

# MISSION ARCHITECTURE FOR ACTIVE SPACE DEBRIS REMOVAL USING THE EXAMPLE OF SL-8 ROCKET BODIES

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## ABSTRACT

Space debris has become a serious problem for the safe operations of spacecraft in low Earth orbit. Attempts such as improving trajectory predictions of non-functional objects in space, guidelines for safer launches nowadays, and an implementation of post-mission disposal however will not stop the growth in debris numbers. One solution for mitigation is therefore the realization of removal missions.

Due to space debris being an issue for all space faring nations, this paper introduces an exemplary removal mission for 5 Russian SL-8 rocket bodies at an inclination of 83° orbiting at an altitude of 970 km - an area crowded with space debris and thus involving a high collision risk. The mission draft presented is based on a main satellite (Autonomous Debris Removal Satellite - ADReS-A) and - according to the number of targets - 5 de-orbit kits. The idea presented includes a parking orbit close to the targets positions, into which the set-up is launched. While the kits are equipped with a de-orbit thruster, the task of ADReS-A is, to approach the uncooperative target, berth it, stabilize the compound system and attach the de-orbit kit onto the target. The main satellite will take each de-orbit kit separately to the individual targets, shuttling between the parking orbit and the target orbits.

A prospect addressing the highly critical situations resulting from the interaction with an uncooperative target is given towards the end of the paper with a preliminary design for a decision process for autonomy.

## 1. INTRODUCTION

This paper was prepared in context of the study project 'Safety in Orbit', supported by Munich Aerospace and the Helmholtz Association. It represents an extension of Peters et al. [1], its crossing parts are condensed partly in the following text and extended by new study results.

### 1.1. Context

During recent years, the awareness for space debris being a risk for a safe operation of spacecraft has recognizable increased. The threat it provides can be quantified with the following numbers:

- *Mass*: Currently about 6500 t of man-made material exists in space, 2700 t of that in the Low Earth Orbit (LEO) [6].
- *Quantity*: 95% of all objects in LEO can be referred as space debris. (cf. [Figure 1](#))
- *Encounter*: According to various experts in the field, every 5 to 9 years a catastrophic collision, resulting in a breakup of the involved objects into smaller parts, is predicted. The last encounter of such event took place in 2009 between Iridium 33 and Cosmos 2251 [5].
- *On-going launches*: In 2013, 78 launches were recorded by NASA, resulting in officially 204 new space objects [3].

This development calls for measures. Along with post-mission disposal and a better understanding of the debris' trajectories, the removal of uncontrolled objects, as accepted by the majority of the community, is mandatory for reducing the collision risk and thus creation of new particles in space. Removal missions will limit an avalanche increase of objects as shown by various studies (see e.g. reference [2]). If these analyses are ignored, the resulting cascade effect will end in a scenario with orbits not safe any more for operations of satellites. The cascade effect in this context results from collisions among space debris itself and in such way creating smaller particles, which eventually become too small to be detected over a large spatial region without high effort.

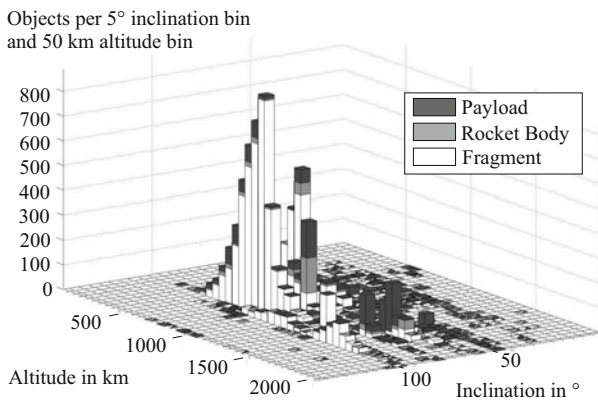
Simulations performed during the same studies, predict a necessary removal of at least 5 large objects per year

to eventually re-stabilize the space environment around the Earth and avoid the escalation of the cascade effect already initiated. After the target identification, which discusses a promising orbit to start a mission with the objective of multiple space debris removal, the mission architecture is presented. A subsequent preliminary budget estimation, regarding  $\Delta v$  and mass, will be followed by a short prospect on the implementation of autonomy to support the system in its complexity in particular for the berthing maneuver.

