Design and Evaluation of an Orbital Debris Remediation System

Collision Risk

Remediation Designs

ADR Design Evaluation
- Launch
- Rendezvous with Debris
- Grapple with Debris
- De-bumble Debris
- De-orbit Debris

Debris Remediation Systems

Utility vs LCC

GMU SEOR Senior Design Project 2015-2016
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Sponsor: Dr. McKnight, Integrity Applications Inc.

*Space objects not to scale
Agenda

• Background
• Problem Statement
• Design Alternatives
• Method of Analysis
• Results and Recommendations
• Business Case
Uses of Space and Revenue

Operational Satellites by Function (left) and Global Satellite Industry Revenues (right)

Source: SIA SSIR, 2015
Contributions to Space Debris Risk

1. State-sponsored active anti-satellite measures
   – Chinese ASAT missile, 2007

2. Random collisions, explosions, and malfunctions
   – Iridium 33 and Cosmos 2251, 2009
   – 3000 pieces of debris

Source: T.S. Kelso, 2013
Population Growth

- 90% Post Mission Disposal (PMD) does not halt growth of population
- 90% PMD along with 2 high-risk objects removed per year slows but does not halt growth
- 90% PMD coupled with 5 high-risk objects removed per year leads to a stable environment

Source: J. C. Liou, 2011
Orbital Mechanics [1]

• In order to attain orbit, a large horizontal velocity is required
• Due to the curvature of the Earth, the ground will “fall away” from the object as it moves fast
• By modifying this velocity, the orbit can be modified as well

Source: S. M. Kanbur, 2006
Orbital Mechanics [2]

• As the mass of the satellite is negligible compared to that of the Earth, the velocity of a circular orbit with an altitude \( R \) (in kilometers) is found by:

\[
V = \sqrt{\frac{398,600 \, \text{km}^3}{s^2}} \div \sqrt{6378 \, \text{km} + R}
\]

• Example: circular orbit with an altitude of 2000 km:

\[
V = \sqrt{\frac{398,600 \, \text{km}^3}{s^2}} \div \sqrt{8378 \, \text{km}} = 6.8976 \frac{\text{km}}{s}
\]
Orbital Mechanics [3]

• Change in velocity:
  \[ \Delta V = |V_1 - V_2| \]

• Counter angular velocity:
  \[ \sum \tau(t) = -I \omega_{initial} \]

• Atmospheric drag:
  \[ F_D = \frac{\rho V^2 C_D A}{2} \]
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Stakeholder Relationships

(1) National Governments
- Russian
- China
- United States
- Europe

(2) Civil Organizations
- NASA
- ESA
- RFSA
- CNSA
- IADC

(3) Commercial industry
- System Manufacturers
  - Lockheed Martin
  - Boeing
  - Airbus
- Transport Companies
  - SpaceX
  - ULA
  - Orbital Sciences
- Insurance Companies
  - XL CATLIN
  - STARR

Contracts
- Spacecraft launch services

Financial issue
- Research, collect data and provide overall guidance
- Approve space policy, and provide funding

Tensions
- Objectives

Political issue
Problem Statement

• Post Mission Disposal (PMD) alone is not sufficient to control debris environment; remediation will be necessary.

• Need: consensus on the best remediation strategy for orbital debris.
Gap Analysis

To date no clear remediation solution prioritization has been performed to include cost, effectiveness, and technology readiness level.
Need Statement

Remediation of at least 5 high-risk objects per year is required to maintain a sustainable space environment
Problem Summary

**Problem:** Debris remediation must occur, but the community is unsure how to proceed

**Solution:** Perform a comprehensive analysis of remediation design alternatives

**Expected Results:** Provide a foundation of work that enhances current capabilities and catalyzes the community to operationalize remediation solutions
Scope and Assumptions

• Orbital plane changes are incredibly expensive in terms of delta-V cost
• The goal is to minimize delta-V cost, and any strategy that involves plane changes will be vastly more expensive than those without plane changes
• Therefore, orbital inclinations can be pre-selected to have the lowest delta-V costs and the highest mass derelicts
• Three high-density inclinations: 71°, 74° and 81°
ADR 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 execute de-orbit maneuver within 2 months of end-of-life.
ADR 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.
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System Integration

