AUTONOMY FOR ACTIVE SPACE DEBRIS REMOVAL: RESEARCH ISSUES AND APPROACHES

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Abstract

Even though the infinite vastness of the universe is an accepted theory, apparently infinity ends when it comes to orbits surrounding the Earth. This was a hard lesson to learn when Iridium 33 and Cosmos 2251 collided in the low Earth orbit in February 2009. Not at least due to this event, the threat of uncontrolled objects in space is subject to a series of activities for the stabilization of the space environment. Besides improved collision propagation and mitigation measurements currently adopted by major space agencies, the active removal of space debris (ADR) needs to be addressed and further developed within the next few years. Based on an introduced reference scenario, this paper introduces autonomy in space for such missions. Existing problems are addressed and possible approaches concerning autonomous remediation of space debris are presented.

1. INTRODUCTION

1.1. Context

Within the last few years, the threat of space debris to functional satellites became more and more obvious. On one hand, the number of man-made objects in space, detectable by commonly used radar- and telescope-techniques, increases every year by averagely 300 pieces since the beginning of operational astronautic [1]. On the other hand – if people still were convinced, that the expanse of space would make it impossible for two objects to collide – with the unintentional hazardous collision of Iridium 33 and Cosmos 2251, the slight possibility of colliding objects in space became reality. Investigations predict a hazardous collision (i.e. the colliding objects fragmenting) every 5 to 9 years, not counting the incidents of a satellite failing due to a small size space debris impact, which is, based on the number of objects increasing with decreasing size [2], essentially more often.

Today, the publicly available satellite catalogue (SATCAT) lists more than 39.200 man-made objects, with sizes of 10 cm and above for the low Earth orbit region (LEO) and bigger sizes of 1 m and above for the geostationary orbit (GEO), with about 16.800 of the generally accessible ones still remaining in space. This amount again is divided into about 65% fragments, 12% rocket bodies and 23% satellites of which about every fourth is still operational.
TAB 1 lists the current orbital population as given in SATCAT as of July 22, 2013. Extracted is the LEO region with about 70.9% of the total count of listed space objects and thus, the most crowded region around the Earth. A closer look reveals that 83.6% of the publicly available fragments are in LEO as well as 39.4% of the rocket bodies and more than every second satellite that orbits the Earth. Based on this distribution, a collision is most likely probable in LEO and active space debris removal should be implemented here at first. Commonly accepted is the theory of removing large and massive objects first, to prevent them from creating smaller fragments with sizes smaller than 10 cm. The danger of such very small fragments lies in the inability to avoid collision with an undetectable object and thus, the inevitable demolition of functional satellites.

TAB 1. Current generally accessible orbital population as of July 22, 2013.

	Objects in Earth orbit	Objects in LEO	Proportion of LEO-objects regarding the available objects
Fragment	10989	9187	83.6%
Rocket body	1991	784	39.4%
Satellite	3834	1958	51.1%
Total	**16814**	**11929**	**70.9%**

The paper is organized as followed: After an introduction about the importance of ADR including its existing challenges, the selection of the mission scenario with target identification is introduced and discussed. Here, multiple target removal missions are revealed as possible and favored. Second, autonomy, its terminology and current use in space are presented. Subsequently, the cognitive automation and its advantages compared to other autonomous approaches are presented. Finally, the challenges for future work are outlined.

1.2. Active Space Debris Removal

Different approaches for minimizing the threat, which space debris forces on operational spacecraft, exist. For one thing, mitigation measures have been adopted by space agencies such as increasing the survivability of satellites, by e.g. reducing degradation failure, or a post mission disposal within 25 years after the end of life of future spacecraft. For another thing, calculations to predict the objects' orbits, and thus, the possibility to forecast potential collisions more precisely, have been improved. One major approach however – the active removal of space debris (ADR) – is still under discussion, even though simulations by Klinkrad [3], Liou [4] and the Inter-Agency Space Debris Coordination Committee (IADC) and references therein [2] show, that the stabilization of the space environment with respect to a constant amount of man-made objects orbiting Earth, does not work without ADR. Reasons for the delay include political and legal issues as well as financial challenges with ADR not being sufficient to remove enough targets and thus, lowering collision probability in an acceptable timeframe. On the technical side, scientists are still arguing about the most promising setup for a removal mission. Olympio [5], Alary [6], Scheper [7] and others give different overviews concerning the application of various systems, according to size, orbit, structure and movement of the target. TAB 2 lists a selection of techniques for the removal of massive targets from LEO. Contactless connections such as an Ion Beam Shepard [8], Laser [9], or just-in-time collision avoidance [10] are more suitable for small sized objects due to the time needed for remediation. Techniques like a solar or magnetic sail as cited in [11], the attachment of a ballute to the surface for an increased atmospheric drag [12], or tethers, have to be connected to the object to be effective. With one of the challenges to be solved for ADR being the berthing onto an uncontrolled object, these techniques will be in demand for post mission disposal (PMD), the task of rendezvous & berthing performed by another technique.

