Design and Evaluation of an Orbital Debris Remediation System

SYST 490 Technical Report

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1 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 hazard 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 an impenetrable sphere of trash orbiting our planet, severely impeding any future development or use of space [2].

The probability of collisions has increased 7-fold over the past 10 years [3, 4]. This increase is attributed to the overall rise in orbital populations, driven by expansion of the commercial space industry [1] and by recent collision events. In 2007 the Chinese launched an anti-satellite missile against their own Fengyun satellite, producing 2841 pieces of debris, and in 2009 there was a random collision between the Cosmos 2251 and Iridium 33 satellites, producing a further 1788 pieces of debris, together doubling the number of objects in orbit below 1000 kilometers [3, 5]. These factors led to an increase in conjunction events, which are directly proportional to collision probability [3].

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.

![Figure 1 - History of Orbital Debris](image)

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.
2 Context Analysis
2.1 Current Investments

There are currently over 1261 operational satellites in orbit. Of these, 52% are communications satellites, with the remaining 48% being spread between meteorological, military, navigational, and scientific purposes [1]. These satellites range in size from 1 kilogram to 18,000 kilograms [7]. Launch costs are generally proportional to the mass of the payload, with a current price of anywhere from $4500 to $22,000 per kilogram [8]. A relative newcomer to the launch services community, SpaceX, claims to be able to provide launches for $1700 per kilogram [9], though this capability has yet to be proven. There are also the direct development costs of each satellite to consider. This information is more difficult to ascertain, as many factors play into each satellite, including fixed costs, learning curves, evolution of technology and miniaturization, and economy of scale. However, we can find estimates for determine the feasible range of development costs, which goes from $7,500 for a Cubesat to $2.2 billion for the ESA’s Envisat [10, 11].

![Figure 2 - Satellite Population, Sep. 2015](image)

All told, the global space industry is worth approximately $203 billion. These investments generate revenue from a variety of sources, including the manufacture and launch of orbital systems. The main drivers of revenue come from satellite services as a whole, such as television and meteorology, comprising over 60% of revenue in 2014. Ground equipment, used to interface with orbiting space assets, constitutes a further 28% of revenue [1].
2.2 Types of Orbits

Orbits are defined in terms of six major elements: semi-major axis, eccentricity, inclination, argument of periapsis, time of periapsis passage, and longitude of ascending node. The semi-major axis is the distance from the center of the orbit (for most satellites, this is the Earth itself) to the farthest point on the ellipse, in essence the altitude of the object. Eccentricity varies from 0 to 1, 0 being a perfectly circular orbit and 1 being a parabola (and technically not truly an orbit at all, but an escape trajectory). Inclination is the angular distance between the orbital plane of the object and the equator of the body being orbited (or primary body), measured in degrees. The argument of periapsis, periapsis being the point in the orbit where the object is closest to the primary body, is the angular distance between the ascending node and the periapsis itself. The time of periapsis passage is self explanatory; it is the time when the object passes through its periapsis. Lastly, the ascending node is the point on the orbit where the orbit crosses the equator of the primary body from south to north [12].

Orbits are chosen depending on the use desired for the given satellite. For example, a geostationary (GEO) orbit, with an altitude of 35,786 kilometers, an eccentricity of 0, and an inclination of 0 degrees, is used to “hover” over a given latitude. This is useful for weather monitoring, allowing long-term tracking of changes. However, this is only usable near the equator. A Molniya orbit has an altitude ranging from 500 to 39,873 kilometers, an eccentricity of 0.7, and an inclination of 63.4 degrees. This leads to a large loiter time over a single hemisphere, allowing for similar effectiveness as a geostationary orbit. Finally, there are many orbits in Low Earth Orbit (LEO) below 2000 kilometers altitude, with various inclinations. A polar orbit, with inclination near 90 degrees, can be used to quickly survey the entire planet. As
the satellite flies pole-to-pole, the earth spins underneath it, allowing total coverage of the planet [13].

![Diagram of Types of Orbits]

Figure 4 - Types of Orbits [56]

The orbital populations, both of operational satellites and debris, vary widely with altitude, inclination, and eccentricity. Some of the most highly populated regions are around 800 kilometers and 1500 kilometers [14].
2.3 Orbital Debris Threat

There are presently over 22,000 objects larger than 10 centimeters in orbit, and approximately 21,000 of those are debris [1, 15]. In addition, there are over 100 million pieces of debris that are too small to track and are estimated based on a variety of factors, including known collision events, simulations, and historical trends [15]. This debris takes many forms, from loose screws or flaky particles to entire obsolete or retired satellites. In addition, some of the largest objects are expended rocket bodies, comprising 97% of the total mass [5]. These derelicts can contain leftover propellant or faulty batteries, and can thus prove to be a serious risk for explosion and further propagation of debris [16].

The energy contained in a given object, a good measure for the potential for damage, is given by the following equation:

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

When velocity is large, as it is for every orbital object, $\varepsilon$ increases dramatically very quickly. In addition, while not as intense of an effect as velocity, increases in mass also have a serious impact on energy.
Ever since the launch of Sputnik in 1957, Earth’s orbits have been getting more and more crowded. In particular, the last 10 years have seen a sharp rise of the number and mass of objects in orbit. Advances in technology, especially in communications, have led to larger numbers of satellites launched, increasing the operational population [1]. In addition, there have been several collision events, notably the 2007 Chinese anti-satellite missile test and the 2009 collision between the Iridium 33 and Cosmos 2251 satellites, which have drastically increased the debris population [5]. The combination of these two factors has led to an increase in conjunction events, which itself leads to an increased collision probability.

Currently, the composite collision rate for an object in low earth orbit is 0.005 per year [16]. This calculation includes collisions ranging from tiny micro-meteor impacts to massive, explosive collisions with other space assets. This risk is projected to continue to climb, even in the face of post-mission disposal (PMD) efforts [14].
Scientists have recognized the potential threat of un-remediated space debris ever since the 1960’s and the first orbital flights. As soon as it was clear that atmospheric drag would not capture all objects above a certain altitude (around 600 kilometers [17]), it also became clear that anything that gets into orbit above that height will tend to stay in orbit. In 1978, Dr. Donald Kessler made the first prediction of what would become known as the Kessler Syndrome. The Kessler Syndrome refers to a chain reaction of collisions, where each collision produce enough debris to further collide with other objects, resulting in a domino effect that would eventually obliterate all satellites in orbit [18]. Acknowledging this threat, the international space community has made strides to prevent further worsening of the danger. To do so, the United Nations Office of Outer Space Affairs (UNOOSA) has published guidelines for all newly launched satellites, essentially requiring total lifecycle planning [6]. Every satellite that goes up into space should have a plan for when it is coming back down. However, this effort alone is not sufficient to prevent the Kessler Syndrome; some from of remediation will be required [5], and this is where our team comes in.

### 2.4 Dynamic Orbital System

We have begun building a first-order dynamic systems model to help up analyze the orbital environment. Many space agencies have developed their own models for simulating debris risk, such as NASA’s LEGNED model. However, these are intense, long-running simulations that we do not have access to. By building our own rough model, mimicking a classic SIR model, we hope to be able to run rapid, easily modifiable simulations. That being...
said, this is not a crucial aspect of our project, but more of a tool for verification and future exploration.

The mathematics behind this model are still in flux, but a brief description of each element is in order:

Post Mission Disposal: this represents the mitigation efforts that have already been put into place, systematically removing objects as they reach a certain age (about 25 years).

Natural Decay: This represents objects that are affected by environmental conditions such as atmospheric drag such that they naturally remove themselves from orbit. This is only really a factor for objects lower that 600 km.

Objects in Orbit: The main body of the model, along with collisions, this includes all objects from operational satellites to debris. Anything that is currently in orbit is counted.