Satellite owners, operators, etc.
Commercial industry
Civil organizations

National government

Satellite Services Users

Space Debris

Risk

$ Population reduction

Debris Remediation System

Run analysis

Political viability and approval

Confirm (Location, Time, and Target)

Insurance & Register (Orbit Coordinates)

Deploy (Location, Time, and Target)

Dispose

Manufacture selected ADR design(s)

Insure & Register (Orbit Coordinates)

Deploy (Location, Time, and Target)

Dispose

Launch Providers

ADR Manufacturer

Insurance & UN registry

Launch Providers

National government

Commercial industry

Civil organizations

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Launch Providers
Overview of Active Debris Removal

Active Debris Removal (ADR) Concept of Operations:

1. Identify and launch towards the target object
2. Maneuver and rendezvous with target
3. Grapple with target
4. De-tumble target, if necessary
5. De-orbit the object from orbit
# Design Alternatives

<table>
<thead>
<tr>
<th>CONOPS Step:</th>
<th>Design Alternatives:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Launch</td>
<td>Chemical Propulsion</td>
</tr>
<tr>
<td>2. Rendezvous</td>
<td>Electric Propulsion</td>
</tr>
<tr>
<td></td>
<td>Chemical Propulsion</td>
</tr>
<tr>
<td>3. Grapple</td>
<td>Robotic Arm</td>
</tr>
<tr>
<td></td>
<td>Throw Net</td>
</tr>
<tr>
<td></td>
<td>Harpoon</td>
</tr>
<tr>
<td></td>
<td>COBRA IRIDES</td>
</tr>
<tr>
<td>4. De-tumble</td>
<td>Electric Propulsion</td>
</tr>
<tr>
<td></td>
<td>Chemical Propulsion</td>
</tr>
<tr>
<td>5. De-orbit</td>
<td>EDDE</td>
</tr>
<tr>
<td></td>
<td>Inflatable</td>
</tr>
<tr>
<td></td>
<td>Electric Propulsion</td>
</tr>
<tr>
<td></td>
<td>Chemical Propulsion</td>
</tr>
<tr>
<td></td>
<td>Electromagnetic</td>
</tr>
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</table>
## 1. Launch and 2. Rendezvous Designs

<table>
<thead>
<tr>
<th>Name:</th>
<th>Stage</th>
<th>Mass (kg):</th>
<th>Cost to LEO ($/kg):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta IV</td>
<td>1</td>
<td>6,747</td>
<td>$13,072</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>301</td>
<td></td>
</tr>
<tr>
<td>Atlas V</td>
<td>1</td>
<td>5,479</td>
<td>$13,182</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>166</td>
<td></td>
</tr>
<tr>
<td>Falcon 9</td>
<td>1</td>
<td>418,100</td>
<td>$4,109</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>96,570</td>
<td></td>
</tr>
</tbody>
</table>

Source: ULA
# 3. Grapple Designs

<table>
<thead>
<tr>
<th>Name</th>
<th>TRL</th>
<th>Mass (kg)</th>
<th>Target Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robotic Arm</td>
<td>6</td>
<td>80</td>
<td>7000</td>
</tr>
<tr>
<td>Throw Net</td>
<td>5</td>
<td>60</td>
<td>10000</td>
</tr>
<tr>
<td>Harpoon</td>
<td>4</td>
<td>9.3</td>
<td>9000</td>
</tr>
<tr>
<td>COBRA</td>
<td>3</td>
<td>140</td>
<td>150</td>
</tr>
<tr>
<td>IRIDES</td>
<td>2</td>
<td>76</td>
<td>8300</td>
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</tbody>
</table>

Source: ESA
## 5. De-orbit Designs

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDDE</td>
<td>System of electrodynamic tethers</td>
<td>80</td>
</tr>
<tr>
<td>Inflatables</td>
<td>Add foam to debris to increase surface area</td>
<td>1000</td>
</tr>
<tr>
<td>Propulsion</td>
<td>Modify the altitude</td>
<td>314</td>
</tr>
</tbody>
</table>

**Images:**
- **EDDE:** System using electrodynamic tethers for de-orbiting, source: Star-Tech Inc.
- **Inflatables:** Inflatable system for de-orbiting, source: ESA
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ADR CONOPS

- Launch
- Rendezvous with Debris
- Grapple with Debris
- De-tumble Debris
- De-orbit Debris
1. Launch and 2. Rendezvous

