IAC-18.E5.1.4x46019

ORDER: Space Station for Orbital Debris Recycling

Ivan Matas[a]*, Sandra Häuplik-Meusburger[b]

[a] *Department of Three-Dimensional Design and Model Construction , Vienna University of Technology, Karlsplatz 13, Vienna, Austria 1040,* ivan.matas@tuwien.ac.at
[b] *Department of Building Construction and Design, Vienna University of Technology, Karlsplatz 13, Vienna, Austria 1040,* haeuplik@hb2.tuwien.ac.at
* Corresponding Author

Abstract

Since the launch of the Sputnik 1 in 1957 the presence of human-made objects in space has drastically increased. As of now, there are about 1900 active satellites orbiting around us, yet they amount to only 10% of artificial objects we currently track in proximity of our planet. The remaining 90% are considered space debris and are mostly the result of decommissioned satellites or upper rocket stages breaking apart after years in orbit. Additionally there are 160 million smaller debris pieces estimated among them, not trackable with present technology.

Besides debris of any size posing an imminent risk to all current and future space missions, already in 1978 Donald J. Kessler proposed that once the debris population reaches a certain density, debris collisions could cascade into one another resulting in a distribution of debris in Earth's orbit that would render our satellite networks ineffective and make future spaceflight attempts nearly impossible.

This paper outlines the architectural design proposal for a crewed space station that is able to capture and subsequently recycle space debris, viewing it as a potential resource. A mission concept is devised by researching and selecting suitable debris types, orbital regions, capture methods and assembly options. A recycling process and applications for the salvaged material are presented. The architectural emphasis lies on habitability, functionality and an efficient configuration .

1. Introduction

1.1. Space Debris Definition, Numbers & Estimates

Any human-made object in space, which is not an active satellite or spacecraft, is considered space debris. The Union of Concerned Scientist provides a database of all operating satellites currently in orbit around Earth, as of April 2018 this number approached 1.900 [1], yet at the same time the US Space Surveillance Network (SSN) reported a total of 18.922 artificial objects in space [2]. These are just the ones large enough to track with current technology. A widely accepted categorization for Space Debris is by size: Small debris (<1cm), medium debris (1-10cm) and large debris (>10cm). The number above refers only to large debris, ESA estimates around 750.000 medium and 166 million small debris among them [3]. Screws, bolts or paint flakes, loosening from a spacecraft and left-behind upper rocket stages or inactive satellites, either intact or broken apart after years in orbit are the main contributors to the high debris number. However the 2007 Fengyun-1C (FY-1C) breakup, after a Chinese anti-satellite missile test and the 2009 hypervelocity satellite collision between Iridium 33 and the inactive Kosmos 2251 more than doubled the debris population under 1000km [4].

1.2. Possible Risks & Kessler Syndrome

Debris pieces of any size pose a risk to current or future space missions, considering their high velocities. Currently a 3-5% chance of mission loss is given over the lifetime of a satellite due to debris impact [5]. This is seen as the short term risk of space debris. The above mentioned hypervelocity collision however is widely agreed upon to be the starting impulse of the "Kessler-Syndrome", described in 1978 by Kessler and Cour-Palais [6]. A scenario that proposes, once the debris density around Earth exceeds a certain threshold, the resulting debris from one collision will inevitably lead to further collisions in a cascading manner, eventually creating a debris population density so high, that it would render our satellite networks ineffective and pose serious limitations to future spaceflight attempts. This is seen as the long term risk of space debris.

1.3. The Necessity for Active Debris Removal (ADR)

Even though the Inter-Agency Space Debris Coordination Committee (IADC) implemented debris mitigation guidelines in 2007, suggesting that spent rocket stages and satellites at the end of their lifetime should be transferred into a 25-year decay orbit [7], numerous studies by Liou, Johnson et al, focusing on simulations of potential debris collisions in the upcoming 100-200 years, using the NASA orbital debris evolutionary model LEGEND, have shown that even if we suspend all future launches and the postmission disposal (PMD) mitigation measures have a success rate of 90%, the debris population will continue to increase. Further simulations were run with an assumed launch rate based on the previous decades of spaceflight. The results suggest that 5-10 large debris pieces have to be removed actively per year to ensure a stable debris population [4, 8-10].

In reality, early estimations from 2010 place the PMD compliance values at roughly 14% with later studies putting the number even as low as 8% [11]. Additionally a future launch rate is fairly difficult to predict and seems to be growing rapidly due the development of new, more efficient and even reusable launchers like Space X's Falcon series. This could imply that even more pieces have to be removed per year to maintain a stable debris environment.

On the other hand, it has to be noted, that late studies and simulations indicate, parameters such as launch and explosion rates, magnitude of solar activity and compliance with PMD might have a higher influence on the outcome of the simulated future debris population than the number of debris pieces removed per year with ADR. More and continuous research is necessary to determine the true necessity for ADR and weather to prioritize addressing short term or long term risks of space debris [11].

Nevertheless space debris has become an acknowledged threat and a lot of effort is being put into designing viable ADR methods and technology. Current approaches focus on deorbiting the debris leading to a burn up in Earth's atmosphere.

1.4. Aims of this paper

This paper aims to emphasize the potential of space debris as a resource. Parameters for a crewed space station that can capture, store and recycle debris with the eventual capability to expand itself or create new spacecraft using the obtained material are defined, subsequently cumulating in an architectural design proposal for said space station

2. Mission Concept

2.1. Choice of debris type

Albeit quantitatively far outnumbered by small and medium debris, large debris represents approximately 99% of the total debris mass in orbit [4] additionally it is well catalogued in terms of orbital properties and can be reliably tracked with current technology. The highest potential for debris proliferation, the long term risk for space missions, comes from catastrophic collisions, an event in which the impact energy to target mass ratio of colliding objects exceeds 40j/g, resulting in a total fragmentation of both objects. The most probable contributors for a catastrophic collision are large intact debris pieces, considering their great mass [8]. Since the ORDER space station additionally to removing debris, aims to recycle the material, it is essential that it will acquire as much mass per debris capture, as possible. Due to these arguments, small and medium debris will be disregarded and large intact debris pieces will be targeted.