TAB 2. Overview of target removal techniques for large sized targets.

Connection	Technique	Example	Ref.
Single point	Robotic Arm	· DEOS · SDMR · FREND 3 · RANGER 8 DOF · OTV	[13] [14] [15] [16] [7]
	Harpoon	· Astrium design · Rosetta	[17] [18]
Distributed	Tentacles	· TENTACLE · OctArm	[19] [20]
	Jamming based Gripper	· Jamming Gripper	[21]
	Microspine Anchoring	· NASA development	[22]
	Net	· ROGER · D-CoNe · REDCROC	[23] [24] [25]
	Electro-adhesion	· SRI International	[26]

Of all the techniques tabulated in TAB 2, robotic arms are the technical development with the largest heritage. However, the Rosetta harpoon will be tested in 2014 and parable flight test have been conducted with a net mechanism. Challenging for harpoon and net technologies is the tether connection of spacecraft and target, especially when considering a tumbling one. To grab an uncontrolled object has the challenge of de-tumbling and stabilizing the whole system. Hence, a robotic arm is applied to be suitable for the mission scenario described below.

The implementation of high leveled autonomy in spacecraft would improve its performance and reduce contact time and thus mission time with financial benefits after all. With the realization of higher on-board autonomy, reactions to unexpected changes can be performed safely and adequately. This includes adjustments to changing environmental conditions as well as adjustments in the spacecraft performance as in the case of a failure or disfunction. Further advantages of autonomy will be presented in chapter 3, after a short introduction of the mission scenario and its selection process.

2. MISSION SCENARIO

2.1. Orbit

As already mentioned, the most crowded area of objects in space is the LEO region. FIGURE 1 displays the distribution of the different types of objects in space of the satellite catalog with known parameters as of July 22, 2013 (fragments (DEB), rocket bodies (R/B) and payloads - which includes all objects not specifically marked as R/B or DEB). Peaks are found at highly frequented orbits shortly underneath 1000 km and with the inclination of high polar orbits (sun-synchronous orbit) or around 83°. In the latter, Russian rocket bodies wait for their remediation.

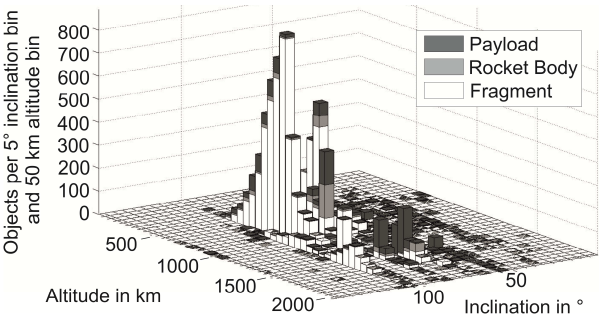

FIGURE 1. Distribution of the different object types in the low Earth orbit region. Inclination bins are set to 5°, Semi-Major Axis bin to 50 km.

2.2. Target Identification

Even though the number of fragments lead the list of man-made objects in space, their removal would be very cost intensive due to their spread orbits and low impact on the requirement to minimize the volume and thus, the collision probability of space debris. More necessary is the remediation of their sources: explosions, mission related objects and collisions. The first two are taken care of by the adopted measurements of space agencies (safer spacecraft with as few as possible objects being released during or after mission time). Collisions, however, can be bypassed by avoidance maneuvers – unfortunately not all propagated collisions involve a maneuverable object. Additionally, small sized debris is not detected by ground control and thus a collision avoidance maneuver will not even be planed. In consequence the collision probability is to be lowered by removing the 'high risk' objects from space. 'High risk' thereby is defined as having a high probability for collision, meaning being close to other objects, and a large volume, since fragmentations of large objects are more distributed than smaller ones. With the current history of launches, a number of 5 objects per year is aimed to be removed for keeping the amount of objects in orbit stable [4].

