REFERENCE SCENARIO AND TARGET IDENTIFICATION FOR AUTONOMOUS ACTIVE SPACE DEBRIS REMOVAL METHODS

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ABSTRACT

To alleviate the threat of space debris, a combination of debris mitigation measures and debris environment remediation techniques with regard to long-term environment stability is required. Hereby, active space debris removal (ADR), which is subject to this paper, addresses the latter. To evolve a concept for autonomous ADR on a representative foundation, a reference scenario placed in the current Low Earth Orbit environment has been generated. Due to cost-effectiveness, a single mission to dispose multiple targets is addressed. The filtering process is presented and a glance on the autonomy concept of cognitive automation is given.

Key words: ADR, SSA, low-Earth orbit, space debris, Autonomy.

1. INTRODUCTION

The threat of space debris to satellites orbiting the Earth is a globally recognized problem, at least after the Fengyun anti-satellite test in 2007 and the Iridium-Cosmos collision in 2009. Simulations show, that an adequate solution to control the space environment in Low Earth Orbit (LEO) can be achieved by a combination of two activities: first debris mitigation, by e. g. limiting the time in orbit of spacecrafts to 25 years after their end of life and second debris remediation, by e. g. removing objects from orbit that no longer serve any useful purpose and have no self-deorbiting capability (active space debris removal - ADR).
Guidelines and requirements of space agencies address the first part and include a recommendation of minimizing debris release during normal operations as well as avoiding on-orbit break-ups. The presented research concentrates on the task of debris removal.
This paper presents a filter process for the generation of a reference scenario for multiple ADR. The scenario is set for multiple targets, because the cost of a single removal is most likely unacceptable.

The research has been accomplished with today's data of the two-line element set (TLE) [1] and DISCOS (Information System Characterizing Objects in Space) database [2], representing a proper foundation for present problems regarding space debris in Section 3. In Section 4 autonomy and its use for space missions is presented. Proposed as promising method is the process of cognitive automation - an approach taken from the unmanned aerial vehicle (UAV) domain.

2. THE THREAT OF SPACE DEBRIS

When it comes to space debris and its capability of hazardous destruction, size does not necessarily play a big role. Smallest particles can develop enormous kinetic energies, as figure 1 displays.

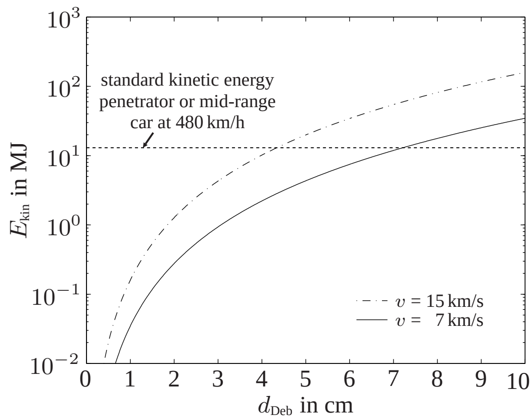

Figure 1. Development of the kinetic energy E_{kin} over the increasing size of an aluminum bullet d_{Deb}.

At sizes of about 4.5 cm (and a velocity of 15 km/s) or a diameter of about 7.2 cm (and a velocity of 7 km/s), debris particles (material: aluminum) have the same energy as a kinetic energy penetrator - a standard high-energy projectile, able to penetrate a battle tank, represented by the upper dotted line in figure 1. The penetrators muzzle energy of 13 MJ results in a penetrating power of 81 cm armor steel at a distance of 2 km [3]. For a mid-range car of 1.5 t a velocity of about 480 km/h would be needed to develop the kinetic energy comparable to the regarding space debris.

Such small particles existing in space however are difficult to detect with the common observation methods. Thus, the prevention to create such small particles is of great importance. The sections hereafter concentrate on finding the most suitable objects to be de-orbited from space with the goal of minimizing the creation potential. Hereby, the kinetic energy, mass, and orbit of the object in relation to others are the important factors to be analyzed.