## 2. TARGET IDENTIFICATION

### 2.1. Orbit Limitation

The most crowded area in space with respect to man-made object is found in the low Earth orbit region with altitudes up to 2000 km [2]. [Figure 1](#) displays a distribution of the known objects, divided into payloads (i.e. satellites), rocket bodies and fragments created for instance by collisions, explosions or degradation of larger objects. The anti-satellite test (ASAT), conducted by China in an altitude of about 850 km (see reference [7] for details) and the orbit of the Iridium-Cosmos collision at 700 km to 900 km altitude contributed to the peak recognizable in the figure. In a slightly higher orbit of 900 km to 1000 km, rocket bodies make up the biggest part.

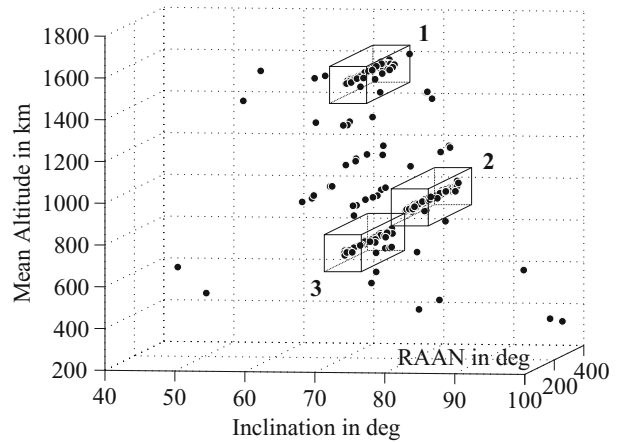


*Figure 1. Distribution of the different object types in the low Earth orbit region. Inclination bins are set to 5°, mean altitude bins to 50 km. [1]*

### 2.2. Target: SL-8 R/B

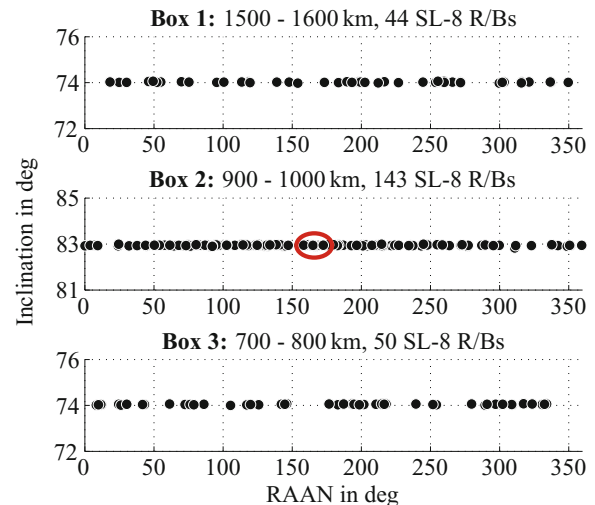
An investigation concerning the space object's size, mass and collision risk and applied to the objective of a multiple removal mission, resulted in SL-8 rocket bodies (SL-8 R/Bs) as most promising targets [1]. [Figure 2](#), shows their known position as of June 2014, data taken from [4]. Highlighted and displayed in [Figure 3](#) are specific

areas where most of the rocket bodies accumulate at similar altitude and inclination.



*Figure 2. Distribution of all known 292 SL-8 R/Bs in low Earth orbit as of June 2014.*

To specify a reference scenario, 5 upper stages in close vicinity regarding their inclination, altitude and right ascension of ascending node (RAAN), emerged out of the total number of currently 292 SL-8 R/B in space. Their position is circled in [Figure 3](#).