2.2.1. Single or multiple target removal

Another point of mission planning is the question of multiple or single target removal. If the first option is chosen, the choice is between one mother ship carrying kits to a transfer-orbit and one spacecraft removing the targets after each other. FIGURE 2 displays the possible scenarios for unmanned missions.

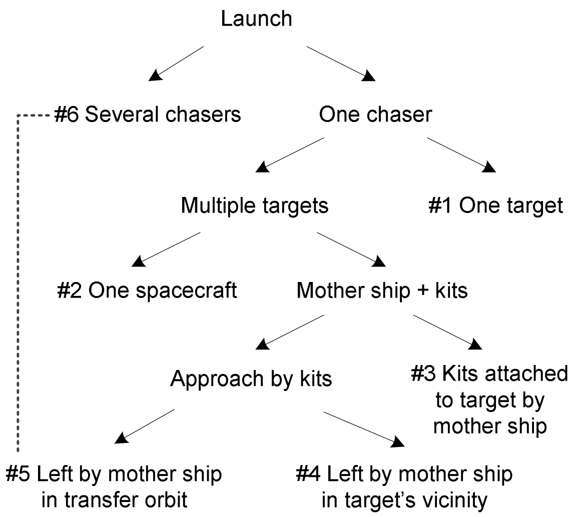

FIGURE 2. Possible launch scenarios for debris removal satellite(s).

As usual, advantages and drawbacks exist for all options.
The advantages for a single target mission (one chaser, one target: #1 in FIGURE 2) are e.g. the concentration onto one object. The catching maneuver will be planned for exactly one geometry. The mission, however, will need a rocket body to carry the removal satellite into space, resulting in no change of the actual number of objects in space for the moment. Still, the collision probability for the target's orbit will decrease, since the rocket body in question will have a different orbit. Moreover, the rocket body can be equipped with a PMD-technique for its own disposal; a measurable effect will be recognized afterwards.
When considering multiple target removal with one spacecraft (#2 in FIGURE 2), the critical situation of the rendezvous & berthing maneuver exists for each of the selected targets and thus, the potential of failure of the removal satellite. If the spacecraft is lost, the mission has to be abandoned with the result of creating more debris in an area with already high collision probability. An advantage is the multiple use of one rendezvous & berthing technique, orbit determination sensors etc. and thus the saving of weight for the whole mission.
The benefit of multiple use of techniques exists as well for the 'mother ship + kits'-mission; the kits would need thrusters for deorbiting (and localization sensors to know where to enter into the Earth's atmosphere), but the rendezvous & berthing technique would be implemented on the mother ship, and thus be weight-saving (#3 in FIGURE 2). Depending on how the kits are equipped, an active debris removal is possible, which would not be the case for one chaser collecting targets after each other, since it would place the target into a lower orbit with less collision probability. Here, the target deorbits due to atmospheric drag and thus, uncontrolled.
If the kits have to rendezvous & berth by themselves and are left in the vicinity of the target (#4 in FIGURE 2), they need the capability to track the target, de-spin it and attach to it, which makes each of them highly complex.
In case the mother ship carries the kits to a transfer orbit (#5 in FIGURE 2), the mission would be build up similar to sending several chasers with one launch into orbit (#6 in FIGURE 2); every kit/chaser needs complex equipment but in case of a failure of one kit/chaser, the mission would not have to be aborted.
Furthermore, cost estimations have to be realized, which is difficult to perform. A rough estimation for instance, done by Wiedemann et al [27], lists the costs for a single chaser/single target mission and seem prohibitive ($ 140 million per re-entry maneuver).

Even though the most suitable mission scenario for the study is still under estimation, a multiple target solution is preferred and will serve as basis for further investigation.