3. TARGET IDENTIFICATION - REFERENCE SCENARIO

The following parts describe the different steps of the filtering process. A Matlab-Script is programmed based on the formulae and data given by Klinkrad [4]. The process results in the most suitable reference scenario for multiple ADR (target identification) at an orbit of 977 km altitude and 83° inclination.

3.1. Endangered zone - a rough selection

Having the TLE-data sorted by their position in space (inclination and mean altitude above a spherical Earth with a radius of 6378 km) and separated according to their type, the distribution of figure 2 comes up. At a first glance it is evident, that the most endangered zone is LEO (altitudes up to 2000 km). It contains about 79% of the objects, whereas about 78% are debris, 15% are payload (operative and non-operative) and 7% are rocket bodies. The following selection process is thus limited to LEO.

3.2. Selection Process

Objects which qualify as a major driver for the generation of new collision-fragments need to be removed first. Different approaches according a ranking of high-risk objects can be obtained from several paper. They vary between object mass × collision probability [5], kinetic energy of the target × collision probability [6] and object mass × spatial density × cross-sectional area [7]. The ranking for high-risk objects for this paper however follows the formulae and data of [4] for low-Earth orbits. With it few adjustments have been made: Since it matters, which kinetic energy the impinging particles have, the kinetic energy flux has been used as one critical parameter. Since it matters as well, which kind of objects have been impinged on, the satellites mass has been taken into account. Consolidated, the objects are sorted concerning the kinetic energy flux per year × object mass.

Script Details

According to Klinkrad [4], the range of altitude H is set to $H_{min} = 186\,\mathrm{km}$ and $H_{max} = 2286\,\mathrm{km}$, where H refers to a spherical Earth of 6378.137 km radius. With the first run, objects below 700 km are excluded from the selection process. Mainly, because they will most likely de-orbit within 25 years [8] and thus follow the ESA-requirements [9]. Subsidiary, because there are a few

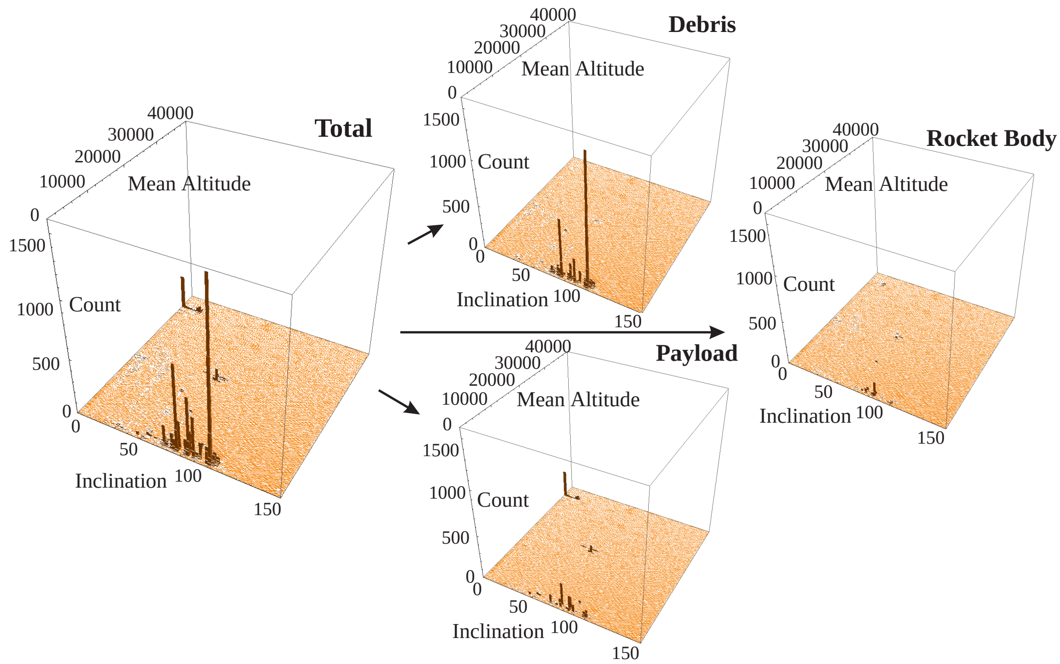

Figure 2. Distribution of TLE-data up to 40 000 km altitude. Interval of inclination: 2.0°, interval of mean altitude: 100 km.

