DELFT UNIVERSITY OF TECHNOLOGY

FACULTY OF AEROSPACE ENGINEERING

AE3200

DESIGN SYNTHESIS EXERCISE

Space Sweeper Executive Summary

Creating Space in Space

Mission: Space Sweeper
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September 10, 2023

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Executive Summary

Relevance, Motivation and Mission

Today, an extensive portfolio of critical services are offered by spacecraft in the altitude bands at and above Low Earth Orbit (LEO). From global navigation satellite systems at 20,000 km altitude, over communication systems both at LEO and Geostationary Earth Orbit (GEO), to Earth observation and mapping, modern societies rely heavily on the access to information and capabilities of space systems. The increasing presence of space debris however threatens the access to space at and above LEO. Donald J. Kessler, a former NASA scientist, was the first to estimate the potential impact of the world's indifference towards the threat of space debris. He hypothesised that the exponential nature of the increase of the number of space debris pieces in low Earth orbit (LEO) would lead to a cascade of collisions that could render this orbital region close to useless, and called this hypothesis the Kessler Syndrome. The exponential trend can already be observed today (Figure 1). After decades of knowing how serious the possibility of this disaster is, a debris detecting and cleaning mission has yet to be flight tested - a sad and frankly embarrassing fact. Only one good thing comes from this, a brand new market to explore. Of course, this market will only generate revenue once our planet's governments turn existing space debris mitigation procedures into law. As things stand, the only thing to gain by cleaning space debris is a sense of sustainability, which is sadly not enough for almost any private business. The Space Sweeper project therefore aims to provide a detailed design of what could be the world's first space-based laser debris removal system, which can leap over the existing socioeconomic barriers and tackle the Kessler syndrome head on, as it is of utmost interest to this project team to convince the world that the space environment should be just as safeguarded as our own planet.

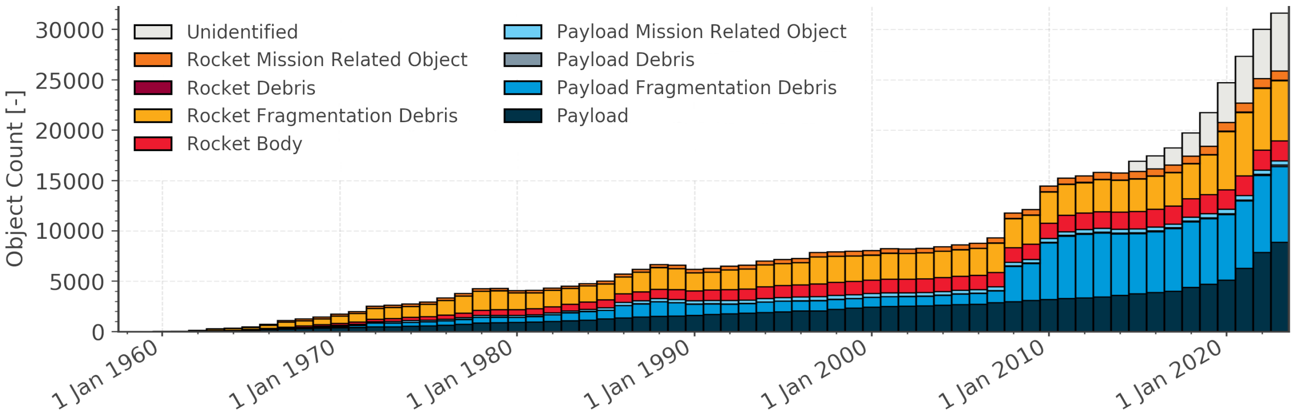

Figure 1: Space debris evolution until 2022 as per ESA Space Environment Report, Edition 6, released 20/04/2022.

Project Space Sweeper was conceived as a conscious effort towards preserving the space environment and access to it for generations to come. As a result, the mission need statement and the project objective statement, are the following:

Mission Need Statement

The continuous use of the orbital region up to 1,000 km altitude must be protected from the threat of space debris.

Project Objective Statement

DSE group 13 will design a modular system to sustainably clean up one to ten centimetre sized space-debris objects, arising from a break-up event, from orbital altitudes below 1,000 km, by 10 engineers in 10 weeks.