Large intact debris can be separated into two categories: Rocket bodies and deactivated or retired spacecraft (satellites). Even though satellites are generally made up of more valuable materials, they pose a lot of challenges for capture and recycling. Firstly they are fragile, any attempt to capture or propel them could cause a breakup of components like solar arrays or antennae, secondly most satellites are unique and mission specific, which makes it difficult to design an efficient recycling process, due to size, mass, component and material variations, thirdly they contain highly developed technologies protected by property claims of the associated nations. Rocket bodies, on the other hand, are built sturdy and are meant to endure huge amounts of structural stress. There are a lot of similar rocket types, in fact 73% of the total rocket bodies (88% of the total rocket body mass) in orbit are accounted for by just 9 different rocket types, making them an ideal target for benchmark missions in order to develop and refine capture and de-orbiting methods. Furthermore they consist mainly of aluminum and steel which are very well recyclable materials, and finally they have less critical technologies, easing the probability of complications through property claims. Rocket bodies make up 42% of the abandoned intact objects in space and 57% of the abandoned mass, 48% of the total mass if active spacecraft are considered. [12]

2.2. Choice of orbital region

According to Liou almost all future collisions will occur in low Earth orbit (LEO) the region of space up to an altitude of 2000km, medium Earth orbit (MEO 2000-35.768km) and the geostationary orbit (GEO 35.768km) will practically not be affected. In an optimal ADR scenario objects with the highest probability of contributing to future debris population growth would be removed first. One way to determine such objects is with the equation given by Liou, based on an object's mass and collision probability at a time t [8-10]. The disadvantage of this approach are the often very different orbital properties of the determined objects. This could be a viable procedure for multiple spacecrafts with single de-orbiting missions, but in the case of a space station that is supposed to continuously capture and process debris, or in the case of any multi-target de-orbiting spacecraft the propellant and energy requirements for radical orbit changes are exceedingly high. It is more efficient to select an orbital region that offers multiple large debris targets in need of removal. Such regions have been identified by various studies [4,12,13] Anselmo has ranked upper rocket stages in orbit based on a normalized and dimensionless ranking index. The 290 Kosmos 3M (SL-8) second stages and the 22 Zenith 2 (SL-16) second stages in LEO make the top of the list. They represent a total mass of 416.150kg and 198.000kg respectively. The SL-8 Kosmos stages are distributed at altitudes between 400-1800km in two inclination bands of ca 74° and 83° The Sl-16 Zenith-2 stages are located between 800-850 km altitude at an inclination of about 71°. The Kosmos 3M rocket bodies are also recommended by a different study as an optimal benchmark target [5]. Additionally their spread throughout almost the whole bandwidth of LEO altitudes suggests a more efficient collision prevention (see Fig. 1).

The Kosmos 3m second stage has a 2,4m diameter, a 6,5m length and a dry weight of ca 1,44 tons. The Zenith 2 second stage has a 3.9m diameter, a 10,4m length and a dry weight of ca 8.9tons. [14,15] These will be the two rocket body types collected and processed by the ORDER space station (see Fig. 2).

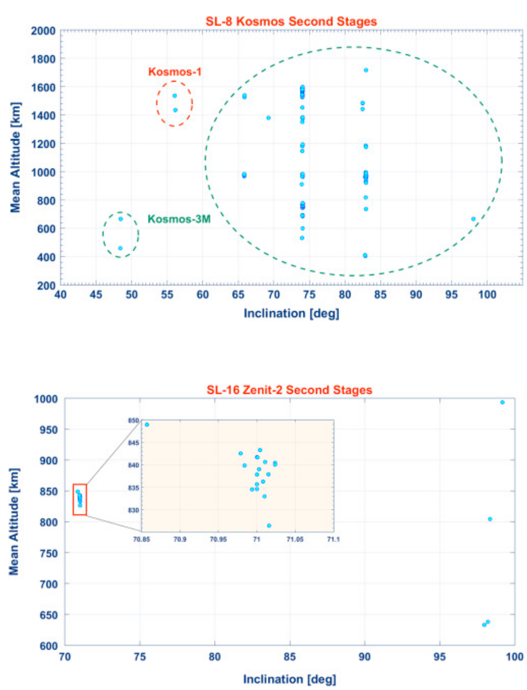

Fig. 1. Distributuion of Kosmos SL-8 and Zenit 2 second stages, taken from [12]

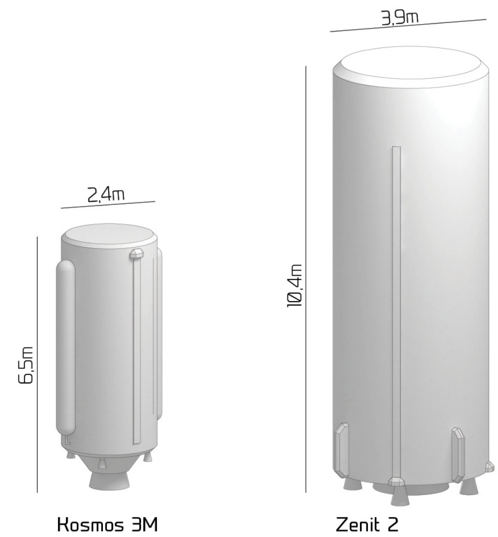

Fig. 2. Dimensions of Kosmos 3M SL8 and Zenit 2 SL16 second stages

2.3. Choice of capture method

Although high cost predictions, a lack of fully developed removal techniques, as well as the question of ownership of debris and general liability, prevented ADR from being seriously considered in the past, the debris environment assessments since the FY-1C breakup event and the Cosmos 2251 and Iridium 33 collision warrant a change of mind [9]. Nevertheless a lot of different approaches for ADR have been suggested over the years. The most popular concepts and techniques will be presented in this chapter and subsequently the method most suited to capture debris for the ORDER Space Station will be chosen.

Since it was already determined that the station will be collecting intact rocket bodies, only methods applicable for the capture of such an object will be considered in this chapter, small and medium debris removal strategies will be disregarded. In contrast to the mission goals of the station, these ADR concepts mainly focus on the capture and sole deorbiting of the debris, using different means to propel the acquired target towards Earth subsequently leading to a burn up during atmospheric reentry. The main technologies considered for this approach can be grouped as follows: Contactless methods (laser, ion beam shepherd), loose-contact methods (net, hook, harpoon, clamp) and rigid-contact methods (electromagnetic tether, robotic arm → either for sole capturing or attaching a thruster deorbiting kit (TDK) or a sail). Each of these technologies has to be installed on to or delivered by a spacecraft that rendezvous with the debris. The categories above indicate how close and precise this rendezvous has to be. An exception can be a ground-based laser or an autonomous TDK which can detect and attach itself to the determined target.

The rendezvous with and capture of debris is highly complex for multiple reasons. Firstly the debris does not contribute to the rendezvous procedure; it lacks visual cues, radar corner-reflectors or any other commonly used equipment for similar missions carried out by the ATV, HTV, Soyuz, Progress or Dragon. Furthermore the debris is potentially Tumbling, with a movement possibly higher than 6°/s, that would have to be passivised in order to guarantee a controlled collection by the ORDER Space Station and lastly the visual and physical state of the debris may different from the one that is expected: in the case of rocket upper stages, the white thermal protection layer covering its surface, could have turned black due to the thermal fluxes encountered during the atmospheric phase of the launch. [5]

2.3.1. Contactless methods

2.3.1.1. Laser

By directing a high powered laser beam onto a debris piece, it causes the targeted surface to ablate (a form of vaporization) which produces a momentum change due to the ejected vapor, similarly to an impulse delivered by a rocket. For this method no contact or close rendezvous maneuvers are necessary and the spacecraft generating the laser beam can keep a safe distance to the debris. Furthermore it requires no extra propellant to move the selected debris. The disadvantages of this method are the limited control, the danger of explosion of the target due to the very high temperatures needed to achieve ablation and the possible disintegration of the optical elements of the laser over time [16].

