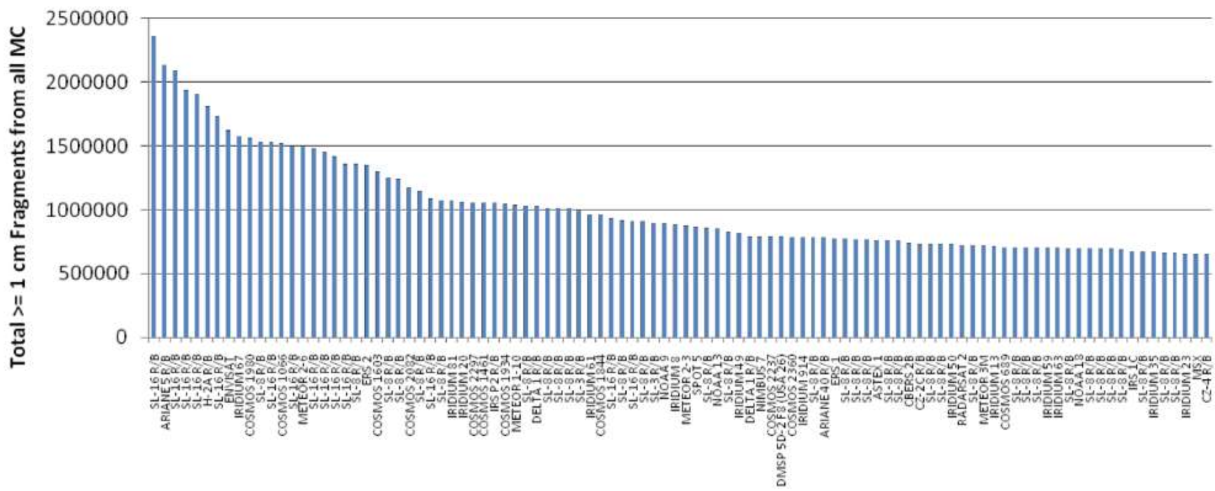


Figure 3-2: Collision probability-severity diagram for top 100 objects (reproduced from [RD.15])

From the two groups of objects, two specific examples are retained for further study; these are Envisat and a generic COSMOS upper stage.

4. DE-TUMBLING STRATEGIES

Three main classes of de-tumbling methods can be distinguished: **contact-based** de-tumbling, **contactless** de-tumbling (both performed by the chaser) and a **de-tumbling package** as a design feature of the target. Figure 4-1 shows a classification of the de-tumbling methods organized according to the type of interaction with the target. The contact-based and contactless methods require a chaser vehicle to de-tumble the target, while a de-tumbling package is a design feature of the target that maintains the target in a stable attitude after the end of its life.

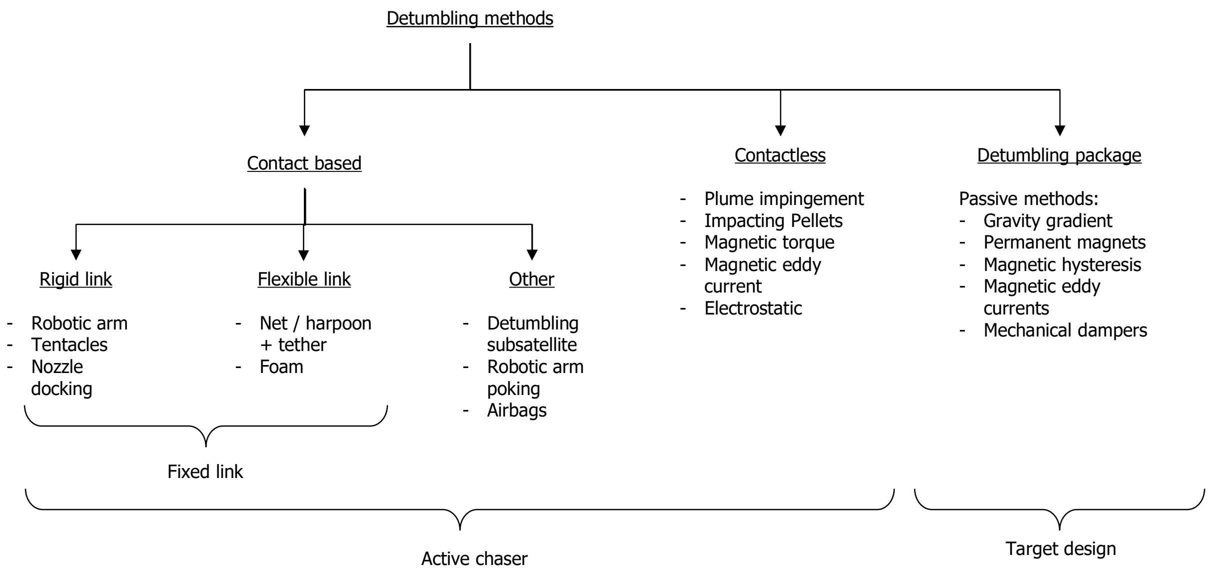


Figure 4-1: De-tumbling methods organized according to type of interaction

The methods that require contact are based on actuators that are present in the chaser and that are partially dictated by other aspects of the mission, such as the capability to perform rendezvous with the target([RD.16],[RD.17]). These actuators are: magnetic coils and torque rods, momentum transfer devices such as reaction wheels and thrusters. Within the contact-based de-tumbling class a distinction can be made between methods that require a **rigid or a flexible link** between the chaser and the target and other contact-based methods

- **Rigid link**, chaser performs synchronization and captures the target with a rigid capture device (such as a robotic arm, tentacles or a docking tool);
- **Flexible link**, chaser does not synchronize and captures the target with a flexible capture device (such as a harpoon or a net connected to a tether);
- **Other methods**. These methods do not fit nicely into the flexible- or rigid-link categories. These methods include attaching a de-tumbling package sub-satellite to the target with a harpoon (which immediately reels in after the harpoon makes contact) [RD.18], poking the target with a robotic arm [RD.19] and pushing the target with an airbag.

A first identification of de-tumbling needs for several capture/deorbiting methods is shown in Table 4-1.

Table 4-1: De-orbiting methods and de-tumbling needs identification

De-orbiting /capturing method	Angular velocity estimation	Synch w debris angular motion	Contact	Robotics	De-tumbling/ Controlling after capture	Force/Torque disturbance during de-orbiting	GNC complexity/ Propellant consumption
Net	Yes (axis)	Yes (partial, with rotation axis)	Yes	No	No	Yes	Small/Medium
Conductive tethers	Yes	Yes	Yes; Installation of tether	Yes; Installation of tether	Yes	No	High/Medium
Momentum exchange tethers	Yes	Yes	Yes; Installation of tether	Yes; Installation of tether	Yes	Yes	High/High
Drag augmentation devices	Yes (axis)	Yes	Yes; Installation of device	Yes; Installation of device	No	No	Medium/Medium
Grappling	Yes	Yes	Yes	Yes	Yes	No	High/High
Docking with nozzle	Yes	Yes			Yes	No	High/High
De-boost engine kit	Yes	Yes	Yes	Yes	Yes	No	High/Medium
Tentacles	Yes (axis)	Yes (partial, with rotation axis)	Yes	Yes	Yes	No	Medium/High
Harpoon (Rigid)	Yes (axis)	Yes (partial, with rotation axis)	Yes	Yes; boom	Yes	No	Medium/High
Harpoon (Non-rigid)	Yes (axis)	Yes (partial, with rotation axis)	Yes	No	No	Yes	Small/Medium
Pushing sock air-bag	No	No	Yes; uncontrolled	No	No	No	Small/Small
Foam projection	Yes	Yes	No; High prox. ops. Required	No	Yes	No	High/High
Ion-beam Shepherd	No	No	No	No	No	No	Small/High
Electrostatic tractor (only for GEOs)	No	No	No	No	No	No	Small/High

*Note that some authors consider it not advisable to attach drag augmentation devices (including foam) to debris objects because it enhances the collision cross-section and causes the object to transit through all occupied orbits below its original orbit. This, in combination with the long duration of the de-orbit process, produces a high probability of eventual collision and the generation of additional debris.

5. DETUMBLING CONCEPTS TRADE OFF

5.1. ANALYTICAL HIERARCHY PROCESS

The analytical hierarchy process was used to perform the trade study in [RD.2]. The Analytical Hierarchy Process was developed by Thomas Saaty in the 1970's as a structured approach to decision making. Two essential features of the approach are the breakdown of the problem into smaller sub-problems that are arranged in a **hierarchy**, and **pair-wise comparison** of elements.

The trade criteria are arranged in a hierarchy that cover risk, technology and reliability aspects. The detailed trade criteria are described in section 5.2. Examples of sub-criteria for the risk criterion are collision risk and debris generation risk. Scores are passed from lower levels of the hierarchy to the corresponding higher level.

Pair-wise comparison is performed to determine the relative weights of the trade criteria. The main justification for using pair-wise comparisons rather than assigning weights to criteria all at once is that a pair-wise comparison is easier to conceptualize mentally and therefore easier to justify than assigning weights all at once.

5.2. DEFINITION OF TRADE CRITERIA

In our application case, the trade criteria are grouped into risk, technical and reliability. Each of these criteria are further divided into sub-criteria. The following trade criteria have been identified:

- Risk
  - Collision risk
    - Attitude motion not precisely known: the quality of the attitude motion estimation may depend on (read: may be negatively influenced by) the capture and de-tumbling method
    - Attitude motion prediction not accurate: the attitude motion during the capture process may be influenced by the capture and de-tumbling method
    - GNC operating at design limits: the GNC design limits are determined by the current state of the art in sensors and actuators, GNC algorithms, but also by control frequency.
    - Ability to verify capture
    - Ability of mechanical interface to withstand capture and de-tumbling loads
  - Debris generation risk
    - Tearing of MLI
    - Breaking off appendages
    - Jettison of capture device
  - Unsuccessful capture
    - Preferred capture point cannot withstand loads
    - Second attempt not possible
  - Unsuccessful de-tumbling
    - Batteries depleted before de-tumbling is completed
    - Not all axes can be controlled
  - Ability to perform CAM during any phase of the mission; for some concepts it may not be possible to perform a CAM during all phases of the mission, for example:
    - The capture mechanism envelops the target, such that a CAM may still lead to collision because the mechanism is all around the target
    - The target is attached to the chaser by means of a tether; in this case, the tether should first be cut before a CAM is performed

  - Risk of uncontrolled re-entry
- Technical
  - Complexity
    - Complexity of rendezvous and synchronization
    - Complexity of capture
    - Complexity of de-tumbling
    - Complexity of AOCS of stack after capture
    - Chaser design complexity
  - Ability to handle multiple types of debris
  - Ability to handle more than one debris object
  - Mass of capture and de-tumbling systems
- Reliability
  - Ability to test on ground
  - Maturity of approach; TRL of concept
  - Ability to perform second capture attempt

The risk criterion has the most elaborate division, followed by the technical criterion.

For more information on the definition of the specific scoring criteria and weights, read [RD.2].

5.3. TRADE-OFF RESULTS AND SENSITIVITY

5.3.1. TRADE-OFF RESULTS

Table 5-1 shows the results of the trade-off. The robotic arm option wins because of its high TRL, followed by the plume-impingement based de-tumbling and the electrostatic tractor.

Of the contact-based methods the robotic arm performs fairly well across all three criteria. It is a method that can partially be tested and that has the highest TRL of all capture and de-tumbling techniques. This means that the least amount of development would be required before an ADR mission featuring a robotic arm could be launched.

The contactless methods tend to perform well on the risk criterion because no physical contact is made and no attitude synchronization is required. Plume impingement-based de-tumbling method and the electrostatic tractor also perform well on the technical criteria, but all contactless methods have a low reliability.

Contactless methods perform well because no contact is required such that they are safer, but in many cases important restrictions apply. It can be explicitly stated in the trade study recommendations that during the trade it became clear that contact-based and contactless methods should better be addressed in separate trade studies, because different sets of criteria apply. Contactless methods tend to have important restrictions (such as requiring a separate capture method in case of plume impingement, or only being useful in GEO in case of electrostatic tractor). The low score on reliability is (amongst others) an indicator of low TRL. The contactless methods all have a far lower TRL than contact-based methods, especially the robotic arm.

Note also that the low TRL can be indicative of risks associated with concepts that have not yet been identified because the concept has not been studied sufficiently: for example, the robotic arm option has been studied extensively and missions with cooperative targets have flown in space. Many of the risks have been identified and so the risks are fairly well known. Electrostatic tractoring has not been performed in space, and the concept has not been studied in any realistic mission design. This means that it is quite possible that not all risks of the method have been identified and that the severity of known risks is underestimated. All this means that the weight on the reliability criterion could justifiably be put (much) higher: this would ultimately rule out the contactless methods because of their low TRL.

The low score of the net and the harpoon options is mainly due to the low score on risk. The low score on risk in turn is due to the fact that the control of the chaser – target combination is difficult (which may lead to serious failures during capture, de-tumbling or de-orbiting) and the fact that the initial interaction of the capture device may lead to additional debris generation.

Table 5-1: Trade results

type	option	risk	technical	reliability	score	rank
Rigid link	Robotic arm	8.64	6.96	7.19	7.60	1
	Tentacles	4.97	4.82	4.42	4.69	8
	Nozzle docking	8.16	5.25	5.87	6.47	4
Flexible link	Net	3.68	4.64	4.42	4.23	11
	Harpoon + tether	3.50	5.48	4.42	4.36	10
	Foam	5.66	6.78	2.87	4.62	9
Contactless methods	Plume impingement	9.29	8.91	4.37	6.94	2
	Impacting pellets	5.70	7.43	3.11	4.89	7
	Magnetic torque	9.72	5.46	2.22	5.33	5
	Magnetic eddy currents	9.72	5.46	2.22	5.33	5
	Electrostatic	9.65	7.95	4.37	6.85	3

5.4. TRADE STUDY RECOMMENDATION

According to the trade study it was recommended to select the **robotic arm** as the capture and de-tumbling method for the current activity because of its applicability to both de-tumbling and de-orbiting and because of the high TRL of this technology. Performing synchronization, capture and de-tumbling with a fast tumbling debris object represents the most challenging design case for a robotic arm capture.