Space Sweeper and similar missions also face a complicating factor in development: The issue of accountability in small-size space debris objects. While virtually all entities that launch space systems generate space debris in one form or another, when it comes to small-size debris, it is not realistic to track the exact origin and responsible entity of each particular part. Often times it is even impossible to trace the owning party of a debris object that was generated in a collision of two space systems. This results in a situation where none of the institutions and business launching space systems feel responsible for small-size debris objects, and thereby do not plan on dedicating funds towards the removal of such debris. This creates a difficult situations for mission proposals like Space Sweeper, as space missions must yield economic return, or must be funded by institutions through explorative funding programmes. Next to the technical development, the Space Sweeper project has also put special emphasis on ensuring that the mission has avenues for funding, even when considering economic and political difficulties around space debris removal.

Space Sweeper - A partial solution to an all-encompassing problem

Technical System Overview

Space Sweeper is a large space platform facilitating the core payload systems: the laser system used for applying thrust to debris object by laser ablation propulsion, as well as the lidar system used for object detection, identification and tracking. For its size, this spacecraft features a very high electrical power generation and supply capability of approximately 27 kW at its peak, primarily to operate the ablation laser during its use, while also keeping other systems operational. This electrical power is generated using large solar arrays, and is partially stored using a modern battery pack. The heat generated by the consumption of this amount of power is controlled and dissipated using a special thermal management system employing advanced heat pipes and radiator materials. Manoeuvring of the Space Sweeper system is done using small sized chemical thrusters, under guidance of a GPS-assisted Guidance, Navigation and Control (GNC) system. Accurate attitude control is also provided by the GNC system through a large set of Control Moment Gyroscopes, in addition to magnetic torquers for desaturation, as well as gyroscopes and star sensors for fine attitude determinations. Operational data, including positions and trajectories of detected debris objects, is gathered by the Command and Data Handling System and then transmitted to the ground station by a redudant system of low-gain patch antennas. All subsystems are integrated into the spacecraft bus along with a cylindrical aluminium load-bearing structure necessary to withstand the harsh launch environment. The full spacecraft structure is shown as part of Figure 2.

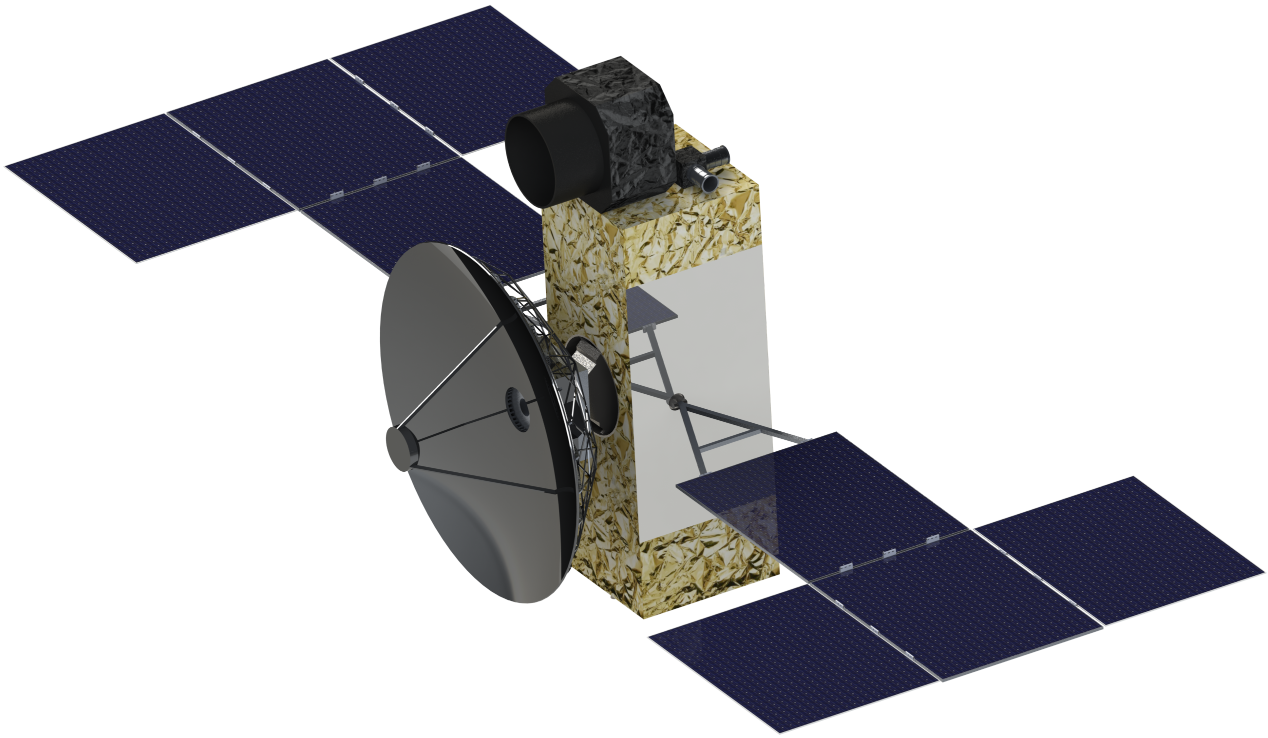

Figure 2: Isometric view of the external layout of the Space Sweeper, showing the bus with Multi-Layer Insulation, solar arrays, the radiator panels, as well as the primary payload components in the ablation laser (left) and the lidar system (top).

