Design and Evaluation of an Orbital Debris Remediation System

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Abstract - **Over the last 10 years the number of satellites has grown 59% from 819 to 1305, and revenues have risen 92% from $105.5 billion to $203 billion. Threatening this industrial sector is orbital debris, including rocket bodies and defunct satellites. Current orbital debris mass ranges from <1 kg to 8300 kg and has grown 124% between 2006 and 2010. It is estimated that population of debris objects >10 cm in diameter will have grown to over 15,000 by year 2100.**

This paper describes an analysis of the Utility vs. Life-cycle Cost for seven Active Debris Removal (ADR) design alternatives with the goal of removing five space debris objects per year for ten years. The Design Alternatives include three physical capture mechanisms, (1) a robotic arm, (2) throw net, and (3) harpoon, and four contactless capture mechanisms, (4) COBRA IRIDES, (5) three-coordinated electromagnetic spacecraft, (6) eddy currents, and the (7) ElectroDynamic Debris Eliminator (EDDE).

The Utility Analysis considered the attributes of Performance, Risk, and Political Viability, each further decomposed into sub-attributes. Performance included measures of effectiveness and delta-v cost. Effectiveness is determined via linear decreasing functions for mass, $E(x) = 1 - \frac{max-x}{max-min}$, and exponential decreasing functions for velocity and rotation, $E(x) = e^{-\lambda x}$, where λ=mean value (velocity or rotation) acceptable. Delta-v cost is determined by calculating the fuel burns required to change velocity in order to maneuver between derelicts: $\Delta V = \sum |V_i - V_j|, \forall i, \forall j, i \neq j$, where V_i is the velocity of derelict i and V_j is the velocity of derelict j.

The throw net has the highest overall utility, but the harpoon has the highest utility per dollar. Reducing the cost of the net by a factor of 10 would make it more competitive with the throw net. In addition, a significant weight of the utility stems from the political viability of the design. If the viability of any of the designs could be improved, then they would quickly become a contender for the optimal design.

Index Terms - Environment, Orbital Debris Remediation, Space, Sustainability

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].

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 they can rip straight through fragile aluminum and silicon bodies. In addition, each collision produces even more debris, which itself becomes a new threat. This may lead to a chain reaction effect, referred to as the Kessler Syndrome [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 two recent collision events. In 2007 the Chinese launched an anti-satellite missile against their own Fengyun satellite and in 2009 there was an accidental collision between the defunct Cosmos 2251 and Iridium 33 satellites, together producing 5000 pieces of debris [4]. These factors led to an increase in conjunction events, which are directly proportional to collision probability [5].

CONTEXT

I. Current Investments

There is currently over $200 billion in revenue dependent on orbital satellites, as well as billions already invested. Over 1200 satellites are currently operational, 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].

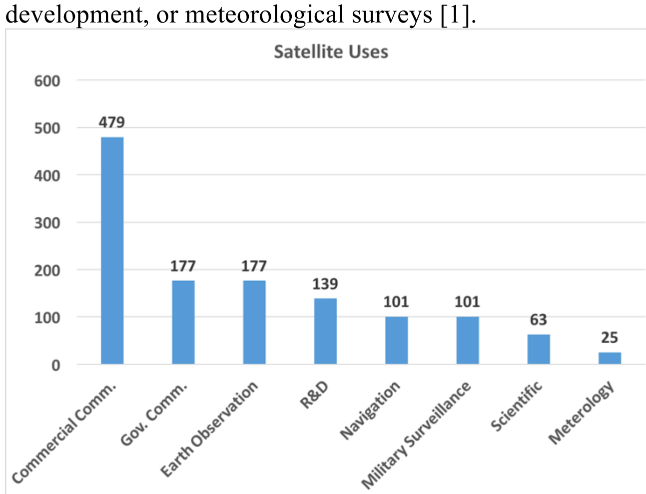

FIGURE I
TYPES OF SATELLITES IN USE [1]

II. 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 ensures that they will have long loiter times over specific locations on Earth. 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 [7].

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.

III. 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 are tracked, 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). The energy contained in these objects can be found by:

$$E = \frac{mv^2}{2} \quad (1)$$

Velocity is incredibly important. Thus, even small objects, when flying at orbital speeds, carry tremendous amounts of energy and potential destructive power.

STAKEHOLDER ANALYSIS

I. 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 existing 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 this 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.