2.3.1.2. Ion Beam

The ion beam shepherd (IBS) is a spacecraft concept that exerts a thrusting force, by producing an ion beam directed towards the debris to modify its orbit and/or attitude. It has a primary and opposing secondary propulsion system in order to keep a safe distance to the object being pushed in front of it. The IBS, similarly to the laser method does not require contact with the debris. The main risks being the failure of maintaining the distance to the targeted object, which most likely will result in catastrophic collision and a loss of mission or the misalignment of the ion beam force to the objects centre of mass, which could cause a breakup of the debris.[16]

Neither of the above mentioned methods provides a controlled re-entry, not only is this against current mitigation standards, that state that debris has to be de-orbited above the pacific, so that no inhabited area may suffer an impact of a potentially not completely burned up object, but it is also disqualifies them as a viable method for delivering debris to the ORDER Space Station.

2.3.2. Loose contact methods

2.3.2.1. Throw Net

This method achieves capture of the target debris by deploying a net, which is closed once the debris is surrounded by it. The advantages being, the relatively large distance that can be maintained between the spacecraft and the target, limiting the collision risk, the material and lower precision requirements for the net opposed to rigid contact methods and the fact that a single sized net can be used for debris of various sizes. However the method may cause fragmentation of the target by exerting shock and vibration loads during the capturing phase or by enclosing a debris piece with large appendages like antennae or solar arrays. The largest risk however is the possibility of missing the target and subsequent failure of the mission since the mechanism normally allows for only a single shot of the net. [16]

Similar advantages and disadvantages can be identified for the harpoon, hook and clamp concepts.

2.3.3. Rigid contact methods

2.3.3.1. Electrodynamic Tether (EDT)

By utilizing the interaction between the current flowing through a conductive tether and the earth's electromagnetic field, the electrodynamic tether presents a form of space propulsion that can generate thrust for a long duration while requiring little to no fuel or expendables. [16] The disadvantages of this method being the requirement of a rigid contact of the space craft with the debris, and the length of the tether which can be up to 10km, posing risks to active spacecraft in orbit. Further it may cause entanglement and subsequent failure during the deployment of the spacecraft [5].

2.3.3.2. Robotic Arm

The operation of robotic arms (RA) in space is by now a highly established technology. The Canadarm was an integral component of the space shuttle program and enabled the construction of the International Space Station (ISS) which now features the second generation Canadarm2 as its Mobile Servicing System (MSS) next to the Japanese Experimental Remote Manipulating System (JERMS), the Russian "Strela" cranes and by 2019 the setup will be joined by the European Robotic Arm (ERA). In addition to this fact removal of debris by RAs is one of the most studied ADR techniques. Similar to the EDT the RA method requires rigid contact with the debris. This poses a risk of fragmentation of the target debris, furthermore a too high relative attitude rate between the spacecraft and the debris could cause damage to the arm. A risk of missing the target during the capture procedure is also given, however it is not as severe as with the previously mentioned net method, since the arm can attempt this procedure several times if no incident occurs

A spacecraft equipped with an RA can also be used to install sails or thruster deorbiting kits (TDK) onto the debris. While the former simply tries to reduce the targets altitude due to enhanced drag with the goal to speed up its orbital decay, the ladder could be utilized to maneuver the debris into the orbit of the ORDER space station where it would be grabbed and captured by one of the station's RAs.

Houman compares the above mentioned methods with an analytic hierarchy and a utility-based process with the conclusion, that the Net, Laser and Arm methods are the most promising techniques for ADR, [16].

The chosen debris capture approach of the ORDER space station is shown in Fig. 3. The main component employed will be a RA attached to a modified Automated Transfer Vehicle (ATV) previously used by ESA for five resupply missions to the ISS. Using an ATV has the advantage that it is an already established, fully developed and even human-rated spacecraft, minimizing the development costs for this project and providing an additional emergency escape vehicle for the crew while the ATV is docked. It is not capable of atmospheric reentry, but it could fare the ORDER astronauts to the ISS or at least remove them from the proximate danger area in case the regular escape vehicles like the Soyuz or the Dragon are inaccessible. Furthermore a spacecraft equipped with an RA will be an indispensable asset in the early assembly stages of the station.

Method a

The ATV will undock from the ORDER space station, boost to increase orbital altitude, rendezvous with and capture the target debris, then reduce altitude by decelerating. After meeting back with the station it will pass on the debris to one of the station's RAs.

Method b

The ATV will be modified in such a way that it can transport several TDKs and attach them to multiple targets during one flight subsequently. The rocket bodies will then maneuver autonomously to the space station, where they will be captured by one of the stations own RAs.

Method c

Some of the Rocket Bodies are at fairly low altitudes of 400-600km (see Fig. 1). The same altitude range the ORDER space station will be orbiting in. The station can maneuver to these objects by slightly altering its altitude or inclination using little fuel and capture the debris with one of its own RAs (see Fig. 3).

Besides its primary purpose of removing and recycling large debris pieces from LEO, the station can be seen as a research facility to test and evaluate different debris capture methods and technologies. The TDK technology from *method b* still needs to be tested and applied in space and an actual space mission. These efforts could be conducted from the station. As mentioned in the previous chapter, the Cosmos SL-8 second stages are an ideal target for benchmark testing, due to their large number, their nearly identical formal and material properties and similar orbital conditions. The so generated data and findings will contribute to the development of new and to the advancement of current ADR concepts.