objects (here: 7 out of 200) below this threshold which fulfill the qualification properties for so-called high-risk objects for this paper.
Further data collection includes a variation of inclination from 0° and 180°. Object size information (length, height and depth of the satellites) are taken from DISCOS database [2] and are used to compute the cross section and the object mass with an average density of $350\,\mathrm{kg/m^3}$. Default values of $0.3^2\,\mathrm{m^2}$ and $0.3^3\,\mathrm{m^3} \times 350\,\mathrm{kg/m^3}$ are assigned in case of missing DISCOS data. Information of the objects like name, NORAD-ID, semi-major axis etc. for the calculations are extracted from the TLE data. The cross section and mass are assigned.
With the collected data a computation of the single object density, the total object density and the flux in the inertial control volumes is performed within the Matlab-Script. As final step, the objects are sorted concerning their height of risk, whereas mass $\times$ kinetic energy flux per year are the driving criterion. The number of extracted objects is set to 200, lowered to 193 by excluding objects below 700 km as mentioned before.

3.3. Target identification

Having the TLE-data ranked according to the described script, the *Top 193* objects are compared to each other regarding their altitude, inclination and right ascension of the ascending node Ω (RAAN). The goal is to identify similarities regarding those three criteria. Here, cluster for multiple target removal are to be found. Even in the likely case that the determined objects do not represent the most important and thus top-positioned high-risk objects, the removal of multiple less-important targets will most probably have a more important tribute to future space environment - due to their number and summarized mass.

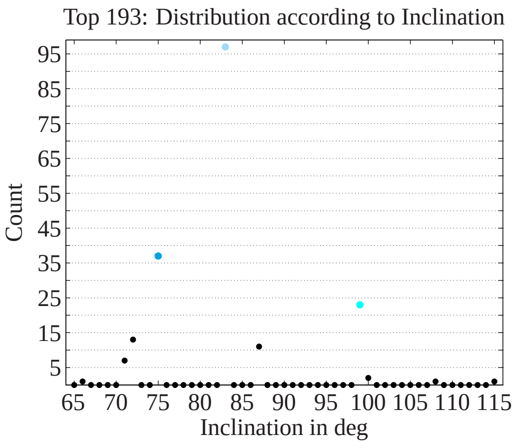

Figure 3. Numerical distribution according to inclination. Inclination is constituted with $\Delta i = 1^\circ$.

The first comparison is made by displaying the distribution of the *Top 193* according to the inclination of the considered objects. Figure 3 highlights the three most filled orbits: 97 bodies in the fixed bin range of 82° to 83°, 37 objects in the fixed bin range of 74° to 75° and 23 objects in the fixed bin range of 98° to 99°. Their allocation according to their altitude, using the same color scheme, is illustrated in figure 4.

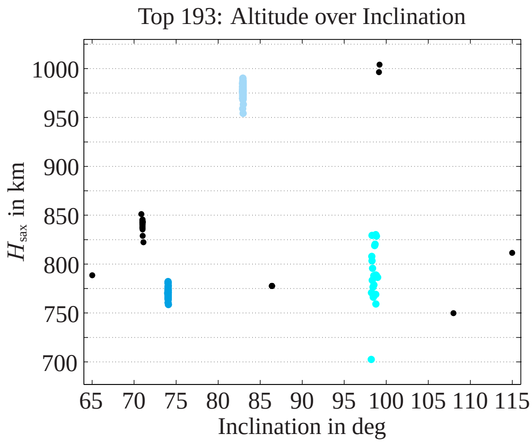

Figure 4. Altitude over inclination. High-risk targets with in the same inclination range (cf. figure 3) are found to be in coherent altitude ranges.