II. 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.

III. 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. The Inter-Agency Space Debris Coordination Committee (IADC) is an international committee whose entire purpose is to bring together scientists from various 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.

IV. 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, there is the tension between commercial companies, including insurance. Essentially, everyone wants debris remediation but nobody 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 [6], but it is unclear whether those have any legal force.

Lastly, there is the issue of time. Debris is a problem on a very long time-scale. Another 200 years could pass before any serious issues affect us all dramatically, or it could occur next week. However, action is required 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 them 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.

PROBLEM STATEMENT

I. Gap Analysis

To date no clear remediation solution prioritization has been performed to include cost, effectiveness, and technology readiness level. This type of analysis is required for further advancement of the space debris community's discussion and remediation development.

II. Need Statement

In order to make any headway dealing with orbital debris, a series of metrics and models must be developed 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.

REQUIREMENTS

I. Mission Requirements

MR.1 The ADR solution shall focus remediation efforts in LEO (below 2000 km).

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

MR.3 The ADR solution shall de-orbit at least 5 high-risk debris objects per year for 10 years.

MR.4 The ADR solution shall release no more objects or vehicles than it recovers.

MR.5 The ADR solution shall de-orbit itself within 2 months of end-of-life.

II. Functional Requirements

FR.1 The ADR solution shall be able to maneuver throughout LEO (up to 2000 km).

FR.2 The ADR solution shall be able to engage with debris up to 8300 kg (dry mass of SL-16).

FR.3 The ADR solution shall be able to remove debris objects from orbit.

CONCEPT OF OPERATIONS

I. 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.

II. 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 the operational satellite, an accurate estimation of the risk for collision can be made. When this happens, the collision is dodged. 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 this current model JCA designs are not considered, though future work should find the model modular enough for easy addition.

DESIGN ALTERNATIVES

Within ADR, seven main design alternatives are considered.

I. Robotic Arm

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

Limitations:

- Can handle debris up to 7000 kilograms
- Complex and heavy payload design
- Contact may cause damage to debris

II. Throw Net

Throw a net towards a debris object and pulls the object along a tether. The net entangles the objects due to masses or a closing mechanism.

Limitations:

- Can handle debris up to 10,000 kilograms
- Risk due to potential failure of throwing a net at a moving target
- Contact may cause damage to debris

III. Harpoon

Shoot a tethered harpoon into the object. After the harpoon penetrates the object, the bars at the point are opened to keep itself sticking in the object. A maneuver is then performed to change the object's orbit.

Limitations:

- Can handle debris up to 9000 kilograms
- Risk due to potential failure of shooting a harpoon at a moving target
- Risk of fragmentation of the target upon impact

IV. COBRA IRIDES

The COBRA is a semi-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.

Limitations:

- Can handle debris up to 144 kilograms
- Impingement may result in damage to target debris

V. 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.

Limitations:

- Can handle debris up to 2000 kilograms
- Requires conductive (ferrous) debris
- Low technology readiness level

VI. 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.

Limitations:

- Can handle debris up to 2000 kilograms
- Requires conductive (ferrous) debris
- Low TRL

VII. ElectroDynamic Debris Eliminator (EDDE)

EDDE uses a net manager to capture large debris, which holds ~100 square house-sized expendable Spectra nets weighing ~50g each. EDDE extends one of the nets and its support lines, using the ~0.015 gee centrifugal acceleration at each end of EDDE. Capture is done by arranging for the target to pass between 2 net support lines at a few meters/sec.

Limitations:

- Can handle debris up to 8500 kilograms
- Risk of tethers being severed by high-velocity debris

METHOD OF ANALYSIS

I. 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, and rotation as inputs and outputs the object scores for each ADR designs, which is then taken as an input for both the network analysis and the utility analysis.

II. 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 these elements are obtained, they are run through a series of calculations to determine delta-v, or the change in velocity, required to maneuver between two orbits. These delta-V calculations are used as "distances", or arc lengths, in the network analysis. A design with similar effectiveness but a lower overall delta-V will be preferred over a higher delta-v approach.

