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Mission concept and autonomy considerations for active Debris removal

Susanne Peters[a,*], Christoph Pirzkall[b], Hauke Fiedler[c], Roger Förstner[b]

[a] Universität der Bundeswehr München, Institute for Space Technology and Space Applications (ISTA), Germany
[b] Universität der Bundeswehr München, ISTA, Germany
[c] Deutsches Zentrum für Luft-und Raumfahrt (DLR), German Space Operations Center (GSOC), Germany

ABSTRACT

Over the last 60 years, Space Debris has become one of the main challenges for the safe operation of satellites in low Earth orbit. To address this threat, guidelines that include a limited debris release during normal operations, minimization of the potential for on-orbit break-ups and post mission disposal have begun to be implemented. However, for the long-term, the amount of debris will still increase due to fragments created by collisions of objects in space. The active removal of space debris of at least five large objects per years is therefore recommended, but not yet included in those guidelines. Even though various technical concepts have been developed over the last years, the question on how to make them reliable and safe or how to finance such mission has not been answered. This paper addresses the first two topics. With Space Debris representing an uncooperative and possibly tumbling target, close proximity becomes absolutely critical, especially when an uninterrupted connection to the ground station is not ensured. This paper therefore defines firstly a mission to remove at least five large objects and secondly introduces a preliminary autonomy concept fitted for this mission.

1. Introduction

The idea of implementing autonomy in spacecraft has been followed by some time and is on some level successfully tested for deep space missions and plane-tary rovers [1]. Different kinds of applications combine a limited timeframe for connecting with ground control and unknown parameters about the environment. These features make it difficult to operate a rover and/or spacecraft for the mission time available. Autonomy and on-board processing within a spacecraft make it possible to improve the mission's data-collection by extending the execution of pre-planned, ground-defined mission operations, expand the available range of objectives and time and limit workload on the ground.

When performing active debris removal, advantages arising from the implementation of autonomy alter slightly, as for instance the close proximity to an uncooperative target needs special attention regarding fast reaction time to a changed working environment. The extension of the mission doesn't have the priority but the safety of the operating spacecraft and the target. Addressing the topic of autonomous active space debris removal, autonomy requirements for such missions have to be defined. They again will build the basis for specifications of high-level on-board procedures.

The requirements stated in this paper are based on the concept of a flexible arm to grab and stabilize a tumbling target. To face unforeseen events or failures, the necessary berthing maneuver needs the capability of goal-oriented mission re-planning. As the close proximity combined with drifting of the objects might end in a collision, the process of switching into safe mode is not an option. Safe mode in this context refers to the procedure coming into operation in case of an unknown failure and results in ceasing all activities until the failure has been resolved by the ground station. To work around the safe mode, advanced failure detection, isolation and recovery concepts need to be involved with the spacecraft able to operate and re-plan by itself.

To provide a starting point for such high-level autonomy, the mission had to be defined first - this paper therefore starts with a concept for active space debris removal, its mission architecture and preliminary spacecraft design. Further on, requirements for the autonomy aimed to be implemented result from this set-up and are stated in the following. The last part presents a possible approach on how to realize such high level autonomy for the designed mission, introducing a concept used successfully for unmanned aerial vehicles in former tests.

* Corresponding author.
E-mail addresses: Susanne.Peters@unibw.de (S. Peters), Christoph.Pirzkall@unibw.de (C. Pirzkall), Hauke.Fiedler@dlr.de (H. Fiedler), Roger.Foerstner@unibw.de (R. Förstner).

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2. Active Debris removal

2.1. Space Debris

The awareness for the threat of space debris to operating satellites and a sustained space environment has increased with the threat itself. More launches, collisions, in-orbit break-ups, or natural decay lead to a growing space occupied by debris, which again increases the collision probability between objects. Depending on size, angle, relative velocity etc. of the impacting debris, satellites being hit can lose their functionality or may be fragmented, adding even more objects to the debris account. Mitigation Guidelines developed by the Inter-Agency Space Debris Coordination Committee (IADC) for a safer operation of spacecraft and launches would result, if applied, in the reduction of growth of debris [2]. These guidelines are supported by most of the space fairing nations, but not legally binding. Additionally, the guidelines include a limited debris release during normal operations, minimize the potential for on-orbit break-ups and address post mission disposal. Furthermore, better prediction models have been developed to track the objects and predict collisions with higher accuracy [3]. A warning system gives satellite operators the possibility to move their objects, as far as the spacecraft has this capability [4]. However, these are short-term solutions; ultimately, active space debris removal (ADR) will be necessary to sustain the space environment in the long run as the number of collision generated debris is about to overtake the debris generating due to fragmentations. This again will result in a rising amount of small objects – if the sources are not removed.

