Design and Evaluation of an Orbital Debris Remediation System

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***Abstract*—Over the last 60 years, our use of and demand for spaceflight has risen precipitously. As more and more uses and easier access is developed, the need for orbital space has increased, along with the finances at stake. Threatening this is the threat of orbital debris. Debris in Low Earth Orbit is moving so quickly that it imparts a tremendous amount of energy with even the slightest of collisions. In addition, a propagating effect called the Kessler Syndrome multiples the risk that each collision poses.**

Remediation efforts have been posited, but none have been agreed upon or implemented by the wider international space community. One of the major hurdles preventing this is a lack of consensus and a lack of a universal metric of evaluation. We seek to bridge that gap by developing an analysis tool that will enable comprehensive comparisons of design alternatives. We do so mainly via simulation of delta-v costs and a network analysis and optimization tool.

I. Introduction

OVER the past 60 years, spaceflight has evolved and expanded tremendously. What was once the realm only of national governments has now become a prime economic feeding ground for corporations and industries around the world [1]. Threatening this fledgling environment is the threat of orbital debris.

The speeds required to reach and maintain orbital velocity are such that terrific amounts of energy are contained in even the smallest of orbital particles. Should these objects impact an operational satellite, the consequences can be dire, ripping straight through fragile aluminum and silicon bodies. In addition, each collision produces even more debris, which itself becomes a new threat. This leads to a chain reaction effect, referred to as the Kessler Syndrome. Should a critical mass and number of objects trigger the Kessler Syndrome, the result would be a sphere of trash orbiting our planet, impeding any future development or use of space [2].

The probability of collisions has increased 7-fold over the past 10 years [3]. This increase is attributed to the overall rise in orbital populations, driven by expansion of the commercial space industry and by recent collision events. In 2007 the Chinese launched an anti-satellite missile against their own Fengyun satellite and in 2009 there was a random collision between the Cosmos 2251 and Iridium 33 satellites, together producing 2500 pieces of debris [4]. These factors led to an increase in conjunction events, which are directly proportional to collision probability [5].

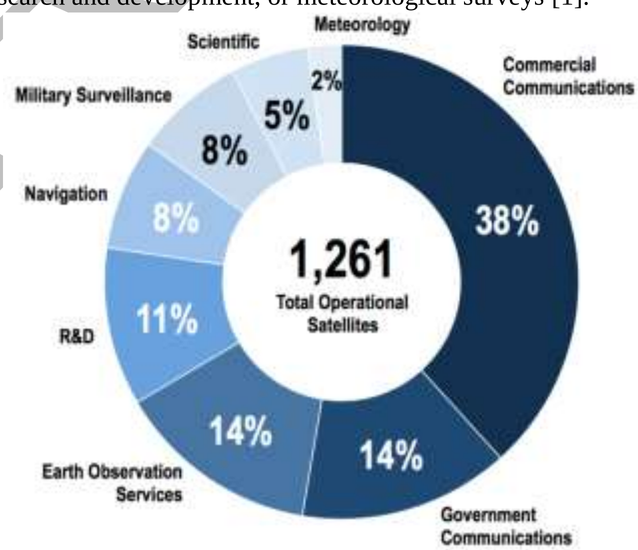
The international space community has made strides to mitigate the propagation of further debris, mostly focusing on total life-cycle planning for new satellite launches [6]. While this reduces further worsening of the problem, it does not directly deal with the issue at hand, that of the current debris population. Thus, it is imperative that a remediation design be chosen and implemented.

There have been dozens of design solutions posited, but there is a need for a rigorous, comprehensive analysis of alternatives. As a part of this effort, a metric for evaluating the effectiveness of designs is necessary.

II. Context

A. Current Investments

There is currently over $200 billion in revenue resting of the shoulders of orbital satellites, not to mention the billions invested in order to access that potential golden goose. Over 1200 satellites have been built and launched, performing a wide variety of tasks. While they are heavily communications focused, there are a large number of satellites performing other tasks, such as scientific research, research and development, or meteorological surveys [1].



B. Types of Orbits

Each satellite is put into a different orbit depending on its desired performance. For instance, a satellite that is designed to survey a particular geographical location constantly would be put into a geostationary, or perhaps Molinya orbit. These are orbits whose geometry ensues that they will have long loiter times. For geostationary orbits, they hover over an equatorial position, while a Molinya orbit loops out in a highly eccentric orbit, slowing down as it does so, such that a long loiter time may be achieved over the northern or southern hemisphere [9].