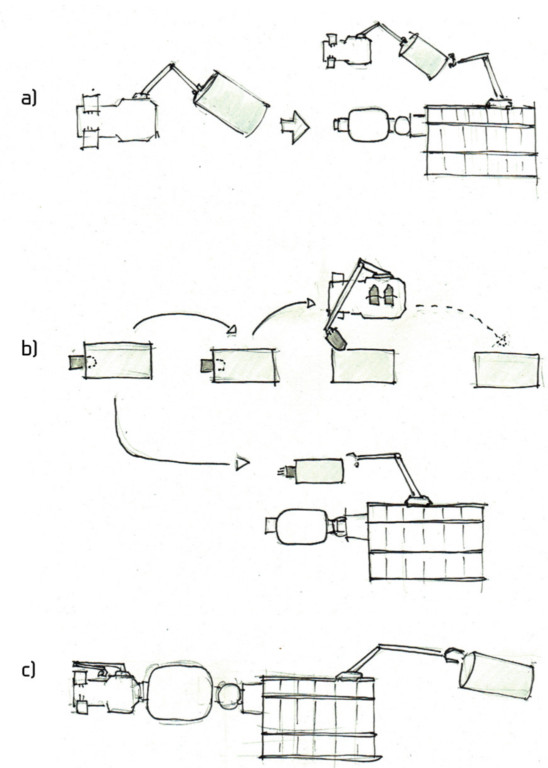

Fig. 3. Capture methods a, b and c

2.4. Choice of construction method

The hangar will be the most challenging component of the station to construct regarding its size. It has to accommodate either the Kosmos 3M SL-8 or the Zenit 2 SL-16 second stage rocket body, the ladder being the larger one with 10,4m in length and 3,9m in diameter (see Fig. 2), in addition to leaving enough maneuvering space for RAs to access and work around the specific debris, and room for deposition and storage of disassembled parts. While the habitation and work modules can be preconstructed on earth and launched respecting current fairing limitations - a Falcon 9 rocket, provides a fairing volume of 4,6m in diameter and 6,7m in height, and an additional height of 4,3m with linearly decreasing diameter to 1,45m [17] - it is clear that this is not a viable option for the Hangar. It will have to be assembled in orbit.

An exception could be provided by the company Bigelow Aerospace, which is working on multiple types of inflatable modules, based on the TransHab concept developed by Constance Adams and NASA in the 1990s [18], that significantly expand their diameter after arrival at their destination (orbit or planetary surface). The B330 type habitation module of the company is set to have a length of 13,7m and an inflated diameter of 6.7m. It could theoretically accommodate an SL-16 second stage and leave, albeit somewhat limited, maneuvering space around it. However these modules are constructed with a pressurized core cylinder running through their whole length, around which the textile layers are fixated and wrapped in their deflated state. This cylinder is the docking and access point to the module and determines, by its diameter, the maximum size of an access hatch. In the case of the B330 this diameter is about 2,60m in dimension, which disqualifies it for a hangar adaptation. There are Bigelow modules in development with larger core diameters like the BA-2100 Olympus module but these also require a fairing size which is not yet available.

The company Made In Space (MIS) teamed up with NASA as part of NASA's IRMA (In Space Manufacturing and Assembly) Program. Together they developed the Archinaut, a platform that can print and assemble large constructions in orbit, solely relying on supply of raw material feedstock [19]. This concept is optimal for the ORDER space station, since the Archinaut robots could be primarily used to construct the station's truss framework and the Hangar without any size limitations. Subsequently, after the initiation of the recycling process, they could utilize the freshly extracted material to expand the station by enlarging the existing hangar, adding additional hangars or even begin to assemble a second generation ORDER space station which would be then sent to a different orbital region.

MIS is also the frontrunner for stationary 3D printers in microgravity. The company operates the Additive Manufacturing Facility (AMF) on board of the ISS, the only commercially owned and operated fabrication system in space, which is solely responsible for raising the TRL of space-based polymeric additive mafucatruing to 9, and is developing printers that can use metals as base material [19]. These would also be a valuable asset to the station, allowing the crew to print spare parts for the repair of RAs or to replace worn toolheads like drills, cutters, shears and circular saw blades, needed for the disintegration of the rocket bodies, all by using the processed recycled material enabling a circular material economy.

2.5. Definition of recycling process

The recycling operation will firstly focus on metal processing, since the targeted rocket bodies are mainly made up of aluminum, steel and titanium. In later stages, after enough material has been collected to expand the station and so provide space for work with different kinds of debris like e.g. satellites, sorting, storing and processing of other materials can be implemented.

The upper stages are captured, relieved of any excess fuel or other hazardous material, brought to the station and stored on the external surfaces of the hangar before being moved inside. Only one rocket body at a time is processed inside the hangar. Here it is cut and disassembled by the RAs into pieces small enough to pass through the airlock connecting the hangar interior with the pressurized work module. The inner surfaces of the hangar are used to store these disassembled components and cut pieces before they are transferred inside the module. Both the exterior and interior storage possibilities serve as a failsafe to help achieve a continuous flow of the capture and recycling process. If the RAs inside the Hangar are behind schedule on processing, the station can still achieve its goal of removing 5-10 large debris pieces from orbit per year, by storing them externally. Similarly if there are any complications leading to a delay inside the work module, the RAs can still continue disassembling further rocket bodies. Since the rocket bodies are limited to two types, the crew and ground personnel is intended to develop command code strands and learning algorithms for the RAs and to tweak and refine them with every upper stage processed. The goal is to create a fully automated disassembly program for each rocket body type, minimizing the need for manual RA control to exceptional situations.

In the work module, the crew inspects, cleans and feeds the cut up pieces into shearing and shredding machinery. The resulting metal chips and flakes are guided into cylindrical furnaces at the station's extremities, heated by parabolic mirrors and energy from the station's solar arrays. This is done by pressurized pipelines connecting the module with the furnaces. Once the temperature inside the furnace reaches the specific melting points of the various metals (aluminum alloy: 463-671 C°, aluminum: 660 C°, steelcarbon: 1425-1540 C°, steel-stainless: 1510C°, titanium: 1670C°), they are sucked out of the furnace through a recoil line, this automatically leads to the separation and sorting of the metals. Finally the metals are pulverized and filled into special containers, creating feedstock for either the Archinaut robots or the onboard 3D-Printers. This establishes a material cycle (as shown in Fig. 4) and will provide the Station with the possibility to either self-expand so that it may accommodate the removal of more debris pieces or the removal and processing of new debris pieces like satellites, or generally enable the in-space production of new spacecraft.

2.6. Mission summary and main components

The ORDER Space Station is located the LEO regime, at an altitude of 400-600km and an inclination of 71°-74°. It captures Kosmos 3M and Zenit 2 second stages and has to remove 5-10 objects from their orbit per year. It processes and recycles the metals in the rocket bodies and generates feedstock for in space 3D-printers. The salvaged material is subsequently used to expand the station or to help construct new spacecraft like a second generation ORDER space station.

The main components are:

- a hangar for rough disassembling and storing of the intact and disassembled debris pieces
- a work module containing a processing section for inspection and shredding of the debris pieces and a workshop section for RA repairs and TDK refurbishment
- an airlock connecting the hangar interior with the work module
- cylindrical furnaces fed and emptied by a pressurized pipeline system and heated by parabolic mirrors and the energy generated from the solar array network
- a habitation module that can accommodate a crew of 2-4, offers a safe haven for solar storms and high radiation events, 2 private quarters, room for sports and leisure activities, a galley and designated food consumption area and storage space for supplies and crates of 3D printer feedstock.