Taking into account the altitude H_{sax}, representing the semi-major axis minus Earth radius, and the inclination, an orbital plane can be extracted. By using the same color scheme as in figure 3, it becomes recognizable, that 97 objects are situated 954 to 990 km above Earth, 37 bodies have an altitude of 758 to 782 km and 23 objects are orbiting 702 to 830 km above ground. Here the cyan-colored objects (23 in total) are more widely spread in altitude than the others. However, all three maxima are in coherent altitude ranges, manageable for small Δv requirements.

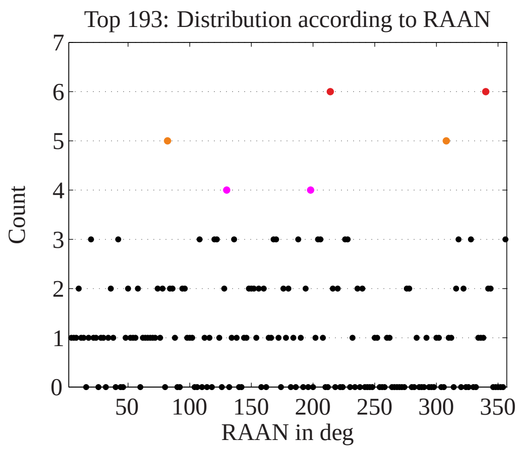

Figure 5. Numerical distribution according to RAAN. RAAN is constituted with $\Delta\Omega = 2^\circ$.

Another important aspect when determining an objects position is its right ascension of the ascending node Ω (RAAN). Due to the constantly changing values (even though the relative value toward each other does not change significantly), a snapshot dated to the 11^{th} of January 2013, is observed in figures 5 and 6. For the same reason - the fact of constant changes and thus the shift of single values into the neighboring range - the range of $\Delta\Omega$ is set to be $2°$ instead of $1°$, like it has been for the hardly changing inclination values.

Displaying the distribution of the *Top 193* according to RAAN, as shown in figure 5, two ranges cluster the most objects (6 bodies: red): $212°$ to $214°$ and $338°$ to $340°$. Two other ranges cluster each 5 objects (orange): $80°$ to $82°$ and $306°$ to $308°$ and again two ranges heap 4 objects: $128°$ to $130°$ and $196°$ to $198°$.

As already mentioned, it hardly pays off for a removal mission to send the removing satellite and its transport mechanism into space to replace one space debris and leave its own (e. g. its upper stage) up there. Because of that, one of the boundary conditions for a reference scenario for this paper is the identification of cluster: objects, that differ little in inclination and RAAN as well as altitude. Since the change of inclination and RAAN requires much more fuel than the change in altitude, focus is put on those two parameters. Figure 6 displays the distribution of the *Top 193* according to these parameters, revealing widely spread RAAN over narrowed inclination ranges.

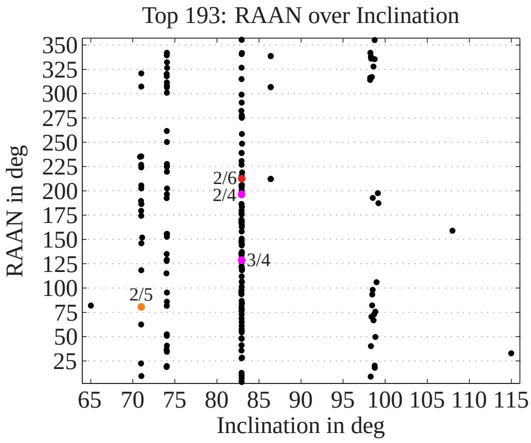

Figure 6. RAAN over inclination. Highlighted and unstitched according to their inclination are the cluster of RAAN from figure 5.

Figures 5 and 6 identify clusters for RAAN. A closer look regarding the parameter and features of the identified targets with the highest cluster-count reveals SL-x rocket bodies and operational satellites of the Iridium constellation. Naturally, the latter are not considered for a removal mission taking place currently. Another recognition is the distribution regarding the inclination. All of the RAAN-clusters of figure 5 are split into smaller groups. By not taken into account the operational satellites and the rocket bodies having a similar RAAN but not a similar inclination, a list as revealed in table 1 can be extracted. It contains the NORAD ID, Name and thus type of debris, the altitude, inclination, eccentricity, RAAN and the position of the ranking process. The latter is highlighted after the same pattern as figure 5.