*Figure 3. Close-up view of [Figure 2](#). The (red) circle frames 5 emerged SL-8 R/Bs, providing the basis for the following scenario.*

Known data of SL-8 R/Bs (Kosmos 3M second stages) is qualified as followed [8]:

- *Mass:* 1440 kg, dry.
- *Dimension:* 6.585 m in length and 2.4 m in diameter.
- *Age:* The first SL-8 R/B ever launched was in 1964, the last one in 2010. The 5 objects chosen have an age between 21 and 41 years [4].

- *Origin*: Soviet Union, now owned by Russia.

SL-8 R/Bs were usually not designed to be removed, therefore they have no predefined point of contact, nor signal reflectors to determine their attitude or tumbling rate. These missing features result in a high planning effort and the necessity to determine e.g. the exact tumbling rate when in close proximity of the target.

### 3. MISSION OVERVIEW

#### 3.1. Mission Architecture

With respect to the recommendations given by Liou [2], the mission time frame to remove five objects is limited to one year, starting in 2020. Accordingly, various scenarios can be designed, Figure 4 gives a short overview of different approaches. When it comes to the design of the kits within this overview, an allocation of functions has to be made. The result has influence on the system complexity of both, the mother chaser and the kit.

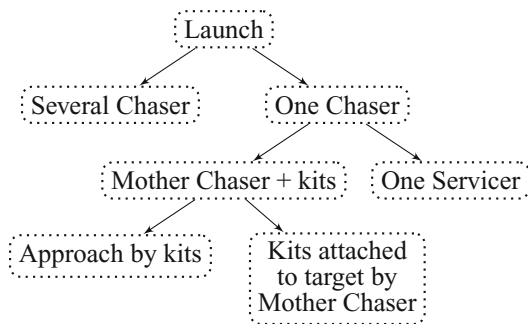


Figure 4. Different approaches for a multiple target removal mission.

The present work focuses on the kits being as simple as possible while most of the system complexity shall be within the chaser itself. This consideration results in a chaser satellite guiding several de-orbit kits to their designated target. Unifying operations such as the target berthing, target stabilization and attachment of the kits, the chaser is named *ADReS-A* for Autonomous Debris Removal Satellite. The autonomy within this context shall concentrate on critical situation and is presented to some extent in Chapter 4.2. The 'A' represents the first of its kind. Since the removal of at least five objects *per year* has to be proceeded over a long period, it is assumed, that *ADReS-A* will be followed by others of its kind, even if the possibility of fuel recharge is given in connection with De-orbit kits provided for further removal missions. A *De-orbit Kit* is equipped with a de-orbit thruster and actively maneuvers its target to the surface of the Earth.

The mission architecture is displayed in Figure 5: *ADReS-A* and five De-orbit Kits are launched into a parking orbit in close vicinity to the five targets.

The targets have nearly circular orbits, are similar in inclination, altitude and their starting RAAN. However, within one year, they will drift due to J<sub>2</sub>-perturbations by approximately 1.6 deg. Choosing a parking orbit up to 20 km underneath their average altitude of about 980 km, the precession rate is maximal by 2.6 deg per year. By co-ordinating these rates within a details analysis, fuel consumption will suit acceptable ranges.

With the system complexity concentrated on *ADReS-A*, the chaser will shuttle between the designated targets and the parking orbit. The parking orbit again will serve as contact point, where the kits wait spin-stabilized for their pick-up. One kit at once will be transported, attached to the chaser. To handle De-orbit kit and target at once, *ADReS-A* is equipped with two robotic arms. One of them has the capability of grabbing and moving the target or kit around various axes, the second arm fixes the De-orbit kit when shuffling and connecting with the target and can move linearly back and forth for dock- and undock procedures.

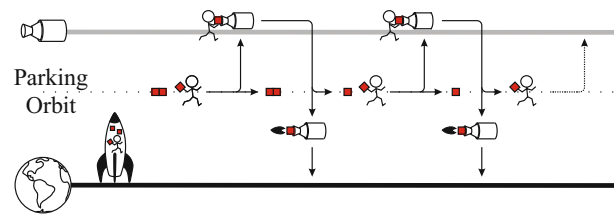


Figure 5. Principle mission architecture

The de-orbit will be performed by the de-orbit kit after *ADReS-A* has left the set-up. While both - the rocket body and the De-orbit kit - perform a timed maneuver to enter over the pacific ocean, *ADReS-A* concentrates on the next kit. The pacific ocean is chosen due to uncertainties during reentry and with the objective to have as small impact on Earth's surface as possible.