Payload

An ablation laser and lidar detection laser are selected as the payload. The combination of these two systems allows for removal operations up to 250 km, and detection up to 300 km. The ablation laser is an Nd:YAG laser, operating at 532 nm. The average power while ablating and mass requirements are 27.7 kW and 1282 kg respectively. The payload is equipped to de-orbit debris with an area-to-mass ratio of 0.0795 kg/m^2, which is found to be the limiting factor for debris removal capabilities rather than characteristic length, as suggested in literature. The lidar system operates at an average power of 243 W and has a mass of 286 kg.

Guidance, Navigation and Control System

The Guidance, Navigation and Control System allows the spacecraft to determine its position required for all orbital manoeuvres by using PODRIX GNSS GPS with precision of 11 cm. Furthermore, its sensors allow the spacecraft to determines its attitude, which has direct impact on the determined accuracy of debris cataloguing. This sensor package consists of two ASTROXP star sensors and 6 gyroscopes inside ASTROgyro, which complement each others performance and allow to achieve accuracy of 0.5 arcsec. Additional PODRIX GNSS GPS sensors are provided to course attitude determination for redundancy during anomalies. The actuators of the spacecraft, 75-75S Control Moment Gyroscopes, are able to provide large torque of 62 Nm to stabilise the spacecraft when laser gimbal is rotated. Finally, large magnetic torquers MT-800B-28V with dipole moment of 800 Am^2 need to be used to dump momentum from external disturbances.

Electrical Power System

By means of a solar array, a set of Li-Ion batteries, an appropriate PCDU, and a set of LI-Ion capacitors to power the laser, the required power at all times can be ensured for each of the components. Even when the system has to ablate 243 particles per day, the capacitors are charged and discharged fast enough for an effective mission. In addition, the subsystem is modular, being able to change the solar array area and the number of capacitors for three different altitudes: 500 km, 750 km, and 1000 km. The maximum total mass of the subsystem was found to be 166 kg, with a solar array area of 35 m^2.

Propulsion System

Following a top-level trade-off between cold gas, liquid monopropellant, liquid bi-propellant, and electric propulsion, and using required propellant mass, volume, power, and complexity as criteria, the liquid monopropellant concept is chosen to be designed in more detail by means of three separate trade-offs. The winners of these three trade-offs for thruster, propellant tank, and pressurant tank are: one MONARC-90HT thruster, four PTD-96 propellant tanks, and one 80586-1 pressurant tank. This configuration results in a total dry mass of 49.6 kg, and a total wet mass of 401 kg. The propellant mass is 344 kg, and the pressurant mass is 7.07 kg.

Command and Data-Handling System

The requirements imposed by the detection system are vast, requiring a data rate of 10 Gbps to allow for the images taken by lidar (at 10 kHz) to be input to the processing algorithm. Therefore, the Airbus NEMO-2 was selected, given its excellent data rate and storage performance. Regarding processing requirements, the algorithm, which may have been infeasible to implement in the past, requires the state-of-the-art Airbus HPDP, which can run the remaining subsystem operations at the same time as the detection algorithm. 5 Gbit of RAM on the Airbus HPDP allow for sufficient storage space for all subsystem code. The final configuration of the system involves one Airbus NEMO-2, and two Airbus HPDPs, at a power of 25.64 W, and mass of 9.32 kg.

Thermal Management System

With extreme power draw during ablation operations at only 25.2% efficiency, the thermal management system (TMS) must be able to transport away and reject approximately 26 kW of waste power during active periods of the ablation laser. This requires a strong thermal connection from the primary payload, as well as connected subsystems like the battery and capacitor units, as well as the power conditioning and distribution unit (PCDU). This calls for heavy use of heat pipes and efficient radiators with optical solar reflector (OSR) surfaces. 35 heat pipes of 8 mm diameter connect the laser system to 16 m^2 of radiators, with four further heat pipes connecting both the PCDU, as well as the Li-ion batteries to another 2.4 m^2 set of OSR radiators. As the average power consumption throughout the mission decreases drastically, variable conductance heat pipes are employed to control the amount of heat rejected. The TMS design chosen has a mass of 65 kg and requires 74 W.