Analysis of the publically available data of about 16,800 objects [5] – there are about 6500 more objects that are either not reliably tracked or military satellites and thus do not appear in the report [6] – reveal the low Earth orbit (LEO) as most occupied region, cf. Fig. 1. The geostationary orbit (GEO), the second most occupied region, can be described by a more tube-like shape. Due to the objects orbiting within a smaller area than in the LEO region, GEO shows a relatively high object density when considering the enclosed area. With GEO being very important for local observation, customers (and thus funding opportunities) might be more interested to invest in active debris removal within this area. However, directly compared to LEO, with the same altitude and inclination bins applied in Fig. 1 (5-degree inclination bin, 1000 km altitude bin), a smaller over-all distribution is revealed. By first applying ADR in LEO, a reliable technique to safely remove objects can be found in a more cost-effective way. A transfer to higher orbits and by such serving the customers in GEO, can be performed after the successful implementation in LEO and thus in a later stage.

2.2. Mission motivation

Space Debris can be generated in different ways, either by fragmentation, explosion, degradation due to the harsh environment, mission related reasons, collision or simply by reaching a satellites end-of-life without disposal measurements. Until today, debris larger than 10 cm due to fragmentations are the biggest contributor, second to collision related debris. The result are collisions at orbital velocities (relative velocities may reach up to approximately 14 km/s), creating even more and smaller debris. The amount of space debris generated by collisions is already that prolific, that it supersedes the amount of space debris created by explosions or environment related reasons. The effect is a cascade effect that will be slowed down or stopped by actual intervention and removal of the source. Even though the main threat [7] to operational spacecraft nowadays are fragments from the size of 5–1 cm, long-term objectives need to concentrate on an overall stabilization of the space environment – by removing objects that are capable of creating large amounts of debris and are thus called the main driver for the population growth. These objects are satellites or rocket bodies with high masses of 1 t and more. To choose among the high number of objects fulfilling this requirement, their collision probability is as well part of the target identification process.

Taking into account the simulation and recommendations given by the IADC, the active removal of at least five large objects per year is desired to sustain the known Earth space environment. Even though this number is somewhat notional with assumptions like an immediate removal of the objects from the environment or a repeated launch cycle from the past eight years, it is at least a ballpark figure.

When considering former re-entries [8], a complete burn up during de-orbit cannot be guaranteed. As a result, a controlled reentry should be preferred, the landing area preferable on uninhabited land or in the oceans. The combination of the desire to remove at least five objects, and a controlled reentry leads to the idea of having five de-orbiting devices, also called de-orbit kits, and a main satellite in one launcher. The devices will be attached to the target by a flexible arm, connected to and controlled by the main satellite. The main satellite will not stay with the set-up but guide the other kits to their designated target, the target and the attached kit will be de-orbited together. With the de-orbiting device being lost during reentry, the technical complexity is concentrated in the main satellite as it will have to coordinate the berthing and stabilizing phases. By using one launch per year, time and cost of the whole clean-up process can be minimized and an effective measure for the coming years can be found.

2.3. Concept

With the main idea of having a one-launcher set-up with one prime satellite that incorporates most of the complexity when it comes to rendezvous, berthing and stabilization, and multiple devices to de-orbit in a controlled way together with a target heavier than 1 t, a more detailed concept can be developed.

Different concepts for capturing an uncontrolled, large object exist. Due to legacy reasons, a high technology readiness level and its feasibility for the mission, a robotic grabbing arm shall be used for further considerations. Examples of such arms can be derived from DEOS [9], SDMR [10], FREND 3 [11], RANGER 8 DOF [12] or OTV [13]. No specific arm will be set for this mission, however, mass and power requirements follow the DEOS design. Due to the close approach to an uncooperative target, the operation of close proximity becomes absolutely critical, especially with an uninterrupted connection to the ground station and thus constant data exchange not ensured. To solve this problem, high-level autonomy with goal-oriented mission re-planning capabilities shall be implemented. A potential autonomy concept probably adaptable for this mission is presented later in this paper.

Rendezvous and docking requires specific flexibility and agility of the berthing spacecraft. Accordingly, the designed spacecraft, as well called chaser, namely ADReS-A for Active Debris Removal Satellite #A, will not carry all de-obit devices with it for the whole mission time, but pick up one kit after another from a parking orbit to shuttle them

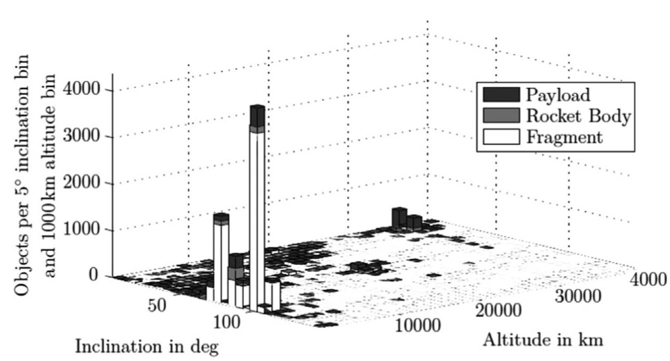

Fig. 1. Distribution of the different object types up to the geostationary orbit. Inclination bins are set to 5°, mean altitude bins to 1000 km.