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This submission is for the graduate category.	

NSF/ASME DESIGN ESSAY COMPETITION 2019

Anaheim, CA

Regenerative rockets and Remanufactured satellites: Are we ready now?

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Overview and frame of reference:

In the year 2035, humans would have expanded their horizon by reaching other planets. They would be in pursuit of exploration of evidence of life in these planets. They will be attempting to implement the proposed theory of terraforming on Mars and other planets. Experiments will be done, and samples will be transferred to and from these extra-terrestrial sites on a regular basis. Meanwhile, space tourism will be booming as a weekend plan with friends and families. Several imports and exports across countries will be heavily dependent on space capsules that can reduce the lead time on the consumer receiving the product. Humankind will have the pleasure of enjoying the internet at a speed that is faster than ever. This will be made possible by telecommunications satellites that go through regular upgrades based on new research and development.

At this time, every company planning a space mission will be motivated to satisfy the needs of the customer with high intent of reusing the available resources. Space Mission Solutions (SMS) is a high-tech global design and manufacturing company that provides the most efficient space mission solutions. It operates primarily from Melbourne, Florida, where they have a launch site to facilitate space missions. SMS has multiple subsidiaries and partner companies across the globe. By 2030, the company would have already sent a discovery mission to Mars. It would start expeditions to retrieve space debris and re-use dead satellites to make some of its missions economically feasible while tackling a larger threat to the future of space travel: the rapidly increasing number of space debris.

A glimpse of the company's missions in the 2030s through the eyes of its employees

In Belfast, Northern Ireland, Cian heads the procurement of re-usable space debris. He maintains an exhaustive database of dead satellites and matches the satellites to prospective missions. Cian's team does a background check on the debris to find out its previous missions, obtain legal rights to retrieve and use the satellite before starting to develop any new mission around it. His team has been interested in recovering the remains of Stardust-NExT spacecraft for its re-manufacture to facilitate the new sample return mission to the asteroid Vesta. After space settlement, the company is looking towards asteroid mining of critical minerals (such as Iridium, Palladium, and Borates) to meet the demands on earth and in their extra-terrestrial settlement in Mars. Cian thinks it would be a good idea to remanufacture and launch the satellite from their Martian settlement.

In Anaheim, California, Maria and her team prepare themselves for a design meeting with the company's settlement in Mars. The lead Engineer at the Martian base, Joseph, is looking to expand the colony to facilitate the arrival of a new batch of astronauts. The expansion will have to accommodate four human astronauts and three humanoid robots and include a greenhouse and a communal area. Maria and her team have already toured the facility in mars using Augmented Reality (AR) technology that works in conjunction with cameras and drones set within the Martian facility. They design four additional residential modules that they will add onto the existing colony which can be constructed entirely from Martian regolith. Jarvis is an intelligent and interactive humanoid encyclopedia on Mars that is capable of natural language processing. He is an integral part of design meetings as he is the only member with a comprehensive understanding of Martian soil and atmosphere. During the teleconference, Jarvis mentions that the nuclear reactors in the current settlement will not be able to accommodate the energy requirements of the greenhouse during the facility's peak energy consumption periods. Maria's team must find a way to bridge the energy gap for the operation of the greenhouse. The payload and the budget of the next mission will not be able to facilitate transporting a nuclear reactor to Mars so they decide to remanufacture solar panels from satellite debris on Martian soil. A dead satellite whose Avionic systems had exploded had been captured from the Martian orbit. Jarvis points out its coordinates so that Maria and her team can design a solar panel using solar cells from the satellite. She will have to conduct a meeting with the remote manufacturing facility in Seattle, Washington that will monitor the telerobots on Mars to build the solar panel.

Explaining the need:

Since the beginning of the space race in 1957, numerous satellites have been launched into the orbit of the Earth. While some of them are actively performing their functions till today, some of the satellites have been through their lifecycle, remaining inactive in the orbit. These are dangerous to the future of space missions as they are prone to collisions. Three accidental collisions have been documented between 1991 to 2005 [1]. Such collisions could harm the active satellites which could cost the company/agency that own the satellite both functionally and financially. For example, one of the major collisions in history occurred between Iridium 33 (owned by the U.S. based Iridium Satellite LLC.) and Cosmos 2251 (inactive Russian communications satellite) in 2009. Although both of them had the data indicating possible collision, it was not analyzed by either of the involved parties, leading to a hypervelocity collision. Following the incident, there were more than 1400 pieces of debris, larger than 10 cm, that were produced [2]. While some debris is expected to decay into the Earth's atmosphere, some of the debris is expected to orbit the Earth, ranging between twenty to hundred years. Major Regina Winchester of the U.S. Strategic Command said: " All countries who have assets in space are going to be concerned simply because when there's more debris, there's a higher chance to hit something."

