Economic Approach for Active Space Debris Removal Services

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Abstract

The space environment is getting more and more populated with first collisions of satellites already happening. This paper presents a technical implementation of a modular system for active space debris removal, which can be implemented gradually and flexible, adaptable to mission needs or future technologies developed. The flexible approach to remove empty upper stages or satellites no longer in operation considers a dual-robotic arm concept to manage the rendezvous with these non-cooperative targets. The concept foresees attaching de-orbit devices to debris elements, based on either chemical propellants or electromagnetic tethers. While these de-orbit devices will burn up with each object being removed, the removal satellite core is maintained and used for additional de-orbit missions.

Besides an efficient technical implementation, special focus is paid to the commercial assessment of such space debris removal service. For this purpose, the constraints as well as the opportunities for an economically viable implementation are presented and discussed, showing that the increasing awareness of the space debris problem bears the chance for a commercially viable business case.

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1 Nomenclature

ADR	Active Space Debris Removal
AOCS	Attitude and Orbit Control System
DEOS	Deutsche Orbitale Servicing Mission
EDT	Electro-Dynamic Tether
LEO	Low Earth Orbit
OOS	On-Orbit Servicing [1]
PDGF	Power Data Grabble Fixture
SSO	Sun-Synchronous Orbit
TDK	Thruster Device Kit
TRL	Technology Readiness Level

2 The Space Debris Problem

Since the dawn of the space age, each space mission has left debris in the Earth's orbit. Initially this debris was thought to be insignificant when contrasted against the vastness of space itself. However, debris left in orbit will remain for decades and more missions will be launched. Collisions with debris are on the rise and today the leading researchers predict that orbital debris, if left unchecked, will render space inaccessible in the near future [2]. This conclusion is unavoidable even if all future launches were to be halted completely.

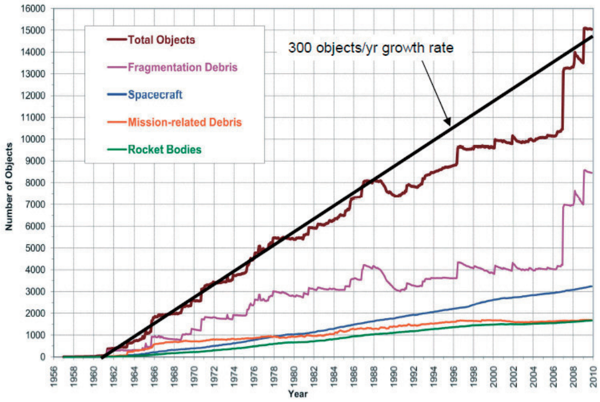

Figure 1: History of orbital debris population and annual growth rate [3]

International agreements on passive, mitigation strategies have been adopted and implemented. However recent events such as the Iridium Cosmos collision and the Chinese anti satellite weapon test have highlighted the need to do more. These two events are clearly visible in the past increase of orbital debris (Figure 1).

The only means to reduce the hazard is by removing debris mass from orbit. The objective here is to reduce the rate of debris generation and slow or reverse this gradual cascaded Kessler effect that is currently underway. Although the greatest threat comes from the smaller particles, the principle sources for these particles are the large debris objects. Impacts with the large debris are more likely and these impacts liberate more small particles. Various authors [2] have identified these large debris objects as the key to a long term reduction of the debris threat. Simulations show that already with active space debris removal of 5 large objects per year the expected future collisions can be significantly reduced (see Figure 2).