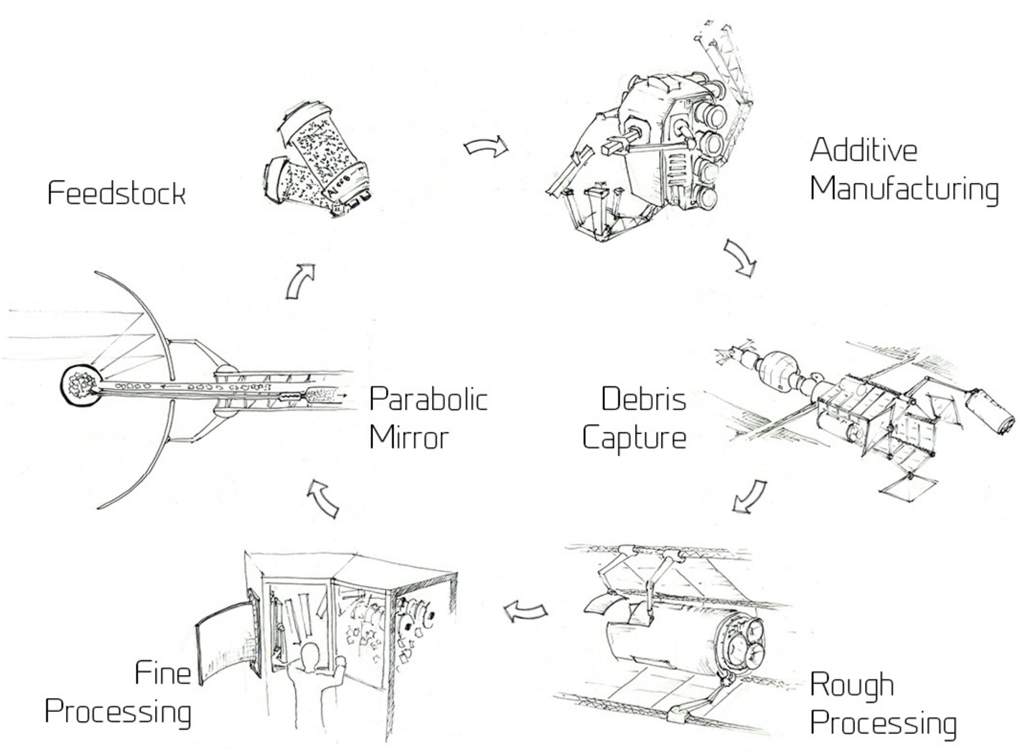

Fig. 4. Material cycle

3. Architecture

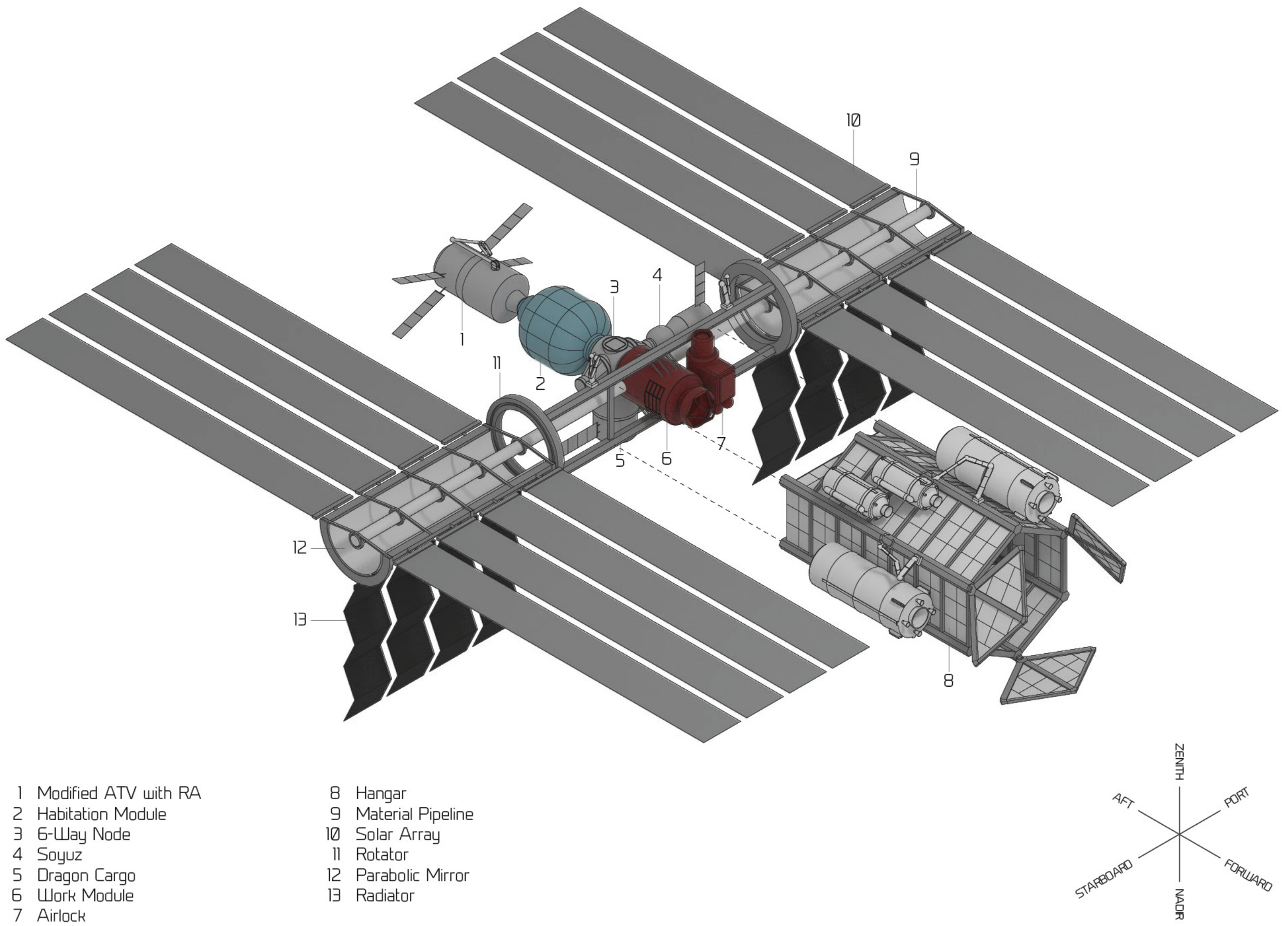

Fig. 5. Components of the ORDER Space Station

3.1. Hangar

The main structure of the hangar is a truss network, sealed with enclosed 3D-printed honeycomb aluminum plates. The hangar is not pressurized, considering the large quantities of air that would be lost each time the hangar is opened and subsequently needed to refill it, after a new debris piece has been brought inside. The sealing of the hangar serves the purpose of preventing fragmented debris pieces, produced during the disintegration of the rocket bodies, from escaping, minimizing the risk of creating additional unintended space debris. This type of seal can be achieved more easily, with less precision requirements and construction difficulties than an air and pressure tight seal would pose. Due to this fact however, the whole disassembly, sorting and storage steps inside the hangar have to be performed by RAs. A RA control center, formally based on the ISS's cupola, attached to the forward end of the work module, grants the crew a nearly unhindered view of the hangar's complete interior, allowing for efficient oversight of the RAs progress.