It is recommended to study plume impingement based contactless de-tumbling in future projects (**not** in the current project) and to consider it for future missions as a complementary technique to robotic capture, as an alternative to attitude synchronization with a fast tumbling debris object, to reduce the overall risk associated with close range capture methods.

6. MISSION BASELINE

6.1. SCENARIO ASSUMPTIONS

Envisat and one of the KOSMOS 3M upper stages (SL-08) were pre-selected as targets to be captured and de-tumbled. Envisat has Spacetrack catalogue number 27386 and COSPAR ID 2002-009-A.The KOSMOS 3M upper stage has Spacetrack catalogue number 21088 and COSPAR ID 1991-006-B. It was also taken into account that eDeorbit B1 phase was about to start and could be taken as reference with the purpose of defining the baseline concept, the technical specifications and interfaces for a mission to remove a single large ESA owned Space Debris from the LEO protected zone, which will likely be Envisat. It is then clear that the full definition and design of the chaser S/C and de-tumbling system to the finer detail level is out of the scope of this activity. No missions to perform ADR of a KOSMOS 3M upper stage are currently planned. Nevertheless, some assumptions need to be made in order to state realistic functional and performance requirements for the de-tumbling system and the GNC and perform later design of the GNC functions.

The sections below will provide some assumptions on orbital parameters, mass properties, attitude motion and other relevant assumptions for Envisat.

6.1.1. ENVISAT

Recent estimations of the orbit of Envisat are provided in Table 8-1.

Table 6-1: Envisat orbital parameters on September 2015

Type	Characteristics
Eccentricity	0.000117
Inclination	98.3274°
Perigee height	765 km
Apogee height	766 km
RAAN	303.2890°
Argument of perigee	81.0316°

Table 6-2 shows the most relevant physical properties of Envisat. The moments of inertia are referenced to the centre of mass. The centre of mass position is given with respect to the body fixed frame.

Table 6-2: Envisat properties

Parameter	Value
Mass [kg]	7827.867
Ixx [kg m2]	17023.3
Iyy [kg m2]	124825.7
Izz [kg m2]	129112.2
Ixy [kg m2]	397.1
Iyz [kg m2]	344.2
Izx [kg m2]	-2171.1
c.o.m. x [m]	-3.905
c.o.m. y [m]	-0.009
c.o.m. z [m]	0.003
Dimensions (body) [m x m x m]	10.02 x 2.75 x 1.6
Dimensions (Solar panel) [m x m x m]	14.028 x 4.972 x 0.01
Length [m]	26.024

Figure 6-1 shows the overall configuration of Envisat, including the definition of the body fixed reference frame axis directions. The origin of the body reference frame is at the interface plane of the spacecraft interface ring, shown on the right hand side of the figure below the Solar panel.

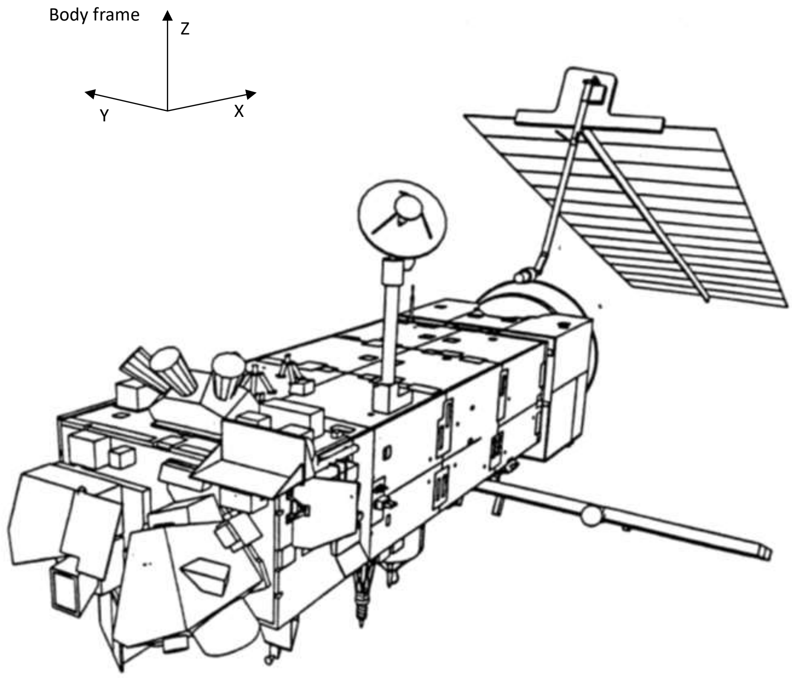


Figure 6-1: Envisat body frame

The work from [RD. 20][RD. 20] collects and analyses available Envisat attitude data from different kind of observations (optical, Satellite Laser Ranging and Radar measurements) from the end of life of the satellite on April 8, 2012, and from simulations performed. Since then, the attitude of the satellite has experienced important changes, but several facts can be stated:

- **Consistency of observation data and models**: There is qualitative matching between radar measurements and SLR measurements but the high rotation rate measured does not fit the predicted rotational state with models and the cause is currently unknown. Several causes are considered such as a micro-meteoroid impact or energy release from the non-passivated ENVISAT.
- **Current rotation state**: The main attitude motion corresponds to a relatively high rotation between 2°/s and 3.5°/s around the body z-axis (as defined in Figure 6-1). There are also smaller rotation components around the other body axes. The spin axis of the satellite is quite stable (within the radial coordinate system, which is fixed to the orbit) and, according to SLR measurements (from [RD. 21]) is pointing in the direction opposite to the normal vector of the orbital plane in such a way that the spin axis makes an angle of 61.86° with the nadir vector and 90.69° with the along-track vector (see Figure 6-2).
- **Long term evolution**: SLR measurements indicate that the spin period is increasing in time by 36.7 ms/day (according to measurements from [RD. 21]). Numerical simulations described in [RD. 20] [RD. 20]accounting for gravity gradient as the dominating disturbance torque but excluding all damping torques show that gravity gradient stabilisation cannot be expected in the medium term (10 years). Numerical simulations described in [RD. 22] include magnetic eddy current damping and find increases in the spin period of an order of magnitude comparable to that found in [RD. 21]. An extrapolation using an exponential fit to the SLR observation data indicates that the rotation rate may drop below 0.4°/s between 2026 and 2028. Simulations with a simulator that includes gravity gradient and magnetic eddy current torques indicate that a transition to libration around a gravity gradient stabilised attitude starts at 0.4°/s. The transition to a gravity gradient may occur before 2035. Because this estimate is based on an extrapolation this value should be taken as highly uncertain.

Figure 6-2 shows the current attitude motion of Envisat. The left-hand side shows the attitude during the mission, that is, nadir-stabilised. The right-hand side shows the situation after May 2013. The satellite now spins in a counter clockwise direction about the spin axis S. The vectors indicated in the figure are radial (R), normal to the orbit plane (N), along-track (AT) and nadir (n).

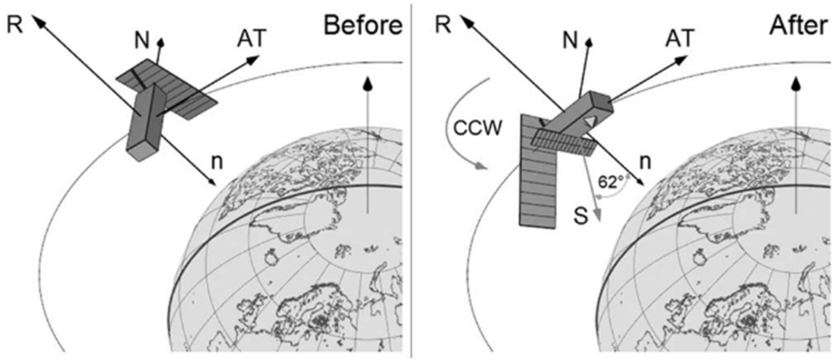


Figure 6-2: Envisat attitude (reproduced from [RD. 21])

The direction of the spin axis in the target body frame has a significant impact on the design of approach strategy and guidance profiles. For the design of the de-tumbling system it shall be assumed that the spin axis can vary between the body-z and body-y axes and that it shall not be fully known until in-orbit characterisation by the chaser.

It was also be assumed that the main spin rate can be between 1°/s and 5°/s and that there are also smaller rotation rate components in the x and y body axes with values below 10 times lower than the main spin rate (below 0.1°/s - 0.5°/s).

Other assumptions on the target state:

- For the purpose of this study it was assumed that the target was electrically passivated and also the AOCS is passivated.
- Envisat fuel is considered to be frozen (according to literature analyses). Thus, no fuel sloshing shall be modelled.
- The solar panel is locked close to the anti-canonical position (since April 2011). Certain angular uncertainty in a range of 10° was considered. Other flexible contributions to be considered (chaser and target link if no tentacles are to be used or before they are fixed).
- Target was assumed to be uncooperative (no inter-satellite of target-ground communications, no hardware helping the rendezvous and capture shall be assumed to be available on the target)

7. CONCLUSSIONS FROM VALIDATION CAMPAIGN

All MonteCarlo cases in the campaign have confirmed stability of the designed controllers for the arm unfolding, chaser close-in and synchronization, composite detumbling and composite detumbling with simultaneous chaser relocation. Specific findings for the different control modes and phases are as follows:

- Arm unfolding phase does not cause significant impact on the chaser attitude stablilisation while in target pointing. The settling time after the end of the unfolding manoeuvre is < 50s and the control actions are within very reasonable limits (<1.5Nm) given an unfolding time of 100s. The conclusion is that the FMC1 control mode, which is specifically designed for the close in and synchronisation phase is also able to cope with the arm deployment phase without major problem (although probably a more efficient control mode could be designed specifically for this phase).
- The synchronisation phase is confirmed to be very demanding for the GNC (considering also the actuation system and navigation sensors) due to very stringent requirements on opposite directions: both, very good agility and low actuation and navigation errors are demanded due to the very high target body rotation rate. In spite of the use of a conventional set of 22N bi-propellant thrusters for position and attitude control, FMC1 mode behaves quite well, achieving mean pointing error <1deg for the whole synchronisation phase. The relative position errors are, on the other hand, higher (mean position error module around 18 cm) and probably in the limit of usability. Improvement of the propulsion system for high agility and lower noise levels seem to be a clear improvement need if dealing with targets rotating at such a high rate.
- The capture phase is equally demanding (as it is the synchronisation phase) for the GNC since both good agility and low actuation errors are required. In fact, synchronisation of the chaser COM must also be kept while the arm is moving to close the tool-tip to the grasping point. The FMC2 mode has demonstrated being able to keep the COM synchronisation errors inside the arm actuation boundaries. The frequency separation for chaser COM and arm joints control has also demonstrated to achieve bounded and low arm tip state error w.r.t. the grappling interface.
- The impact of the large rotation rate and size of the target is also evident within the detumbling or braking manoeuvre. Analyses have shown that just centripetal loads while in composite configuration could be able to cause mechanical problems in the robotic arm. To avoid that, keeping an almost perfect synchronisation of the chaser to the target tumbling moment is required, but it cannot be achieved with current relative navigation technology. An indirect way of measuring the synchronisation error is through loads occurring in the arm joints. So, it seems highly desirable the use of sensored arms for this phase. When not relying on that (as is our study case), careful selection of the nominal arm geometry has demonstrated being able to contain the maximum loads on joints. In this case, also relying on efficient feed-forward laws that help reducing the composite kinetic energy quicker (before chaser desynchronization is large) have demonstrated to be very useful.
- Simultaneous Composite braking and chaser relocation to the final relative pose for de-orbiting has demonstrated to be feasible with FMCC2 mode. Nevertheless, no significant advantages are evident for the study case (it must be observed that the chaser/target mass and inertia ratios are very low for the study case, which makes target relocation a not very significant perturbation on composite rotational state). On the other hand, to properly perform the relocation manoeuvre, significantly high torques provided by the joint control inner loops are required to withstand the high centripetal loads (it must be noted that in the detumbling case with no relocation, the joint brakes cope with the loads appearing in the joint axes directions instead of the joint motors since the arm works in locked configuration).

8. ANALYSIS OF EXTRAPOLATION FACTORS

In this section a number of variability factors are analyzed in more detail:

Class of target debris

For the selection of the most interesting application cases to the present study, the debris database was filtered using two sets of criteria:

- European build, high mass, SSO, lifetime greater than 25 years.
- Many high mass, similar objects in similar orbits, lifetime greater than 25 years

Based on the first criterion, the following objects were identified (and finally Envisat was kept as reference case):

- **Envisat, ERS family, Spot family, MetOp-A** (still operational, but at end of life and heavy)
- **Rocket boosters:**
  - **(Ariane 4) H-10**, 1780 kg, 9 objects in SSO, 2 of which have a predicted lifetime < 25 years
  - **Cosmos-3M**, 1420 kg, approximately 236 objects, 210 of which with predicted lifetime greater than 25 years

The rationale for selecting defunct European satellites as targets for removal missions is that design information (such as mass, inertia and shape) is more easily available. It is also expected that legal issues can be addressed more easily for European objects. Another selection criterion is to opt for objects of civilian build. It will likely be easier to obtain design information on the object and more importantly it will be easier to obtain permission to obtain and remove it. Rocket boosters are particularly interesting targets for debris removal missions because of their high similarity as a group. This means that a (possibly multi-object) debris removal mission can use a similar interface to handle the debris objects. It should also be noted that the 82-83° (where many of the Cosmos-3M upper stages can be found) orbit is inclination-paired with SSO [RD.12][RD.12], that is, the orbits precess in opposite direction and when the orbital planes meet, the debris meets head-on which increases the probability of collision. Removing rocket boosters and other large objects from the 82-83° inclination orbit helps to protect Sun-synchronous orbit. Characteristics of rocket boosters are available in [RD.13].