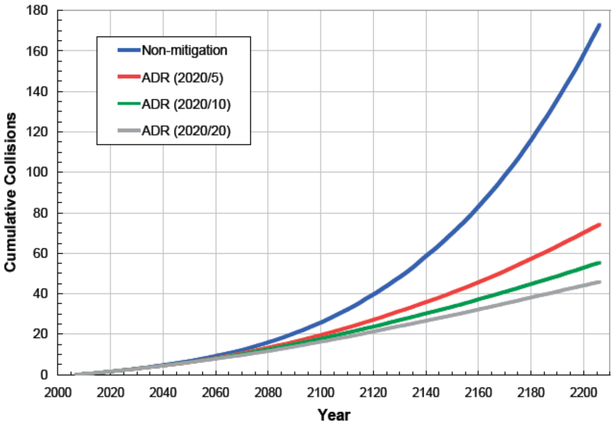

Figure 2: Impact of active debris removal (ADR) on future collision probability [4][1]

Any study of the current database of objects in orbit will reveal the fact that the material is clustered around several key orbits. While this exacerbates the threat, it simplifies the removal strategy. Removal of the largest objects from the most economically attractive orbits will have the greatest impact. These orbits have been identified in several studies [2], furthermore substantiated through a questionnaire sent out and evaluated during these study activities. They are considered as the primary orbits of interest for active debris removal activities.

Table 1: Primary orbits of interest

Orbit Altitude [km]	Inclination [deg]
1000 ± 100	82° ± 1°
800 ± 100	99° ± 1°
850 ± 100	71° ± 1°

These low earth orbits (LEO) have subsequently been used for the re-orbit system requirements definition for the considered debris re-orbit mission. The primary orbit of interest is the sun synchronous orbit (SSO) with an inclination of 99º. This is a relatively accessible circular orbit with a moderate orbital energy requirement. It is also one of the most threatened and active orbits. As a preliminary design driver the largest objects in this orbit were selected and assessed.

3 Technical Concept

The proposed technique is characterized by a 3 axis stabilized satellite as orbiting platform (servicer satellite) equipped with several de-orbiting devices. The servicer has the capability to maneuver and approach the selected debris, is able to capture, stabilize and de-orbit a single space debris object using one of these de-orbit devices per debris object.

The major drawback when removing several objects per year and per satellite is the delta-v needs when roving from one target to the next one. This consideration and the cost saving aspects required for an economically viable business case led to a concept with the basic principle of resupplying the space segment with propellant and de-orbiting devices. The resupply approach implies a modular design of the space segment. Refueling operation and a propellant depot is abandoned, due to the complexity and the long-term storage problems of propellant in space; instead the entire propulsion module will be substituted.

3.1 Modular Design

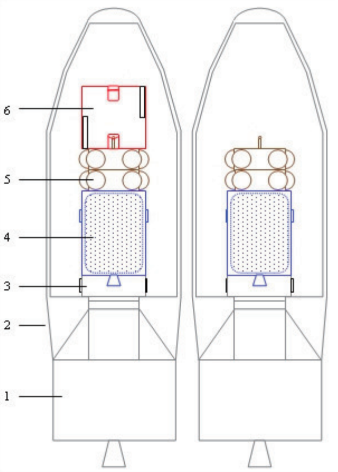

Figure 3: Space segment elements: initial set-up configuration (left), resupply configuration (right)

1 – Launcher upper stage
2 – Fairing
3 – Payload adapter of upper stage
4 – Filled propulsion unit, incl. AOCS thrusters
5 – Loaded payload module with PDGF
6 – Central unit

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[1] E.g. ADR(2020/5) corresponds to Active Debris Removal of 5 large objects per year, starting in 2020

The space segment consists of three modules; the propulsion unit, the payload module, and the central unit (Figure 3).

The central unit houses the platform including the AOCS subsystem, the command and data handling unit, power subsystem, the two end-effectors, and the payload with the two robot arms and visioning system. The length of the edge is 1.5 meters (1.5 x 1.5 x 1.5 m^3).

The payload module consists of an adapter ring, the power data grapple fixture (PDGF), and the de-orbit kits. The diameter is 1.7 m with a width of 1 m, using two de-orbit segments with five chemical thruster de-orbit kits (TDK) or alternatively 8 electro-dynamic tether (EDT) de-orbit devices in each module.