With the increasing number of space missions, it has been predicted that there will be a drastic increase in the number of Low Earth Orbit (LEO) objects [1]. According to the LEO-to-GEO Environment Debris model (LEGEND) proposed by NASA as shown in Figure 1, it is predicted that the Effective number of objects could reach around 8000. The effective number is the fractional time, per orbital period an object spends between 200- and 2000- km altitudes.

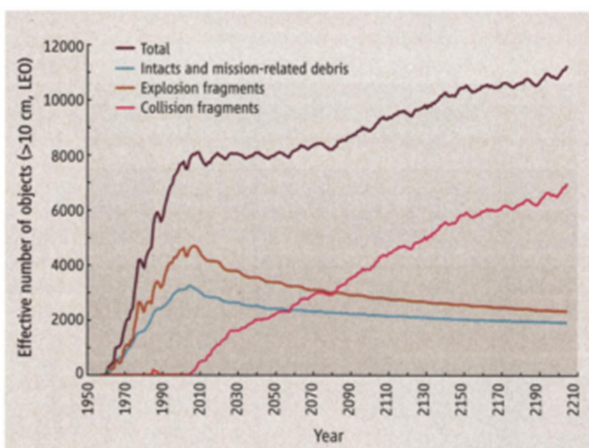

Figure 1 Predicted population growth of debris by the LEGEND simulation

According to the study conducted by NASA Langley Research Center, smaller fragments are usually more dangerous than larger ones as they travel at higher velocities [3]. Therefore, when small particles are formed due to accidental collisions, they are prone to do more damage to the operating satellites. The increase in launch rate is not helping to improve the current situation.

With the procedure followed currently companies spend $50-400 million in launching a satellite up to space. Most of this technology has not been upgraded. Some companies have been testing their solutions for reusable booster systems as a step towards attaining the ultimate goal, a fully reusable vehicle. According to Elon Musk: ”If one can figure out how to effectively reuse rockets just like airplanes, the cost of access to space will be reduced by as much as a factor of a hundred.” While there is still more room for making the process of launching a satellite more efficient.

Therefore, it is imperative for mankind to use the resources available at their disposal in a conservative manner in planning space missions. This can be possible only if efficiency is a factor in every decision-making step along the way. The working structure of this company allows keeping the efficiency of the mission as a top priority by using the already available resources, such as space debris.

The current state-of-the-art in Space Debris Removal

From about 2000km above the surface of the Earth (beyond the Low Earth Orbit, LEO), space is becoming a junkyard collecting debris such as retired spacecraft, fragments from collisions, and other items discarded during space missions. Almost 60+ years after the launch of the first ever man-made satellite, Sputnik 1, about 5450 rocket launches have taken place which has placed about 8950 satellites into the Earth’s orbit. 5000 satellites are still in space out of which only 1950 are functioning. Other sources of space debris include exploded rocket fuel tanks, fragments from satellite collisions or explosions, etc. Space Surveillance Networks have tracked about 22300 pieces of space debris that weigh more than 8400 tonnes orbiting beyond LEO [4]. As the number of space missions increases in our future due to our interests such as extra-terrestrial colonization, asteroid mining, etc, so will the amount of debris. Debris around the Earth’s orbit poses threats to existing satellites, the International Space Station, and to future space missions as well.

As of yet, there have been no missions to retrieve or remove space debris from LEO’s; however, numerous theoretical concepts have been proposed to tackle this emerging issue. A modern review of current technologies of Active Debris Removal (ADR) methods breaks them down into debris capture and debris removal methods, both of which are summarized below [5].