[RD.14] includes mass times collision probability as a debris selection criterion. This criterion seems very useful, although SSO and its inclination paired orbit of 82-83° should have a higher priority, because of the usefulness of SSO. The conclusions reached in [RD.14] are ultimately similar to the selection made here, that is to say, rocket bodies in the 82-83° inclination region and objects in SSO.

[RD.15] proposes yet another object selection criterion, namely the probability-severity criterion. This is the kinetic energy of the object times the collision probability. Figure 8-1shows the collision probability-severity diagram from [RD.15]. Envisat is in the 8th place regarding the collision probability-severity criterion. The first seven places are rocket bodies, the majority of which are S/L 16 rocket bodies, or Zenit upper stages. COSMOS is S/L 8, which also occurs many times in the diagram. Based on these considerations, the COSMOS upper stage remains the preferred target for the class of rocket bodies, while Envisat remains the prime target for the class of defunct satellites. It should be noted that it may be interesting to include a smaller object as well; such objects may serve as targets for smaller scale trials of ADR and de-tumbling techniques.

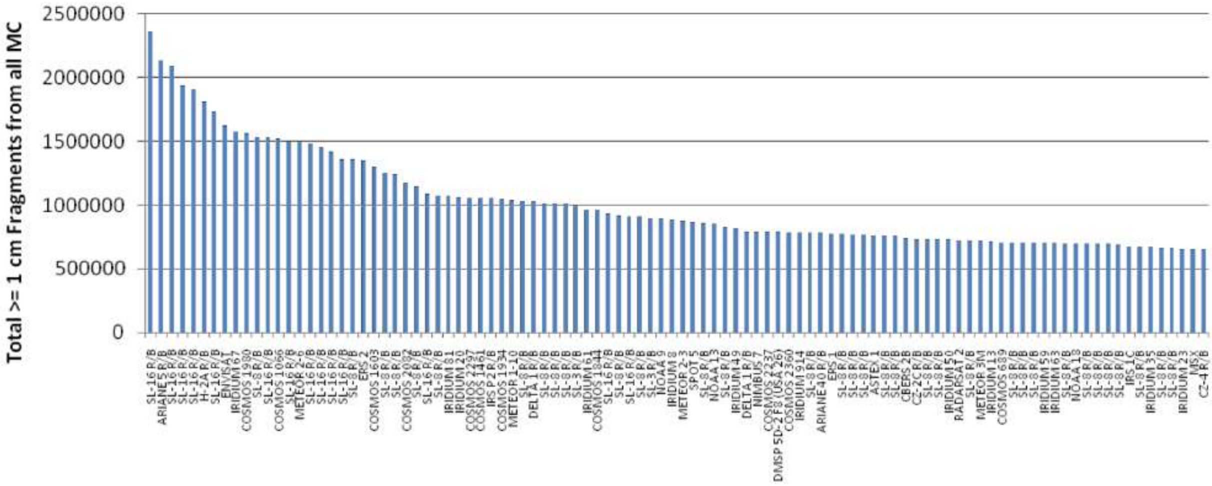


Figure 8-1: Collision probability-severity diagram for top 100 objects (reproduced from [RD.15])

The other factors, associated to the class of target debris itself are analysed in the following paragraphs:

Debris Orbit

In this section, the implications of the debris orbit on the scalability of the study results are analysed.

Earth orbits can normally be assigned to three regions, LEO, MEO and GEO. Remote sensing and Earth observation satellites are often placed in LEO, more in particular, in sun-synchronous near polar orbits as is the case of ENVISAT (see Table 8-3). Also many rocket upper stages remain in this region after the launch of LEO satellites, as is the case of the other pre-selected target along this study (see Table 8-2).

Table 8-1: Envisat orbital parameters on September 2015

Type	Characteristics
Eccentricity	0.000117
Inclination	98.3274°
Perigee height	765 km
Apogee height	766 km
RAAN	303.2890°
Argument of perigee	81.0316°

Table 8-2: COSMOS 3M upper stage (#21088) orbital parameters on September 2015

Type	Characteristics
Eccentricity	0.0022639
Inclination	82.9447°
Perigee height	958 km
Apogee height	991 km
RAAN	146.3429°
Argument of perigee	354.5013°

MEO is used for navigation and communication satellites, such as GPS, Glonass and Galileo, most commonly using orbits with a period of around 12 hours.

GEO is used for communications and weather satellites. Spacecraft in each of these types of orbits are faced with different perturbation environments, and different strategies are used to counter perturbations and stabilize the attitude.

Figure 8-2 shows the distribution of debris in LEO. It is observed that the highest concentration can be found at an inclination of 82-83° and around the sun-synchronous inclination. A large portion of the population at inclination 82-83° consists, in fact, of objects launched using the Cosmos-3M launch vehicle. The sun-synchronous orbit is of particularly high importance because of its usefulness for remote sensing and Earth observation purposes.

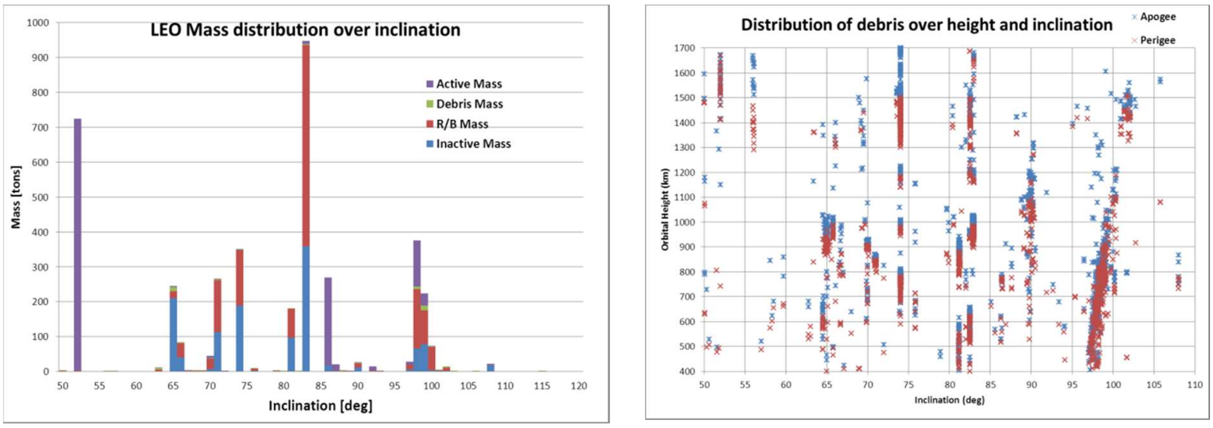


Figure 8-2: Debris distribution in LEO orbits

The first indirect implication of the debris orbit altitude is the different degree of heterogeneity of the debris that can be found at each region. LEO is probably the region where the highest heterogeneity in terms of classes and sizes of debris can be found while, on contrary, there are certain orbit inclination ranges highly populated as explained above.

On the other hand MEO is populated by constellations of satellites that are identical among them or that present small variations and that are placed in (approximately) circular orbits at several orbital planes at a given inclination (e.g. 55º for GPS and 56º for Galileo). Also, in GEO can be found several families of satellites that are based on the same commercial platform with small differences or custom adaptations between them.

Regarding the presence of upper stages in other orbits different from the LEO region, special consideration requires the case of the highly elliptical GTO (Geostationary Transfer Orbits). Space debris in these orbits could enter into the LEO and GEO protected regions and could also interfere to other MEO orbits such as the Galileo ones.

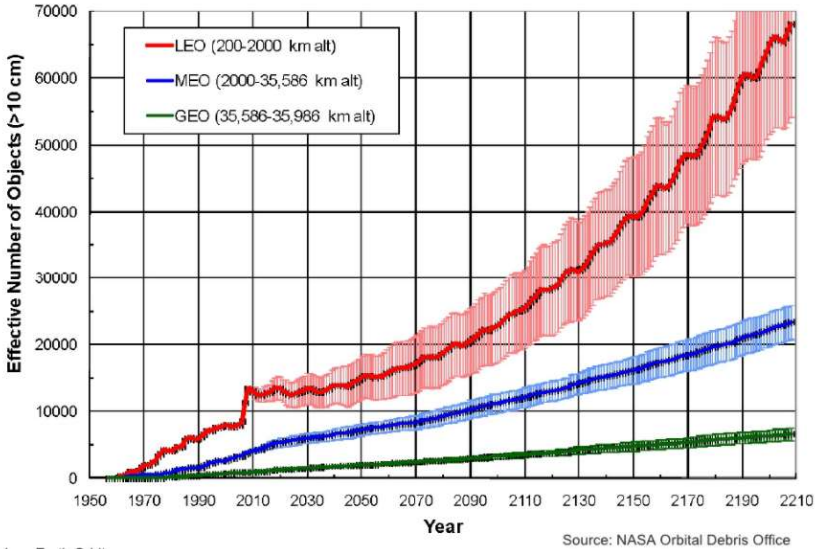


Figure 8-3. Estimated debris distribution by space regions

The target debris orbit determines other factors, whose impact on the scalability of the results of this activity can be more directly analysed. These factors are as follows:

Dominant Torque Perturbations

The main torque perturbation sources in orbit were identified within TASK1 of the study and are summarized here below for later discussion:

- **Random torques** – these torques may either spin-up or spin-down an object
  - Leakage or outgassing,
  - Hypervelocity impacts,
  - Momentum transfer,
  - Spurious activation of thrusters or reaction wheels (if S/C is non-passivated),
  - Wind milling torques under the action of SRP.
- **Dissipative torques** – these torques dissipate energy and spin down objects
  - Magnetic eddy currents in non-ferromagnetic metals such as aluminium and copper,
  - Magnetic hysteresis in ferromagnetic metals and alloys, such as Permalloy and Permendur,
  - Damped mechanical vibration (nutation and libration damping),
  - Propellant sloshing (nutation and libration damping).
- **Orienting torques** – these torques orient an object towards a preferred attitude
  - Gravity gradient torque,
  - Magnetic torques (due to the presence of permanent magnets),
  - Aerodynamic torques,
  - Solar radiation pressure torques.

The torques mentioned above are different for the different orbital regions. The perturbation environment in LEO differs qualitatively from the perturbation environment in MEO and GEO. Magnetic and gravity gradient torques decrease to third power of the orbit radius, which means that compared to LEO these torques are a factor of 50 to 200 lower in MEO and GEO, respectively.

Many sources point out that, in the long term, the attitude dynamics of **LEO space debris** is dominated by dissipative terms. Eddy current damping in aluminium or copper structures is mentioned as a leading cause of long-term attitude rate reduction. The expectation is that debris objects will eventually settle down in an attitude **motion that is either coupled to the gravity gradient or to the magnetic field**. In the former case, the rotation rate is about 1 revolution per orbit, in the latter about 2 revolutions per orbit. The terminal state would depend on the inertia and magnetic characteristics of the object.

In **MEO and GEO** the magnetic and gravity gradient torques are far less effective in spinning down debris objects. In this environment, **mechanical damping and orienting torques** act together to put objects that originally were spinning axially into a **flat spin** about the major axis. Some upper stages are put in an axial spin prior to or after payload release. In addition, it is estimated that over a hundred defunct geostationary satellites were originally spin-stabilized with rates of up to 360°/s.

In summary, it is expected that most debris in **LEO** (with some exceptions) is in a **slow rotation state**, while in **MEO and GEO** a large amount of objects is in a **fast rotation state**.

In addition to literature review, a first sizing of the torque sources magnitudes was also carried out within the activities of TASK1, focusing on the orienting torques and the dissipative torques (in this case, eddy current torques). These torques were expected to be the prevalent influence on the long term behaviour and thus on the initial target rotational state to be considered as contour condition for a detumbling and deorbiting mission. That is to say, based on the observations of space objects, the expected behaviour of space objects is as follows:

- Damped mechanical vibration brings the space object into a rotation state with minimum energy,
- Eddy current torques slow down the rotation of the space object,
- Orienting torques capture the space object in a preferred orientation, for example:
  - The axis of maximum inertia aligned with the local vertical, leading to one rotation per orbit,
  - The magnetic dipole aligned with the Earth magnetic field, leading to two rotations per orbit,
  - The body aligned in such a way that the centre of pressure is behind of the centre of mass with respect to the incoming flow.

The relative magnitudes of the **orienting torques** determine the terminal state of the space object. The expectation is that large objects in orbits above around 400 – 500 km that have a clear difference between their minimum and maximum moment of inertia will eventually settle in a gravity gradient stabilized orientation. This applies to, for example, rocket upper stages and defunct satellites. For small, nearly symmetric satellites (e.g., cubesats), the magnetic torque may dominate, and the satellites will eventually settle in an orientation aligned with the magnetic field. Lastly, for objects in orbits above 400 – 500 km with large aerodynamic surfaces, the object may eventually orient itself in an aerodynamically stable orientation.

Table 8-3: Order of magnitudes for ENVISAT using the simplified models

Torque	Order of magnitude from simplified models (angular acc $1/s^2$)	Assumptions
Gravity gradient	~181 mNm (1.46μ (*))	(*)acceleration about Y
Magnetic	~0.86mNm	
Drag	View from X: 0.7626 mNm (0.006μ (**)) View from Z:5.45mNm (0.043μ (**))	(**)acceleration about Y
Solar radiation	~7.41mNm (0.059μ(***)) ~8.34mNm (0.067μ(***))	q=0.6 q=0.8 (***)considered acceleration mostly about Y

Table 8-4 shows that the gravity gradient is the main source of torque for the COSMOS 3M (rocket upper stage debris class) as well.