The shape of the hangar is an extruded hexagon with a side length of 6,2m. The six main truss elements also have a hexagonal section with a side length of 50cm, attached to two of these sides are the secondary truss beams with a rectangular section in an interval of 3m. The remaining four sides of each main truss as well as the external and internal sides of the secondary truss are used for RA movement, either by an integrated rail system or, equally spaced grapple fixtures. The seal of the hindmost segment of the hangar only connects four of the main truss elements, forgoing the zenith and nadir oriented ones, creating an extruded rectangular shape. This is a consequence of the work module being centrally immerged in the aft part of the hangar. Since the cupola is located on the forward part of the module, the space behind it is not visible for the crew, and is additionally reduced by the diameter of the work module, so the zenith and nadir part of this hangar segment were scrapped on account of being dead space. The rectangular shape provides enough room for the modules portside airlock and grants the RAs access to the starboard-side toolhead exchange. The hangar is closed by three separately operable rhombus shaped doors attached to the end of three main trusses. Every hangar side has a total area of 112m² that can be used externally and internally, effectively generating 224m² of storage area per side. Each side can accommodate up to one Zenith 2 and two Kosmos 3m or up to six Kosmos 3m upper stages externally, allowing for the storage of 18-36 rocket bodies at any given time. The total volume of the enclosed space is approximately 2000m³.

The hexagonal shape was chosen due to its good volume to mantle properties, the easier accessibility of the 6 sides for the RAs over the main trusses and its good expandability preconditions.

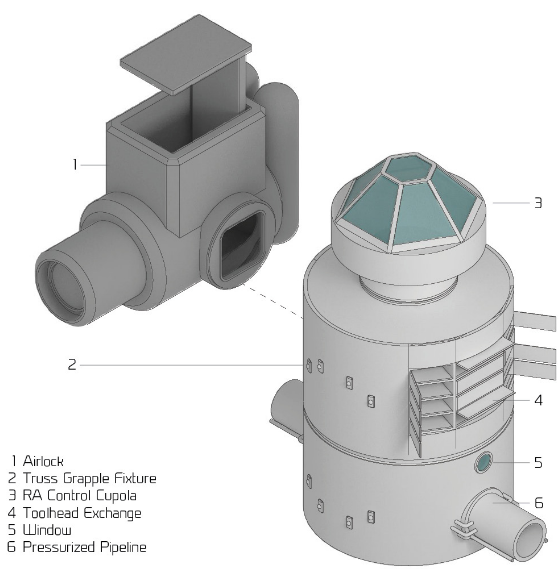

Fig. 6. Work module components

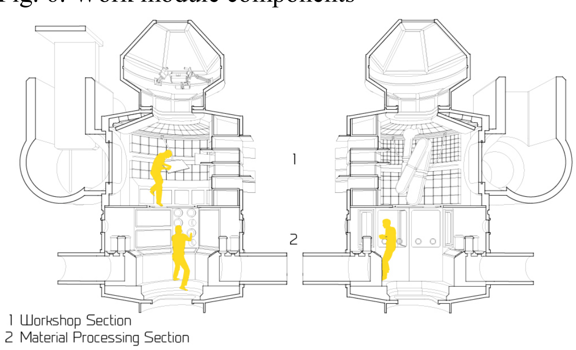

Fig. 7 Work module interior

3.2. Airlock + Work Module

The airlock has a net inner volume of 12,5m³, and a total of three egresses. The hatch leading to the hangar is fixed to an extendable panel onto which the RAs can stack the disassembled and cut pieces of the rocket bodies or place themselves or other RAs onto it in a collapsed state, in case repairs are necessary. The size of the hangar-side opening is 1,5m x 2,4m in dimension. The connection to the work module is upheld by a common berthing mechanism (CBM) this results in square shaped hatch size with a side length of 1,27m, this opening dictates the maximum size for the cut debris. RAs can be disassembled in the airlocks cavity, while pressurized, and then transferred to the workshop section of the module in parts. The final egress hatch is circular in shape with a diameter of 1,1m and leads to the external zenith side of the hindmost hangar section. It is used for crew EVAs.

The work module is a cylinder with the external dimensions of 6,5m in length and 4,5m in diameter. It has three CBMs, two openings to accommodate the pressurized pipeline on the port and starboard side of the aft section, two windows 40cm in diameter above them and 12 containers with external and internal hatches for RA tool heads on the starboard forward half connected to the interior workshop section, allowing for quick tool head changes and refurbishment. Externally it features 16 fixation points for the truss system and a circumferential groove for installing the hangar's isolation panels (see Fig. 6). The orientation inside the module is local vertical and the volume is separated into the repair and refurbishing workshop for RAs, tool heads and TDKs and the material processing lab. Each section is 2,7m in height. The workshop contains a vast number of crates and pouches fixed to the walls and ceiling to store spare parts and tools for repair activities, a circumferential rail at the seam of wall and ceiling to accommodate flexible fixation elements, work tables and lamps. Furthermore the CBMs connected to the airlock and the RA control cupola are located here.

The cupola is attached to the forward side of the module, is 3,3m in diameter, 2,85m in length and has 6 trapeze and one hexagonally shaped window arranged at its top, allowing for maximum visibility of the hangar interior.

The material processing lab is equipped with one large and two smaller 3D printers next to two extensive machines for shearing and shredding of the metals. These accommodate hatches for intake of the unprocessed debris pieces, feature thick transparent polymer fronts with science glovebox mechanisms and have a direct internal connection to the pipeline system leading to the external furnaces. Finally the lab contains two filling ports for the processed material which are directly connected to recoil line coming from the external furnaces (see Fig. 7). This way no metal flakes will contaminate the space stations interior, only large metal pieces and feedstock containers filled with the pulverized material will be handled outside of the closed processing circuit.

3.3. Parabolic Mirrors, Rotators and Solar Array

The Rotators are large circular truss guide rails with a diameter of 8m. They are located at the port and starboard end of two main trusses attached to the work module and perpendicularly connected to the hangar. A semicircular framework is connected to the rotators, it houses the parabolic mirrors and grapple fixtures for the solar panels and radiators. The rotators plus framework allow the cylindrical furnaces and the pipeline system coming from the work module to stay in a stationary position, while rotating the mirrors and solar panels around the furnaces to achieve a maximally sunlit area. The solar array has a total area of 2350m², the distance from the outer boundaries of the hangar to the array panels is 8m, allowing for unhindered storage of upper stages and future expansion of the hangar (see Fig. 5).