The propulsion module includes the propellant to move from one target to the next, either with electrical (e.g. Xenon), or chemical propulsion (e.g. bi-propellant). Furthermore it contains the propellant for AOCS maneuvers (mono-propellant) and the corresponding thruster system, as well as body mounted solar panels.

If control moment gyroscopes are used, they shall be accommodated in the base-station module. Both locations providing a sufficient lever arm. The total dimensions are 1.5 x 1.5 x 2 meters equal to 5 cubic meters.

To de-orbit the empty propulsion module as well as the empty payload module, the upper stage can be utilized. The upper stage must contain sufficient remaining propellant to de-orbit it self as well as the attached modules no longer used by the debris removal system.

The overall dimensions of the space segment are 1.5 x 1.5 x 4.5 m^3 without nozzle extension and the payload adapter of the upper stage. The fully loaded payload module increases the base diameter to around 2 m. The servicer has a wet mass of approximately 2.2 metric tons whereas 1.5 tons are dedicated to the TDK or EDT de-orbit devices. The central unit inclusive propellant (bi-propellant, I_{sp} 313 s) has a mass of 700 kg.

3.2 De-orbit Device Technologies

The most promising space debris removal technique is an electro-dynamic tether (EDT). Today's technology readiness level (TRL) of EDT is in the order of 4 and not sufficient to design a technically feasible end-to-end system within the next few years. An available alternative is based on a solution with chemical thrusters for the de-orbit devices. It shall be noted that the use of TDK is preferred to the EDT only because of their high TRL. As soon as the EDT dynamic control is successfully demonstrated it will substitute the TDK, mainly because of the 2-3 times higher mass factor; the volume ratio is even higher. To attach the de-orbit kit robotic arms form part of the space segment. The modular concept allows implementing different debris removal systems, and is not exclusively designed for either TDK or EDT. The same applies for the propulsion system, which will be replaced as a whole once the available propellant is used.

3.3 Robotic Arm

The robot arm captures and stabilizes the target, visualize the final docking with its own camera, attaches the de-orbit devices, and supports the resupply process. The robot arm grasps the target in 'slack mode' then progressive stiffening the joint and blocking all degrees of freedom. Two arms are recommended as the potential targets do not necessarily provide adequate docking ports e.g. a nozzle, so that one robot arm stiffens the compound, while the second arm grasps the de-orbit device and attaches it to the target. The arms are mounted on the front and rear end, providing maximum operating distance. The robot arms can be folded and stowed during launch and while roving to a target (Figure 13). The robot arm is equipped with a camera, which can be used to visualize the capture process and the de-orbit device installation.

DLR's Institute of Robotics and Mechatronics has developed a state-of-the-art lightweight robotic arm, derived from the space qualified ROKVISS technology, in use on the ISS. The robotic arm (Figure 4) is designed for the first German orbital servicing mission DEOS, and fulfils all requirements of the system proposed in this paper. It characteristics are given in Table 2.

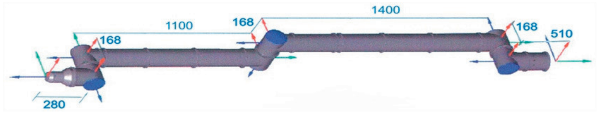

Figure 4: DLR's robot arm based on space qualified ROKVISS technology (Credit DLR)

Table 2: DEOS Robotic Arm

Item	Dimension
Mass	45 kg
Length	3.2 m
Diameter	12 cm
Volume in launch configuration	20 x 20 x 190 cm^3
Degree of Freedom (DOF)	7
Power:	
Average	60-70 W
Peak	120 W
Per joint	7 W
Torque:	
Joint	120 Nm
Gripper	10 Nm

4 Mission Operations

4.1 Concept of Mission Operations

The Warehouse architecture is composed of the following major mission phases:

(1) Initially the satellite (also called servicer) will be launched into the orbit of interest. The direct injection avoids fuel and time costly maneuvers of the servicer.