Table 8-4: Order of magnitudes for COSMOS 3M using the simplified models

Torque	Order of magnitude from simplified models	Assumptions
Gravity gradient	<25mNm	
Magnetic	<0.05mNm	Residual dipole inexistent or below 1 Am2
Drag	<0.25mNm	
Solar radiation	<0.3mNm	

Given a considerable uncertainty in some of the parameters, the solar radiation pressure and drag torques were evaluated w.r.t. several arm configurations (figure 8-4), and the gravity gradient is evaluated for variations in the inertia principal elements, figure 8-5.

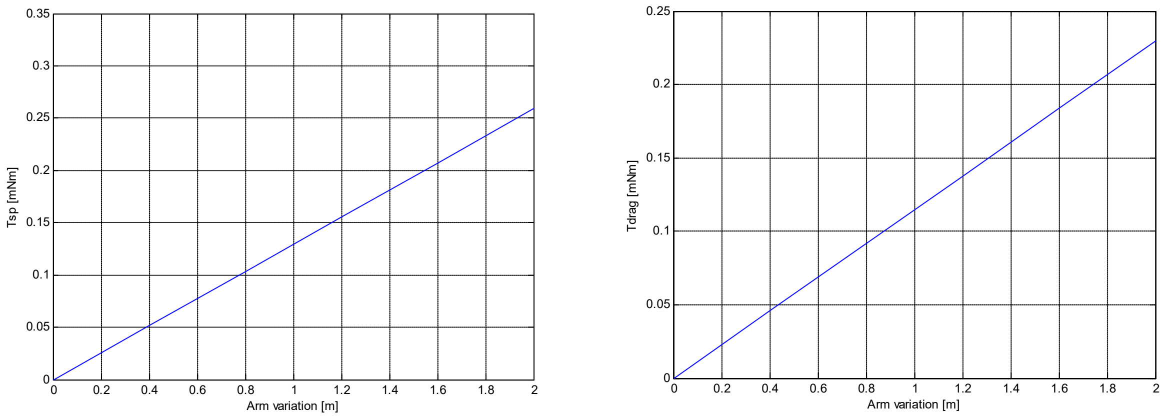


Figure 8-4: Variation of solar radiation pressure torque (left) and drag torque (right) with distance between c.o.g. and centres of pressure

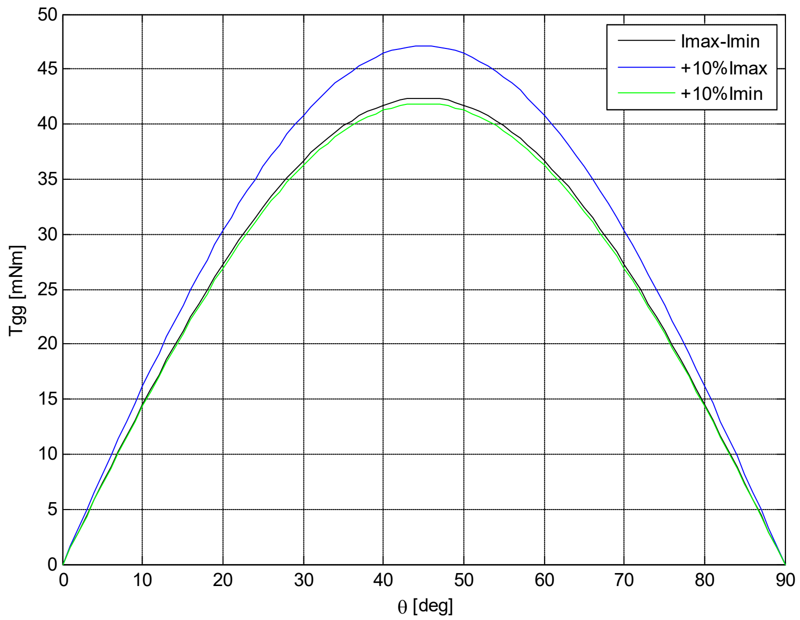


Figure 8-5: Variation of upper-bound with θ and variations in the principal axis

In addition to the long term rotational state determination of the tumbling debris, the torque perturbation environment must also be considered from the point of view of the short term impact on the attitude control of the chaser and COMPOSITE. In this respect, Figure 8-6, Figure 8-7 and Figure 8-8 show respectively gravity gradient, sloshing torques (chaser fuel and oxidizer tanks with membranes) and flexible mode torques from the Envisat solar array occurred while in the detumbling manoeuvre with simultaneous chaser reconfiguration. Our application case shows that torques coming from liquid sloshing (especially if the tanks are not equipped with anti-sloshing membranes) and flexible appendages (if present) are very likely to be the dominant effects for the short term and needed to be carefully handled in the control synthesis phase.

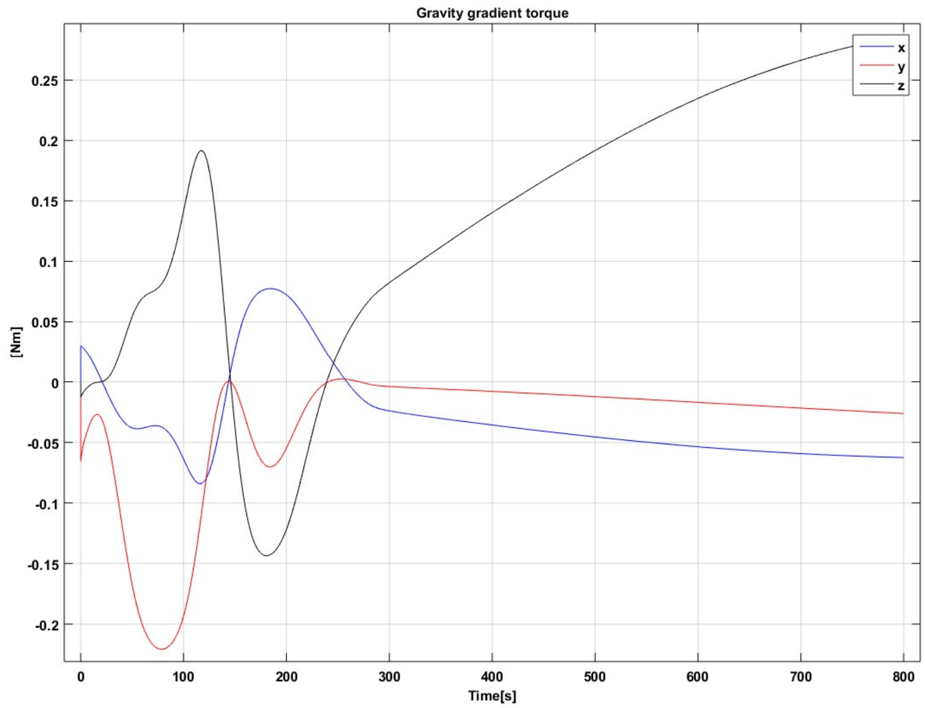


Figure 8-6. Gravity gradient torques on COMPOSITE (while in in 10DOF simultaneous Detumbling and Chaser relocation).

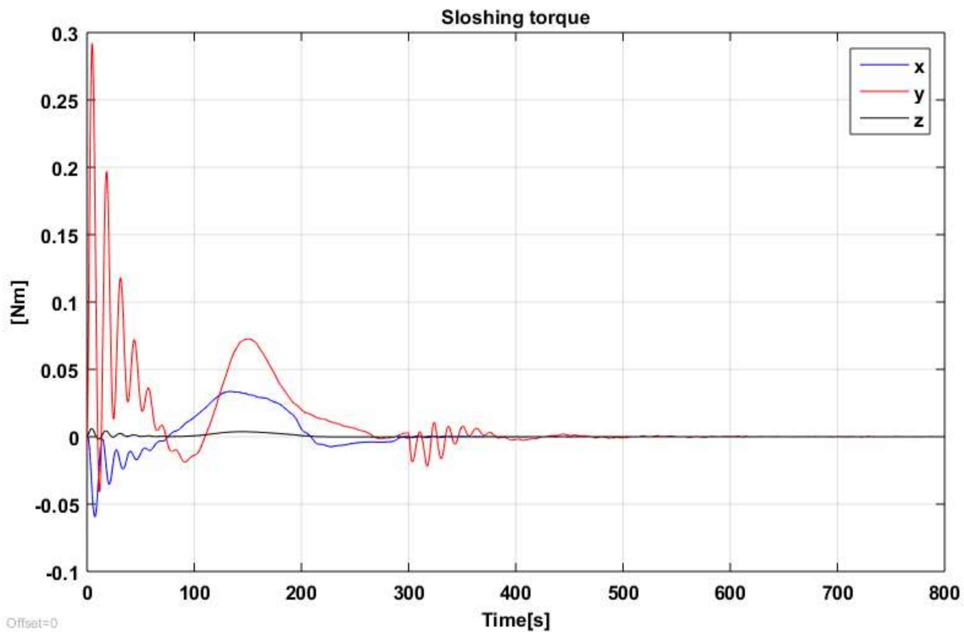


Figure 8-7. Sloshing torques on COMPOSITE (while in in 10DOF simultaneous Detumbling and Chaser relocation).

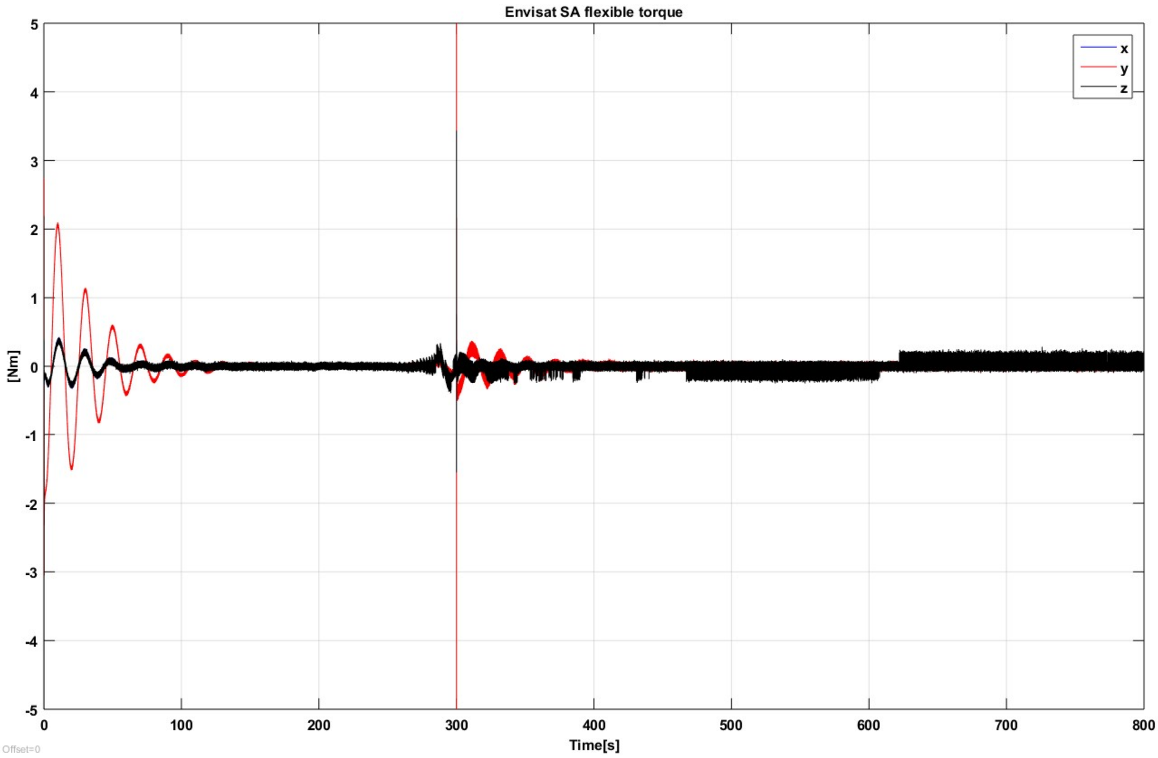


Figure 8-8. Torques from Envisat SA flexible modes (while in 10DOF simultaneous Detumbling and Chaser relocation).

Target rotational state

Before the analysis of the potential impact of the variability of the target rotational state on the feasibility and performance of the close-in, capture and detumbling of the target debris, we will recall most important findings on the physical relations between target debris angular momentum, angular velocity and the guidance strategy designed:

The attitude motion of Envisat was a key input to the design of the terminal approach strategy and synchronization manoeuvre of the chaser as well as for the detumbling manoeuvre itself.

Figure 8-4 shows that in the nominal Envisat case, either the angular momentum vector or the negative angular momentum vector will always come close to the overall desired approach direction. It was therefore possible to perform station-keeping on the angular momentum direction vector at a pre-selected distance until the favourable conditions occur for the terminal approach. The terminal approach would consist of an approach to around 7 m over the angular momentum direction vector, a fly-around to the z-axis of the body frame and a forced motion to the terminal position. Favourable conditions meant that the angular momentum direction vector stays as close to the z-axis of the body frame as possible during this entire sequence of manoeuvres.