Table 1 and figure 6 reveal a maximum of three targets in close proximity at an inclination of about $83°$ and an altitude of about 970 to 985 km. Their ranking according to the described parameters is relatively low.

Table 1. Properties of identified targets for ADR

Norad ID	Name	H_{sax} in km	Incl. in deg	Ecc. $\times 10^{-3}$	RAAN in deg	Pos.
11804	SL-8 R/B	978.20	82.94	2.19	212.58	81
14085	SL-8 R/B	977.59	82.94	3.25	212.38	158
23088	SL-16 R/B	843.96	71.00	0.27	80.81	5
17974	SL-16 R/B	835.45	71.01	1.51	80.32	10
10020	SL-8 R/B	971.64	82.95	3.21	128.37	50
14625	SL-8 R/B	984.67	82.93	2.05	128.42	161
16292	SL-8 R/B	975.38	82.93	2.90	129.02	188
18161	SL-8 R/B	975.36	82.93	3.21	196.72	47
16494	SL-8 R/B	976.90	82.93	2.06	196.07	74

3.4. Results

Table 1 and figure 6 contain the result of the *Top 200* selection. After filtering TLE objects concerning their kinetic energy flux per year multiplied by their mass and sorting the first 200, clusters for minimal RAAN ($\Delta\Omega = 2°$) and inclination ($\Delta i = 1°$) differences where extracted. At the maximum three objects in close proximity where found. Their altitude differs by $\Delta H_{sax} = 13.03$ km, their inclination by not even half a degree, their RAAN by not even one degree and all their eccentricities are smaller than 0.01, which makes the orbits virtually circular. Changes of this data will appear over time, however, they will stay in close proximity. Another advantage of all the found pairs is, that, respectively, they are the same type of rocket body. A catch mechanism therefore might be easier to be implemented.

Further concentration for a reference removal scenario is thus put in the orbit of 977 km altitude and $83°$ inclination with multiple SL-Rockets as targets.

3.5. Future Improvements

The target identification process so far was done with an average density. The determined rocket bodies however have verifiable deviant densities. Deductively, the filter process has to be optimized in terms of density, size and type. It is however not expected for the targets orbit to change to much.

4. AUTONOMY

Autonomy as term has wide-ranging usage and so does automation. Most of the times it is actually difficult to draw the line between those two. While automation follows a step-by-step procedure and thus usually a predefined way, autonomy claims to do so without human intervention and based on self-made decisions based on given and measured knowledge and data. One can argue, that the given knowledge and the measured data is implemented by humans again and thus it is actually automation. The line to draw for this paper thus is the behavior of the system in case of unforeseen events. While the understanding of automation hereby would put the system in a waiting status for the human to interact, also called *safe mode*, the autonomy system would find, based on the existing knowledge, a way to fulfill its designated task. To do so, the required autonomy needs situational awareness regarding its own capabilities and the environment as well as a priority list for tasks e. g. a hierarchical structured plan. Cognitive automation, implemented in the cognitive process and frameworked by the Cognitive System Architecture (COSA) is herefor a promising candidate, following the argumentation of Wander [11].

As this paper shall give a first glance on cognitive automation for implementation in ADR, the goals of spacecraft on-board autonomy need to be illuminated. In general, systems become more complex and the workload for ground control operators increase. At the same time increasing computer power would enable the transfer of ground processes into the spacecraft itself with less human operator intervention. Especially in the case of an unforeseen event, todays spacecraft usually go into *safe mode* waiting for the operator's decision. Even if the event is found to be uncritical, a lot of time has passed and with it the time the spacecraft could have fulfilled its task. If the spacecraft again would be able to decide for itself how to categorize the event, time and with it costs will be reduced. Another advantage of on-board autonomy is the reaction time. Especially in case of close approach and thus in the vicinity of 1 - 3 m of the object, reaction time is a critical parameter. Such close approach is necessary for a removal satellite when capturing its target. Human intervention can be too late in case of a failure at this point. Additionally a fulltime monitoring would not be necessary anymore, even though it is highly unlikely that maximum observation during a highly critical phase will be given up any time soon.