2.2.2. Cluster for multiple target removal

For a multiple target mission, the targets have to be relatively close to each other so fuel requirements for orbit changes are limited. With changes in altitude having less impact on the fuel requirements than changes in inclination or the Right Ascension of the Ascending Node (RAAN), concentration on limitations are set to those parameters (about 250 km changes in altitude are equivalent to an adjustment of 1°, in LEO).
The selection process described in reference [28], intending to find suitable targets for a removal mission of 'high risk' objects, was slightly adjusted for this paper. The 'high risk' criterion was changed from mass to volume, which made no difference in this case, since every object was assigned with the same density. Adapted were the formerly used bins for inclination and RAAN into lapping ones, active satellites are excluded from the process, which limits the selected 'top200' to 170 possible targets, all of them being rocket bodies (R/B). FIGURE 3 displays their distribution on January 11, 2013, and highlights clusters with targets no more than 2° (RAAN and inclination) apart from each other.

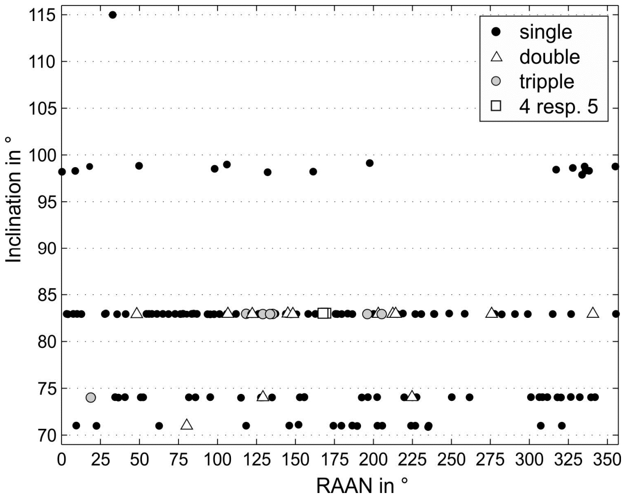

FIGURE 3. Clusters of R/B for different inclination and RAAN, where the objects are no more than 2° apart (11th January 2013).

At about 83° inclination and 170° RAAN 4, respectively 5, of the rocket bodies in FIGURE 3 cluster, with two objects being in either one of the groups (the other objects of every group are more than 2° apart from the other one). Their type is uniformly SL-8 R/B (stage 2: diameter 2.4 m, dry mass 1434 kg, length 6.6 m [29]). Concerning the altitude of the rocket bodies, inclinations of about 71° are found in 825 to 850 km altitude, inclinations of 74° in 750 to 780 km and inclinations of 83° in 950 to 1000 km. Rocket bodies in sun-synchronous orbits of about 98° are distributed from 600 to 1000 km.
Mission scenarios therefore will take place in 83° inclination, 950 to 1000 km altitude and the respective RAAN. Based on the mission scenario, a system concept will be developed in further studies.

3. AUTONOMY

3.1. Motivation

Following Olive [30], today's spacecraft operations reach autonomy level E2, defined by the European Cooperation for Space Standardization (ECSS) [31] and listed in TAB 3. Some interplanetary spacecraft, however, have decision making capability implemented after launch, using On-Board Control Procedures, and are therefore considered as level E3 on subsystem level [32].

ADR missions with a robotic arm include the highly critical situation of rendezvous & berthing with an uncontrolled, probably tumbling, target. The autonomy proposed in this paper attempts to take over in such risky situations: here, the possibility of unforeseen, time critical events is most serious. Even with ground connection available, the ground operator needs time to develop a strategy to bypass the problem. With a higher level of autonomy implemented than used nowadays (aimed is level E4 in TAB 3), reaction time can be significantly reduced. Moreover, in cases of restricted connection due to e.g. the covering of the antenna, the spacecraft will have the possibility to decide situation relevant with weighing of contradictory goals such as low battery in combination with collision avoidance. Since the autonomy does not aim to control the spacecraft from launch to de-obit, the human operator has to interact with the system.

With computing power rapidly increasing, decision making processes have the capability to be transferred from ground to the spacecraft itself. The human operator can be eased from observing an increasing large volume of data; the performance accuracy of the spacecraft itself will improve and be safer. Besides an enhanced performance of the spacecraft in critical situations, autonomy offers a high prospect of reducing overall cost by reducing communication devices and thus weight as well as personal support.