(2) The system uses ground-based tracking to determine the location of the medium-sized space debris object (an inactive satellite or spent rocket stage). These data are uploaded to the servicer, which automatically proceeds from his parking position to the debris at around 1 km distance. The drift takes 1-20 days assuming out of sight / out of contact, and 1-5 days for in sight / in contact. The proximity operation from 1 km to 100 m is achieved within 1-5 orbits [5].

(3) The close range rendezvous from the safe point (100 m), where the debris will be identified, to a close hold point (10 m) is user controlled. It will last 45 to 90 minutes. The capture process inclusive mating can be accomplished in up to 15 minutes, meaning that a telecommunication link of two successive ground stations for approximately seven minutes each has to be secured. Alternatively a tracking and data relays satellite could be used providing around 40 minutes contact time.

(4) The front robotic arm grasps the target and slowly reduces the remaining relative motion between servicer and target. Once the servicer controls the compound, the rear robotic arm will attach a de-orbit kit, while the first still holds the target (Figure 5).

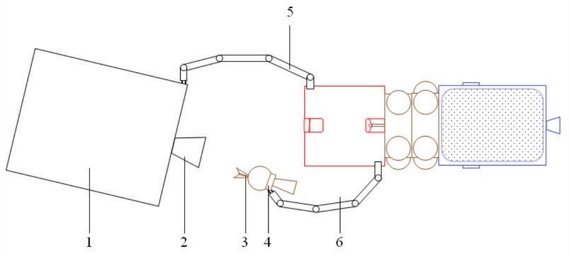

Figure 5: Debris capture and TDK de-orbit device installation for rocket bodies

1 – Debris, e.g. spent rocket stage
2 – Nozzle extension
3 – Expanding umbrella
4 – Thruster Device Kit (TDK)
5 – Front robot arm
6 – Rear robot arm

(5) After the installation and re-orientation of the debris for de-orbiting, the servicer disengages from the debris and moves to a safe point (300 m) from which the de-orbit sequence is initiated remotely.

(6) The debris with the attached de-orbit device will lower its perigee with high aerodynamic drag, finally enter the atmosphere and burn-up. An optional destruct charge combined with a telecommand receiver would allow disintegrating larger objects before entering the atmosphere.

(7) The servicer moves to the next target when the mission is accomplished. The target selection is based on a mission planning, which allows re-supplying TDK's tailored to the specific target mass. This allows optimization of launch mass of the re-supply module.

(8) Once all attached de-orbit devices are spent, the servicer returns for its periodic re-supply. The re-supply vehicle, typically an upper stage, is advantageous launched in the vicinity of the current servicer position.

(9) The re-supply maneuver is a standard docking process with a cooperative target. The upper stage with the empty container for the modules will de-orbit itself avoiding pollution of the space environment.

4.2 Debris Capturing and De-orbit Sequence

The front robotic arm captures the debris, while the rear arm supports the process utilizing his camera for monitoring.

4.2.1 TDK De-orbit Device

Once the debris is captured and the composite is stabilized, the rear robotic arm picks a TDK and installs it into the nozzle extension of the spent rocket stage (Figure 4). The expandable umbrella (or fast curing foam) blocks itself into the combustion chamber. After attaching the TDK, the second arm also grasps the empty rocket stage, re-orientates it for de-orbit, and spinning-up the composite minimizing thrust misalignment effects. Finally the servicer releases the debris and escapes to a safe position. The ignition of the TDK is activated using a time-delayed ignition system, or alternatively via Wi-Fi communication between servicer and TDK.

4.2.2 EDT De-orbit Device

Different to the TDK, where a careful insertion of the thruster device is required to control the thrust vector, the mounting of an EDT is less critical and easier. The forces initiating the de-orbit are through the interaction of the tether with the magnetic field of the earth, independent of the exact orientation of the tether at the beginning of the maneuver.