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Many satellites currently in operation are bunched in Low Earth Orbit, 200 to 2000 kilometers in altitude. Some of this has to do with lower launch costs (shorter distance to travel) than other orbits. In addition, the recent proliferation of miniature "CubeSat" satellites has enabled the non-scientific, non-governmental population to put their own instruments in space for relatively low cost. This widens the user base, and expands total usage.

C. Orbital Debris Threat

All the above developments and revenues are faced with the threat of orbital debris. There are over 20,000 pieces of debris in orbit that we track, each of which poses a distinct threat. Orbital speeds vary, but 7 km/s is not an unreasonable speed for LEO (the International Space Station flies at around 7.6 km/s). If we look at the energy contained in these objects:

$$\varepsilon = \frac{mv^2}{2}$$

We can see that the velocity is incredible important. Thus, even small objects, when flying at orbital speeds, carry tremendous amounts of energy and potential destructive power.

In addition, there is the risk of a chain reaction. One collision may produce 2000 fragments, and then each of those fragments now has the potential to causes its own collision. This propagating effect, called the Kessler Syndrome, poses a severe risk to the space environment.

III. Stakeholder Analysis

Pretty much everyone is affected in some way, shape, or form by space debris. Whether its John Doe on his smartphone, using GPS to get directions to dinner or whether it's the US Military using SATCOM to coordinate rescue missions, everyone has a stake in the future of our satellite population. That being said, some actors are certainly more involved than others, and here we will be analyzing some of the top-level stakeholders.

A. National Governments

From the United States of America to Russia, China, and the Eurozone, national governments around the world are easily one of the most important stakeholders. Over 20% of our satellites are used for military or government communications. Not to mention the fact that GPS was originally developed as a military tool only becoming available to the public later.

National governments have many conflicting tensions, most often including military goals. Every government has the responsibility to its own citizens to protect them, and hand-in-hand with that comes the objective of military superiority. Logically, not all national militaries can be superior to each other, thus enters a tension.

This relates to our project particularly in terms of weaponization potential. Debris removal strategies can very easily be modified for military use, disabling crucial enemy communications or observational satellites. Every military wants this sole access to this type of capability.

B. Commercial Industry

Commercial industry is comprised of many parts, but effectively constitutes any privately owned corporation that provides services or products that affect space debris. Examples of these would be transport companies like the Untied Launch Alliance (ULA) or SpaceX who build rockets for travel to orbit, system manufacturers like Lockheed Martin or Boeing that design and build space assets, and insurance companies that underwrite the whole process.

In all cases, commercial industry is seeking to maximize profit. As such, they need to maximize the products that they can produce and operate, which provide them revenue. Therefore, the threat of space debris, which can potentially demolish expensive space assets, is crucial for industry. However, maximizing profit necessarily entails minimizing costs. Any remediation effort will unavoidably be expensive. While investing in this may be a wise long-term move, it is unlikely to happen on a purely commercial scale.

At play here is a classic tragedy of the commons. Every company wants to maximize their benefit from the shared space environment, but no one wants to spend money to maintain it. It's like a game of chicken; every company wants to wait until the absolute latest moment, hoping that someone else will jump in, spend their money, and save the day.

C. Civil Organizations

Civil organizations are those like the National Aeronautics and Space Administration (NASA) or the European Space Administration (ESA). They are associated on some level with a national government (or governments), and not considered private, but they are divorced from much of the political and military associations that plague the national governments themselves. That being said, ultimately they are funded via national governments, so a push for a specific agenda by the USA would certainly have ramifications in NASA policy.

Civil organizations have played arguably the most significant role in space debris research up to this point. There is an international committee called the Inter-Agency Space Debris Coordination Committee (IADC) whose entire purpose is to bring together scientists from various international civil organizations to solve the space debris problem. This organization serves as a wealth of information regarding remediation strategies, particularly for Active Debris Removal (ADR) strategies.

D. Interactions and Tensions

There are four main tensions between stakeholders: international political tensions, insurance-commercial tensions, regulations, and the timing of collision events.

As mentioned previously, many remediation methods have high potential for weaponization. This creates the first, political, tension. Every government wants to ensure that they are the only ones who have access to the most powerful, critical space systems.

Second, we have the tension between commercial companies, including insurance. Essentially, everyone wants debris remediation but no body wants to pay for it. Bridging this gap will require a convincing plan of action, along with possibly exploring direct financial incentives (i.e., contracting on Debris Remediation System (DRS) development and deployment).