Collisions: Collisions is exactly what it sounds like, any collision between two (or more) objects in orbit. There is a positive feedback loop between this and “Objects in Orbit” because, similar to the SIR model, as more collisions occurs, more objects appear, which in turn raises the possibility of collisions. We want to minimize this bubble by modifying the “Objects in Orbit”.

Figure 8 - Dynamic Orbital System Model
Launches and Gain, A and B: This is a somewhat abstract element, referring to any and all launches, whether they be from the same organization or not. The reason that “Launches” and “Gain” are broken out into A and B is to highlight the potential for the Tragedy of the Commons. When two entities, A and B, share a pooled resource, “Objects in Orbit”, yet have separate rewards, “Gain”, then they are both incentivized to exhaust the pooled resource before their competitor does. This leads to an arms race of sorts, destroying the space environment.

Debris Remediation System: this represents our system, as described throughout the rest of this report.

We have a preliminary model currently being built in Simulink, see section 10 for more.
3 Stakeholder Analysis

The top-level stakeholders consists of three groups: National government, commercial industry, and civil organizations. Each top level stakeholder consists of sub-level stakeholders. National governments that is considered are: the United States of America, Europe, Russia, and China. For commercial industry, we have considered three sub-level stakeholders: Transport companies, systems manufacturers, and insurance companies. For civil organization, we took into account six organizations: Inter-Agency Space Debris Coordination Committee, National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, European Space Agency, Russian Federal Space Agency, and China National Space Administration.

3.1 National Governments

All of national government follow the same process regarding space programs, however, each national government distributes responsibilities in space programs differently. The following is the process that each national government follow in space-related activities:

In the United States of America, the President’s office is responsible for creating a space policy based on proposals of space activities by NASA; the US Congress has the authority of determining whether or not to approve funding for the proposed space policy. Then, the White House offices is responsible for execution of findings that will be available to NASA to perform the space policy [19, 20].

In Europe, we have considered the European Space Agency as a main stakeholder; the European Space Agency is an intergovernmental agency that is not a body of the European Union, however, the European Union is the largest financial contributor to the ESA space programs [21]. The space policies of the European Space Agency are proposed to its member states for agreement; Each member state has one vote, regardless of its size or financial contribution [22]. the European Space Agency is responsible for implementing space activities that are determined [23].

In Russia, the Federal Space Agency is an executive governmental body that has the authority of determining the policies in aerospace industry [24] and implementing government policy and legal regulation [25].

In China, The State Administration on Science, Technology, and Industry for National Defense (SASTIND) is responsible for executing space-related regulations [26]. China Space Agency sets overall guidance and policy [27]. Afterward, the Chinese State Council is the government body that has the authority of approving funds, and issuing a five-year space plan [28]. Funds execution and operating space activities is the responsibility of the People’s Liberation Army [29].

3.1.1 United States of America

In the United States of America, we have considered four main departments that has interactions related to space debris remediation programs: The President’s office, the Congress, the Department of Defense, and the White House offices which includes the Office of Science and Technology Policy, the National Security Council, the Office of Management and Budget. The overall objective is to create a space policy that has been advised by NASA, afterward, space policies that has been created would either get approved for funding or rejected by the Congress. If a space policy gets approved, it will be funded by one of the White House offices, the Office of Management and Budget [30].
The Department of Defense main objective is to maintain and protect the security of the United States of America. It uses different types of operational satellites, such as communications and monitoring satellites to achieve its goals [31].

3.1.2 Europe

In Europe, we have considered two top-level stakeholders: the European Union, which is the largest financial contributor to the European Space Agency (ESA), and Non-European Union state members, which are members of European Space Agency that are not a part of European Union. The European Union consists of three main departments: the European Commission, the European Parliament, and the Council of the European Union [21].

The European Commission is an independent governmental body of national governments of the European Union state members that represents the European Union interests as a whole. Its main objectives are to propose new European laws to both the European Parliament and the Council, and to implement decisions that are made by the European Parliament and Council. The European Parliament is elected by citizens of the European Union to represent their interests [32]. It has three main objectives: approval of European laws, democratic supervision, and authority over European Union’s budget. The Parliament shares the approval of European laws and authority over European Union’s budget with the Council [33].

The Council of the European Union is the main decision-making body in the European Union that represents the interests of the European Union member states. It has two main objectives: approval of European laws, jointly with the Parliament, and approval of the European Union’s budget, jointly with the Parliament [34].

3.1.3 Russia

In Russia, we have considered two main stakeholders: Aerospace Forces of the Ministry of Defense of the Russian Federation, and the Prime Minister of Russian Federation offices. Aerospace Forces objectives are to provide reliable information of any warning about missile attacks, observe and detect space threats against Russia, launch spacecraft, and control military and dual-purpose satellite systems [35]. The Prime Minister of Russian Federation offices are responsible for implementing governmental policies regarding the development of defense, rockets, and spacecraft [36].

3.1.4 China

In China, three stakeholders have been considered: Chinese State Council, the State Administration on Science, Technology, and Industry for National Defense (SASTIND), and People’s Liberation Army (PLA), which is a component of China’s Ministry of Defense. The Chinese State Council is the highest ranking government body of China; it holds the responsibility for both funding decisions for space activities and issuing a five-year space plan as a form of government White Paper [28]. SASTIND is the main civilian regulatory authority in China [37]. SASTIND objectives are to coordinate and manages China’s space activities, and execute space regulations. People’s Liberation Army’s objective is to operate the manned spaceflight program, and execute funding for space activities [29].

3.2 Commercial Industry

3.2.1 Transport Companies

Commercial space transport companies including SpaceX, United Launch Alliance (ULA) and Federal Aviation Administration are the main transport companies that have interactions related to space debris remediation programs [38]. Their overall objectives are to enable people to live on other planets, provide spacecraft launch services to the government of
the United States and provide safety, efficiency and environmental responsible to the stakeholders [38].

3.2.2 System Manufacturers

The commercial space systems manufacturers including Lockheed Martin, Boeing and Orbital Sciences, are companies that manufacture and design space systems and has interactions related to space debris remediation programs. Their objectives is to solve complex problems, advance scientific discovery, deliver innovative solutions, design, build and support aircrafts, spacecraft, rockets and satellites and build and deliver defense, space and aviation to the whole world [40].

3.2.3 Insurance Companies

XL Catlin, AGCS space coverage and STARR are a global insurance companies and considered part of our stakeholders. All of them provides space and satellites insurance including, AIT, pre-launch, launch, commissioning and in-orbit life, in-orbit incentives, service interruption/loss of revenue, third party liability, captive risk management launch plus in-orbit risks, In-orbit coverage, satellite incentive coverage, launch risk guarantee, and space third-party legal liability.

3.3 Civil Organizations

3.3.1 Inter-Agency Space Debris Coordination Committee (IADC)

The Inter-Agency Space Debris Coordination Committee is an international governmental meeting for the worldwide coordination of activities to deal with space debris of manmade and natural debris. The overall objective of the IADC is to allow the member agencies to exchange information on space debris research activities and identify debris mitigation options [41].

3.3.2 National Aeronautics and Space Administration (NASA)

The National Aeronautics and space Administration is the United States government space agency program. NASA headquarters are located in Washington, D.C., and there are ten NASA research centers like Johnson Space Center and Kennedy Space Center and their objectives is to provides overall guidance and direction [42]. NASA main objectives are to develop the future in space exploration, explore the the earth and solar system and aeronautics research [43].

3.3.3 National Oceanic and Atmospheric Administration (NOAA)

The National Oceanic and Atmospheric Administration is a federal agency focused on the conditions of the oceans and atmosphere. Their main objectives are to provide information about oceans and atmosphere including environmental monitoring and severe weather prediction, as well as providing sea surface height measurements, that is used to determine ocean circulation, climate change, and sea level rise [44].