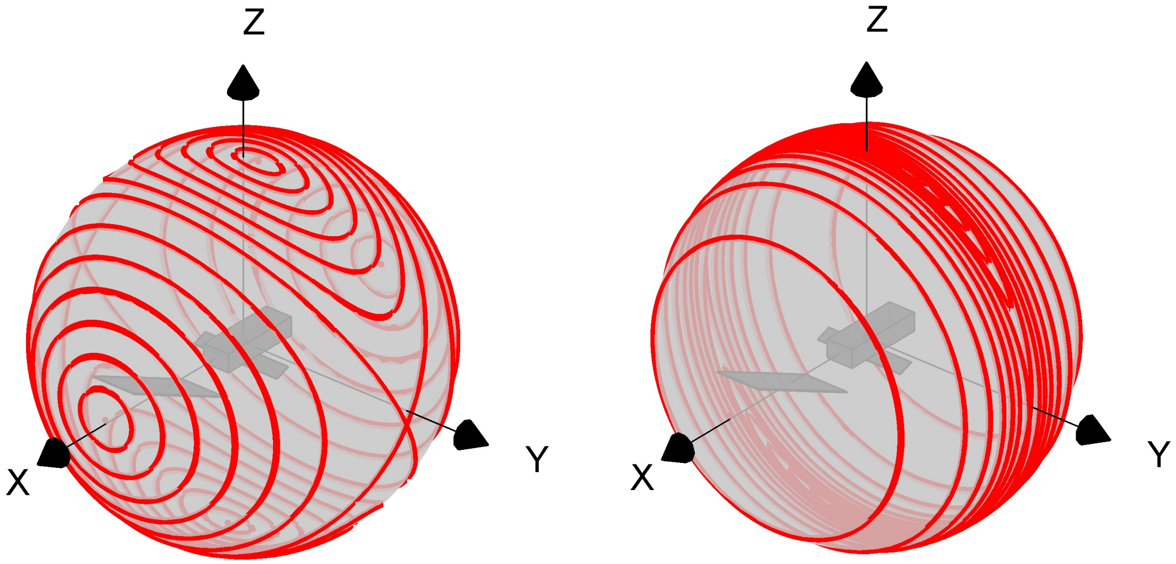


Figure 8-9: Locus of angular velocity (left) and angular momentum (right) direction in the body frame under free precession for the nominal mass distribution

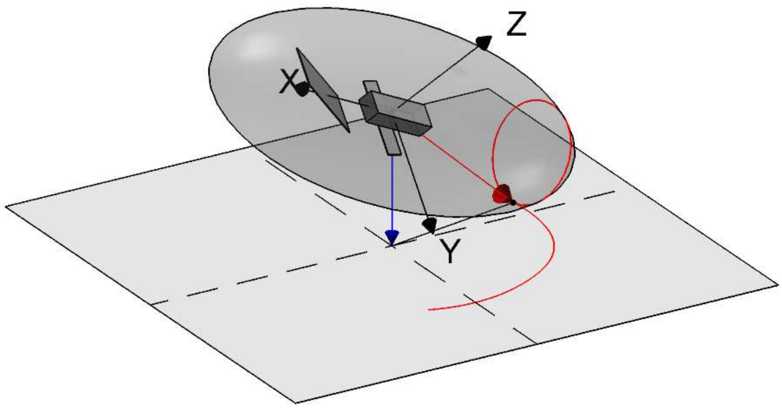


Figure 8-10: Free attitude motion in inertial space showing inertia ellipsoid rolling over invariant plane

Figure 8-10 shows that the approach over the angular momentum vector (blue arrow in figure) can be performed safely and without collisions. Poinsot's description of the motion can be used to guarantee that the approach over the angular momentum vector is collision-free (the inertia ellipsoid can be scaled in such a way that the whole spacecraft just fits inside). In this case, the scaled inertia ellipsoid will fit fairly closely to the body if the mass distribution is fairly uniform with respect to the shape. This means that the inertia ellipsoid can effectively be used to determine a *stay-out zone around the body* that fits around the body reasonably snugly. There exists an **invariable plane at a fixed distance** from the target and the **stay-out ellipsoid will never cross** this plane. So, if the chaser remains on the angular momentum vector at a distance greater than the distance to the invariable plane, then there is no risk of collision.

The angular momentum vector of the target was also important for other reasons. It is constant in inertial space, and nearly constant in the LVLH frame. As such, the **cost of performing station-keeping at the angular momentum vector** is very **low** compared to other strategies. Furthermore, the angular momentum vector **moves reasonably slowly in the target body frame**. The change in velocity to enter into the body fixed frame from the angular momentum direction vector is therefore fairly low.

Finally, it is important to recall that the relationship between the approach direction and the angular momentum vector has an important impact on the ΔV. In fact, the geometry of the angular velocity direction vector and the approach direction vector determine the level of thrust and the amount of propellant required to compensate for the centrifugal acceleration. In the worst case, the angular velocity vector is perpendicular to the approach direction. In this case, the force that needs to be provided by the chaser to compensate for the centrifugal acceleration is given by:

$$F = m\omega^2 r \quad (1)$$

On the other hand, if the chaser is performing station-keeping exactly at the rotation vector, then the force would be close to zero. At intermediate angles between the position and the angular velocity vector, the centrifugal force is proportional to the sine of the angle between the position vector and the angular velocity direction vector.

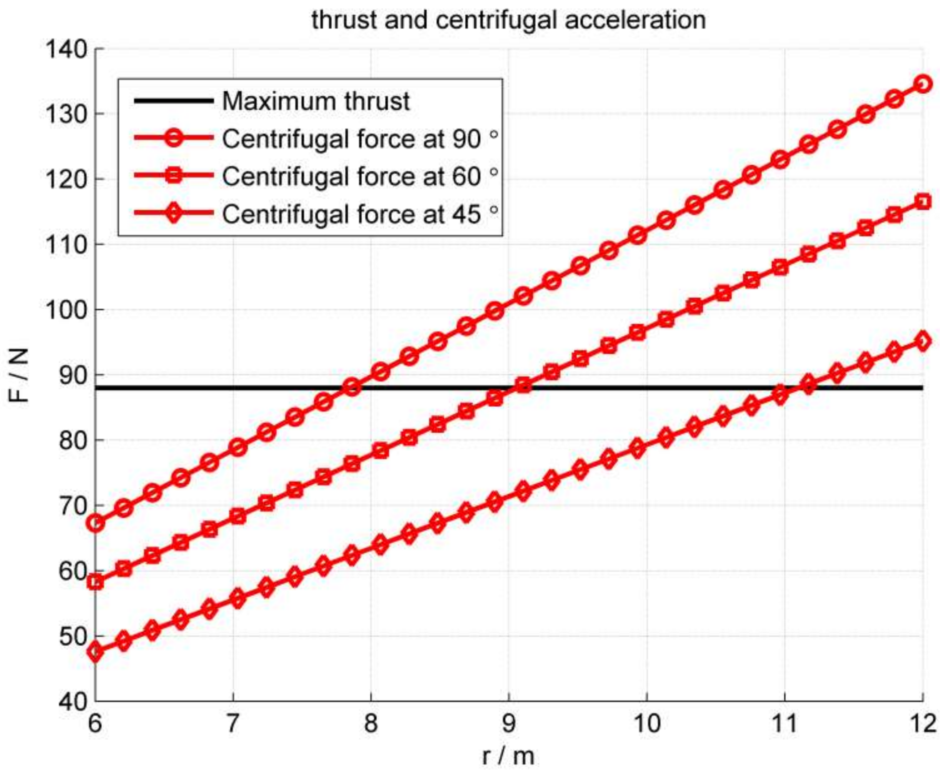


Figure 8-11: Centrifugal acceleration as a function of distance at different angles between position vector and angular velocity vector

Figure 8-11 shows the centrifugal force that needs to be compensated for, when a chaser with a mass of 1473 kg performs station-keeping at various stations in the target body frame rotating at a constant angular velocity of 5 °/s. The figure also indicates the maximum thruster force available to compensate the centrifugal acceleration, namely 4 x 22 N = 88 N (according to our design case). It shows that if the chaser needs to perform station-keeping in the body frame at a point perpendicular to the angular velocity vector, then the maximum distance that can be achieved is at most 7.8 m. In this case, the chaser would need to dedicate all available thrust to compensating the centrifugal acceleration. This means of course that if margins need to be taken into account, then the chaser can only perform station-keeping at a distance smaller than 7.8 m. At an angle of 45° to the angular velocity vector the chaser can perform station-keeping in the target body frame at a distance of at most 11 m. This means that the chaser needs to approach Envisat to a distance of at most 11 m before it can start station-keeping in the target body frame.

The maximum dimensions of Envisat are of the order of 20m from the centre of mass to the furthest points of the body. Clearly the chaser cannot safely approach the target from a safe distance greater than 20 m to a distance of 7.8 – 11 m from any given direction without risking a collision. The angular momentum vector provides a safe intermediate approach direction that can be used to bridge the gap between the hold point at safe distance greater than 20 m to the maximum body-frame station-keeping distance of 7.8 – 11 m.

Putting into context all the above analysis leads us to the following conclusions when applied to other target classes:

- The module of the angular velocity of the target debris directly determines the thrust capability required from the chaser spacecraft given the distance at which synchronisation needs to be performed and the angle between the approach direction desired and the angular velocity vector.
- In turn, the distance at which the synchronisation in body frame needs to be performed for a final safe approach depends on the size of the target debris. The larger the size of the target, the longest the distance at which synchronisation must be performed.
- It must also be observed that the amount of propellant consumed to keep synchronisation in target body frame depends on the distance at which it is performed and the angle between the position vector of the chaser w.r.t. target COM and the instant target angular velocity.
- The assumptions of the Envisat application case are very demanding from the point of view of the size of the S/C and the initial target angular velocity module (between 3 deg/s and 5 deg/s). In fact, the capabilities of the propulsion system are pushed close to the limit when keeping synchronisation in target body frame. The assumptions made for the Envisat application case are, in many respects, a "worst case" when considering only the LEO scenario. For most LEO objects, it is expected that rotational state is more favourable and synchronisation error performance as well as propellant consumed can be scaled down.

For some of the space debris in MEO and GEO, nevertheless, very large spin rates (up to 360º/s) conform a very different capture and detumbling problem w.r.t the study case (Envisat rotating at rates between 3º deg/s and 5º/s). The chaser synchronization in target body frame and later capture by means of a robotic arm is no applicable/scalable to these cases.

Target size, mass and inertia properties

The target mass determines, given the target orbit, the required amount of fuel for the de-orbiting manoeuvre as well as the sizing of the required chaser engines to perform it. The amount of fuel to perform the de-orbiting entails the most significant contribution to the overall fuel budget of the mission. Therefore, it indirectly poses a lower bound on the chaser platform size, mass and inertia.

Following with this design chain implications, the chaser inertia determines, together with the target rotational state (according to the considerations made in the previous chapter) the sizing of the attitude control system, in order to provide the required agility while in synchronization to the target debris body frame.

Recalling from previous considerations on the target size, it indirectly determined also the distance at which target body synchronization should be performed and thus the propellant consumption to accomplish with the overall synchronization and capture phase.

The Envisat case, analysed within this study, is from this point of view a "worst case" in the LEO scenario since almost no other potential target debris in this region will overcome the large size, mass and inertia values from Envisat. For example, the two rocket upper stages mentioned in the study present the following mass ratios w.r.t. the Envisat case:

- **Ariane 4 M10 upper stage**: Mass ratio to Envisat: **1/3.6**
- **COSMOS 3M**: Mass ratio to Envisat: **1/5.5**

It cannot be expected that the scaling function of the required chaser mass to smaller target debris to be exactly linear with the target mass value since there are other significant contributions to the overall platform mass that remain close to constant independently from the fuel mass to be stored. Nevertheless, it would be expected a significant reduction in the overall chaser mass for smaller targets such as the rocket upper stages mentioned (except in the case that a multi-target mission is foreseen).

Al already highlighted, the overall inertia properties of the chaser and the target rotational state and approach direction determine the sizing of the attitude control system thrusters. The outcomes from the study point to the importance of the signal to noise ratio obtained from the attitude and position control thrusters, mainly for the synchronization phase where both high agility and thrust precision are required. In principle, smaller thrusters doesn't provide better (relative to total) thrust noise and MIB than larger thrusters, since main technology limitation comes from the valve actuation. Table 8-5 shows the main performance FOMs for the thrusters modelled in our application case. Thus, main driver of performance while in synchronization phase would still be the target rotational state unless a technology improvement in the attitude control system is achieved.

Table 8-5. 22N attitude control thrusters performance assumptions

Nominal Thrust	Isp [s]	MIB [s]	Thrust noise (3σ)
22N	290	0.04	5%

Target passivation state

The target debris (Envisat) was assumed to be passivated in our study case.

There is the possibility that in the case of other defunct satellites, passivation of all the systems cannot be assumed. In that case, and depending on the type of expected risk, there can be limitations on the selection of the final approach direction and grasping point. Additionally, there can also be constraints on the selection of the final chaser relative pose w.r.t. the target body for the de-orbiting manoeuvre. These resctrictions (if any defined) need to be analysed on a particular basis in view of the general rules defined within the Target Rotational State analysis section of this document, which have an impact on the thrust levels required to compensate for the centripetal acceleration terms as well as on the propellant consumed to do that.

Existence of adequate grasping points.

The Envisat Capture and Detumbling Mission baseline definition within the present study stated the following:

- The grasping point is assumed to be the base of the Envisat Solar Array mast.
- Once the arm is safely gripped to the target anchorage point, the arm can move to reconfigure the stack for de-tumbling and later deorbiting.

For different application cases, the most appropriate grasping interface at the target debris needs to be selected in a case by case basis according to the following criteria:

- Mechanical compliance of the selected debris interface. It means that the grasping area is able to withstand the expected loads on it both along the grasping and the detumbling or braking manoeuvres. It is something that can only be done if detailed information from the manufacturer is available or with the explicit participation of the manufacturer.
- Accessibility of the selected gasping point and convenient approach axis. It means that the approach motion to grab the selected interface can be done in a direction that is both the safest possible from the point of view of collision risk and that at the same time is convenient from the point of view of energy (lowest possible fuel consumption). It can be evaluated according to the analysis of the target rotational state, as described in the section devoted to the Target Rotational State from this document.

Since the case of the rocket upper stages was consider significant according to this debris class occurrence in LEO and also according to the collision risk criteria, we will briefly discuss it in the following paragraphs.