TAB 3. Mission execution autonomy levels. [31]

Level	Description	Functions
E1	Mission execution underground control; limited on-orbit capability for safety issues	Real-time control from ground for nominal operations; Execution of time-tagged commands for safety issues
E2	Execution of pre-planned, ground-defined, mission operations on-board	Capability to store time-based commands in an on-board scheduler
E3	Execution of adaptive mission operations on-board	Event-based autonomous operations; Execution of on-board operations control procedures
E4	Execution of goal-oriented mission operations on-board	Goal-oriented mission re-planning

3.2. Autonomy Concepts

Autonomous approaches in the area of space have been done in navigation and orbital control, for example with the Solar Terrestrial Relations Observatory mission. It has been proven, that autonomy is of great advantages especially in formation flying of multi-spacecraft missions [33]. Other applications are interplanetary missions or rovers on other planets. It is however difficult to find literature revealing the underlying theory of their algorithms.
Wander [34] presents in her work studies covering soft-computing and artificial intelligence with respect to fault diagnosis of the (aero-)space domain. The investigation leads to the one already tested approach on actual flight hardware – the cognitive automation. Other theories like Bayesian Networks, Fuzzy Logic or Neural Networks are less reasonable for the human operator; possible mistakes have the capability to escalate more easily [35].

3.3. Cognitive Automation

The cognitive automation technology was developed by the Institute of Flight Systems of the Bundeswehr

University Munich and has been tested successfully on actual flight hardware (in unmanned aerial vehicles – UAV). Originally, it was designed to ease the interaction between human operator and computer, to show goal-consistent and transparent behavior and use cognition by following the human knowledge-processing scheme which is based on knowledge more than on setting thresholds. Meitinger [36] describes its implementation on multiple UAVs which work together without human intervention, thus, the application to spacecraft is promising. Parallels observed between UAVs and spacecraft include the processing of huge amounts of data, deciding mission relevant goals and reacting appropriately to unpredicted situations – either environmental or system component related. Other similarities like evasion from a dangerously close aircraft, parallel decision making and time critical moments (and thus fast processing data) exist.

3.3.1. Terminology

In some cases the terms autonomy and automation are used substitutive. It is difficult to draw the line between them, since every author seems to have his own idea of how far automation goes and where autonomy starts. Proposing cognitive automation as autonomy concept is only one example. For this work, the definition of the terms follows Truszkowski [33]: “Both terms refer to processes that may be executed independently from start to finish without any human intervention. Automated processes simply replace routine manual processes with software/hardware ones, which follow a step-by-step sequence that may still include human participation. Autonomous processes, on the other hand, have the more ambitious goal of emulating human processes rather than simply replacing them.” The key self-managing properties of autonomous systems are:

- self-configuration: ability of own adaption to changing circumstances or to assist with the other properties,
- self-healing: identification and recovery of upcoming failure (reactive mode) or prediction of problems by the use of recorded signals (proactive mode),
- self-optimizing: knowledge of ideal performance and reconciliation with actual execution, including reaction to changes by the user, and
- self-protecting: protection of the system from accidental or vicious external attacks.

To achieve the self-regulating goals (or self-managing properties), the system needs to be *self-aware* of internal capabilities and status of the managed component, and *environmental aware* of external circumstances. Changing conditions are detected by *self-monitoring,* by sensors, and *self-adjustments* are made.

With this definition in mind, cognitive automation, introduced in the following, can be listed as autonomous concept.

3.3.2. The Cognitive Process

The cognitive process is based on Rasmussen’s model of human performance [35]. This knowledge-based approach separates knowledge from knowledge processing. The model, illustrated in FIGURE 4, divides the aspect of human cognitive behavior into three layers with increasing cognitive demands:

- Skill-based behavior: highly automated control tasks, with hardly any mental effort or consciousness e.g. riding a bike,
- Rule- or procedure-based behavior: pre-defined procedures exist and are followed, e.g. fasten one’s shoes, and
- Knowledge- or concept-based behavior: no pre-defined solution exists; a new approach is developed with respect to background knowledge e.g. first time rollerblading.

Especially the knowledge-based behavior is a tool that needs to be implemented into technical systems to enable the system to have environmental awareness and self-regulating goals about which it has to reason and decide to plan and execute appropriate actions.
The gray blocks in FIGURE 4 represent cognitive subfunctions, connected by situational knowledge (red) and based on a-priori-knowledge (blue). The exchange with the environment is displayed in green.