3.3.4 European Space Agency (ESA)

The European Space Agency is an international organization with 22 member states. ESA headquarters are located in Paris, French and there are five ESA centers like the European Space Operations Center (ESOC) and The European Space Astronomy Center (ESAC) and their objectives is to provides overall guidance and direction. ESA main objectives is to find more about earth, space environment, solar system and the universe, as well as developing satellite technologies and services [45].
3.3.5 Russian Federal Space Agency

The Russian Federal Space Agency (which is also commonly called Roscosmos) is the Russian government space agency program. RFSA headquarters are located in Moscow and their main objectives is to provide state services and administration of the state space assets and manage the international cooperation in joint space programs and projects. RFSA is also responsible for overall regulation of the activities at the Baikonur spaceport [46]. The Cosmonauts Training Centre (GCTC) is a Russian training center and it is to responsible for training cosmonauts (Astronauts) for their space missions [47]. The Baikonur Cosmodrome and the Plesetsk Cosmodrome are an operational space launch facility. All space station flights using launch vehicles is launched from these facilities [48].

3.3.6 China National Space Administration (CNSA)

The China National Space Administration is the national space agency of the People’s Republic of China. CNSA headquarters are located in Beijing and the overall objectives of CNSA is to plan and develop space activities, sign governmental agreements in the space area on behalf of organizations, intergovernmental scientific and technical exchanges, enforcement of national space policies and sets overall guidance and policy for the entire space program. CNSA includes the Department of General Planning, Department of System Engineering, Department of Science, Technology and Quality Control and Department of Foreign Affairs [37].

3.4 Stakeholder Interactions and Tensions

For the top level stakeholders which includes the national governments, and it is divided to United States, European Union, China and Russia. Then we have Civil Organizations and it has NASA, ESA, CNSA and RFSA. And finally we have the Commercial Industry and it is divided to system manufactures companies, transport companies and insurance companies. Each national government approve and fund their own space agency, while each space agency research, collect data and provide overall guidance to their national governments. NASA, ESA, CNSA and RFSA exchange information on space debris research activities and identify debris mitigation options [41]. Finally, The Commercial Industry provide space services and insurances to both National governments and Civil Organizations.

There are four main tensions among stakeholders that we considered: International political tensions, insurance companies, time of occurrence of large debris collisions, and regulations.

For the political tensions, Russia owns most of satellites and debris in space [53], and doesn't want anyone to touch their objects which will lead to a roadblock with other national governments. Also, some of the methodologies may be construed to have the potential dual use as a weapon to either disable or de-orbit. When a country launches a rocket for space activities, it is possible that other countries will suspect the purpose of the launch [54].

Another political tensions is that some of the removed objects using removal alternatives might be an international issue due to inaccuracy of dropping locations. For the insurance companies there are two type of tensions. The first type is the tension between the commercial companies and the insurance companies, where insurance companies’ objective is to manage risks, while commercial companies’ objective is to minimize cost. The second type is the Competitiveness between insurance companies, whether they consider collision risk in their policies.

Time of occurrence of large debris collision is how frequent does a large debris getting hit by another object which will cause debris population to grow. According to XL Catlin Vice President and Global Underwriting Manager, Christopher Kunstadter, the growing risk of
collisions of large objects in space is not considered important enough to be covered separately, and competition between insurance companies (along with slim profit margins) guarantees that no excess costs will be incurred to cover space debris unless absolutely necessary. Similarly, commercial companies would not pay attention to the issue since they are fully insured. On the other hand, growing risk of collision of large debris is a vital issue to all government space agencies since one of their objectives is to remediate space debris until it reaches stable condition.

Another tension is between regulations issuing organizations and satellite launchers. Organizations such as, IADC requires launchers to have an end-of-life plan; however, not all satellite launchers follow their guidelines and regulations [55].

Table 1 - Stakeholder Tensions

<table>
<thead>
<tr>
<th>Type</th>
<th>Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Political</td>
<td>● Russia owns most of satellites/debris in space, and doesn't want anyone to remove their debris objects.</td>
</tr>
<tr>
<td></td>
<td>● Some of the methodologies may be construed to have the potential dual use a weapon to either disable or de-orbit (China and Russia).</td>
</tr>
<tr>
<td></td>
<td>● Removing objects using ADR alternatives could be an international conflict due to inaccuracy of dropping locations.</td>
</tr>
<tr>
<td>Commercial</td>
<td>● Insurance companies’ objective is to manage risks. While commercial companies’ objective is to minimize cost.</td>
</tr>
<tr>
<td></td>
<td>● Competitiveness between insurance companies if considers collision risk in their policies</td>
</tr>
<tr>
<td>Time of occurrence of larger effects (large debris)</td>
<td>● for insurance companies: Problem doesn't matter that much (make profit in present time)</td>
</tr>
<tr>
<td></td>
<td>● for commercial: They are insured, it wouldn’t matter</td>
</tr>
<tr>
<td></td>
<td>● military/national government:</td>
</tr>
<tr>
<td></td>
<td>● for government agencies: concerned</td>
</tr>
<tr>
<td>Time of occurrence of smaller effects (small debris/fragments)</td>
<td>● Not considered</td>
</tr>
<tr>
<td>United Nations – Satellite manufacturers – Organizations involves/owns satellites</td>
<td>● Policy that requires owner of satellite to have a re-entry controlled plan</td>
</tr>
<tr>
<td></td>
<td>● Not all owners/satellites manufacturers would agree/register.</td>
</tr>
<tr>
<td></td>
<td>● IADC &amp; COPUOS regulations.</td>
</tr>
<tr>
<td>Financial</td>
<td>● Space agencies (NASA) would like more funds for their research and projects.</td>
</tr>
<tr>
<td></td>
<td>● Government wants to reduce budgets as much as possible (US)</td>
</tr>
</tbody>
</table>
3.5 Process for Implementing ADR

As mentioned earlier, space debris population is increases; which causes to decrease the space safety for both current and future spacecraft. In other words, increase of space debris population has a positive correlation with risk of collision of operating spacecraft in space. Moreover, satellite demand has been increasing in the last decade. Implementation of Active Debris Removal is driven by such changes that are considered the triggers for considering Active Debris Removal efforts. Process of implementing Active Debris Removal consists of three major phases: Pre-launch, launch, and in-orbit life phase. Each phase consists of objectives of top level stakeholders.

For the pre-launch phase, all top level stakeholders are involved; furthermore, it is the phase where most of processes and objectives are done. It starts with civil organizations, such as NASA that conduct research, collect data, and provide proposals to national government such as the United States government. National government's objectives are to approve the proposed space policy and to provide funding for the proposed space policy. After national approval of a space policy, it needs to politically viable for all countries. In other words, space policy should be approved internationally to avoid any political conflicts and tensions. Both national and international approval of a space policy are very important processes because governments are potential executive bodies that considered a main decision making body in implementing Active Debris Removal. Afterwards, commercial industry is responsible for designing and building the specified Active Debris Removal design(s) based on the proposed space policy. At the end of the pre-launch phase, insurance companies will evaluate the spacecraft and then determine pre-launch insurance costs.
At the beginning of the second (launch) phase, Active Debris Removal design(s) would be built and ready for launching. Civil organizations will be responsible for both determining launching type and site; Selection of launching type and site would be heavily dependent on targeted debris object(s) that is planned to be removed from space. After selection of launching type and site, insurance companies appear once again to cover launching risks. Eventually, commercial industry is responsible for providing launching services for the spacecraft.