Figure 8-12 shows the overall shape and size of the Ariane4 H10 upper stage, which is a quite frequent debris in the LEO region.

Figure 8-12. Ariane4 H10 upper stage (one of the most frequent large debris in LEO)

For this kind of debris, several potentially suitable grasping points have been proposed in the literature:

- Nozzle cone
- Inter-stage mounting ring
- Launch adapter

In addition to the mechanical constraints analysis, the selection of the final candidate interface would need also to be guided, if possible, by the analysis of the debris rotational state. As mentioned from the general analysis of dominant perturbations at different space regions, a body such as the Ariane4 H10 or a similar rocket upper stage could end in a rotational state that is either **coupled to the gravity gradient or to the magnetic field**. It will basically depend on the overall inertia properties and magnetic properties of the debris but the most likely case for upper stages is the gravity gradient coupling since they present a clear difference between their minimum and maximum moment of inertia. In this case, the expected rotation rate would be about 1 revolution per orbit and probably close to the flat spin configuration. In that case, the considerations on the approach direction and control cost associated would be very similar to the Envisat case with the additional advantage of lower rotation velocity (~0.06deg/s) and safer approach due to the fact that there are no large appendages as in the case of Envisat.

The latter case (coupling to the magnetic field) is much less probable. In that case,the expected rotation rate would be about 2 revolutions per orbit and the spin axis would depend on the orientation of the magnetic dipole in the body frame. It could also happen that the object has not yet achieved a final steady state and the rotational state is somewhere in between. Both cases require from a case by case analysis since no general rule can be derived a priori.

9. TECHNOLOGY READINESS ASSESSMENT

Table 9-1 contains a summary of the preliminary identification of candidate sub-sytems to be included within a technology development roadmap. The two left columns identify the requirement or set of requirements that is related to each specific subsystem (third column). Fourth column contains the reference to the chapter section where it is discussed and the right column the preliminary assessment conclusion.

Table 9-1. Preliminary Technology Readiness Assessment

ID	Requirement	Subsystem	Reference	Candidate for technology roadmap [Y/N]
GNCR-FUNC-GEN-0170	Close rendezvous	GNC S/W	9.1	N
GNCR-FUNC-GEN-0170	Capture phase	GNC S/W	9.2	Y
GNCR-FUNC-GEN-0190	Detumbling phase	GNC S/W	9.3	Y
GNCR-FUNC-NAV-0070 GNCR-FUNC-NAV-0090 GNCR-FUNC-NAV-0130 GNCR- PERF-NAV-0060 GNCR- PERF-NAV-0080 GNCR- PERF-NAV-0090	Visual camera and LIDAR Relative position and attitude estimation performance	GNC H/W	9.4	N
FS-CAP-10 FS-CAP-220 FS-CAP-230 FS-CAP-240 FS-CAP-250	Robotic subsystem Robot arm performance requirements	Payload – Robotic arm	9.6	Y
MIS-ARC-160 OPS-PHA-270 GNCR-FUNC-CON-0100 GNCR-PERF-CON-0150 GNCR-PERF-CON-210 GNCR-PERF-CON-0220 GNCR-PERF-CON-0230 GNCR-PERF-CON-0320 FS-PRO-30	High target mass High target rotational speed 6 DOF control Position/velocity and attitude control performance Generic performance requirements	Propulsion	9.8	N
OPS-AUT-10 FS-DAT-120	On-board processing	Data handling	9.7	TBD

Since TRL levels are referred to later in the following chapter subsections, a recall to TRL definitions according to ESA definitions is shown in Table 9-2.

Table 9-2. The basic technology readiness levels

Readiness Level	Definition	Explanation
TRL1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.
TRL2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented and R&D started. Applications are speculative and may be unproven.
TRL3	Analytical and experimental critical function and/or characteristic proof-of concept	Active research and development is initiated, including analytical / laboratory studies to validate predictions regarding the technology.
TRL4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together.
TRL5	Component and/or breadboard validation in relevant environment	The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
TRL6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	A representative model or prototype system is tested in a relevant environment.
TRL7	System prototype demonstration in a space environment	A prototype system that is near, or at, the planned operational system.
TRL8	Actual system completed and "flight qualified" through test and demonstration (ground or space)	In an actual system, the technology has been proven to work in its final form and under expected conditions.
TRL9	Actual system "flight proven" through successful mission operations	The system incorporating the new technology in its final form has been used under actual mission conditions.

9.1. GNC S/W: CLOSE IN

The start of the close in sub-phase is at 100m (±50m) from the target in V-bar. From the initial point a close in up to 30m from the target is then performed by using relative navigation means. The requirement for absolute orbit determination in order to cope with the initial conditions required is within the precision that can be obtained with precise orbit determination (POD) and propagation and that has been achieved by formation flying missions such as PRISMA.

On the other hand, the target is not cooperative and does not provide any telemetry, such that its orbit needs to be determined by radar/laser tracking and/or visual imaging from the chaser. While the later sub-phases (synchronization, capture and detumbling) will be challenging and substantial effort will be required to develop the necessary tools, this phase is not considered to require any specific technology development.

9.2. GNC S/W: SYNCHRONISATION AND CAPTURE PHASE

During the synchronization and capture of the Space Debris Target by the chaser S/C, both will fly very close to each other and the chaser position and attitude are precisely synchronized to the target rotational state according to the guidance strategy described in detail in [RD.6]. The risk for (undesired) collision will hence be very real and will impose important constraints on the relative sensors (LIDAR, visual cameras), the onboard GNC autonomy and the FDIR approach and the operations.

Another challenge associated to the capture phase, is the fact that it combines several complex elements: the robotic arm, the relative navigation sensors, the propulsion subsystem and the GNC subsystem. The results of the present study show that all the phases of the reference mission are feasible according to the control architecture stated and to the control synthesis and analysis procedures followed (by means of MIMO robust synthesis/analysis and S/W simulation campaigns using MonteCarlo method). It can be considered that the required GNC technology is at least at TRL3. This calls for dedicated end-to-end testing of the GNC subsystem with hardware-in-the-loop in a relevant environment (ground testbed), so that TRL6 can be reached.

These tests shall consider realistic conditions for the visual camera, as mentioned in section 9.4, as the potentially rapid motion of the uncooperative target may induce strongly varying illumination conditions. The LIDAR performance is less sensitive to the illumination conditions, but still needs to cope with fast dynamics.

The development of the robotic arm is discussed in section 9.6, it is probably the single most challenging part of the system. The control of the robotic arm is to be performed by the GNC S/W. This study has demonstrated the feasibility of several combined control modes platform/arm and has highlighted the critical points to be considered for successful implementation of them. Implications on robotic arm technology are discussed in section 9.6.

9.3. GNC S/W: DETUMBLING PHASE

The detumbling phase is similar to the capture phase in terms of GNC complexity. Here as well the end-to-end performance needs to be demonstrated with hardware-in-the-loop in a relevant environment to rise the TRL level from TRL3 to TRL6.

9.4. GNC H/W: VISUAL CAMERA

Camera's for visual based navigation exist and have high TRL levels. They are therefore not directly subject to any technology development. The camera's may however be used in a quite challenging environment with relatively rapid motions and varying lighting conditions. It is hence necessary to test the visual camera in realistic conditions, together with the GNC subsystem. This requirement is tracked within section 9.2.

9.5. GNC H/W: LIDAR

The technology of LIDAR systems is well established and several LIDAR units are available on the market, with relatively high TRL. As for the visual camera, the challenge is not the development/qualification of the equipment, but the integration into the complete system and coping with the operational constraints. This requirement is hence also tracked within section 9.2, where system-level development is considered.

9.6. PAYLOAD: ROBOTIC ARM

The robotic payload is a complex subsystem that needs to combine high performance (both from point of view of high joint torque actuation as well as tip control accuracy), robustness to a varying environment and reliability. While robotic manipulators exist both on earth and for space applications, the specific requirements of a detumbling mission calls for a dedicated development.

Several challenges need to be considered in the development of the robotic arm:

- Flexible dynamics induced by robotic arm and gripper, which are to be accounted for by the GNC S/W
- Grasping and associated contact dynamics
- Clamping mechanism
- Verification approach in 1-g environment
- Reliability of the arm
- Increased joint torque capability able to withstand large centripetal loads created by targets at high rotational velocity. The study results (in **[RD.6]**) have demonstrated that to be able to perform arm

movements while in COMPOSITE phase the arm joints must be able to provide torques equivalent at least to the appearing centripetal loads on the chaser (in synchronized state to the target rotational state).

- Sensorized arm joints able to provide torque readings that can be used to properly control the loads on the arm and grasping tooltip along the capture and detumbling manoeuvres. The results of the study have demonstrated that the ability to measure indirectly the synchronization errors between chaser and target by means of force/torque sensing in the arm joints is of high importance for the reduction of these loads when dealing with target debris rotating at high speed.

The development of such robotic arm can benefit from experience gathered by different parties (e.g. DLR for the eDeorbit project) and lightweight robotic manipulator components with demonstrated performance are available. The development needs can however only be assessed after a dedicated design exercise.

9.7. DATA HANDLING: GNC PROCESSING POWER

Apart from the GNC S/W, no computationally intensive calculations are expected for the detumbling mission. On-board computers are available based on a LEON2/LEON3 processor that can deliver sufficient computing power for regular AOCS activities. It is at this stage unclear how much processing power would be required for a detumbling mission. If it exceeds the capability of readily available space qualified computers, specific qualification or development campaigns may be necessary.

This data handling aspect is withheld in the technology roadmap list as a placeholder, pending additional information on the real processing needs.

9.8. PROPULSION SUBSYSTEM

The objective of the mission is the subsequent rendezvous, synchronisation, capture, detumbling and de-orbiting of the Space Debris Target. The rendezvous, detumbling and especially the de-orbiting require a large amount of propellant. The **size, mass and rotational state** of the Target will drive the propellant mass, which will then likely drive the S/C mass and moments of inertia and hence the S/C agility and the S/C structure. The high propellant need is a critical mission driver, as it may have a significant impact on the S/C design.

In order to capture (using a robotic arm) and detumble (larger) targets, the chaser needs to precisely synchronize its motion with the target. Depending on the target rotational movement, this may impose relatively high linear and angular accelerations on the chaser as confirmed from the application case, hence driving the agility requirements.

For the propulsion subsystem, all these aspects have the following consequences:

- Large amount of propellant is needed.
- 6 DOF capability is required (high amount of thrusters, certainly if considering redundancy).
- Plume impingement to be addressed, including interference with the robotic arm and the target.
- Sufficiently high thrust levels needed to support the agility requirements. For the Envisat application a system composed of 6 groups of 4 22N thrusters was selected according to the last eDeorbit baseline known. This configuration was demonstrated to cope with thrust requirements but being close to the application limits during the synchronisation sub-phase.
- Sufficiently low thrust levels (and repeatability) needed to support the pointing and relative position accuracy requirements that allow a safe approach and capture of the target. In this respect, the performance obtained from the baselined propulsion system in terms of thrust error is clearly in the limits of usability for the synchronisation phase and would need improvement for guaranteeing the required safety levels.

These are challenging aspects in terms of spacecraft design. However, a myriad of propulsion subsystem components exist (propellant tanks, thrusters, valves, pressure regulators, etc.) that are readily available and have high TRL. Thrusters with 1N, 5N, 10N or higher force capability can be used depending on the outcome of the design exercise.

Effort will hence be necessary to inject the mission requirements into the spacecraft and propulsion subsystem designs, but no specific technology developments are envisaged at the moment. Delta-qualifications may however be needed, but these are to be identified after a first design iteration including structural and thermal analyses. And of course, the stringent mission requirements will have an important impact on mass, volume and cost of the propulsion subsystem.

10. PRELIMINARY TECHNOLOGY ROADMAP

This section on the technology roadmap only discusses the more critical and resource (budget/time) consuming developments. The following developments are considered:

- Prototyping and hardware-in-the-loop testing of essential rendezvous, capture and detumbling GNC S/W functions.
- Development of a robotic arm with grasping mechanism and sensored joints for the capture and detumbling phases.

Other developments required for the implementation of a detumbling mission that are relatively limited, non-critical, already ongoing or seen as normal work within phases B/C/D are not presented. These are for example standard spacecraft development activities such as the qualification of the structure and the equipment and the tailoring of remote interface units and on-board software.

10.1. CLOSE PROXIMITY GNC S/W

The GNC S/W is considered as one of the critical components of a robotic arm detumbling mission. It is considered to need specific development (in addition to the work already performed within this study and other relevant activities in the area) to rise the TRL level up to TRL6.

10.1.1. MAIN DRIVERS

There are several challenges associated to the GNC S/W. Some of them have been pointed out along this study (mostly those related to control, propulsion and robotic arm capabilities). Some others (such as those related to specific sensor processing and estimation algorithms) were out of the scope of the activity but are addressed here below. The main needs identified to consolidate and rise overall TRL level up to TRL6 are:

- Consolidation and test in relevant environment (with HW in the loop) of state-of-the-art **image processing** algorithms able to provide accurate relative position and attitude measurements at fast rates while ensuring robustness against strongly varying illumination conditions and relatively fast spacecraft motion.
- Consolidation and test in relevant environment (with HW in the loop) of specific algorithms (**estimation** filters) for the relative position and attitude estimation in the case of tumbling targets rotating at large speeds. It includes the fusion of the required sensors according to the system baseline stated (e.g. navigation camera/s, LIDAR, star trackers and IMU) and the use of ground provided target dynamics information. Also the use of robotic arm joint encoders and force/torque sensors readings for the indirect estimation of chaser de-synchronisation w.r.t. the target debris has been identified as a key driver within this study.
- Consolidation and test in relevant environment (with HW in the loop) of the estimation algorithms for the **target rotational state** evaluation from visual information previous to the synchronisation and capture sub-phases. These algorithms should provide the estimation of the current rotational state of the target as well as a confirmation or re-estimation of the physical target parameters (mass and inertia) known a priori.
- Consolidation and test in relevant environment (with HW in the loop) of the specific required **FDIR** functions, which ensure the safety of the chaser and perform collision avoidance if needed.
- Test in relevant environment (with HW in the loop) of the **guidance** algorithms (developed and SW validated within this study) for the generation of trajectories and feed-forward laws to synchronize the chaser with the target's motion, for the actual capture and for the attitude control of the stack after capture.
- Test in relevant environment (with HW in the loop) of the **control** algorithms (developed and SW validated within this study) for the 6DOF control of the chaser along the close in and synchronisation phase and the 6DOF + 4DOF (arm) control for the capture and detumbling phases.
- Prototyping, SW testing and test in relevant environment (with HW in the loop) of the control algorithms for the **contact phase** (grasping of the target interface point).