Debris could be captured using the following proposed methods: (1) using robotic or biologically inspired tentacles that clamp the space debris by holding a point on the target or using mechanical grippers that stabilizes the target and captures them via a gripple, (2) using single or multiple robotic arms to capture the debris which are telerobotically controlled from ground, (3) using mechanical effectors such as universal grippers, robotic hands, two finger mechanisms, etc., (4) using a large net that wraps itself around the target (5) a tether gripper mechanism that is a three finger gripper designed to grab onto the target or (6) using a harpoon mechanism that uses barbs from a chaser satellite to penetrate the debris [5,6].

Removal of space debris occurs after its capture or as a separate mission of its own. Popular debris removal methods suggested by literature are as follows: (1) Using a foam or inflated method where a chaser satellite ejects foam or an inflated ball that sticks onto the target debris to increase the area to mass ratio of the debris, following which the foam/inflated ball is deorbited using a propulsion mechanism, (2) Using an electrodynamic tether that is installed onto the debris which uses Lorentz force generated from the Earth’s geomagnetic field to reduce the orbit of (and essentially deorbit) the debris, (3) Creating an artificial atmosphere around the debris that decelerates and deorbits the debris, (4) Shooting pulsed laser beams that decelerates and deorbits the debris, (5) Shooting highly collimated neutralized plasma beams to deorbit the debris by lowering its altitude, (6) Using a slingshot method that spins the debris after capture and ejects it towards the Earth (to burn on re-entry), and (7) Using adhesives installed into deorbiting kits that attach themselves onto debris [5,6].

All the methods discussed above are theoretical propositions. On 2nd April 2018, SpaceX launched a research satellite called RemoveDEBRIS as a part of a resupply mission to the International Space Station. The project was manufactured by an Airbus subsidiary – Surrey Satellite Technology Ltd. It intends to test the efficacy of some of the ADR technologies. It will conduct experiments on capturing debris using a net and a harpoon and removal of debris by lowering its altitude using a drag sail [7]. Current and planned expeditions prioritize the removal of debris by deorbiting the debris and burning it up during re-entry to Earth or disposing it in the spacecraft cemetery. Defense Advanced Research Projects Agency (DARPA) developed the Phoenix program that upgrades retired satellites on-orbit to accommodate new technologies instead of launching new satellites from the Earth for specific missions – this plan is not only economically lucrative but it also repurposes the satellites instead of deorbiting them into the spacecraft graveyard [8]. No updates on that project are available since 2013.

Figure 2 RemoveDEBRIS spacecraft

Mode of operation:

The company will tackle the problem of attaining more efficient missions by focusing on designing missions around regenerative technology or remanufactured space debris. Either of these two approaches is chosen as a solution for the space mission depending on the scenario. For example, If a telecommunications contractor that owns a satellite approaches our company in need for a design to be able to launch their satellite, the company will check the eligibility of their current inactive satellites (explained in section Using the space debris in mission support) for the remanufactured solution and design the mission around it. Whereas when a company that already has established systems for new missions approach our company, we will provide solutions to make their mission more efficient by incorporating regenerative technology. In some cases, a combined solution may be required for the mission to be more efficient.

Designing space missions using regenerative solutions:

The company's path forward as an aerospace design and manufacturing giant is difficult to realize if they are not sustainable in their approach. All space missions commissioned by the company or any of its subsidiaries will have to be regenerative in their approach. By being regenerative, the mission does not add on to the space junk issue that will only worsen as time passes. Instead, it also repurposes the space debris by remanufacturing large and usable pieces of debris. The approaches the company will have to take in the future for regenerative space missions are listed below.