The meat of the network calculations involves finding the delta-V costs between two objects. This can be done by solving Lambert's problem, as follows [7]:

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 $\Delta\theta$:

$$\Delta\theta = \begin{cases} \cos^{-1}\left(\frac{\boldsymbol{r_1} \cdot \boldsymbol{r_2}}{r_1 r_2}\right), if\ \boldsymbol{r_1} \times \boldsymbol{r_2} < 0\ and\ retrograde \\ 360^{\circ} - \cos^{-1}\left(\frac{\boldsymbol{r_1} \cdot \boldsymbol{r_2}}{r_1 r_2}\right), if\ \boldsymbol{r_1} \times \boldsymbol{r_2} \geq 0\ and\ retrograde \\ \cos^{-1}\left(\frac{\boldsymbol{r_1} \cdot \boldsymbol{r_2}}{r_1 r_2}\right), if\ \boldsymbol{r_1} \times \boldsymbol{r_2} \geq 0\ and\ prograde \\ 360^{\circ} - \cos^{-1}\left(\frac{\boldsymbol{r_1} \cdot \boldsymbol{r_2}}{r_1 r_2}\right), if\ \boldsymbol{r_1} \times \boldsymbol{r_2} < 0\ and\ prograde \end{cases} \quad (2)$$

Find A:

$$A = \sin\Delta\theta \sqrt{\frac{r_1 r_2}{1 - \cos\Delta\theta}} \quad (3)$$

Iterate through the following equations to find z:

$$z_{i+1} = z_i - \frac{F(z_i)}{F'(z_i)} \quad (4)$$

$$F(z) = \left[\frac{y(z)}{C(z)}\right]^{\frac{3}{2}} S(z) + A\sqrt{y(z)} - \sqrt{\mu}\Delta t \quad (5)$$

$$F'(z) = \frac{1}{2\sqrt{y(z)C(z)^5}} \{\left[2C(z)S'(z) - 3C'(z)S(z)\right]y^2(z) + \left[AC(z)^{5/2} + 3C(z)S(z)y(z)\right]y'(z)\} \quad (6)$$

$$y'(z) = \frac{A}{4}\sqrt{C(z)} \quad (7)$$

$$C(z) = \sum_{k=0}^{\infty} (-1)^k \frac{z^k}{(2k+3)!}, S(z) = \sum_{k=0}^{\infty} (-1)^k \frac{z^k}{(2k+2)!} \quad (8)$$

Find $y(z)$:

$$y(z) = r_1 + r_2 + A\frac{zS(z) - 1}{\sqrt{C(z)}} \quad (9)$$

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

$$f = 1 - \frac{y(z)}{r_1}, \dot{f} = \frac{\sqrt{\mu}}{r_1 r_2}\sqrt{\frac{y(z)}{C(z)}}[zS(z)\text{-}1] \quad (10)$$

$$g = A\sqrt{\frac{y(z)}{\mu}}, \dot{g} = 1 - \frac{y(z)}{r_2} \quad (11)$$

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

$$v_1 = \frac{1}{g}(\boldsymbol{r_1}\text{-}f\boldsymbol{r_2}) \quad (12)$$

$$v_2 = \frac{\dot{g}}{g}r_2\text{-}\frac{f\dot{g}\text{-}\dot{f}g}{g}r_1 \quad (13)$$

$$dV = |v_1\text{-}v_2| \quad (14)$$

A matrix of delta-V values is generated, where the 1st index is the interceptor orbit and the 2nd index is the target orbit, with zeroes on the diagonal. The score generated by matching the design alternative with the debris object is taken and divided by the delta-V required to reach the object. This produces a new matrix of total value for each debris object, of which the maximum is found. This object is selected and removed from further consideration, and the time of flight is adjusted, and the process is repeated until the delta-V budget is expended or there are no feasible targets left.

III. Utility Analysis

Once results have been obtained from object categorization and network analysis, aggregating them via a utility analysis into a meaningful number is needed. Below is a value hierarchy for use in evaluating the total utility of design alternatives. Weights are determined via an Analytical Hierarchy Process (AHP) methodology, using pairwise comparisons.

This value hierarchy consists of three major elements, all of which are further decomposed. These elements are performance, risk, and political viability. Performance is broken down into object scores and delta-V cost, risk is broken down into safety and reliability, and political viability is broken into agreeability and verifiability. Safety, reliability, agreeability, and verifiability are all further decomposed as well.

Performance: The overall quality of the remediation system, as further defined via "Object Scores" and "Delta-V Cost".

Risk: Any danger including accident, failure, or delay in a process to remediate space debris, further defined by "Safety", "Reliability", and "TRL".

Political Viability: The viability of a solution in the international sphere, as further defined by "Agreeability" and "Verifiability".