10.1.2. ROADMAP

The following steps are proposed for rising GNC S/W technology for a detumbling mission TRL3 to TRL6:

Table 10-1. GNC S/W Roadmap summary

Step	Description/Remarks	Status
GNC S/W consolidation (prototyping and validation in S/W environment)	Focused to the following areas (not included within the present activity): - State-of-the-art image processing algorithms for fast rotating targets and robustness to illumination conditions - Estimation filters for fast rotating targets - Specific FDIR functions - Contact phase controller	Algorithms already exist but need to be consolidated, tuned and validated in S/W environment.
Hardware-in-the-loop simulations (close in & synchronization)	Testing the overall integration of GNC S/W and sensors in a realistic environment in terms of relative dynamics/kinematics and optical properties. Targeted to the following areas: - State-of-the-art image processing algorithms for fast rotating targets and robustness to illumination conditions - Estimation filters for fast rotating targets - Specific FDIR functions - Guidance function - Close in and Synchronisation phase control algorithms (6 DOF).	On going activities (e.g. COMRADE) include validation with H/W in the loop in relevant ground environment (robotic facilities)
Hardware-in-the-loop simulations (capture & detumbling)	Testing the integration of S/W and robotic arm, including sensors. Targeted to the following areas: - State-of-the-art image processing algorithms for fast rotating targets and robustness to illumination conditions (focused on visual servoing of the capture phase) - Specific FDIR functions for the last approach and capture - Guidance function - Capture (6 DOF & 6DOF + NDOF arm) control algorithms - Contact phase & grasping control algorithms	On going activities (e.g. COMRADE) include validation with H/W in the loop in relevant ground environment (robotic facilities)

Step	Description/Remarks	Status
	- Detumbling (6 DOF & 6DOF + NDOF arm) control algorithms	

10.2. ROBOTIC ARM PAYLOAD

Capture and detumbling by contact (robotic arm) requires a physical interface between the chaser and the target. The baseline of this activity consisted on accomplishing this by means of a robotic arm with gripper.

10.2.1. MAIN DRIVERS

The following drivers can be identified for the development of the robotic arm:

- While the interface is well-known at the chaser side, it may not be well characterized at target side. Moreover, the target interface point shall depend both on the mechanical compliance of the specific element/area of the target debris and, as discussed in [RD.7], on the target rotational state, which determines safe and minimum energy approach directions.
- The robotic arm needs to provide good dexterity (determined by the number of degrees of freedom, lengths of the segments and proper analysis of the arm singularity points), so that allows the capture of the target while complying at the same time with the positioning accuracy and the rate requirements.
- The robotic arm and gripper need to withstand the forces and torques induced by the target/chaser dynamics during the capture and detumbling phases. The results of the present study highlighted two major facts:
  - Loads on arm joints and gripper can be significantly high while in composite phase due to chaser desynchronization w.r.t the target rotational movement. To avoid that, the performance of the state-of-the art visual based relative navigation systems are not enough but measurement of the joint loads can be a very good indirect way of measuring that and avoiding surpassing maximum allowed loads.
  - Simultaneous arm movements (e.g. for relocation of the chaser) while in composite phase need to be supported by joint motor torques in the order of centripetal loads being experienced by the chaser while in this synchronised state. These torque values can be significantly high for targets rotating at high speed (as is the case of Envisat). It needs to be considered in the arm design if this kind of manoeuvre is intended to be performed.
- The system needs to be verified in a 1-g environment, which may lead to a complex GSE and/or over-dimensioning of the design.

10.2.2. ROADMAP

The following steps are needed for the development of the robotic arm for the detumbling mission:

Table 10-2. Robotic Arm for Capture. Roadmap Summary

Step	Description/Remarks	Status
Preliminary design of the robotic arm	Identification of the necessary components and their technology readiness for the specific application case. It would include evaluation of the present study findings: - Sensored arm joints - Increased motor torques required if simulataneous arm movement while in composite stack for targets at a high rotational speed.	Designs already exist but need to be consolidated/modified for the specific application case
End-to-end performance simulator with robotic arm	Embed design into overall S/C simulator to assess the end-to-end performance	Results already coming from this study (except fot the contact phase). To be consolidated and reviewed when a consolidated design of the arm exists
Development of robotic arm components	As needed and identified during the preliminary design phase. Joint motors and sensors are probably the key points.	H/W already exists and
Robotic arm breadboard activities	It is recommended to consider hardware-in-the-loop testing with platform dynamics and GNC S/W in order to test the end-to-end performance	On going activities (e.g. COMRADE) include validation with H/W in the loop in relevant ground environment (robotic facilities)

11. RECOMMENDATIONS FOR FUTURE S/C DESIGN

The first activities performed within the S/C design cycle are normally related to the determination of main vehicle physical characteristics, including relevant budgets (mass, fuel and power consumption) as well as a first iteration on the sizing of principal sub-systems.

Though, well known for system and GNC designers, here the process is described from the perspective of the study findings and every step put in relation to main drivers identified.

The process would be as follows (observe that it is basically an iterative process, where the different steps must be run more than once and be progressively refined as the design process advances):

- Mission analysis of the de-orbiting manoeuvre is a key activity to approximately determine the amount of fuel required to perform the de-orbiting manoeuvre. The main driver for the mass determination of the chaser S/C is the amount of fuel required for this manoeuvre (if the vehicle is intended to be a multi-mission S/C, in addition to the de-orbiting manoeuvre for each target the transfer to each orbit shall be taken into account). The analysis of fuel consumption for the synchronisation/capture and debris detumbling within this study has shown not to be a driving figure when compared to the required mass for deorbiting.
- Once the overall ΔV is known, the determination of the total fuel mass required is function of the propulsion technology use (Specific impulse of the actuation system) and the number and mass of the satellites to be deorbited.
- The analysis of the Rotational State of the target debris/s is needed also for the determination of the fuel mass required to perform the overall rendezvous, synchronisation and capture manoeuvre, which adds to the overall fuel and mass budgets.
- Once determined the overall fuel budget, a first rough estimation of the overall Chaser S/C mass can be performed according to engineering knowledge and experience, tough it will be refined as the design advances.
- Again, from the analysis of the rotational state of the target debris and according to the analysis and guidelines offered in [RD.4] , the analysis of the best capture strategies and approach directions as well as on the best candidate target grasping interfaces must be done.
- The sizing of the attitude control system thrusters must be done in view of this latest analysis, which determines:
  - The distance at which the transition to target body frame synchronisation must be performed, which determines the centripetal terms which must be counteracted by the actuation system.
  - The distance from the best last approach axis to the angular momentum axis, which also determines how costly is to perform the fly-around from the angular momentum direction to the last approach direction as well as the last approach itself.
  - The required thrust levels according to the above constraints regarding the compensation of the centripetal terms, which are the driving figure of merit according to the results of the study.
  - The maximum allowed error to the thrust levels to accomplish with the reference tracking requirements.
- The consolidation of navigation accuracy requirements in view of the target rotational state and requirements imposed by the gripping tool and target debris interface point.
- The determination of the onboard processing needs to cope with sensor processing (e.g. image processing algorithms, which are expected to be the driving need) and with guidance/control algorithms (not expected to be the driving ones).

The following paragraphs, discuss recommendations for key S/C sub-systems in view of identified improvement areas and problematic points.

AOCS equipment:

The results of the present study put into relevance that the performance of the attitude and position control thrusters is key to the success of the mission. The selection of the adequate propulsion system should be central part of the S/C design process. Major findings on that are:

- Very good S/C agility is required both for the synchronisation phase, see Figure 11-1 and Figure 11-2 (principally for the sub-phase in which the Chaser is synchronised within the target body frame, which is the sub-phase relevant for the capture) and for the detumbling phase, see Figure 11-3 and Figure 11-4 (since the synchronisation of the Chaser must be kept in order to lower the resulting loads on the grasping point and arm joints).
- At the same time, low MIB and actuation errors are required to fulfil relative state control error requirements while in these phases.
- The baselined AOCS actuators in this study (6x4 22N thrusters) are very in the limit for usability while in the synchronisation phase for the assumed initial target rotational state. Review of that baseline should be mandatory in order to improve performance of the synchronisation manoeuvre for proper placement of the capture arm close to the target interface point.

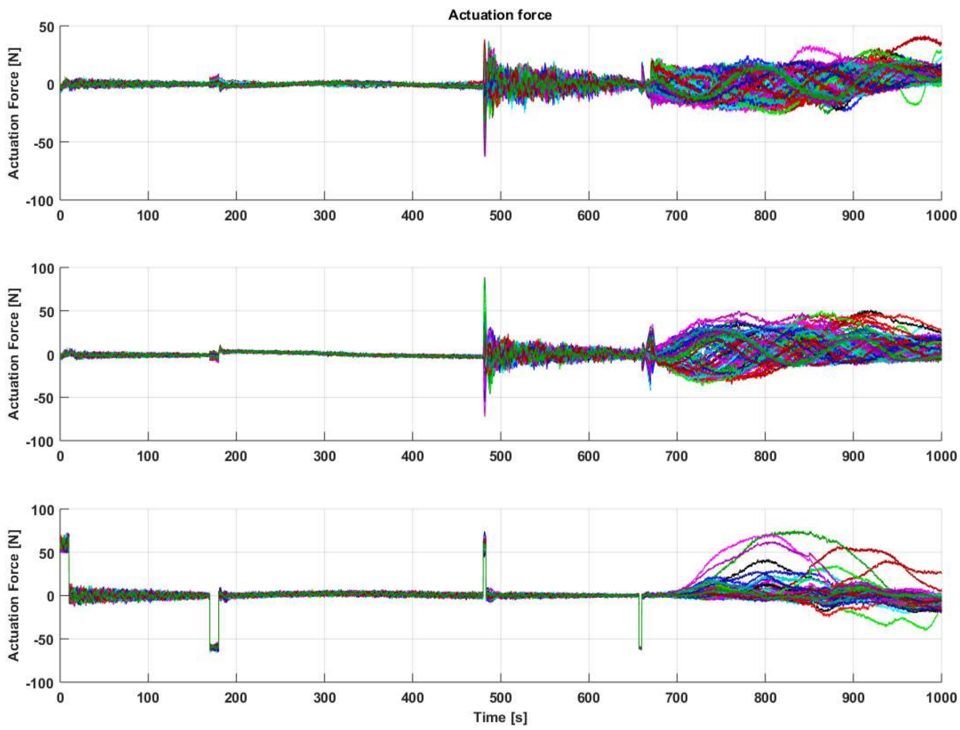


Figure 11-1. Actuation forces along the overall close in and synchronization phase (body frame FG0) [N]

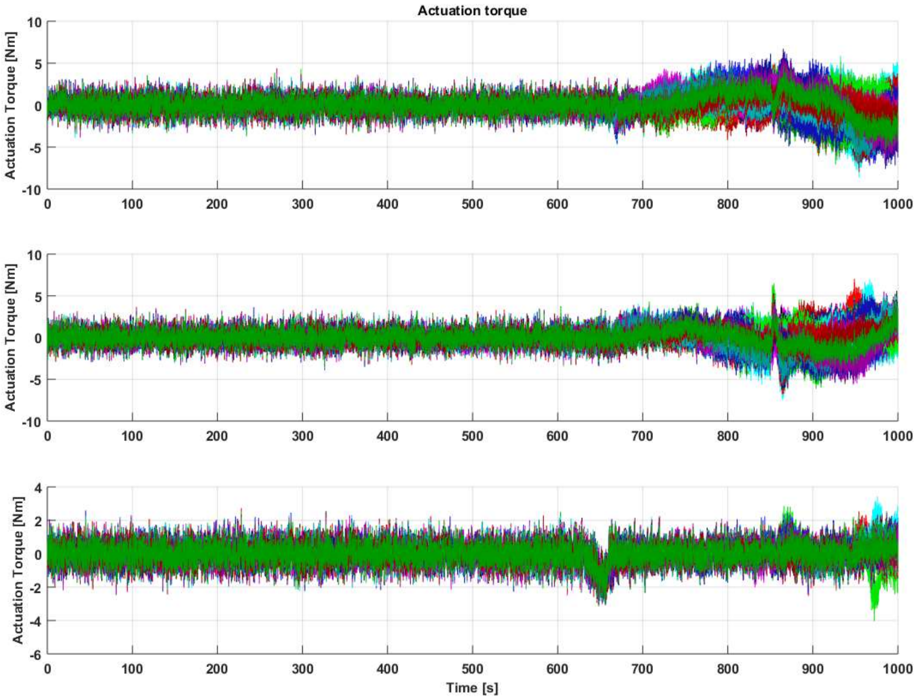


Figure 11-2. Actuation torques along the overall close in and synchronization phase (body frame FG0) [Nm]