In the last phase, in-orbit life phase, all stakeholders are involved in the beginning. Civil organizations are responsible for monitor the progress of capturing targeted debris object(s) from space, while national governments and commercial industry are working simultaneously in providing space surveillance and detection of movements of objects in space to avoid any collision. Figure 10 describes the processes and objectives of stakeholders in implementing Active Debris Removal design(s):

![Figure 10 - Process for Implementing ADR](image-url)
4 Problem Statement

4.1 Overview

Probability of collision can be assumed to be directly proportional to conjunction rates. Conjunction rates, and thus collision probability, between objects in Low Earth Orbit has increased from 1419 conjunctions per day in 2006 to 10,704 conjunctions per day in 2010 [3, 4]. Much of this expansion stems from new low-cost, high-volume satellite designs, particularly Cubesats [1]. In addition, there have been two major events in the past 10 years that contributed to the debris population. In 2007 the Chinese launched a SC-19 anti-satellite missile against the defunct Chinese Fengyun satellite. The test was a success for the missile, and a tragedy for the rest of the satellite community, producing 2841 pieces of debris [3]. In 2009 there was a collision event between the Iridium 33 and Cosmos 2251 satellites. The Cosmos 2251 was a defunct Russian communications satellite whose orbit happened to intersect the Iridium communications satellite’s orbit. They collided, producing 1788 pieces of debris [3]. The combination of these two events, along with continued and expanded launches, has increased the overall population from 0 objects in 1956 to over 100 million objects today [15].

4.2 Gap Analysis

There have been dozens of remediation 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. As it currently stands, differing designs have no universal metric for comparison, leading to ineffective and fruitless evaluations, essentially apples-to-oranges assessments. Without a common sounding board, there is no way to successfully rank or equate designs.

4.3 Need Statement

Without remediation, the number of objects and the number and frequency of collisions are expected to climb, even with complete cessation of future launches [5]. Thus, it is imperative that a remediation design be chosen and implemented. In order to facilitate this, we will design a method and strategy for measuring the quality and value of designs, along with performing an initial trade-space analysis and positing our recommended solution (or solutions).
5 Requirements
5.1 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]:
\[
R_i(t) = P_i(t) \times m_i
\]
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.

5.2 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.

5.3 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.


6 Concept of Operations

In order to address the lack of a rigorous examination of remediation designs, we will perform a thorough analysis of design alternatives. To do so, we will construct a value hierarchy and utility function with which to compare and contrast designs.

6.1 Design Alternatives

There are two general categories of debris remediation examined for prevention of collisions: active debris removal (ADR) and just-in-time collision avoidance (JCA).

6.1.1 Active Debris Removal (ADR)

ADR is to remove debris object from orbit above and beyond the currently-adopted mitigation measures [5]. Since 2006, with the Kessler Syndrome, the studies for removal of derelict spacecraft or satellites have been conducted by researchers across the world. The general concept of those studies is that:

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

The catchers for the ADR system have also been studied by researchers over decades to provide the best feasibility. Among those studies of the ADR system, this paper includes robotic arm, throw net, tentacles, harpoons, Pac-Man, COBRA IRIDES, and three-coordinated electromagnetic spacecraft.

6.1.1.1 Robotic Arm

A robotic arm is used to physically grab the debris and perform a maneuver to change its orbit. In one instantiation, it has a deployed length of 3.7 m and a mass of 80 kg, and it has an estimated peak power demand of 360 W. The capture maneuver process is in following steps:

1. Rendezvous and forced translation
2. Target inspection and attitude estimation
3. Capture planning (on ground)
4. Final approach
5. Capture
6. Target stabilization
7. Characterization of stack
8. Orbit transfer and de-orbit

Single debris that the robotic arm can catch at a time is up to 6,000 kg, which would include RADARSAT-1, ERS 1, SPOT 4, MIDORI II, and MIDORI satellites. The robotic arm allows a rigid and controlled connection to the target and allows repeated capture attempts, but it cannot offer a safe removal of debris target via controlled entry. International Astronautical Congress (IAC) stated a limitation of the robotic arm, “since a number of high priority debris do not disintegrate during an entry, this would cause an on-ground casualty risk not compliant with regulations.” [49]

6.1.1.2 Throw Net

In this method, the system throws a net towards a debris object and pulls the object along a tether. The total area of the net is 3,600 m$^2$ connected to a tether with a length of 70 m. The net entangles the objects due to masses or a closing mechanism. It is a single-shot mechanism, thus in case of a miss, there is a second net for capture attempt. The capture maneuver with the throw net is very similar to the robotic arm:
1. Rendezvous and forced translation
2. Target inspection and attitude estimation
3. Capture planning (on ground)
4. Final approach
5. Capture (second attempt in case of missing)
6. Target stabilization
7. Characterization of stack
8. Orbit transfer and de-orbit

This mechanism can capture a debris with a mass up to 10,000 kg which covers all the derelict satellites in LEO.

6.1.1.3 COBRA IRIDES

COBRA was proposed as a solution to one of the challenges issued by ESA within the framework of the SysNova competition and it was eventually declared the winner. According to the paper, “The COBRA IRIDES Experiment” [50] the COBRA IRIDES experiment is to be performed after the completion of the IRIDES experiment, the goal of which is to perform close rendezvous with a non-cooperative satellite (Picard, dry mass = 144.72 kg). After the IRIDES experiment ends, Mango satellite (dry mass = 137.815 kg) will be in close proximity of Picard. The objective of the COBRA experiment is to use plume impingement of Mango’s thrusters on the surface of Picard to induce torque on the Picard and impart a new rotational state. The rotational state before and after the thruster firing will be determined by means of observations with Mango’s on-board camera. Basically, 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.

The main feasibility of the experiment depends on the observability of the torque effect of the plume impingement during post-processing of the experiment data. Mango satellite observes the target, rotates the thruster towards the target, performs the push, rotates back and continues observing.

The main concern during the experiment is to ensure that the plume impingement occurs in a favorable configuration with the thruster plume impacting on the solar panel to maximize the torque imparted on Picard. Thales Alenia Italy evaluated the possible damaging effects on it. Considerable effects are paschen discharges, chemical contamination, thermal loading, erosion, and force loading.

6.1.1.7 Three-Coordinated Electromagnetic Spacecraft

Three-coordinated electromagnetic spacecraft is studied at College of Aerospace Science and Engineering, National University of Defense Technology in China. 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 [51]. By exploiting the actuation of the inter-craft electromagnetic force, the collision between the servicer satellite and the disabled satellite can be avoided. The configuration of the three electromagnetic working satellites and the disabled satellite can be seen below, where electromagnetic satellite 1 is located at the front of the disabled satellite, D, and electromagnetic satellites 2 and 3 are equally located both sides of the D with the rotation angle θ with respect to the electromagnetic satellite 1.
6.1.2 Just-in-time Collision Avoidance (JCA)

Beside the ADR, there is another strategy for prevention of collisions involving space debris, called just-in-time collision avoidance (JCA). The JCA system is to deflect a debris object’s trajectory to avoid a collision. For the concept of the JCA, the first step is to identify an imminent collision object from ground and orbital systems, then an air-launch system is used to deploy the JCA system on board. After deploying the JCA, cloud of high density gas is deployed in path of one of the potentially-colliding objects. If the object’s orbit is altered enough, then the collision will be prevented. The total time for intervention is 10’s of minutes to hours, and the air-launch system takes less than 30 min [52]. The effect on a debris object is dependent on the density and size of the JCA gaseous cloud in addition to the area to mass ratio of the object. The higher the area to mass ratio of the object is, the greater the change in the object’s orbit from the gaseous impulse will be.

Compared to the ADR, the JCA has advantages. The JCA has better cost efficiency. Since the JCA uses the air-launch system instead of a rocket launch system, it costs about 10 times less. Using the gas cloud enables the JCA system to skip the process of capturing and de-tumbling which reduce operational time and increase safety for other unexpected collision by non-trackable objects.

There is also disadvantage which is that the debris object is still on the Earth orbit. Even if an imminent collision is prevented, since the object is left on orbit, it can cause future collision. There is no decrease in overall collision probability.