3.4. Habitation Module

The habitation module is an inflatable, based on the size of Bigelow's Sundancer module. The central cylinder has length of 8,8m and is 2,4m in diameter, the inflatable part of the module has a length of 6,5m and a diameter of 6,4m with a quadrant radius of 2m on either end. The various layers of the inflatable combine to a total thickness of 50 cm, so the inner volume of the inflatable segment is 5,5m in height, 5,4m in diameter and a has quadrant radius of 1,5 m on either end. Coupled with the emerging parts of the cylinder the total pressurized volume of this module is approximately 115m³. The module is attached to the aft of the station in a horizontal orientation. The module description is in a local vertical orientation, top representing the aft part and bottom the forward part.

In the center of the module is the safe haven, with an inner diameter of 2,1m and a height of 2,2m, it is surrounded by 15cm thick walls incorporating a lead protection layer and water containers, to achieve high radiation protection. It can house 4 astronauts, provides emergency supplies for up to 10 days and is equipped with ship control panels and communication displays. It is accessed by either a top or bottom hatch with a diameter of 90cm. Revolving around the haven vertically is a 1,2m wide and 1,5m high corridor (see Fig. 10). It grants quick access to all of the module's areas and additionally can be used for sport and game activities. Horizontally the haven is to ¾ encompassed by the storage area 2,4m in height, housing up to 60 crates of 60cmx60cmx60cm arranged on the inflatable walls leaving a 90cm aisle between the crates and the

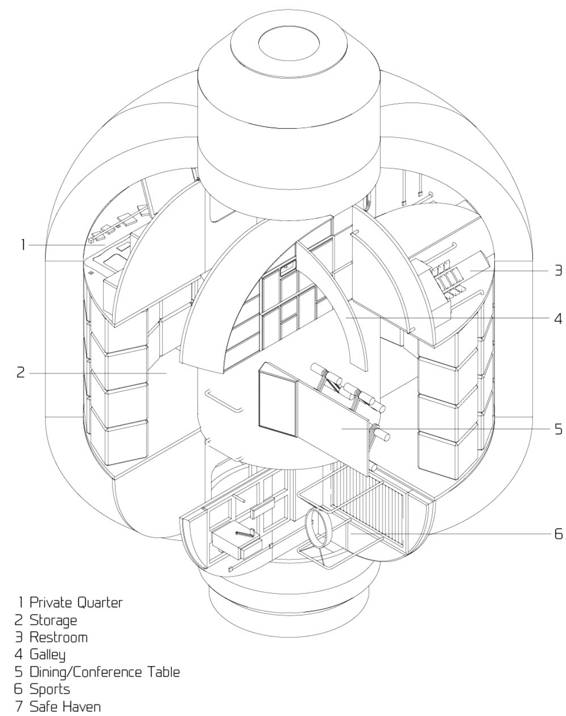

Fig. 8 Habitation module components

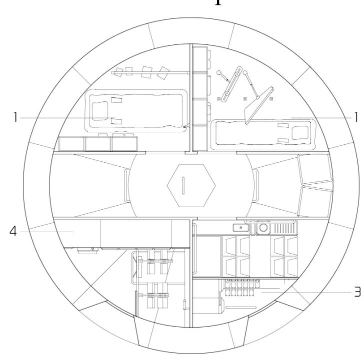

Fig. 9 Habitation module plan top level

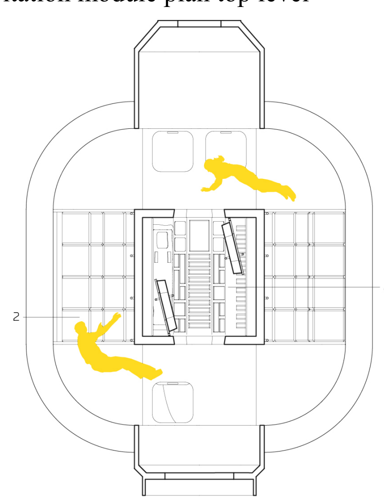

Fig. 10 Habitation module section

haven. The remaining quarter is utilized for a generous dining and conference table that can seat four astronauts and opens up the corridor to the sports, leisure and dining area (see Fig. 8).

The top part of the module is separated into four sections, two enclosed private quarters, an enclosed hygiene area including the restroom and finally a galley which opens up towards the dining table section (see Fig. 9). The width of these sections is 2m, the length 2,6m and the height 1,5m, capped by the spherical shell of the inflatable, resulting in a total volume of 4,1m³ each. The bottom part houses an enclosed waste storage with 8,2m³ volume, an enclosed room for life support systems and the sports area containing a treadmill and a bicycle, open towards the dining section with 4,1m³ each (see Fig. 8). The galley, the restroom and the sports area each feature a 40cmx 30cm window; the dining section features a 40cmx 90cm one. Since this part of the module is always oriented towards nadir, the astronauts are presented with unhindered views of Earth. The restroom is accessible without being seen by the other astronauts and the private quarters are in the located in the hindmost part of the space station, separated from the restroom by a total three wall elements and far from the hangar and the life support systems with the highest noise potential.

The private quarters are designed in such a way, that rearrangement of the furniture and components is encouraged. The rooms feature a grid of fixation points in 50cm spacing that can be mounted with different elements like: lamps, a table, a sleeping bag, storage crates and elastic bands (see Fig. 11). A lot of past astronauts expressed the wish to be able to customize their private quarters [20]. Every person has different preferences, besides it is helpful to break monotony on a 6 - 12month mission.

All the spaces have been designed and arranged based on the minimum required dimensions and criteria for the specific activities presented in Adams' paper on habitability and Heuplik-Meusburger's guide book for space architecture [18,20].

3.5. Escape Options

The configuration of the station guarantees escape routes from anywhere on the station, no matter where an incident occurs or what sections are made inaccessible. The forward part of the habitation module is connected to the six way node, where an escape vehicle is docked at all times, the ATV is docked at the aft part of the habitation module. The work module is connected to the six way node and additionally poses an escape option through the airlock attached to its forward part (see Fig. 5).