#### 3.2. Target Approach

Following known and tested approach procedures, *ADReS-A* (with one De-orbit kit attached) will converge with the target as displayed in Figure 6. A change from absolute to relative navigation is planned from a distance of 10 km.

The phases after reaching the parking orbit with the *launch* are divided into *phasing* to limit the phasing angle between target and *ADReS-A* incl. kit, *far approach*,

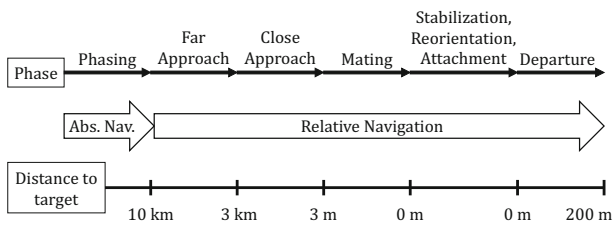


Figure 6. Principle target approach displaying the different phases, the appropriate distance to the target and the kind of navigation used.

close approach, mating and subsequently departure of ADReS-A without the kit.

*Launch:* Regarding mass and dimension of ADReS-A and five De-orbit kits being orbited at once, the Delta II launcher or the Antares launch system would be potential launcher to reach the appropriate circular orbit of about 960 km altitude and 83 deg inclination.

*Phasing:* Starting from the parking orbit, ADReS-A, carrying a De-orbit kit, phases forward from the lower orbit into the targets vicinity, its navigation based on absolute navigation. During this phase, inclination and RAAN deviations are minimized, the control lies with the ground station. For this maneuver, a  $\Delta v$  of about 50 m/s can be assumed for one orbit change, given that enough time to slowly (e.g. over multiple periods) decrease the phasing angle. This assumption results in a total of at least 450 m/s (5 times up, 4 times down).

*Far Approach:* Switched to relative navigation with the target in focus, the far approach provides first data about the actual position of the target and thus a first aim point to maximize the accuracy.

*Close Approach:* During the close approach, ADReS-A gets into very close vicinity of the target and thus the safety-critical operations with particular safety features take place. The close approach ends by reaching a defined holding point.

*Mating:* Mating in the context of ADReS-A is a berthing process with a predefined virtual berthing box close enough to the target so the robotic arm can follow the rocket bodies movement and grab it at a desired position. Berthing box in this context means a three dimensional virtual box of about  $1 \times 1 \times 1$  m within whose dimension the chaser is allowed to move without the target getting out of reach or to close to the chaser. The spacecrafts task is, to stay in the berthing box for as long as the grabbing process takes place, with minimized relative velocity to the target. Together with far and close approach, mating is estimated to about 25 m/s in  $\Delta v$  for the approach of the

(uncooperative) target. For the approach of a (cooperative) kit, which has to be performed in the parking orbit, 20 m/s are assumed.

*Stabilization, reorientation and attachment:* Initially, the target has to be stabilized regarding its tumbling mode, followed by a reorientation for the attachment of the De-orbit kit. With the kit locked onto the linear robotic arm, the free arm brings the target in such position, that the linear arm can extend the kit into the nozzle (promising grabbing and attachment point). A mechanism fixes the kit to the target, followed by the detach from ADReS-A.

*Departure:* For departure, ADReS-A and the kit perform different and locally separated tasks. The idea is, to spin stabilize the system "target & kit" by ADReS-A and departure into a safe distance before the kit fires its thruster. The 400 N thruster of the kit will perform one well-timed burn, leading the set-up to the pacific ocean for the case, they will not burn in the atmosphere during reentry. The footprint estimated will spread over a length of about 500 km and a width of approximately 80 km.