6.1.3 Expansion of Property Rights

An alternative to a traditional, direct remediation would be to explore political strategies. The root of the orbital debris problem stems from the tragedy of the commons. As no one truly owns outer space, and orbits are rarely policed, there is little to no incentive to mitigate or remediate your own space waste. Therefore, it is possible that the best solution would involve a long-term solution of this problem. The classic approach to the tragedy of the commons is property rights. Thus, a potential remediation design would be an expansion and allocation of property rights in outer space. There are several assumptions involved, along with many complex issues with implementation, but this is a promising, enduring solution that would have ramifications and ripple effects far beyond the immediacy of this project.
6.2 Method of Analysis

Our method of analysis will consist of three major steps: object categorization, network analysis, and utility analysis. Figure 12 shows the inputs and outputs from each element, culminating with a best strategy recommendation from the utility analysis.

6.2.1 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.

The effectiveness of the object’s mass is calculated through linear decreasing distribution, taking into account the minimum and maximum range that each ADR design is capable of handling. On the other hand, the effectiveness of the object’s velocity and rotation is calculated through exponential decreasing distribution, taking into account the energy and shear forces that an ADR design can handle.

Each targeted object is given a score for each ADR design, which determines the “best” design to remove the object from space. Once we obtained the data for each ADR designs, we can apply it to determine the object score for all the targeted objects.
6.2.2 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.

6.2.2.1 Classic Orbital Elements

There are six COE’s that together provide a comprehensive description of where an object is in orbit. They areas follows:
Semi-major axis: the size of the orbit, specifically the length from the center of the orbit to the longest edge of the ellipse. In other words, the semi-major axis is half the distance of the long axis of an ellipse.

Eccentricity: the shape of the orbit, where eccentricity of zero is a circular orbit and eccentricity of greater than or equal to one is a parabolic or hyperbolic orbit (and thus no longer truly in orbit around the original body).

Inclination: the tilt of the orbital plane with respect to a fundamental plane, in our case the equatorial plane. Inclination of 90 degrees is a polar orbit, that is it passes directly over the poles, and inclination of 0 or 180 degrees is an equatorial orbit.

Longitude of the ascending node: this tells you where exactly the orbit intersects with the equatorial orbit (and thus is undefined with inclination is 0). A “node” is the point at which two orbits intersect, and from simple geometry we know that two intersecting circles will have two points of intersection. We use the longitude of the ascending node, or the point of intersection where the satellite is going from south to north, to define the swivel of the orbit.

Argument of perigee: the perigee is the point in an orbit that is closest to the body being orbited. We measure the argument of perigee as the angle from the ascending node to the perigee, giving us an orientation of the orbit within the orbital plane (handy for knowing whether we’re in the northern or southern hemisphere, for example).

True anomaly: the final COE tells us exactly where within the orbit we are at a specific time, measured as the angle from the perigee to the exact position of the spacecraft at a given time.

6.2.2.2 State Vectors

State vectors are a more traditional, familiar format for position and velocity, using vectors. These are convenient in our calculations, as the mathematics of vector multiplication, vector calculus, etc. are far more well-known to us than the esoteric orbital elements.

6.2.2.3 Initial Model

As we will be analyzing pairs of orbits, we are faced with an initial hurdle for object selection. Looking at the formula for combinations:

\[
\binom{n}{k} = \frac{n!}{k!(n-k)!}
\]

And plugging in values the total population \(n\) and the sets to be combined \(k\), we see that we will quickly reach a factorial explosion. For \(n=500, k=2\):

\[
\binom{500}{2} = \frac{500!}{2!(500-2)!} = 124,750
\]

As the orbital population consists of 500,000+ objects, it is easy to see how an exhaustive analysis is nigh impossible, at least without much larger computational capabilities. Thus, we begin by reducing the population to be analyzed by selecting high-mass objects.

Once we have our target population, we begin our object categorization and network analysis steps concurrently. In the network analysis, we much first take in TLE data, convert and store it as COE data for ease of future use. This COE data is then fed into the main driver of our model, our maneuver selection. We have two nested loops, one for interceptor selection and one for target selections, ensuring that we check each target for each interceptor. As long as targets exist for a given interceptor, we convert the COE data to SV data, then send the SV data through a Lambert problem solver to calculate delta-v. We loop over all targets and combine this with calculations from our object categorization to determine the overall value for a given target. Once we’ve looped through all possible targets, we can pick one for the actual maneuver by:
\[ \text{bestTarget} = \max \left\{ \frac{\text{objectScore}_i}{\Delta V_i} \right\}, \text{where } i \text{ is each potential target} \]

This best target is chosen for the actual maneuver, which is then “performed”, advancing the internal clock by the Time Of Flight (TOF) of the maneuver. This time change, or delta-T, is fed back through the system, as this time delay affects the position vectors of all objects. The target that was chosen is removed from the catalog, and the process is repeated until some constraint is broken (maximum payload or delta-v, minimum scores reached, etc.). These constraints will be varied and modified as experiments are performed and knowledge of the performance of the model is better understood.

Aside from conversion between COE’s and SV’s and TLE’s, the main network analysis function is performed by Lambert. Essentially, this is a method for taking two position vectors and a time of flight and calculating velocity vectors. This allows us to do a variety of things, including constructing our network of delta-v costs. This can be computationally intensive, and there are still some kinks to work out (namely, the finding the minimum point in a non-linear system of equations), but there have been similar efforts utilizing the Lambert problem in a similar method before [57].

The steps to solve Lambert’s problem are as follows [58]:

1. Calculate \( r_1 \) and \( r_2 \) using \( r_1 = \sqrt{r_1 \cdot r_1} \) and \( r_2 = \sqrt{r_2 \cdot r_2} \).
2. Choose prograde or retrograde trajectory and find \( \Delta \theta \):
   \[
   \Delta \theta = \begin{cases} 
   \cos^{-1} \left( \frac{r_1 \cdot r_2}{r_1 r_2} \right), & \text{if } r_1 \times r_2 < 0 \text{ and retrograde} \\
   360° - \cos^{-1} \left( \frac{r_1 \cdot r_2}{r_1 r_2} \right), & \text{if } r_1 \times r_2 \geq 0 \text{ and retrograde} \\
   \cos^{-1} \left( \frac{r_1 \cdot r_2}{r_1 r_2} \right), & \text{if } r_1 \times r_2 \geq 0 \text{ and prograde} \\
   360° - \cos^{-1} \left( \frac{r_1 \cdot r_2}{r_1 r_2} \right), & \text{if } r_1 \times r_2 < 0 \text{ and prograde} 
   \end{cases}
   \]
3. Find \( A \):
   \[
   A = \sin \Delta \theta \sqrt{\frac{r_1 r_2}{1 - \cos \Delta \theta}}
   \]
4. Iterate through the following equations to find \( z \):
   \[
   z_{i+1} = z_i - \frac{F(z_i)}{F'(z_i)}
   \]
   \[
   F(z) = \frac{y(z)^3}{C(z)} S(z) + A \sqrt{y(z)} - \sqrt{\mu \Delta t}
   \]
   \[
   F'(z) = \frac{1}{2 \sqrt{y(z) C(z)^5}} \left\{ \left[ 2 C(z) S'(z) - 3 C'(z) S(z) \right] y^2(z) \\
   + \left[ AC(z)^{5/2} + 3 C(z) S(z) y(z) \right] y'(z) \right\}
   \]
   \[
   y'(z) = \frac{A}{4} \sqrt{C(z)}
   \]
   \[
   C(z) = \sum_{k=0}^{\infty} (-1)^k \frac{z^k}{(2k + 3)!}
   \]
\[ S(z) = \sum_{k=0}^{\infty} (-1)^k \frac{z^k}{(2k + 2)!} \]

Find \( y(z) \):
\[ y(z) = r_1 + r_2 + A \frac{zS(z) - 1}{\sqrt{C(z)}} \]

Find \( f, g, \) and \( \dot{g} \):
\[ f = 1 - \frac{y(z)}{r_1} \]
\[ \dot{f} = \frac{\sqrt{\mu}}{r_1 r_2} \frac{y(z)}{C(z)} [zS(z) - 1] \]
\[ g = A \frac{y(z)}{\mu} \]
\[ \dot{g} = 1 - \frac{y(z)}{r_2} \]

Calculate \( v_1 \) and \( v_2 \):
\[ v_1 = \frac{1}{g} (r_1 - f r_2) \]
\[ v_2 = \frac{\dot{g}}{g} r_2 - \frac{f \dot{g} - \dot{f} g}{g} r_1 \]

In section 9. Preliminary Model Code you can see the actual MATLAB functions that are used in our model. In Figure 14 the functions used are labeled below the title of the block.