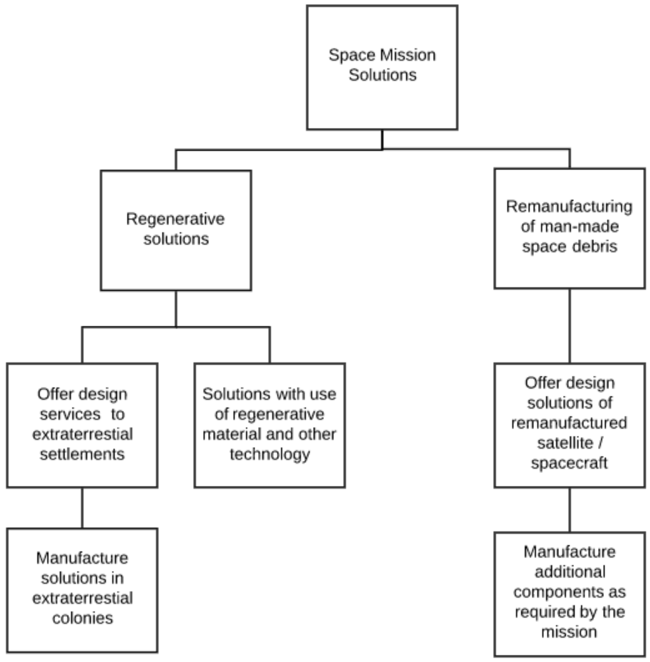

Figure 3 Flow chart explaining the company's approach

Use of regenerative fuel tanks.

About 25% of the recorded debris and possibly a larger portion of the untracked debris is comprised of debris generated from the explosive breakups of liquid-fueled rockets caused by residual propellant towards the end of a mission [9]. One of the 12 problems identified by NASA as Space Technology's grand challenges includes the availability of affordable power in space [10]. The company by 2030 would need to change its space missions to use regenerative fuel cells to propel rockets. This will allow for longer space missions. At the end of the mission, the rockets will have to vent the fuel from the regenerative cells and burn once separated from the spacecraft.

Use of space debris to fuel satellites.

Satellites launched from the company will be fuelled using technology that converts solid space debris collected from LEO's into fuel. A lot of the smaller debris in space could be comprised of metal parts from exploded satellites or breakups of rockets. While the repurposing of larger debris such as satellites has a monetary incentive – there is no reuse to broken shards of metal, yet. The company will, by 2030, use pieces of metal found in space to fuel satellites. Satellites sent on orbits around the Earth can survive longer in space using debris as a fuel as it will be the most abundant available resource at that altitude.

Use of extra-terrestrial manufacturing facilities

The company is already planning an expedition with four astronauts as early settlers to Mars. Our proposal recommends the building of a small-scale manufacturing facility within the first Martian colony to facilitate repairs, refurbishing, or reuse of satellite and spacecraft debris. Instead of hauling collected debris to Earth, payloads would be sent to Mars for remanufacturing and upgrades. The satellites can then be used to collect more data and samples form not only mars but also the resource-rich asteroid belt. Asteroid mining could be a massive source of revenue for the company in the future as critical minerals on Earth run out – investing in manufacturing facilities near the asteroid belt, such as on Mars, will benefit the company in the long haul.

The manufacturing facility will comprise of telerobots that are controlled from the Earth and be equipped with state of the art facilities that can 3D print metals from shards and chunks of space junk, build strong and durable parts using Martian regolith, fine-tuned micro-robots capable of handling the most intricate circuitry of the control systems, etc. Most of this facility will be controlled by Artificial Intelligence and Telerobots to reduce the labor required to manufacture on space. The manufacturing facility will produce regenerative solutions for design and engineering problems for early mars settlements and also offer the remanufacturing of retired satellites.

Using the space debris in mission support:

Once the debris is recovered, it will be analyzed to assess the state of its stability, quality, and ability to perform its prior intended function. Based on the results of the analysis, the path of recovered material will be decided, whether it is recycled in other mission to provide support or it can be remanufactured to perform original functions. The recovered debris will be carried over to the space module that is equipped with the ability to remanufacture/refurbish the component. These space modules are also in the Low Earth Orbit making them easily accessible. By having the remanufacturing/ refurbishing facility in space the rocket bodies need not be brought back to the Earth. This will help in planning longer space missions, as the payload can be transferred over to the remanufactured Solid Rocket Body in the space module.