Telecommunication System

The telecommunication architecture uses the ESTRACK core and augmented network for longer communication windows, with a minimum time of communication of 11% of the time for 350 km orbital altitude. The subsystem on the spacecraft makes use of a fully redundant architecture, with two low-gain patch antennas to be positioned on the lower side of the spacecraft and two transceivers. Diplexers are used to use the same antenna for both receiving and sending activities. The lowest link budget estimation was 16.66 dB, using the lowest G/T figure of merit ground station is 16.36 dB and the BPSK modulation method along a Convolutional coding method.

Spacecraft Bus

The final configuration of the spacecraft consists of a cylindrical, load-carrying internal structure, fully aluminium 7075-T6. The thickness of this cylinder varies along the length of the spacecraft, as the load, that the structure is subjected to during the launch, is higher at the bottom of the spacecraft. The gimbal for the laser antenna dish is assumed to be load carrying, as well. In addition, the supporting platforms that translate the loads to the cylindrical shell have been analysed using FEM, ending up at a weight-optimised design.

System Analysis

An important aspect of the design is how well the different subsystems are integrated, and the system performs as a whole. Varying different key parameters, shows that the chosen final design is indeed optimal, by means of a sensitivity analysis. Also, the final design is within the initially determined mass and power budgets, and almost all mission requirements are satisfied. The most important requirement that is not met, is minimal launch cost, which is deemed infeasible with the current design. The system also encounters many risks during its mission, with the most critical risk being system collision with debris, which is mitigated using shielding.

Risk Analysis

The risk analysis is grouped into risks from all subsystems. Any risks, that have a high likelihood and a high consequence, need to be mitigated. This is the case for a total of 16 risks, of which the most critical risk is SS-TL-MI-RISK-ENV-005: **System collision with debris**. This is because the spacecraft is sent to an orbit, which is highly populated with debris. This risk is mitigated by having a slightly higher orbital altitude than the debris orbit to be cleared.

Launch and Reliability

For launch vehicle selection for the Space Sweeper vehicles, a trade-off between the Falcon 9, Ariane 62, and H-IIA202 was carried out using orbital insertion, allowable loads, reliability and cost as criteria, with Ariane 62 coming out as the winner. In terms of operations and logistics, the Space Sweeper is to be used as an emergency mission, to be launched within 20 days of the collision or explosion event. This requires final assembly near the Kourou launch site and a launcher to be quickly available. The latter is ensured using a fast-lane contract with ArianeSpace. Additionally, special End of Life procedures are automatically started in case a hacking is detected. The reliability and the availability of the spacecraft are to be maximised to ensure a successful mission and, as a result, not becoming part of the space debris itself. The reliability and the availability of the Space Sweeper are 0.915 and 0.993 respectively.

Development Strategy & Planning

Dedicated research into the debris properties that influence the ablation process (size, shape, material, and rotational rates) is discussed, as well as further development of the novel laser payload. Two facilities in the US are selected, and one in the EU, which will provide adequate facilities to perform laser development and debris research. A brief summary of interested third parties is given, to allow for faster development of current technologies, and shared costs if applicable.

The aim of the project team is to create a system that deserves a platinum certified rating in the newly created Space Sustainability Rating (SSR) of the World Economic Forum. To accomplish this, the team will take into account all debris mitigation guidelines published by the IADC, and perform a thorough Environmental Life Cycle Assessment (E-LCA), following the ESA's "*Space System Life Cycle Assessment Guidelines*" handbook.

Economic Valuation

Lastly, economics are a vital aspect for Space Sweeper due to the previously addressed problem of space debris accountability. Space Sweeper therefore needs solid economic analysis, for which a rigorous cost estimation process was adopted, estimating the labour, component, and facility costs for all phases of the project. The total cost of the project was estimated at €652 million, with a contingency margin of 20%. This estimate includes the launch costs with launch insurance considered. A large portion of this cost was allocated to research and technology development, at 47% of the total mission cost. This is expected, as prototyping and testing facilities are highly expensive and the novelty of the mission demands extensive research and testing.

The market value of LEO is considerable, and the debris removal market is an ever-growing field that is bound to gain a lot of attention in the years to come. However, due to the issue of accountability and liability for debris producing fragmentations, the marketability of the debris removal system depends largely on global political action in the future. However, the socio-economic risk of losing space services that are critical to today's society cannot be described with a price tag. Space Sweeper's real economic value comes from offering a concept and system that is capable of preserving humanity's access to space, and with it, preserving to the ever important space infrastructure of today.