We merge the results of these calculations with the results from the object categorization and maximize the following objective function (subject to some varying constraints):
\[ \text{Max Score} = \sum_{i}^{n} \left[ \left( \sum_{j}^{m} \text{ObjectScore}_j \right) - \text{LaunchCost}_i - \Delta \text{VCost}_i \right] \]
6.2.3 Utility Analysis

Once we have results from steps 1. and 2. (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.

Initial weights and sample values can be seen in tables 2 through 4, but keep in mind that these weights will be varied in different experimental runs.
6.2.3.1 Object Scores

Object scores come from a combination of steps 1. and 2. in our approach. The scores that come from the object categorization are assigned to specific debris objects. If that object is selected in the network analysis phase, then the score associated with that object is assigned to the overall score of that deployment. This will be a linear increasing value function.

6.2.3.2 Path Length

The path length scores come from step 2. in our method of analysis, the network analysis. Our output from that step comes in the form of a total delta-v cost for a given deployment strategy. This will be in the form of meters per second, and is a linear decreasing function (as delta-v costs increase, the value decreases).

6.2.3.3 Risk

To remediate current space debris, there are many types of risk we have to consider, such as the risk of accidents, failures, or delays. In this paper, risk is specified in terms of safety and reliability.

6.2.3.3.1 Safety

- Chance for DRS itself to become debris by accidental collision or other failure/problem in the system.
- Risk on controlling the debris object during de-tumbling phase which can cause damage on spacecraft and astronauts
- Risk of debris causing damage on Earth
  - On-ground casualty risk

6.2.3.3.2 Reliability

Reliability will be evaluated on a component level. Each component that contributes to each step in the operation of the ADR design will be evaluated on its reliability depending on whether it is in series or parallel.

Parallel Components:

\[ R_T = \prod R_i \]

Series Components:

\[ R_T = 1 - \prod (1 - R_i) \]

---

**Table 4 - Overall System Utility**

<table>
<thead>
<tr>
<th></th>
<th>Object Score</th>
<th>Path Length</th>
<th>Risk</th>
<th>TRL</th>
<th>Political Viability</th>
<th>U(t)</th>
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</thead>
<tbody>
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<td>Weights</td>
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<td>0.306</td>
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<td>Alt1</td>
<td>10.5</td>
<td>8</td>
<td>3.6</td>
<td>7</td>
<td>4.5</td>
<td>5.8646</td>
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<td>5.6</td>
<td>6</td>
<td>6.5</td>
<td>6.686</td>
</tr>
<tr>
<td>Alt3</td>
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<td>6</td>
<td>5.2</td>
<td>5</td>
<td>4.5</td>
<td>5.3164</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.2.3.4 Technology Readiness Level

We will include the technology readiness level (TRL) of each ADR design as an element of our utility analysis. This is a good metric for several reasons: the TRL gives insight into the actual feasibility for the design, as well as a metric for future cost creep. The TRL definitions according to NASA are as follows:

- TRL 1: Basic principles are observed and reported upon.
- TRL 2: Concept has been developed or a purpose and function has been identified.
- TRL 3: Either mathematical or experimental proof has been provided for the concept.
- TRL 4: Prototypes have been built and successfully tested in a laboratory setting.
- TRL 5: Testing of prototypes in a relevant environment (though not in a full implementation).
- TRL 6: Prototypes have been built and successfully tested in an environment representative of an operating environment (partial integration).
- TRL 7: Prototypes have been built and successfully tested in a live operating environment at or near full-scale.
- TRL 8: Actual completion and implementation, full integration, full and finalized testing and validation.
- TRL 9: System has successfully completed mission operations in fully realistic environment.

The value for each TRL will be a linear increasing function, with a range of 1-9. In addition, TRL’s also influence system cost estimation, but that will be dealt with in a separate analysis.

6.2.3.5 Political Viability

6.2.3.5.1 Description of space debris political challenges:

Since there are many different object types, there is no international agreement of what type is considered as a space debris. Monitoring space debris effort has been approached by U.S, Europe and Russia. However, monitoring with mitigation plans are not good enough to remediate debris from space. In addition, complications regarding liability and licensing regulations expose mitigation efforts to high risks.

The international space law is not contributed effectively to solve political conflict with the issue of space debris. As well as that space debris issue is not considered in the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space. Since implementing ADR is considered risky due to the overpopulated space environment, the lack of space situational awareness and limited traffic management capabilities, licensing to private companies is discouraged.
In order to reach political viability, some action need to be done:

- First, reach an agreement on the definition of space debris, so that the development and research on ADR could be improved.
- Second, public and private partnership is needed for responsibility sharing.
- Third, reach high TRL level on ADR designs.
- Fourth, increase the monitoring capabilities to reach an accurate information about space debris.
- Finally, increase the efficiency of traffic management system to allow reduce operation risk of ADR and therefore reduce licensing cost.

There are five criteria that reflects the influence of current laws, strategy, countries involved, proposed project and risk of dual use of the technology.

6.2.3.5.2 Probabilistic political viability methodology

The approach to the probabilistic political viability methodology start with a predictive political economic model that consist of four components:

- First, a set of policies options
- Second, a set of stakeholders that are involved directly to the space debris mitigation process
- Third, political prediction derived from policies options and outcome of stakeholders expected utilities
- Finally, a prediction concept

6.3 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.

As we further refine our models, we will likely be expanding the variable parameters. For instance, the “Object Categorization” model may allow for some flexible elements when determining effectiveness distributions. That is yet to be determined, and as such is not present in the below table.
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Min Object Score</th>
<th>Min Reached</th>
<th>Object Score</th>
<th>Path Length</th>
<th>Safety</th>
<th>Reliability</th>
<th>TRL</th>
<th>Agreeability</th>
<th>Verifiability</th>
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<td>5</td>
<td>0.10</td>
<td>6</td>
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<td>0.2</td>
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</tr>
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<td>0.10</td>
<td>6</td>
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<td>0.15</td>
<td>0.2</td>
<td>0.119</td>
</tr>
<tr>
<td>E3</td>
<td>0.6 of max</td>
<td>5</td>
<td>0.10</td>
<td>6</td>
<td>0.144</td>
<td>0.156</td>
<td>0.15</td>
<td>0.2</td>
<td>0.119</td>
</tr>
<tr>
<td>E4</td>
<td>0.65 of max</td>
<td>5</td>
<td>0.10</td>
<td>6</td>
<td>0.144</td>
<td>0.156</td>
<td>0.15</td>
<td>0.2</td>
<td>0.119</td>
</tr>
<tr>
<td>...</td>
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</tr>
</tbody>
</table>

Table 5 - Design of Experiment
7 Preliminary Results

As we have not yet finished our model, we do not have any explicit results yet. We can conceptualize what we expect our results to look like in format and structure, but our model is complex and will likely require many iterations of revision and polishing, all with the potential to drastically change our output.

In theory, our model would take in TLE data for debris objects and output a recommendation for a launch and deployment plan.