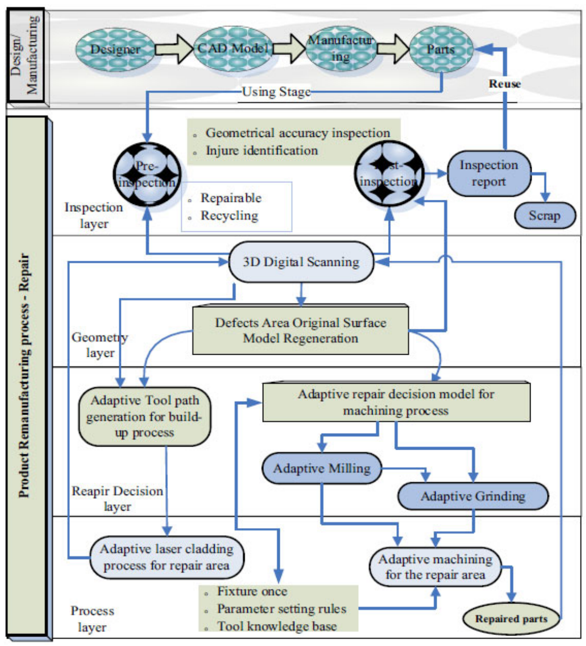

Figure 4 The adaptive remanufacturing procedure[12]

The missions will be designed around the remanufactured components. At this stage, the engineering team gathers knowledge about every aspect of the retrieved component such as its geometry, mass distribution, etc. The data is gathered for all the retrieved components. They will go through the remanufacturing process as needed for the mission. The company will maintain a catalog of all the retrieved debris and they will be treated as "bin items" during the design of the mission. According to the Union of Concerned Scientists, a group of 250 scientists, analysts, policy and communication experts, there are currently 2062 satellites operating, out of which 1338 are in LEO. They have a lifetime ranging from 0.25 to 30 years [11]. Through research a 4 layer adaptive repair solution has been proposed. This provides a framework for what can be accomplished in the space module, including inspection, geometry recording, repair decision, and process layer as shown in Figure 4. This procedure has to be refined further through research and experiments.

Remanufacturing technology in the automotive industry:

Remanufacturing is the process of disassembling the worn out assembly, rebuilding its components and assembling the parts back together to form a reusable subassembly that can perform just the same as the original. Remanufacturing has been heavily used in the automotive industry due to the high quality of the rebuilt component, improved efficiency, and sustainability solution. The component is usually like-new and is functionally similar to the original part. Additionally, it resolves the need for new raw materials, thereby saving money for the consumer. The technology has become so common that consumers are easily influenced to buy remanufactured part over a new part when it comes to replacement.

An approach similar to the one proposed in the automotive industry as shown in Figure 5 will be used to remanufacture the spacecraft in the space module. It is expected that in 2035 remanufacturing in space will be so common in the aerospace industry that it will have similar influence as it does on the automotive industry now.

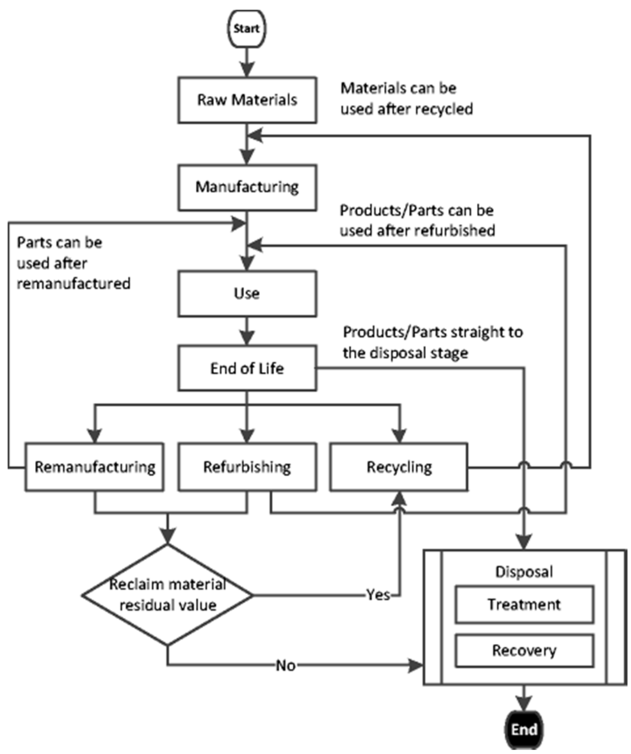

Figure 5 The main End of Life options for the material [13]

Challenges faced by the company:

It is expected that the company will face some of the following challenges,

- Lack of major incentive- cleaning the debris and remanufacturing is not in the interest of major companies as it may not have a quick financial payback.
- Investment capital- The company will need resources to be standalone and conduct their operation without much dependence on other agencies. For example, in order to have the

remanufacturing operation set up in the space module, the company has to invest in researching remanufacturing equipment that is suitable for the zero gravity environment, have these machines built and launched up.