The EDT can be mounted in principle on any suitable point of the debris object. The remaining sequence is again the same as for TDK: The satellite will release the debris object, retract, while the tether will be deployed and the continuous de-orbit initiated.

4.3 Re-supply

4.3.1 The Power Data Grapple Fixture

The key of the modularity and connection between the modules is the so called grapple fixture. It is attached to the bus of the payload module and interacts with the base-station. The power data grapple fixture (PDGF) consists of a foot-long metal pin, a base plate and a target (Figure 6). The end of the end-effector has three snare wires which wrap around the grapple fixture using small motors. The wires are then retracted, and the servicer is pulled snugly against the end of the resupplying vehicle (Figure 7). Grapple fixtures have an electrical connector on the end of the pin, which can join with an electrical adaptor (called a 'special purpose end-effector'). This allows electrical power and data communications to move from the central unit to the propulsion module when it is grappled.

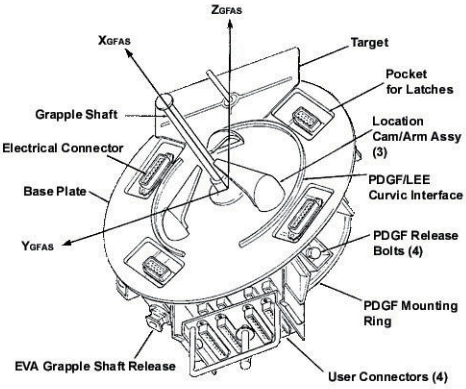

Figure 6: Power data grapple fixture (Credit NASA)

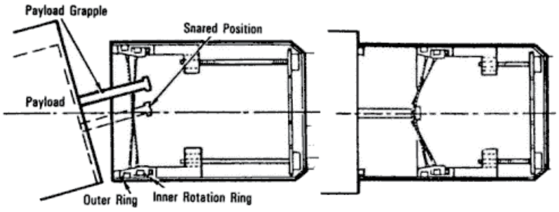

Figure 7: End effector open (left) and closed (right) (Credit NASA)

4.3.2 The In-orbit Re-supply Sequence

The final approach with the resupply segment is quite similar to capture space debris, such as a spent rocket stage. The difference is that it is a cooperative target with reflectors, distance markers, handholds for grasping and the AOCS control of the upper stage. The phasing process is the first step, which aligns the attitude of both systems, supporting the docking process. In a second step the front robotic arm grasps a handhold of the propulsion module from the resupply segment (Figure 8). The second, rear located arm visualizes the process with its near-range camera. Finally the grapple fixture and the end-effector engage and mate. The compound now can separate from B, perform a 180 degree turn and dock to B with C (the empty propulsion unit). Another possibility is that the front robotic arm grasps the handhold on the payload adapter, keeps it fixed, and turns the compound as described above. This requires an arm sufficient in length, or a mast from the payload adapter. Finally the new resupplied satellite separates at D and moves to its next target. The upper stage now equipped with the empty container of the de-orbit modules is ready for de-orbiting. The process described above requires user operated interaction.

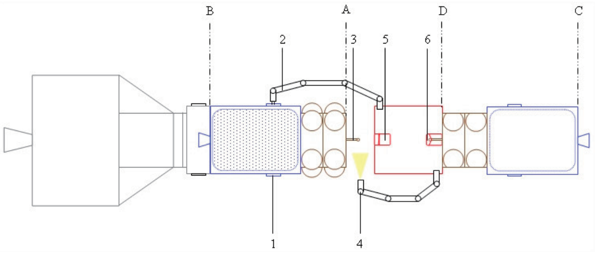

Figure 8: Resupply operation

1 – Handhold, to support grasping
2 – Front robot arm, grasping resupply segment
3 – Grapple fixture
4 – Rear robot arm, visualizing ARD&C
5 – End-effector (open)
6 – End-effector (closed)

A – First mating plane
B – First separation plane
C – Second mating plane
D – Second separation plane

5 Commercial Scenario

5.1 Revenue Mechanisms

Removal of space debris per se does not provide added value in terms of commercial business to a satellite or launcher operator yet. As such it is difficult to identify a direct relationship between debris removal and individual commercial aspects of a satellite operator. Moreover, the added value is mainly given by the reduction of collision risk and thus provides benefit to anyone operating in the corresponding orbital regime, being it already operational or newly deployed spacecraft.