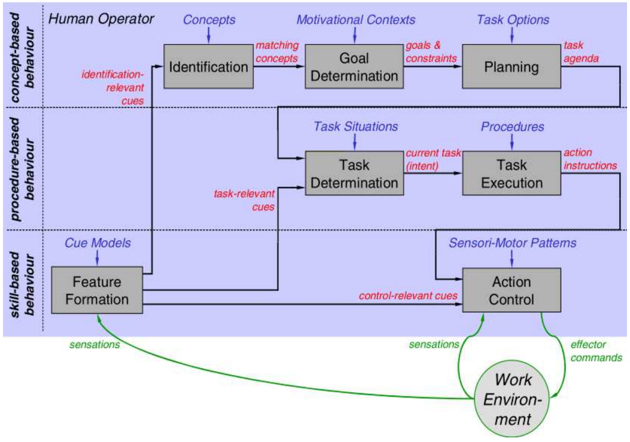

FIGURE 4. Interpretation of Rasmussen's model of human performance incorporating an information technology approach by Onken and Schulte [35].

Since a central knowledge representation is the essential feature of the cognitive process, FIGURE 5 gives a more compact understanding with the knowledge displayed as oval with all subfunctions (arrows outside the oval) having full access to the full range of the knowledge. Having the same color distribution as in FIGURE 4, the a-priori-knowledge (blue / dark gray oval) is modeled by the developer representing the domain expert’s knowledge about the system and is thus generated during design time. The situational knowledge (red / light gray oval) is created during runtime, representing the actual situation. The cognitive subfunctions are represented by arrows, using the situational knowledge to run the process. Although each subfunction has a preferred area where processed information is added to the situational knowledge, the full access to the whole body of knowledge remains and so does the possibility for self-awareness.

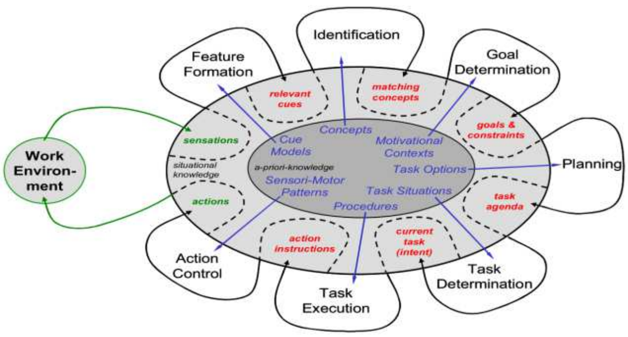

FIGURE 5. The information processing cycle of the cognitive process with central knowledge divided into a-priori (dark grey oval) and situational (light gray oval) knowledge. [35]

3.3.3. System Architecture

To implement the theory of the cognitive process, the Cognitive System Architecture (COSA) has been developed as framework by Putzer [37]. COSA provides an implementation of the application independent inference mechanism, so that the development of a cognitive system is reduced to the implementation of interfaces and the acquisition and modeling of a-priori-knowledge. It provides a front end for knowledge modeling, is based on a kernel that uses Soar as processor, and uses the Cognitive Programming Language (CPL). The cognitive process method described in [37] defines five steps to model a system within COSA:

- Model necessary desires,
- Action alternatives,
- Instruction models,
- Identify environment models and
- Create a dynamic model.

Future investigations will follow these five steps.

3.3.4. Next Steps

Based on the concept of cognitive automation, an application for an autonomous debris removal satellite is in progress. Following the five suggested steps of the system modeling within COSA, case studies will be developed. Most important hereby are inconsistent goals such as collision avoidance and direct insolation on solar panels in close proximity of the target and low battery status. The system has the task to decide which goal has the higher priority, a situation-based plan and its execution will be derived and performed.

4. CONCLUSION

The paper gave an overview on the importance of active space debris removal, revealed the advantages and possibilities of multiple target removal and identified a mission scenario with an orbit and specific targets for removal.
Based on the scenario, the concept of cognitive automation is revealed as promising candidate for an increased autonomy implementation into spacecraft.
Future work has to be done concerning the spacecraft design and case studies for the cognitive automation.

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