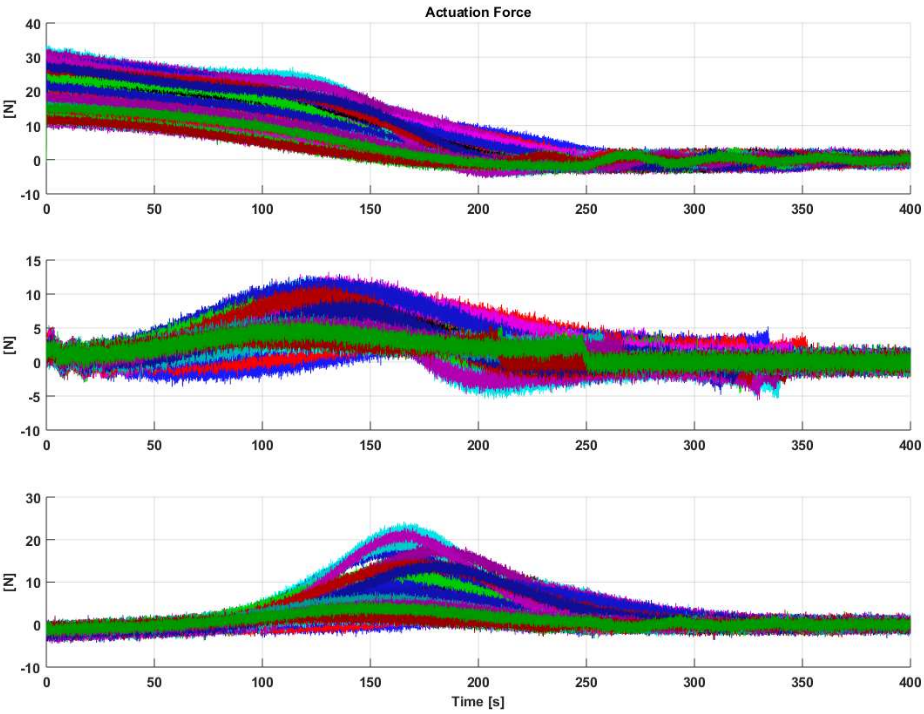
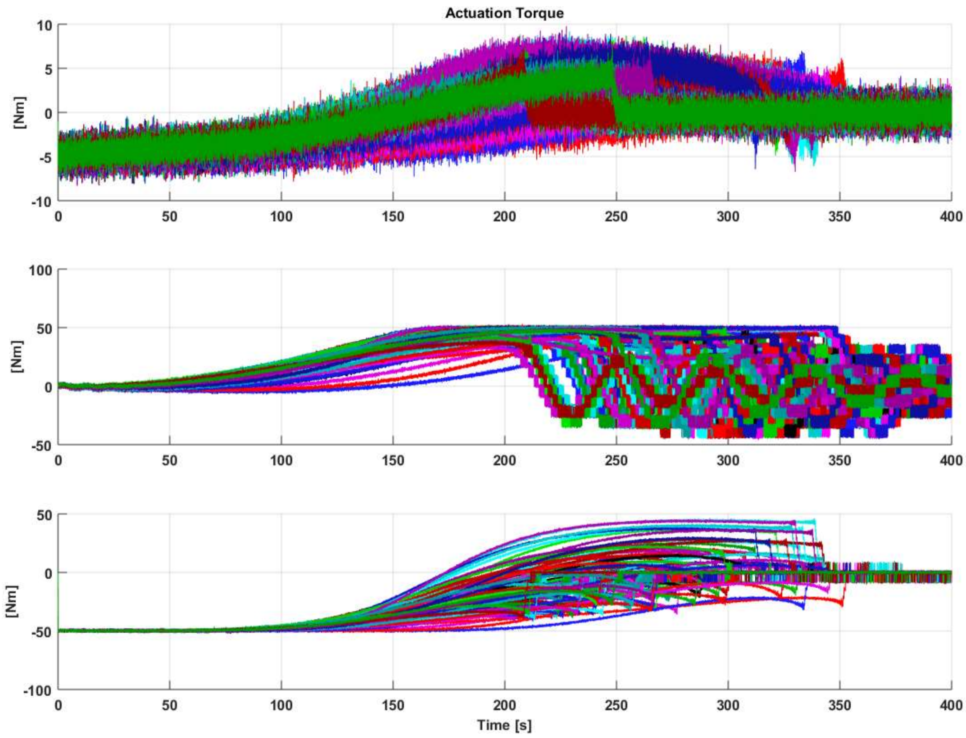


Figure 11-3. Actuation force (x-y-z components) in body frame FG0 [N] along the detumbling (braking) manoeuvre.



/a

Figure 11-4. Actuation Torque (x-y-z components) in body frame FG0 [Nm] along the detumbling (braking) manoeuvre.

Navigation:

- Absolute Chaser state determination is not a problem, according to commonly used sensor performances specification
- On the other hand, relative Navigation is a key challenge for the activity. The Performance numbers assumed for this study regarding the estimation of the target rotational state w.r.t. chaser (error <1º, <0.1º/s , 3σ) seem also to be quite in the limit for the synchronisation phase. In this phase, the knowledge of the target rotational state and of the relative state of the Chaser are of key relevance to compute safe approach profiles and to track them properly.
- Consolidation of state-of-the-art relative navigation by means either of image processing or LIDAR sensors seems then mandatory for the feasibility of the mission.

Robotic arm:

Several facts are also pointed out from the GNC design/analysis process itself and from the validation campaign within non-linear models regarding the design of a robotic arm for capture of a tumbling S/C.

Currently, arms being proposed for this purpose in the frame of other activities, can be characterised as follows:

- Arm maximum length: ~3m
- Arm mass: ~45 Kg
- Maximum bearing torques allowed: 120Nm
- Maximum grasping and joint torques: 10Nm

According to the results of our non-linear validation campaign, the above mentioned characteristics would allow to successfully accomplish with all the sub-phases proposed under the following assumptions:

- No problem is found to perform the arm deployment according to the deployment profile assumed (~100s duration). Figure 11-5 shows that motor torques demanded at joints for the deployment are limited to 5Nm without showing problems to follow the angle profiles.
- Maximum bearing torques produced during the detumbling manoeuvre itself are also under 60Nm (below the 120Nm above mentioned specification). Nevertheless it is important to observe here that the nominal detumbling mode is assumed to be performed with arm locked to a given configuration. In this case, it is assumed that joint brakes withstand the torques in the joint rotation axis (limit assumed to be the same or higher than the bearings one). In the case that simultaneous relocation of the chaser needs to be performed at the same time, the loads (see Figure 11-6) would be withstand by the joint motor, thus violating the above mentioned reference specification. For that case, arm design with higher joint actuation capacity would be required.
- In order to limit the loads appearing on the arm while in composite phase because of chaser desynchronization w.r.t. the target tumbling movement it has been pointed out that the design of force/torque sensored arms is a must. It would help both, braking while in arm locked configuration (as an indirect way of measuring desynchronization) as well as progressive rigidisation of the arm or chaser relocation by arm movement
- Finally, the design of compliant grasping devices could also cope with part of the expected misalignments and relief somehow the arm from the task of fully nulling relative errors up to capture.

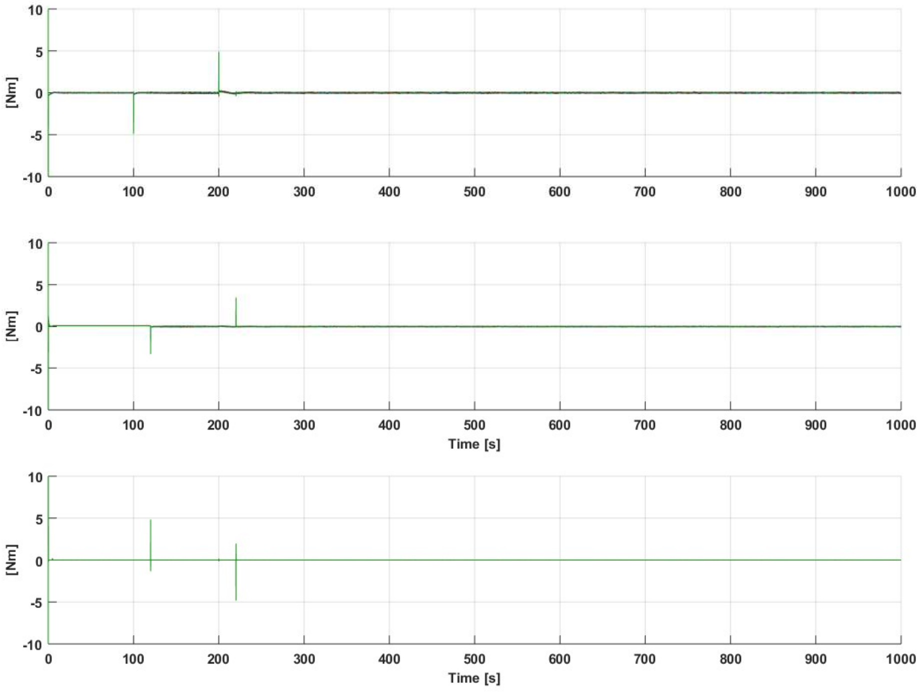


Figure 11-5. Arm joint control torques (joints 2,3 and 4) while deploying arm.

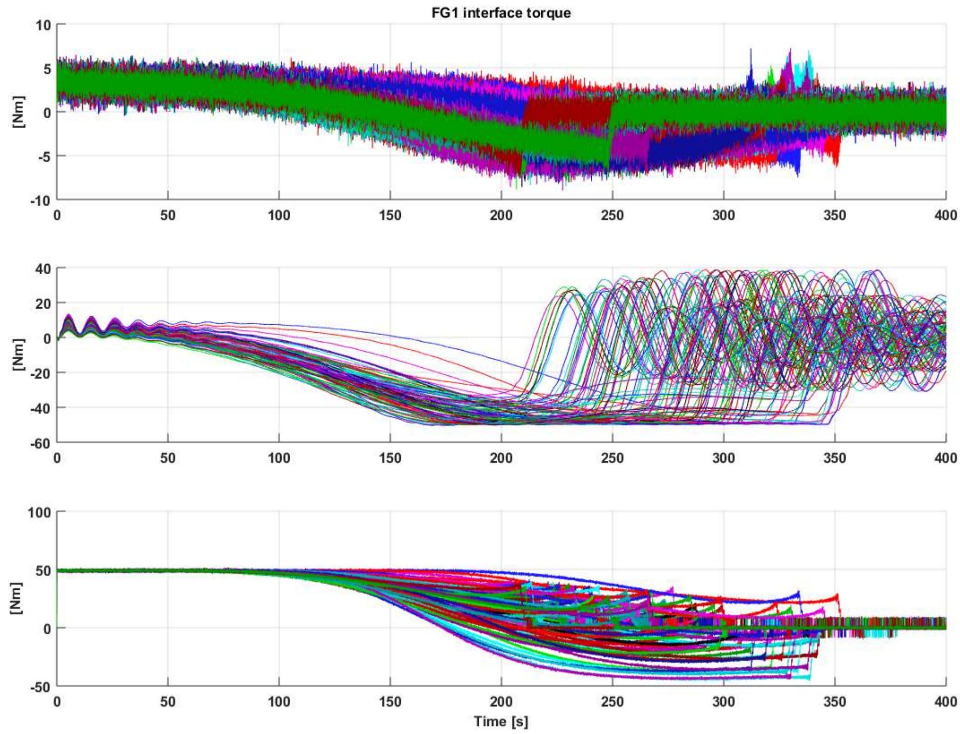


Figure 11-6. Interface torques (x-y-z components) at joint 1 (FG1) [Nm].

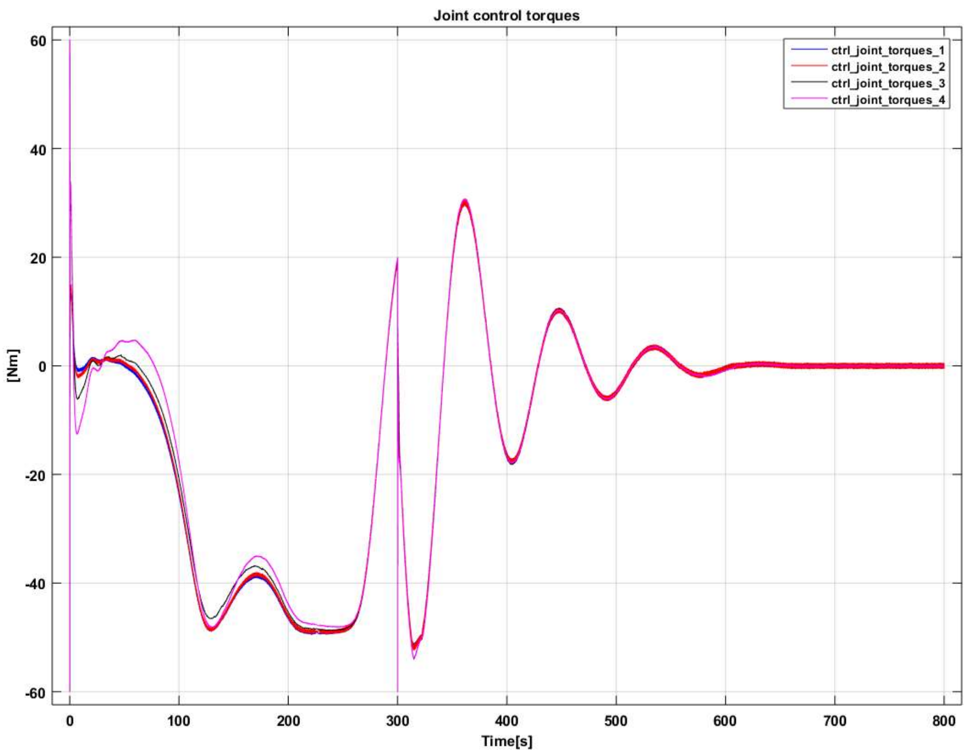


Figure 11-7. Joint actuation torques (from joint 1 to joint 4) [Nm].

END OF DOCUMENT