After the departure, ADReS-A follows the same procedures, this time aiming the next De-orbit kit. Since the kit has a predefined contact point and reflecting signals, it is assumed, that the approach is somewhat easier. Thus, the fuel requirements for the approach of a kit is set 5 m/s less that for the approach of a SL-8 R/B.

### 3.3. Preliminary Budget Estimation

The following table gives an overview of the  $\Delta v$ -budget estimated for ADReS-A approaching 5 targets and 4 kits, with the first de-orbit kit already attached during launch onto the chaser, so the rendezvous with the kits can be limited to 4 approaches. Phasing to the parking orbit is set to 4 times as well, as for now, the chaser stays in the orbit of the last target, de-orbiting itself after end-of live. Optimizations at this point are easily be found in either approaching a further target to de-orbit together or refilling ADReS-A for further use in attaching kits to SL-8 R/Bs. As indicated in Chapter 2, there are numerous rocket bodies of the same type left in a similar orbit. Some of the data was already mentioned in Chapter 3.2, others result from calculations. A 20% margin was added for uncertainties during this early phase of the study.

The parametric mass estimation is given in Table 2. The preliminary design of the satellite is oriented on a payload implementing the DEOS robotic arm [10] as the flexible one, and thus having similar mass and power requirements. It is however suggested to implement more flexibility for a better handling of the target. For identifi-

Table 1.  $\Delta v$ -budget including 20% margin.

Mission Part	$\Delta v$	Maneuver
Phasing to target	50 m/s	5 times
Rendezvous with target	25 m/s	5 times
Rendezvous with kit	20 m/s	4 times
Phasing to parking orbit	50 m/s	4 times
Controlled Reentry	324 m/s	1 time
<b>Total ADReS-A</b>	<b>979 m/s</b>	
<b>Total De-orbit kit</b>	<b>324 m/s</b>	5 times

cation of a detailed tumbling rate of the target, a 'visual light camera' is implemented as further payload, when closer than 8 m, a 'time of flight camera' will be used for the berthing attempt. Further information concerning the preliminary design can be extracted from reference [9].

Table 2. Parametric mass estimation.

Subsystem	$m_{ADReS-A}$	$m_{De-orbit\ kit}$
Robotic Arms	113 kg	-
Structure	190 kg	35 kg
Thermal Control	36 kg	15 kg
AOCS	40 kg	5 kg
Propulsion	51 kg	29 kg
Data Handling	21 kg	3 kg
Communication	6 kg	1 kg
Power	51 kg	5 kg
<i>Total Dry incl.</i>	<i>610 kg</i>	<i>112 kg</i>
<i>20% margin</i>		
Propellant incl.	322 kg	190 kg
20% margin	(Hydrazine)	(LO2/LCH4)
<b>Total</b>	<b>933 kg</b>	<b>302 kg</b>

Following Table 2, a total mass of approximately 2400 kg has to be launched into the given orbit. As already indicated in Chapter 3.2, various American launcher provide sufficient capacity to fulfill this task, which makes this mission a very international one with a Russian target, a European chaser and an American launcher. Even though political aspects are still unsolved, they are not part of further investigation within this study.

## 4. AUTONOMY FOR ADR

### 4.1. Challenges

*Uncooperative target:* The fact of uncooperative targets leads to highly critical situations. Uncooperative in this context implies a tumbling rate, which is predetermined

with high uncertainties from ground, missing signal reflectors on the targets surface, which put immense challenges onto the sensors to determine its attitude and position, as well as an absent point of contact for berthing, which result in the necessity to predefine the nozzle for docking.

*Unexpected situations:* Even with years to plan for a mission, unexpected events will happen - may that be the failure of a system component or attitude uncertainties between the target and the chaser, the last example possibly leading to a failed berthing attempt to which a fast reaction has to be created. During the common operation of a satellite, the switch to safe mode is one possibility to wait for further instructions from the ground crew. During an approach of an uncooperative target, however, such switch could end in the loss of the mission with both object e.g. colliding. Alternatives therefore have to be found.