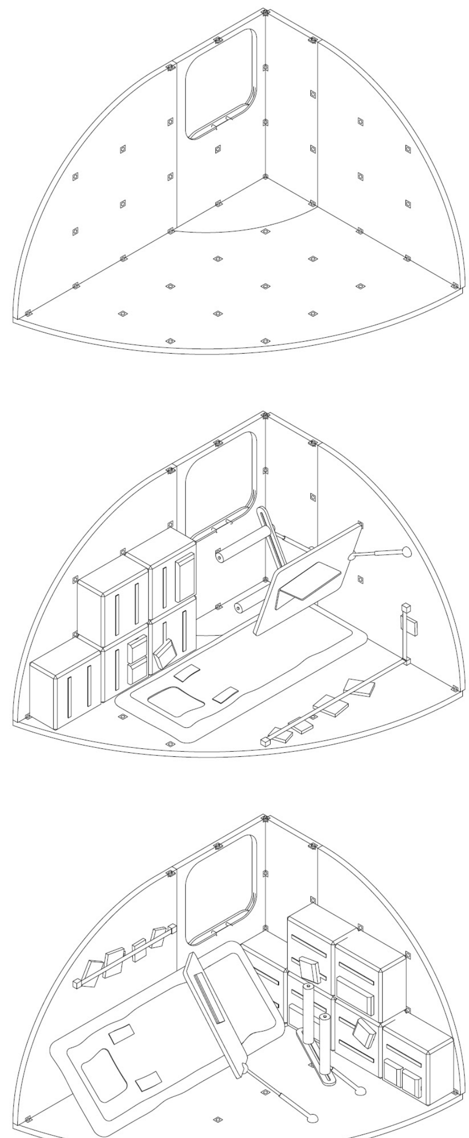

Fig. 11 Private quarter variability

3.6. Assembly Steps

1. The 6 way node with an attached pressurized mating adapter (PMA) is launched, the modified ATV with an RA rendezvous and connects with it.
2. The habitation module and work module, with the attached cupola are launched and connected with ATV's RA to the 6 way node, subsequently the airlock and the first large solar panels and a radiator are launched and attached, the first crew arrives and deploys ARCHINAUT robots to start assembling the truss framework.
3. The rotators for the parabolic mirrors are printed and assembled, the station receives

continuous material deliveries through the 6 way node, RAs are deployed to the existing truss framework, further solar panels and radiators are attached and the hangar truss framework construction is initiated.

4. The first parabolic mirror segments are placed, the solar panels and radiators relocated and further ones are added beside them. The sealing of the hangar is initiated.
5. The last parabolic mirror parts, solar panels and radiators are attached, the furnaces and pipeline system are installed. The station is operational.
6. Possible expansion with additional hangars, work and habitation modules to enable satellite processing, spacecraft assembly or rocket body to module conversion.

4. Conclusion

Parameters for a mission to capture and recycle spent rocket stages were defined and subsequently worked with to develop the design proposal for the ORDER space station. The main goals were to minimize the risk of an overpopulated LEO debris environment whilst seeing the debris as a resource, to define a feasible recycling process, to propose applications for the salvaged material and to conceive a habitable and economical architectural configuration that is able to accomplish this task.

Admittedly, the cost of developing, assembling and operating a single station would most likely outweigh the financial benefits gained from being able to use the processed debris as a resource at first. However, it can be argued, that through constantly refining the capture methods, the recycling process and the additive manufacturing machinery, their efficiency will be increased and their maintenance costs reduced. Combined with the possibility of self sustained expansion or construction of second generation stations, enabling the processing of larger quantities, can make debris an affordable and economically viable resource in the long run.

Acronyms/Abbreviations

ADR	Active Debris Removal
AMF	Additive Manufacturing Facility
ATV	Automated Transfer Vehicle
CBM	Common Berthing Mechanism
EDT	Electrodynamic Tether
ERA	European Robotic Arm
ESA	European Space Agency
EVA	Extra Vehicular Activity
FY-1C	Fengyun-1C
GEO	Geostationary Orbit
HTV	H-II Transfer Vehicle
IADC	Inter-Agency Space Debris Coordination Committee
IBS	Ion Beam Shepherd
ISS	International Space Station
JERMS	Japanese Experimental Remote Manipulating System
LEGEND	A LEO-to-GEO Environment Debris Model
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MSS	Mobile Servicing System
NASA	National Aeronautics and Space Administration
ORDER	Space Station for Orbital Debris Recycling
PMA	Pressurized Mating Adapter
PMD	Postmission Disposal
RA	Robotic Arm
SSN	US Space Surveillance Network
TDK	Thruster Deorbiting Kit
TRL	Technology Readiness Level

References

[1] Union of Concerned Scientists, UCS Satellite Database, 10 August 2018, https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database, (accessed 25.08.2018)
[2] NASA, Orbital Debris Quarterly News, May 2018, https://www.orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/odqnv22i2.pdf, (accessed 25.08.2018)
[3] ESA, Space debris by the numbers, January 2018, https://www.esa.int/Our_Activities/Operations/Space_Debris/Space_debris_by_the_numbers, (accessed 10.09.18)
[4] J.-C. Liou, An active debris removal parametric study for LEO environment remediation, ASR 47 (2011) 1865-1876
[5] C. Bonnal, J.-M. Ruault, M.-C. Desjean, Active debris removal: Recent progress and current trends, Acta Astronautica 85 (2013) 51-60

[6] D.J. Kessler, B.G. Cour-Palais, Collision frequency of artificial Satellites: The creation of a debris belt, JGR 83-A6 (1978), 2637-2646
[7] Inter-Agency Space Debris Coordination Comitee, IADC Space Debris Mitigation Guidelines, IADC-02-01, 2007, accessible at https://www.iadc-online.org, (accessed 10.09.18)
[8] J.-C. Liou, Collision activities in the future orbital debris environment, ARS 38 (2006) 2102-1206
[9] J.-C. Liou, N.L. Johnson, A sensitive study of the effectiveness of active debris removal in LEO, Acta Astronautica 64 (2009) 236-243
[10] J.-C. Liou, N.L. Johnson, N.M. Hill, Controlling the growth of future LEO debris populations with active debris removal, Acta Astronautica 66 (2010) 648-653
[11] A.E. White, H.G. Lewis, The many futures of active debris removal, Acta Astronautica 95 (2014) 189-197
[12] L. Anselmo, C. Pardini, Ranking upper stages in Earth orbit for active removal, Acta Astronautica 122 (2016) 19-27.
[13] N. van der Pas, J. Lousada, C. Terhes, M. Bernabeu, W. Bauer, Target selection and comparison of mission design for space debris removal by DLR's advanced study group, Acta Astronautica 102 (2014) 241-248
[14] Space Launch Report, Kosmos 3M, October 2005, http://www.spacelaunchreport.com/kosmos.html, (accessed 12.08.18)
[15] Space Launch Report, Zenit Data Sheet, December 2017, http://www.spacelaunchreport.com/zenit.html, (accessed 12.08.18)
[16] H. Hakima, M.R. Emami, Assessment of active methods for removal of LEO debris, Acta Astronautica 144 (1018) 225-243
[17] Space X, Falcon 9 Launch Vehicle – Payload User's Guide, October 2015, https://www.spacex.com/sites/spacex/files/falcon_9_users_guide_rev_2.0.pdf ,(accessed 25.08.2018)
[18] C.M. Adams, M.R. McCurdy, Habitability as a tier one criterion in advanced space vehicle design: Part one-habitability, SAE technical paper 1999-01-2137, 29th International Conference on Environmental Systems, Denver, Colorado, 1999, 12-15 July
[19] S.C. Patané, E.R. Joyce, M.P. Snyder, P. Shestople, Archinaut: In-Space Manufacturing and Assembly for Next-Generation Space Habitats, AIAA 2017-5227, AIAA Space Forum, 2017, 12-14 September
[20] S. Häuplik-Meusburger, Architecture for Astronauts, Springer, Vienna, 2011