The project itself does not address a specific kind of catching mechanism. Like a target identification has taken place, mechanisms will be investigated, however the deployment of a net or the grabbing of a robotic arm etc. will take place on a different level. The autonomy will be implemented on the service platform, acting on the whole system of the satellite with e. g. navigation data as a separated input.

4.1. Autonomy in Space

4.1.1. Theory

The European Cooperation for Space Standardization (ECSS) offers a classification of autonomy levels as cited in table 2. While todays spacecraft reach level E2 according to Olive [12], cognitive automation has the capability to reach level E4 [11].

Table 2. Mission execution autonomy levels. [13]

Level	Description	Functions
E1	Mission execution under ground 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

Theoretical work has been done in the field of fault detection, isolation and recovery (FDIR). However, according to Wander [11] only a few authors like ESA's SMART-FDIR study [14] and the remote agent experiment [15] aiming a level high enough to reduce the number of *safe mode* commands.

4.1.2. Praxis

Autonomous systems, e. g. systems, that have the capability to react without human intervention in case of unforeseen events, have already been tested it space. The missions can be separated into rendezvous-missions, rendezvous & docking missions and rendezvous & capture missions while the latter so far solely exists on paper - examples are given in table 3. It could not be identified which kind of autonomy concept was used for the specific missions.

In case of **rendezvous-missions**, the military projects XSS-10 (2003) and XSS-11 (2005) led by the USA performed (autonomous) close approaches to space objects. In a similar project called DART (2005) the autonomous safety system failed during the docking phase. One demonstration flight led by the Swedish Space Corporation and named PRISMA (2010) brought a satellite system (Tango and Mango) into space. They performed a

Table 3. *Overview of autonomous missions*

Year Country	Project	Orbit/ Inclination	Remark
1997 Japan	ETS-VII	550 km/ 35°	Rendezvous & Docking
2003 USA	XSS-10	815×531 km/ 39.8°	Rendezvous
2005 USA	XSS-11	839×875 km/ 98.9°	Rendezvous
2005 USA	DART	747×395 km/ 96.6°	Rendezvous
2007 USA	Orbital Express	492 km/ 46°	Rendezvous & Docking
2008 Europe	ATV	300×400 km/ 51.6°	Rendezvous & Docking
2010 Sweden	PRISMA	757 km/ 98.28°	Rendezvous
TBD Japan	SDMR	SSO	Rendezvous & Capture
TBD Germany	DEOS	600 km/ 87°	Rendezvous & Capture
TBD Germany	SMART-OLEV	GEO	Rendezvous & Capture

formation flight where the orbital control was completely autonomous.

Rendezvous & Docking-missions increase the complexity of rendezvous in space by the fact of actually interacting with another object. The projects performed so far have brought their own object with them into space (exclusion: ATV/ISS). A double control - of the chaser and the target - is thereby provided. In this way more information can be gathered and thus mistakes be minimized. As displayed in table 3, all three projects are in a relatively low orbit. Reasons herefor are their application (ATV) and safety in case of failure with no interruption of highly used orbits. Another advantage is the relatively fast re-entry of objects from low orbits.
It has to be mentioned, that these satellites are designed for orbital servicing e. g. fuel exchange, maintenance etc. Nevertheless, the step to perform an unaided rendezvous- and docking maneuver with an uncooperative target, as it is the case of space debris removal, points in the same direction.

Rendezvous & capture missions are not yet flown. Most promising seems to be the project DEOS by DLR. Similar to the already performed rendezvous & docking missions, DEOS will have its own client for an easier proof of technology. Another German project is the orbiting servicer SMART-OLEV, which is planned to serve satellites autonomously in geostationary orbit (GEO). Other concepts, like the SDMR, will use tethers to lower the objects orbit. This project is particularly designed for space debris removal in sun-synchronous orbits (SSO).