*Reaction time:* Taking the example of a failed berthing attempt between two objects in space, the time for recalculation of the new situation is limited and does not allow the switch into safe mode. Especially if the situation does not allow the ground station to intervene, a maneuver still has to be performed to keep the spacecraft safe and operational.

Therefore, future effort in the field of autonomy have to be taken into account. The following chapter gives a short overview, of what is needed for high-level autonomy.

### 4.2. Autonomy

When referring to autonomy in space, different level can be defined. Following the European Cooperation for Space Standardization (ECSS), the autonomy needed for active debris removal is qualified as level E4, with a "Execution of goal-oriented mission operation on-board", resulting in the function of "goal-oriented mission replanning" (see reference [11]).

Mission re-planning requires the capability to perform decision making processes. The decision again is based on planning capabilities with a list of multiple goals and a time management to perform scheduling. After all, the plan has to be executed by giving commandos back to the subsystems. In the following context, the knowledge about the system and subsystems, needed to perform planning, is divided into two different kind of knowledge: the *A-priori Knowledge* is modeled by the developer, representing the expert's knowledge about the system and generated during design time (naming follows Onken and Schulte [12]); *Situational Knowledge* represents the actual situation and created during run-time. Together they

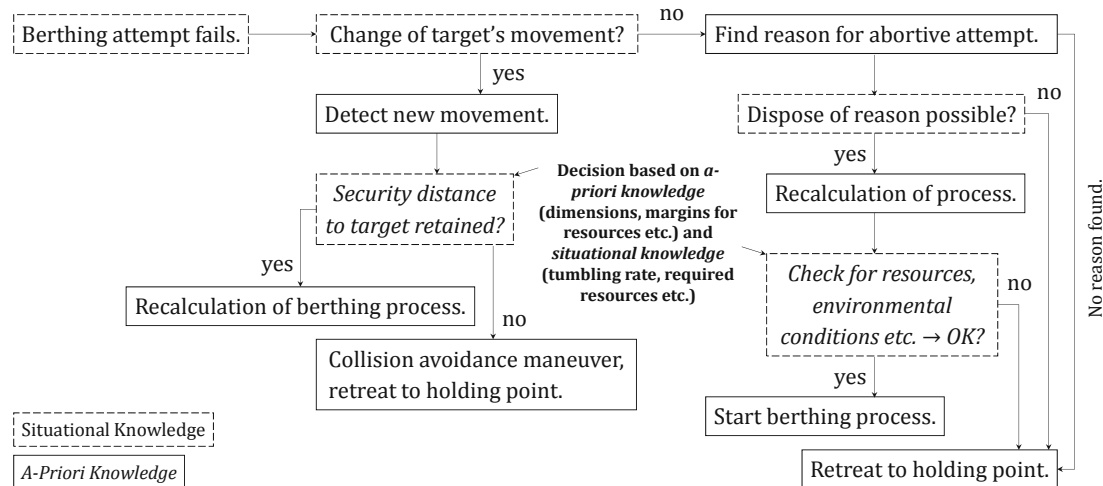


Figure 7. Decision process after a failed berthing attempt.

provide requirements and constraints, temporal and resource wise. An additional priority-list and various rules are necessary for conflicted decisions. With all those subdivisions developed, a decision making process can be derived and thus the required level of autonomy.

Figure 7 gives the decision process after a failed berthing attempt. Easily more branches can be derived, however for a preliminary attempt to the problem, this will be the representative minimal example for future developments.

## 5. CONCLUSION AND FUTURE WORK

With this paper, the mission architecture for the active removal of five SL-8 R/Bs from a circular orbit at approximately 980 km altitude and 83 deg inclination is presented after the target itself and the decision process for this target are introduced. Preliminary budget estimation of the  $\Delta v$  as well as a parametric mass estimation for the chasing spacecraft as well as for the De-orbit kits are drafted. The last chapter gives an introduction into autonomy for removing missions. As indicated goal, rules and priority lists have to be developed to make the autonomy work. For a testbed, a simulation environment has to be generated in addition. Future development will therefore concentrate to design these features with respect to the minimal example given in Figure 7.

## ACKNOWLEDGMENTS

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