- Overcome the current competition- There are several companies that already work towards regenerative solutions. Therefore, they will have a head-start in designing better missions. It is important to be ready to collaborate with such companies until the company can start generating solutions on their own.
- Legal issues- indemnity policy to protect the company from any prosecutions if the debris of an inactive satellite is not remanufacturable.

Research challenges:

The company will have to address research challenges on several fronts to fully realize the goals established by the proposal by 2035. Some of the major research issues are:

1. Scientific research into the development of regenerative fuel cell technology. Such technology will be crucial in developing long haul space missions necessary for both effective retrieval of space debris and missions to farther planets and asteroids within the solar system. Currently, small scale lab experiments on reversible fuel cells are being conducted on Earth [14], but these technologies need to be tested at much larger scales and in space conditions for fruitful discoveries and advancements.
2. Scientific research on using space debris as fuel for satellites. This is already set in motion by an Australian physicist, Horst Neumann who proposed the idea of an ion drive to fuel space crafts using metals as fuel [15].
3. Research on design and manufacturing of compact manufacturing facilities that can be built on extraterrestrial sites such as Mars. This include (1) anticipating the missions that will be performed on Mars – asteroid mining, satellite launches onto Martian soil, discovery missions to farther celestial objects like Europa, etc., (2) building an intelligent manufacturing facility that could be remotely operated from Earth and launching it to Mars along with its Mars discovery project, and (3) Conducting research on acquiring raw building materials from Mars and processing them into usable products on-site. Building mission components using Basalt, a common material found on volcanic sites in Mars is already underway [16].
4. Building a database of retired satellites that are still in orbit and tracking the orbits of those satellites is also important to plan and retrieve them for re-manufacturing.
    a. The database has to use Artificial Intelligence to predict satellites that are at a high risk of a collision so that their retrieval can be prioritized.
    b. The database has to offer all engineering documents of the retired satellites in orbit so as to plan effective remanufacturing process before sending a retrieval mission. It is important to realize that satellites will have separate missions based on their usability. Some may require hauling them and completely updating them whereas others may only need on-site updates (as planned by the Phoenix mission).
5. Acquiring legal rights to remanufacture the satellites. The satellites in orbit do not belong to the company, therefore research into fields of international and space laws is going to be fundamental in keeping the company from being prosecuted.

Partnerships:

The company will actively have partnerships with both government and commercial companies that work in the same direction to provide optimal space missions. Some of the proposed commercial partnerships are:

Institution	Company
University of Surrey- Surrey Space Centre	Astroscale Holdings Inc.
École polytechnique fédérale de Lausanne (EPFL)	SpaceX

Through collaboration with the research institutes the company will address the research challenges and through collaboration with other companies, Space Mission Solutions will develop more regenerative solutions.

Discussion:

With the implementation of regenerative and remanufacturing solutions in space missions, a new field of focus, Design for Remanufacturing (DfRem) arises. This allows engineers to think about design considerations that need to be followed so that the component can be easily remanufactured. Having these considerations ahead of time, during the early stages of product design will reduce the number of components that will get scrapped. This emerging field will also become a part of education for students majoring in Mechanical and Aerospace engineering because both the industries will be expected to incorporate such practices while they design in order to avoid wastage of raw materials. As a result, several research topics will be branching out, analyzing applications of DfRem.

Conclusions:

Thus, it is predicted that space missions in the future will be much different than what it is today. In order to accommodate such changes, the industry should shift its focus towards streamlining missions such that the focus is not just towards attaining the goal but also attaining with less footprint. This can be possible only if a conservative approach is followed in completing the missions. The two approaches presented here, regenerative and remanufactured solutions, are just a starting point to a plethora of options to solve the problem. Through these approaches, Space Mission Solutions will be leaving a sense of responsibility to the community that urges them to think ahead while designing missions in the future. In addition, the use of such technology in the industry will enhance the use of Design for Remanufacturing practices from the early stages while designing space missions. Finally, the company is expected to move forward in providing sustainable solutions to space missions by meeting the research challenges mentioned earlier.

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