Third, there is the issue of regulations. Similar to international waters, space is non-territorial. Thus, it is often vague as to what jurisdiction and regulations are applicable. This comes up as an issue in debris mitigation. The UN has published guidelines recommending mitigation strategies [], but it is unclear whether those have any legal force. Is a US systems manufacturer bound to honor UN guidelines?

Lastly, there is the issue of time. Debris is a problem on a very long time-scale. We could go another 200 years before any serious issues affect us all dramatically. However, we need to act now in order to prevent any further tragedy. That being said, very few governments, more specifically, politicians, like to think or plan on long-term. Politicians worry about immediacy, their next election in two or four or six years, not problems that will plague us in 200 years. Therefore, there is a hurdle to overcome in convincing decision makers to action. This may take the form of developing a plan that only stretches over 20 years, focusing on the most immediate benefits we can.

IV. Problem Statement

A. Gap Analysis

There is a problem with orbital debris and remediation design have been built and posited. What is missing is consensus. No one can agree on the best overall strategy or plan of action, much less the specifics of implementation.

B. Need Statement

In order to make any headway dealing with orbital debris, we must develop a series of metrics and models that will enable universal comparison of design strategies. This includes deployment methods and ADR design selections, as well as exploring the potential of other remediation strategies such as JCA.

V. Requirements

A. Mission Requirements

MR.1 The Debris Remediation System (DRS) shall de-orbit at least 5 high-risk debris objects per year.

MR.2 The DRS shall select high-risk objects as a function of mass and collision probability.

Risk for a given object i at time t is defined as a function of collision probability (P(t)) and mass (m) [5]:

$$R_i(t) = P_i(t) * m_i$$

MR.3 The DRS shall focus remediation efforts in Low Earth Orbit (below 2000 kilometers in altitude)

MR.4 The DRS shall not be intentionally destroyed while in orbit.

MR.5 The DRS shall release no more objects or vehicles than it recovers.

MR.6 The DRS shall allow end-of-life passivation within 2 months.

B. Functional Requirements

FR.1 The DRS shall be able to identify debris objects larger than 10 cm in diameter.

FR.2 The DRS shall be able to maneuver throughout LEO (up to 2000 km).

FR.3 The DRS shall be able to engage with debris up to 8900 kg (dry mass of SL-16).

FR.4 The DRS shall be able to remove debris objects from orbit.

C. Simulation Requirements

SR.1 The simulation shall output optimal network paths for given parameters.

SR.2 The simulation shall modify the optimal network for different designs.

SR.3 The simulation shall account for multiple possible launch sites.

SR.4 The simulation shall account for combinations of ADR designs.

SR.5 The simulation shall target objects with the highest scores.

VI. Concept of Operations

A. Active Debris Removal (ADR)

Active Debris Removal's general concept of operations is relatively simple:

1. Identify the target object
2. Maneuver to and rendezvous with the target
3. Grapple with the target and de-tumble (if necessary)
4. Remove the object from orbit

However, this structure takes on many different forms with each specific ADR design. Fundamentally though, they all agree in this: remove the debris from orbit.

B. Just-In-Time Collision Avoidance (JCA)

Just-In-Time Collision Avoidance (JCA) differs from ADR in that it does not attempt to remove objects from orbit but rather to dodge collisions. By tracking the highest risk objects, along with our operational satellite, we should have a pretty good idea of with the risk for collision is high. When this happens, we simply dodge the collision. This is far cheaper in terms of cost per collision avoided, but does have some drawbacks. First and foremost, is does not solve the long-term problem; the debris is still in orbit, posing a risk. For simplicity's sake, in our current model we are not evaluating JCA designs (though future work should find our model modular enough for easy addition).

C. Expansion of Property Rights

Another strategy is to ignore the physics of the problem and look at the political situation. In particular, what might happen if we expanded property rights in space? If a certain company has exclusive rights to area in space, then in theory they would be incentivized to protect their territory. This approach attempts to solve our tragedy of the commons not by direct intervention in the commons, but by removing the commons as a whole and moving towards privatization.

This method is rife with potential for failure, but is interesting to consider, perhaps as more of an economics question that an engineering one.

VII. Design Alternatives – ADR

Within ADR, we are considering six main designs:

A. Robotic Arm

A robotic arm is used to physically grab the debris and perform a maneuver to change its orbit.

B. Throw Net

In this method, the system throws a net towards a debris object and pulls the object along a tether.

C. COBRA IRIDES

The COBRA is a contactless ADR method using plume impingement from a hydrazine monopropellant propulsion system to impart momentum on a target debris either to change its orbit or its attitude.