>>>Read in TLE data
>>>Read in parameters from DOE
>>>OUTPUT:
>>>Deploy NET to remediate object 00011 at time 0
>>>Deploy NET to remediate object 01584 at time 543
>>>Deploy NET to remediate object 01314 at time 674
>>>Deploy HARPOON to remediate object 04964 at time 721
>>>etc…

We would write this data to an Excel file and analyze for trend information, such as a heavily preferred cluster of objects or a heavily preferred ADR design.
8 Project Plan

8.1 Statement of Work

8.1.1 Objective

Collisions between orbital debris and operational space assets would have significant consequences, rendering those assets inoperative and near space dangerous, increasing the likelihood that others will have their operational lifetimes cut short due to debris impact. Without remediation, the number of objects in low earth orbit and number of collisions will continue to climb, even without additional launches. There is currently no consensus on the optimal strategy for remediation of orbital debris. This lack of agreement stems from the absence of a rigorous, comprehensive analysis of design alternatives. We will close this gap by performing a traditional risk management investigation, focusing on technical and operational risks, collision hazard evolution, political viability, and costs.

8.1.2 Scope

Our scope will include operational satellites and debris objects in Low Earth Orbit (below 2000 kilometers). We will explore a wide range of design alternatives, but will focus on designs with high feasibility, particularly in terms of timeframe of implementation. In other words, our scope will be restricted to designs with implementation schedules that will not be of prohibitive length, with a working goal of less than 50 years.

In terms of deliverables, we will be delivering a series of briefs and reports detailing our status throughout the coming months. We will also deliver iterations of our model throughout the Spring semester (specific deliverable dates still to be determined). Finally, before the 21st of April 2016 we will be delivering a final report detailing our research, a complete description of our models and methods, and our final recommendations for further work and action.
8.2 Work Breakdown Structure

![Work Breakdown Structure Diagram]

Figure 17 - Work Breakdown Structure
8.3 Schedule

1. Context analysis
   1.1 History of problem
   1.2 Current proposed strategies

2. Stakeholder analysis
   2.1 Determine stakeholders
      2.1.1 Gather data
      2.1.2 Describe stakeholders
   2.2 Stakeholder relationships
      2.2.1 Gather data
      2.2.2 Describe relationships
      2.2.3 Diagram relationships
   2.3 Stakeholder tensions
      2.3.1 Gather data
      2.3.2 Describe tensions
      2.3.3 Diagram tensions

3. Problem statement
   3.1 Read pertinent previous research
   3.2 Discuss with sponsor

4. Brief 1

5. Need statement
   5.1 Gap analysis
      5.1.1 Analyze current system
      5.1.2 Determine gaps
      5.1.3 Determine system boundaries
   5.1.4 Define proposed system structure

6. Requirements
   6.1 Mission requirements
      6.1.1 Contact stakeholders
      6.1.2 Elicit requirements from stakeholders
   6.1.3 Aggregate requirements
   6.2 Functional requirements
      6.2.1 Contact stakeholders
      6.2.2 Elicit requirements from stakeholders
   6.2.3 Aggregate requirements
   6.3 Design requirements
      6.3.1 Contact stakeholders
      6.3.2 Elicit requirements from stakeholders
   6.3.3 Aggregate requirements
   6.4 Simulation requirements
      6.4.1 Determine desired outputs
      6.4.2 Determine necessary inputs
      6.4.3 Trace stakeholder requirements to sim

7. Brief 2
8.4 Critical Path

By analyzing our schedule, we determine our critical path, which leads from our problem statement definition (specifically, conducting research), to requirements development, to the actual construction of the model, and finally to the analysis of our results.

8.5 Project Risks

The major risks associated with our project all relate the stoppages on our critical path. We have attempted to mitigate these risks early on by building a sizeable amount of slack into the project schedule in the first place.
<table>
<thead>
<tr>
<th>Risk</th>
<th>Description</th>
<th>Mitigation Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantitative requirements</td>
<td>Stakeholders are not forthcoming with requirements</td>
<td>Develop requirements independently and later ask for verification</td>
</tr>
<tr>
<td>elicitation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Political feasibility metrics and</td>
<td>Determining a solid, quantifiable metric for political feasibility is not</td>
<td>Make contact with political insurance underwriters to gain further knowledge</td>
</tr>
<tr>
<td>calculations</td>
<td>simple</td>
<td></td>
</tr>
<tr>
<td>Acquiring datasets</td>
<td>Datasets can be unreliable, using differing definitions, or sometimes wholly</td>
<td>Prepare for a large amount of data cleaning before use</td>
</tr>
<tr>
<td></td>
<td>contradictory</td>
<td></td>
</tr>
<tr>
<td>Modeling (coding)</td>
<td>Modeling complex orbital networks may prove technically difficult</td>
<td>Further research into feasibility, previous similar work, and discussion with</td>
</tr>
<tr>
<td></td>
<td></td>
<td>experienced SEOR faculty</td>
</tr>
<tr>
<td>Verification of accuracy</td>
<td>The time scale for our project is too long for any immediate verification of</td>
<td>Be honest with this weakness in our presentation of data, and include generous error</td>
</tr>
<tr>
<td></td>
<td>results</td>
<td>bounds where appropriate</td>
</tr>
</tbody>
</table>

### 8.6 Earned Value

At the end of the project, we expect to have around 1275 hours worked. We have an hourly rate of $30 with 2x overhead modifier for a total hourly cost of $60. This gives us a total budgeted cost of $76,500. Currently, we are approximately 24% complete with the project, with 458 hours worked. We are scheduled to be 23.45% complete with 299 hours worked.

<table>
<thead>
<tr>
<th>Actual Cumulative Hours</th>
<th>458.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Percent Complete</td>
<td>24.00%</td>
</tr>
<tr>
<td>Scheduled Cumulative Hours</td>
<td>299.00</td>
</tr>
<tr>
<td>Scheduled Percent Complete</td>
<td>23.45%</td>
</tr>
<tr>
<td>Cumulative PV</td>
<td>$17,940.00</td>
</tr>
<tr>
<td>Cumulative AC</td>
<td>$27,480.00</td>
</tr>
<tr>
<td>Cumulative EV</td>
<td>$18,360.00</td>
</tr>
<tr>
<td>CPI</td>
<td>0.668122271</td>
</tr>
<tr>
<td>SPI</td>
<td>1.023411371</td>
</tr>
</tbody>
</table>

Our schedule performance index (SPI) is hovering around 1, but our cost performance index (CPI) has dropped precipitously. Much of this can likely be attributed to a late modification to our approach. Originally, we were planning on building a model for trajectory analysis across a sector of the sky. However, conversation with our sponsor and with other faculty convinced us that that effort was outside the realm of feasibility for our team with the given schedule and capability constraints. Thus, much of our development work from the first half of the semester was no longer applicable.
Figure 19 - CPI, SPI
Figure 20 - Earned Value
9 References
American Astronautical Society (AAS), Feb. 2010
Beijing Orbital Debris Mitigation Workshop, Oct. 2010
Feb. 2011
Committee on the Peaceful Uses of Outer Space”, Dec. 2007
[7] Union of Concerned Scientists (UCS) Satellite Database
Services
http://www.esa.int/Our_Activities/Observing_the_Earth/Envisat_FAQs. [Accessed: 21- Oct-
2015].
[16] “Massive Collisions in LEO – A Catalyst to Initiate ADR”, Darren McKnight, Frank Di Pentino,
Stephen Knowles, 2014
Oct- 2015].
the European Union and the European Space Agency (ESA)”, Jun. 2014

45
10 Preliminary Code
function [ r, v ] = sv_from_coe( coe )
% sv_from_coe Summary of this function goes here
%  Detailed explanation goes here

global mu

h = coe(1);  %Angular momentum  
e = coe(2);  %Eccentricity  
RA = coe(3);  %Right ascension of the ascending node  
incl = coe(4);  %Inclination  
w = coe(5);  %Argument of perigee  
TA = coe(6);  %True anomaly

rp = (h^2/mu)*(1/(1+e*cos(TA)))*(coe(TA)*[1;0;0]+sin(TA)*[1;0;0]);
vp = (mu/h)*(-sin(TA)*[1;0;0]+e+cos(TA))*[0;1;0]);