The presented missions demonstrated the capability to orbit spacecrafts autonomously, even though the autonomy used so far is partial, mostly in the field of navigation. Difficulties have been shown when increasing the autonomous part. To minimize such problems, the process of cognitive automation is proposed. In the following section, a short overview of the system is given.

4.2. Cognitive Automation

As already mentioned, terminology can drift apart and represent the same. This paper for example recommends cognitive *automation* as concept for autonomy. In the following section, the basics of the cognitive process, which is based on cognitive automation, are presented.

The approach of cognitive automation is designed to use cognition, to work in cooperation with the human operator and to show goal-consistent and transparent behavior. By following the human knowledge-processing scheme, the technical process mimics human information processing and eases the human-computer interaction. As depicted in figure 7 instead of setting thresholds, the system is based on a so-called a-priori knowledge (inner gray oval), which is specified during design time. Together with the situational knowledge (outer light gray oval) which is created during runtime and represents the actual situation, they process the behavior. The knowledge again is processed by the so-called transformers (black arrows in figure 7). The transformers can read from the whole body (inner and outer gray oval) to retrieve their necessary input and write their results back into the body. Even though the system works for the whole body, the most used information for the transformers is within the dashed area. The transformer *planning* for example uses the goals as triggering elements and the a-priori knowledge about strategy models. Resulting, a plan how to achieve these goals is generated. The plan can include alternative operations, however, it is hierarchically structured. [16, 17]

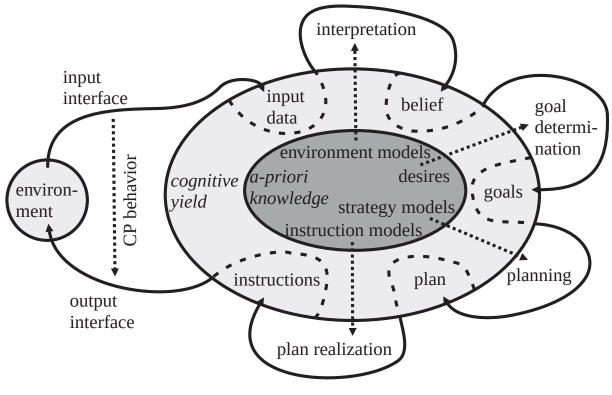

Figure 7. The cognitive process. [16]

The cognitive process as displayed in figure 7 can be extended optional with transformers and knowledge.

As example, in case of a removal satellite, the goals of collision avoidance as well as direct insolation on the solar panels might be set. In close proximity and the case of low battery, these goals compete due to too low energy for task performance and the system has to decide which goal has the higher priorities at this point. Situation-based a plan and its execution will be derived and performed. As a framework herefor the cognitive system architecture (COSA) has been developed by Putzer [18]. Although the example application for COSA is an autonomous unmanned air vehicle (UAV), the process is proposed to be convertible for other technical processes. Hereby UAVs and satellite systems in particular have similar problem-setting like the evasion from a dangerously close aircraft, situation-related behavior, parallel decision makings and both systems are time critical and thus in need of fast processing of data. Based on that, cognitive automation is identified as promising candidate for innovative autonomy concepts for active space debris removal.

5. CONCLUSION AND FUTURE WORK

A target orbit for multiple active space debris removal has been identified based on the presented filtering process. Further concentration for a reference removal scenario for autonomous methods will be put in the orbit of 977 km altitude and $83°$ inclination with multiple SL-Rockets as targets.

The term *Autonomy* has been defined for this paper. Space missions with autonomous sections that have been launched or seem most promising to be launched are listed. As autonomy concept for the active space debris removal mission, for which the target orbit has been identified, *cognitive automation* is a promising candidate.

Future work will include an optimized filtering process concerning a more accurate mass of the targets. Further, the concept of cognitive automation will be subject to further investigation concerning its portability onto removal satellites and efficiency in doing so.

ACKNOWLEDGMENTS

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