Object Scores: The appropriateness of the given ADR design for the types of debris that are being remediated.

Delta-V Cost: The delta-v cost incurred by the deployment of the given Debris Remediation System.

Safety: It considers any damages caused by failures or problems during the project. Further decomposed by "Accidents", "Debris Control", and "Landing".

Reliability: The quality of ADR system to remediate or remove debris object. Further decomposed by "Approach", "Maneuver", "Grapple", "De-tumble", and "De-orbit".

TRL: The Technology Readiness Level of each ADR system, as defined by NASA.

Accidents: Accidental collisions and failures/problems in system that can alter the system itself to new debris object.

Debris Control: Risk of failure in processes of grabbing and de-tumbling debris object.

Landing: Damage by debris object in case of that debris object does not fully burn upon the atmosphere.

Approach: A process for DRS (carrying ADR system) to reach debris object in a certain distance.

Maneuver: A process for ADR system to operate and propel itself throughout the LEO environment.

Grapple: A process for ADR system to catch debris object. It is only applied to certain ADR systems which require the physical contact with debris object.

De-tumble: A process for ADR system to stop the rotation of debris object.

De-orbit: A process for ADR system to change an orbit of debris object.

Agreeability: The ability for multiple sides to have same views and opinions. Further decomposed by "Weaponization", "Legal Framework", and "Strategy".

Verifiability: The ability to confirm that requirements/policy/laws are met correctly. Further decomposed by "Type of Cooperation" and "Nationality".

Weaponization: The possibility of using a certain ADR design for military or other non-peaceful uses would violate Outer Space Treaty and international space law.

Legal Framework: Ease of implementing an ADR design within the current international space law.

Type of Cooperation: Cooperation of two or more countries in effort of remediation (single country vs. multiple countries).

Nationality: The nationality of both space debris and the initiative country to (apply) the space policy could affect the political verifiability of a space policy. Further defined by "Initiative" and "Objects".

Initiative: Nationality of the country that is associated with applying the space policy, in other words, the country that plan and deploy ADR.

Objects: Nationality of objects in space is also important to consider and affect political viability. For example, Russia has most space debris and doesn't want any other country to remove their debris from space.

DESIGN OF EXPERIMENT

While there are stochastic elements in the field of space debris, particularly in terms of conjunction analysis, this paper describes a deterministic evaluation. The model mathematically determines object scores and delta-v costs, which are then optimized. The experiments performed focus on varying constraints for the network, as this is the most adaptable element.

Several runs were performed for each performance parameter, and high, likely, and low values were determined. Similar ranges of values were ascribed to the other attributes, as many elements of political viability are not deterministic or objective, but rather depend on a subjective political environment.

RESULTS

After running all the ADR designs through the object categorization, network analysis, and utility analysis, overall utility scores were generated for each. In addition, a low and a high bound were generated by varying some of the subjective elements, such as political viability. These values are then compared to the costs, as seen below. Certain designs, such as robotic arm, COBRA, eddy currents, and 3-coordinated spacecraft, failed to meet functional or mission requirements, and thus earned a utility of 0.

TABLE I
DESIGN ALTERNATIVES UTILITY AND COST

	Utility			
Alternative	**Low**	**Likely**	**High**	**Cost**
Robotic Arm	0	0	0	$67,620,000
Throw Net	4.7	6.4	7.2	$84,180,000
Harpoon	4.3	5.8	7.0	$7,960,000
COBRA	0	0	0	$302,150,000
3-Coordinated	0	0	0	$462,670,000
Eddy	0	0	0	$241,980,000
EDDE	4.5	5.9	7.1	$314,350,000

CONCLUSION

The throw net had the highest likely utility, with 6.4. However, looking at utility per dollar allows more conclusions to be drawn.

With this data, it is clear that the harpoon, while not the highest utility, is the most cost efficient solution.

TABLE II
DESIGN ALTERNATIVES UTILITY PER DOLLAR

Alternative	Utility	Cost	Utility/Cost*10^8
Throw Net	6.4	$84,180,000	7.6
Harpoon	5.8	$7,960,000	72
EDDE	5.9	$314,350,000	1.9

In addition, if the focus is put on the attributes with the highest weights political viability is clearly crucial to the success of any design alternative. It becomes clear then while most designs are feasible and competitive, but that the most viable design alternative will be the one that is most agreeable to the international community.

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