Although there are already international guidelines and recommendation for end-of-live disposal of satellites and used upper stages in place, these don't have binding character if seen from the legal perspective. Nevertheless there are trends observable indicating that more and more spacecraft operators are trying to implement these guidelines, but this affects only the future and does not resolve the problem of the already existing debris elements in space.

Consequently it requires the public sector to stimulate initially also activities, which are not limited to a global space surveillance network acquiring the current status of the space debris environment, but also to support the active removal of space debris financially.

5.1.1 Levy on Launches

It is considered that raising a levy on each additional object to be deployed in space is the only short term viable opportunity providing an incentive for maintaining the unique environment of space usable in the medium and long term future. The basic principle considered in this assessment is that international governments and organizations will agree and set-up this specific space debris removal fund. The corresponding levy is expected to be raised at launch through the launch service provider, who in term could request a refund from the satellite operator. This fee will be paid then into the international fund with the option to be refunded once the satellite operator or the launch service provider has demonstrated that they are removing the objects from space after their decommissioning. As there are currently no commercial incentives demonstrated with this approach, it requires that this scheme is implemented in a regulatory environment and cannot be built on a voluntary basis.

5.1.2 Debris Removal Fee

Complementary funding is considered through the direct service provision based on a fixed removal fee per piece of debris. This fee is expected from the direct customers, being it governmental organizations or private satellite operators.

5.2 Deployment Scenario

The mission design considers elements with technology which is already available and proven in past missions. Therefore the development and manufacturing process can be initiated soon with an assumed begin in 2011, leading to a projected launch date end 2016.

The deployment of the space segment elements is implemented following a gradual increase of elements and corresponding removal capabilities. After the first element produced and deployed in orbit, the series production of the elements will occur considering lessons learned from early operations of the first unit (Figure 9).

This deployment schedule is characterized by the interest to ensure besides a gradual increase of service capability a constant workload to the spacecraft manufacturer with a launch every second year. Assuming a corresponding production cycle this will allow the manufacturer to maintain a stable basis of experienced workforce without disruption or peaks leading to a cost-effective production and high quality standards..

The procurement of the corresponding re-supply modules and the de-orbit devices is consequently driven by the satellites in orbit and the mission expectations of 5 space debris removals per year and satellite.

5.3 Cost Assessment

5.3.1 Investments (CAPEX)

The major investments required are mainly for the space segment elements. For both types of de-orbit devices there are no launch cost, as they are part of the complete re-supply compound and thus the corresponding launch cost covered there. While the satellite is considered to be covered by insurance, the other elements are relatively simple devices and the risk for those elements not being covered by insurance is acceptable.

Concerning the Ground Segment elements of the mission scenario, it is considered not to develop dedicated facilities, but to put a leasing agreement in place, covering the required TT&C ground station elements and the control center. This is justified by the fact that most of the mission phases are routine operations. The exception is the rendezvous and docking phase, for which dedicated ground equipment will be developed, but still hosted in the control center. Consequently only limited development and production investments are required, while the majority of the ground segment costs are part of the OPEX budget.