D. Three-Coordinated Electromagnetic Spacecraft

With the application of inter-spacecraft electromagnetic force, disabled satellite with functional magnetorquer could be removed in a non-contacting manner without propellant expenditure and complicated docking or capture mechanisms.

E. Harpoon

A harpoon is just what it sounds like, a harpoon. A rod is shot into the debris object, and then prongs are extended to hold it in place. This has some advantages for large, tumbling objects, but also greatly increases risks of explosions, malfunction, and fragmentation.

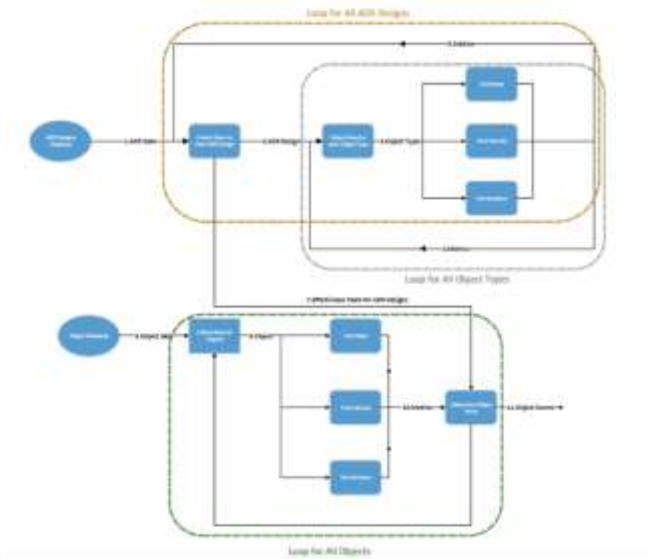
F. Eddy Currents

It is based on the computation of the Magnetic Tensor which depends on how the conductive mass is distributed throughout the debris object, using the open cylindrical shell and flat plates.

VIII. Method of Analysis

A. Object Categorization

Object categorization analyzes the effectiveness of each active debris removal design for all types of objects, which are operational satellites, defunct satellites, rocket satellites and fragments. The metrics used to measure the effectiveness are mass, velocity and rotation. The Object categorization takes in mass, velocity, rotation and object type as input and outputs the object scores for each ADR designs that considered an input for both network analysis and utility analysis.



B. Network Analysis

Built in MATLAB, the network analysis takes in TLE data and object scores (from part 1.) as inputs and outputs a series of maneuvers, delta-v costs, and overall scores. A series of functions take in Two-Line Elements (TLE) data, the standard for the US Space Surveillance Network, and converts it to more accessible Classic Orbital Element (COE) and State Vectors (SV).

Once we have these elements, we run them through a calculation to determine delta-v, or the change in velocity, required to maneuver between two orbits. We use these delta-v calculations as our “distances”, or arc lengths, in our network analysis. We want to minimize the distance traveled, as delta-v can be effectively used as a proxy for fuel costs, a significant portion of total launch costs. A design with similar effectiveness but a lower overall delta-v will be preferred over a higher delta-v approach.

The meat of our network calculations involves finding the delta-v costs between two objects. We can do this be solving Lambert’s problem, as follows [9]:

Calculate r_1 and r_2 using $r_1 = \sqrt{\boldsymbol{r_1} \cdot \boldsymbol{r_1}}$ and $r_2 = \sqrt{\boldsymbol{r_2} \cdot \boldsymbol{r_2}}$

Choose prograde or retrograde trajectory and find $\Delta\theta$:

$$\Delta\theta = \begin{cases} \cos^{-1}\left(\dfrac{\boldsymbol{r_1} \cdot \boldsymbol{r_2}}{r_1 r_2}\right), if\ \boldsymbol{r_1} \times \boldsymbol{r_2} < 0\ and\ retrograde \\ 360^\circ - \cos^{-1}\left(\dfrac{\boldsymbol{r_1} \cdot \boldsymbol{r_2}}{r_1 r_2}\right), if\ \boldsymbol{r_1} \times \boldsymbol{r_2} \geq 0\ and\ retrograde \\ \cos^{-1}\left(\dfrac{\boldsymbol{r_1} \cdot \boldsymbol{r_2}}{r_1 r_2}\right), if\ \boldsymbol{r_1} \times \boldsymbol{r_2} \geq 0\ and\ prograde \\ 360^\circ - \cos^{-1}\left(\dfrac{\boldsymbol{r_1} \cdot \boldsymbol{r_2}}{r_1 r_2}\right), if\ \boldsymbol{r_1} \times \boldsymbol{r_2} < 0\ and\ prograde \end{cases}$$