R3_W = [cos(RA) sin(RA) 0 -sin(RA) cos(RA) 0 0 1];
R1_i = [1 0 0 0 cos(incl) sin(incl) 0 -sin(incl) cos(incl) ];
R3_w = [cos(w) sin(w) 0 -sin(w) cos(w) 0 0 0 1];
Q_pX = R3_W'*R1_i'*R3_w';

r = Q_pX*rp;
v = Q_pX*vp;

r = r';
v = v';

end
function [ coe ] = coe_from_sv( R, V )
%coe_from_sv Returns coe = [h e RA incl w TA a] from R and V
%   Detailed explanation goes here

global mu
eps = 1e-10;

r = norm(R);
v = norm(V);

vr = dot(R,V)/r;

H = cross(R,V);
h = norm(H);

incl = acos(H(3)/h);
N = cross([0 0 1],H);
n = norm(N);

if n ~= 0
    RA = acos(N(1)/n);
    if N(2) < 0
        RA = 2*pi - RA;
    end
else
    RA = 0;
end

E = 1/mu*((v^2-mu/r)*R-r*vr*V);
e = norm(E);

if n ~= 0
    if e > eps
        w = acos(dot(N,E)/n/e);
        if E(3) < 0
            w = 2*pi - w;
        end
    else
        w = 0;
    end
else
    w = 0;
end

if e > eps
    TA = acos(dot(E,R)/e/r);
    if vr < 0
        TA = 2*pi - TA;
    end
else
cp = cross(N,R);
    if cp(3) >= 0
TA = acos(dot(N,R)/n/r);
else
    TA = 2*pi-acos(dot(N,R)/n/r);
end
end

a = h^2/mu/(1-e^2);

coe = [h e RA incl w TA a];
end
function [ V1, V2, dV ] = lambert( R1, R2, t, dir )
%lambert Summary of this function goes here
% R1 = initial position vector
% R2 = final position vector
% t = time of flight between R1 and R2
% dir = direction, 1 if prograde and -1 if retrograde (default prograde)

global mu

global r1 r2 A

r1 = norm(R1); %Magnitudes of R1 and R2
r2 = norm(R2);

c12 = cross(R1,R2);
theta = acos(dot(R1,R2)/(r1*r2)); %Angle between R1 and R2

if dir > 0 %Prograde
    if c12(3) <= 0
        theta = 2*pi - theta;
    end
elseif dir < 0 %Retrograde
    if c12(3) > 0
        theta = 2*pi - theta;
    end
else
    dir = 1; %Default prograde
end

A = sin(theta)*sqrt(r1*r2/(1 - cos(theta)));

z = -100;
while F(z,t) < 0
    z = z+0.1;
end

tol = 1e-10;
nmax = 5000;
ratio = 1;
n = 0;
while (abs(ratio) > tol) && (n <= nmax)
    n = n+1;
    ratio = F(z,t)/dFdz(z);
    z = z-ratio;
end

f = 1-y(z)/r1;
g = A*sqrt(y(z)/mu);
gdot = 1-y(z)/r2;

V1 = 1/g*(R2-f*R1);
V2 = 1/g*(gdot*R2-R1);
dV = norm(abs(V1-V2)); %Include delta-V calculations
%Subfunctions

function dum = y(z)
    %global r1 r2 A
    dum = r1 + r2 + A*(z*S(z)-1)/sqrt(C(z));
end

function dum = F(z,t)
    %global mu A
    dum = (y(z)/C(z))^1.5*S(z)+A*sqrt(y(z))-sqrt(mu)*t;
end

function dum = dFdz(z)
    %global A
    if z == 0
        dum = sqrt(2)/40*y(0)^1.5+A/8*(sqrt(y(0))+A*sqrt(1/2/y(0)));
    else
        dum = (y(z)/C(z))^1.5*(1/2/z*(C(z)-3*S(z)/2/C(z))... +3*S(z)^2/4/C(z)... +A/8*(3*S(z)/C(z)*sqrt(y(z))... +A*sqrt(C(z)/y(z)));
    end
end

function dum = C(z)
    dum = stumpC(z);
end

function dum = S(z)
    dum = stumpS(z);
end

end
%%networkScript.m

clear
global mu
deg = pi/180;
mu = 398600;

%Cull TLE data to select high-mass objects
%Read in TLE data
%Read in object score data
%Convert TLE's to COE's
%Store database of COE's

%Repeat until no more targets or dV >= maxdV or score >= minScore
%Choose/take initial interceptor orbit
%Register time

%Repeat for all potential targets
%Convert COE's to SV's (including time)
%Find dV's from interceptor to target
%Store all dV's
%Match object scores and dV's

%Choose bestTarget = max(score/dV for all targets)
%Set new interceptor orbit to bestTarget
%Set time to TOF of bestTarget
%Remove bestTarget from database
%Record pertinent data (total dV, total time, total score, etc.)

%Put TLE file in the same folder as this file
fileName = 'tle.txt';
fileID = fopen(fileName,'r');
List1 = fscanf(fileID,'%24c%*s',1);
List2 = fscanf(fileID,'%d%6d%*c%*5d%*c%*d%5d%*c%*d%5d%',[1,9]);
List3 = fscanf(fileID,'%d%6d%f%f%f%f%f%f%f',[1,8]);
fclose(fileID);
%Separate the above and put in its own function

epoch = L2(1,4)*24*3600; % Epoch Date and Julian Date Fraction
in1 = L3(1,3); % Inclination [deg]
RAN1 = L3(1,4); % Right Ascension of the Ascending Node [deg]
ecc1 = L3(1,5)/1e7; % Eccentricity
AoP1 = L3(1,6); % Argument of periapsis [deg]
M = L3(1,7); % Mean anomaly [deg]
n = L3(1,8); % Mean motion [Revs per day]

a1 = (mu/(n*2*pi/(24*3600))^2)^(1/3); % Semi-major axis [km]
\( p = a_1(1 - e_{cl}^2) \);
\( \text{angMom}_1 = \sqrt{p \cdot \mu} \);

\% Calculate the eccentric anomaly using mean anomaly
\text{if } M < \pi
\qquad E = M + \frac{e_{cl}}{2};
\text{else}
\qquad E = M - \frac{e_{cl}}{2};
\text{end}

tol = 1e^{-10}; \% Error tolerance
ratio = 1;
\text{while } \text{abs(ratio)} > \text{tol}
\qquad \text{ratio} = \frac{(E - e_{sl} \sin(E) - M) / (1 - e_{sl} \cos(E))}{1 - e_{sl} \cos(E)};
\qquad E = M + e_{sl} \sin(E_0);
\text{end}

toe1 = [a e inc RAN w E];
toe1 = [\text{angMom}_1, e_{cl}, \text{RAN}_1, \text{in}_1, \text{AoP}_1, \text{tAnom}_1]; \% "sv_from_coe" format
toe2 = [\text{angMom}_2, e_{cl}, \text{RAN}_2, \text{in}_2, \text{AoP}_2, \text{tAnom}_2];

\% Convert to position vectors
sv1 = sv_from_coe(toe1);
sv2 = sv_from_coe(toe2);
r1 = sv1(1); \% Interceptor (begining) position vector
r2 = sv2(1); \% Target (final) position vector

dt = 3600; \% Time of flight between r1 and r2
dir = 1; \% 1 for prograde, -1 for retrograde
\text{for } k=1:500
\qquad \text{for } n=1:N
\qquad \qquad \text{lambert}
\qquad \text{end}
\text{end}

[v1, v2] = lambert(r1, r2, dt, dir);
\text{dV} = \text{norm(abs(v1-v2))};

toe1 = coe_from_sv(r1, v1);
tAnom1 = toe1(6);
toe2 = coe_from_sv(r1, v1);
tAnom2 = toe2(6);