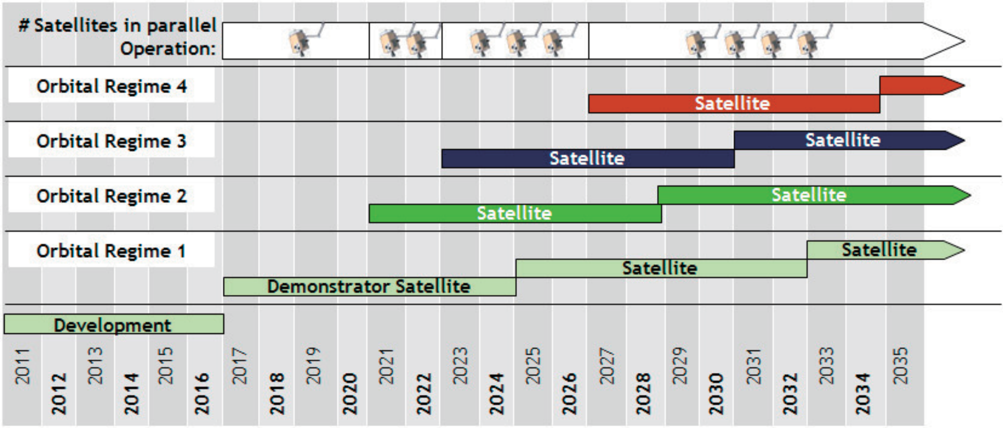

Figure 9: Mission deployment schedule over projection period

Table 3: Recurrent CAPEX elements of the system (all values in [US$ M])

Element	1st Unit (total)	Add. Units (total)	Launch (total)	Insurance (total)
Satellite	59.5	395.6	382.4	113.8
Re-supply	13.9	323.7	1693.1	–
TDK	0.9	35.8	–	–
EDT	5	256.8	–	–

5.3.2 Operational Expenses (OPEX)

The operational expenses are mainly driven by the needs of the operational phase, being it the lease cost of facilities (Control Center, TT&C stations), which includes the routine operations staff as integral element. The other major contribution to OPEX elements are the staff members required for running the business for the provision of the end-to-end removal service.

5.3.3 Cost of Goods Sold (COGS)

The business case does not only consider providing the end-to-end debris removal service, but also to bring the qualified space elements (satellite, re-supply module, de-orbit devices) on a limited market to allow customers perform the corresponding operation under their own control. These cost items are related to the procurement of these elements by the corresponding manufacturer.

6 Business Set-up

The analysis as described in this paper assume a special-purpose company to be setup providing an end-to-end space debris removal service dealing with all activities related to customer interaction, legal, regulatory and insurance issues with the removal a specific piece of space debris from orbit.

6.1 Phased Business Approach

In order to set-up this business in an economic way, a phased approach in building up the commercial and technical solutions is considered. This process is divided into the following major phases, each of them further broken down as described in the following corresponding sections:

- Development & Production phase
- Proof-of-Concept phase
- Operations Phase

6.1.1 Development & Production Phase (2011 – 2016)

The development phase is characterized by the conceptual fine-tuning, the design and technical development of the mission and the technical system. It is considered unlikely to convince in this early phase private commercial operators to agree on a multi-year contractual relation ensuring basic operation guarantees with the projected 5 debris removals per year. This is due to the fact on the one hand side that a single operator does not own sufficient debris elements (satellites or rocket bodies) in the primary orbital region if interest, on the other hand because the commercial incentive to remove already existing debris elements is quite low.

Consequently a major international organization or an individual government or agency is considered to be the appropriate partner as major launch customer. To secure the early operational capabilities, it is required to establish a service level agreement between the company and the flagship customer already in the development and production phase.

6.1.2 Proof-of-Concept Phase (2017 – 2020)

This phase provides the first revenues, composed by the access to the described Space Debris Removal Fund, but also by direct removal fees based on a per-object scheme through the launch customer.

Analysis considering the expenses for infrastructure procurement and operations including the administration required to manage all related legal, regulatory and contractual issues in relation to debris removal was performed. This led to the assumption of a price per debris removal mission in the order of 12 US$ M. Compared to cost and expensed required for a satellite mission (in average 500 US$ M per active earth observation satellite[2]) this is considered a competitive price, that will be in the later phases of the business attractive also to the commercial market.