Find A:

$$A = \sin\Delta\theta \sqrt{\frac{r_1 r_2}{1 - \cos\Delta\theta}}$$

Iterate through the following equations to find z:

$$z_{i+1} = z_i - \frac{F(z_i)}{F'(z_i)}$$

$$F(z) = \left[\frac{y(z)}{C(z)}\right]^{\frac{3}{2}} S(z) + A\sqrt{y(z)} - \sqrt{\mu}\Delta t$$

$$F'(z) = \frac{1}{2\sqrt{y(z)C(z)^5}}\{[2C(z)S'(z) - 3C'(z)S(z)]y^2(z) + [AC(z)^{5/2} + 3C(z)S(z)y(z)]y'(z)\}$$

$$y'(z) = \frac{A}{4}\sqrt{C(z)}$$

$$C(z) = \sum_{k=0}^{\infty}(-1)^k \frac{z^k}{(2k+3)!}$$

$$S(z) = \sum_{k=0}^{\infty}(-1)^k \frac{z^k}{(2k+2)!}$$

Find $y(z)$:

$$y(z) = r_1 + r_2 + A\frac{zS(z) - 1}{\sqrt{C(z)}}$$

Find $f, g, and\ \dot{g}$:

$$f = 1 - \frac{y(z)}{r_1}$$

$$\dot{f} = \frac{\sqrt{\mu}}{r_1 r_2}\sqrt{\frac{y(z)}{C(z)}}[zS(z) - 1]$$

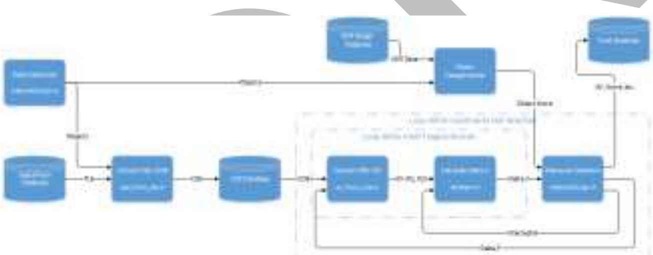
$$g = A\sqrt{\frac{y(z)}{\mu}}$$

$$\dot{g} = 1 - \frac{y(z)}{r_2}$$

Calculate $\boldsymbol{v_1} and\ \boldsymbol{v_2}$:

$$\boldsymbol{v_1} = \frac{1}{g}(\boldsymbol{r_1} - f\boldsymbol{r_2})$$

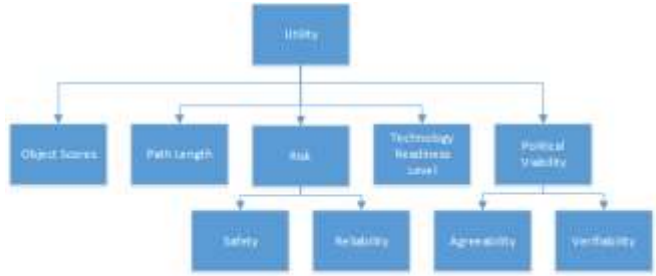
$$\boldsymbol{v_2} = \frac{\dot{g}}{g}\boldsymbol{r_2} - \frac{f\dot{g} - \dot{f}g}{g}\boldsymbol{r_1}$$



C. Utility Analysis

Once we have results from object categorization and network analysis we need to aggregate them into a meaningful number, and we do this via our utility analysis. We developed a value hierarchy for use in evaluating the total utility of design alternatives. Weights have not been finalized yet, but will be run past our stakeholders for review and verification.

This value hierarchy consists of five major elements, two of which are further decomposed. There elements are object scores, path length, risk, technology readiness level, and political viability. Risk is broken down in safety and reliability, while political viability is broken into agreeability and verifiability.



IX. Design of Experiment

While there are stochastic elements in the field of space debris, particularly in terms of conjunction analysis, we will be performing a deterministic evaluation. Our model mathematically determines object scores and delta-v costs, which are then optimized via network analysis. In our experiments we will be focusing on varying constraints for our network, as this is the most adaptable element. In addition, the weights for our utility function are not set in stone and will change depending on the preferences of the decision makers. Thus, to prevent pigeonholing, we will be including weights as variable parameters to ensure that we cover a wide range of possible results.

X. Results

As our model is still in infancy stages, we do not have meaningful data to report on in this draft.

XI. Conclusion

At this point, we do not have enough data to back up any form of conclusion.

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