With the demonstration of the technical feasibility of the system concept including the re-supply with propulsion module and de-orbit devices, the joint venture with the strategic partner is expected to be dissolved, transferring the whole operational and commercial risk to the special-purpose company. The satellite manufacturer will act from this point on as a traditional subcontractor for the provision of required space segment elements. Nevertheless he is still shareholder in the company through the equity contributions invested in the early phase with the corresponding financial perspectives.

After an initial operation of 2 years the first satellite of the serial production will be contracted to the satellite manufacturer, implementing lessons-learned through the initial demonstration phase.

6.1.3 Operations Phase (2021 onwards)

The launch of this satellite marks the end of the demonstration phase and the company will enter the commercial operations phase. This phase is dominated by the incremental setup of additional satellites in space

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[2] Euroconsult 2009

with a production rate of one satellite every two years. These satellites will be deployed in order to

- Replace satellites that have reached the end of their lifetime, and
- Deploy up to 4 satellites in parallel operation to increase the removal capabilities allowing a deeper market penetration

During this phase it is also expected to adjust the customer basis from one or more governmental organizations as the selected launch customer towards also commercial and institutional customers. This allows not only to ensure a customer diversification, but also to enter new markets and increasing the business.

The increasing revenues allow starting the repayments of the bank loans that were required in the design and development phase.

6.2 Corporate Financials

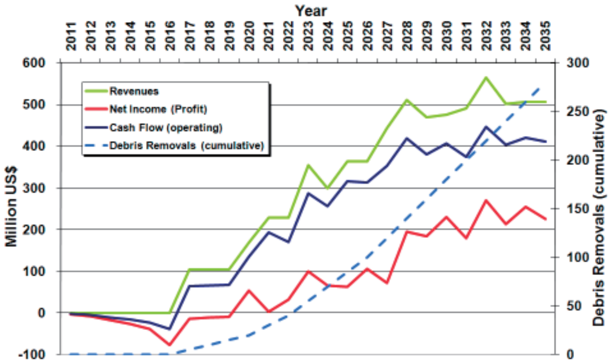

Figure 10: Key financial figures

Based on the gradual deployment of the infrastructure and the phased business implementation, the key financial figures are shown in Figure 10. Based on the described assessment of required funding, the corresponding financing plan and the early operations of the business the profitable region is achieved after 9 years of company operation. Considering that

- in the first two years of the company the financing need is considerable small with the first significant needs in 2013, and
- the initial equity required to be provided mainly through the partner of the joint venture with the long-term perspective of the company as customer with corresponding order intake,

this period of profitability is reduced to 7 years, making it attractive also to investors outside the space business.

In order evaluate against the primary mission objectives of space debris removal, the number of debris elements removed is shown on the right scale, cumulating up to 280 debris removals over the company projection period of 25 years, with the first removal and the corresponding revenue 6 years after start of company operations.

7 Conclusions

Active space debris removal is a challenge, both technically and commercially. The presented modular concept applies space robotics through two robotic arms. This flexible approach is based on existing technologies (chemical propellant based), but also can be tailored for future technologies like electro-dynamic tether devices to de-orbit large space debris elements.

The core satellite element can be adapted to various space applications involving robotics. Furthermore it is not limited to a single orbital regime, but is suited to operate in a wide variety of orbits to reduce the collision risk for active and passive satellites.

The analysis performed in the technical and business domain of this project demonstrated that under the presented assumptions active space debris removal could be set-up as a profitable business undertaking. The globally increasing awareness of the space debris problem will generate a new momentum supporting these given assumptions. The identified approach however does not rely on a fully public funded environment, but identifies realistic schemes for a commercial approach, that is based only partially on implementation of mechanisms in the regulated domain. The results achieved demonstrate that under the described realistic assumptions, active space debris removal can be setup as a commercial viable business. This business will not only achieve the initial objective of the protection of the unique space environment for the benefit on earth, but can also act as a precursor and incubator for future technology applications like on-orbit servicing (OOS) [1], based on the developed and demonstrated robotics capabilities.

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