- \( X(t) = \begin{bmatrix} 0 & x_{12}(t) & \cdots & x_{1n}(t) \\ x_{21}(t) & 0 & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1}(t) & \cdots & 0 \end{bmatrix} \)

- \( x_{ij}(t) = \Delta V = |V_i - V_j| \)

- Convert TLE data to state vectors

- These matrices vary over time
3. Grapple

- **Metrics:**
  - Mass
  - Altitude
  - Rotation

- **Output:**
  - \( ORS_i(X) = mass_i(X) + alt_i(X) + rot_i(X) \)
  - \( X \) is a debris object and \( i \) is an grappling design

- **Linear Decreasing:**
  - \( mass_i(X) = 1 - \frac{Max - X}{Max - Min} \)
  - Used with mass: mass has linear effect on energy

- **Exponential Decreasing:**
  - \( alt_i(X), rot_i(X) = e^{-\lambda X} \)
  - Used with altitude and rotation: velocity has squared effect on energy
4. De-tumble

• Debris will cease rotation when: $\omega_{final} = 0$

$$\alpha = \frac{\omega_{final} - \omega_{initial}}{t}, \sum \tau(t) = I\alpha$$

$$\sum \tau(t) = I(\omega_{final} - \omega_{initial})$$

$$\sum \tau(t) = -I\omega_{initial}$$
5. De-orbit

- Time to de-orbit decreases as $F_D$ is increases
  \[ F_D = \frac{\rho V^2 C_D A}{2} \]
- $\rho = \rho_0 e^{-\text{Altitude}/H}$
  - $\rho$ increases as altitude decreases
- $V = \sqrt{\frac{398,600 \frac{km^3}{s^2}}{6378 \text{ km} + \text{Altitude}}}$
  - $V$ increases as altitude decreases
Agenda

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## Results [1]

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Weight</th>
<th>Value</th>
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<tbody>
<tr>
<td><strong>Throw Net</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performance</td>
<td>0.47</td>
<td>7.01545</td>
</tr>
<tr>
<td>Object Scores</td>
<td>0.86</td>
<td>8.1575</td>
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<tr>
<td>Delta-V Cost</td>
<td>0.14</td>
<td>0</td>
</tr>
<tr>
<td>Risk</td>
<td>0.19</td>
<td>2.128</td>
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<tr>
<td>Safety</td>
<td>0.80</td>
<td>2.24</td>
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<tr>
<td>Reliability</td>
<td>0.20</td>
<td>1.68</td>
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<tr>
<td>TRL</td>
<td>0.14</td>
<td>5</td>
</tr>
<tr>
<td>Political Viability</td>
<td>0.20</td>
<td>2.154</td>
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<tr>
<td>Agreeability</td>
<td>0.86</td>
<td>1.65</td>
</tr>
<tr>
<td>Verifiability</td>
<td>0.14</td>
<td>5.25</td>
</tr>
<tr>
<td><strong>Utility</strong></td>
<td></td>
<td>4.8312356</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Weight</th>
<th>Likely</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Harpoon</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performance</td>
<td>0.47</td>
<td>8.3463</td>
</tr>
<tr>
<td>Object Scores</td>
<td>0.86</td>
<td>9.705</td>
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<tr>
<td>Delta-V Cost</td>
<td>0.14</td>
<td>0</td>
</tr>
<tr>
<td>Risk</td>
<td>0.19</td>
<td>1.52</td>
</tr>
<tr>
<td>Safety</td>
<td>0.80</td>
<td>1.6</td>
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<tr>
<td>Reliability</td>
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<td>1.2</td>
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<tr>
<td>TRL</td>
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<td>4</td>
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<tr>
<td>Political Viability</td>
<td>0.20</td>
<td>0.735</td>
</tr>
<tr>
<td>Agreeability</td>
<td>0.86</td>
<td>0</td>
</tr>
<tr>
<td>Verifiability</td>
<td>0.14</td>
<td>5.25</td>
</tr>
<tr>
<td><strong>Utility</strong></td>
<td></td>
<td>4.918349417</td>
</tr>
</tbody>
</table>
Results [2]

### Grapplers - Utility v Cost

<table>
<thead>
<tr>
<th>Design</th>
<th>Utility/Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throw Net</td>
<td>5.74</td>
</tr>
<tr>
<td>Harpoon</td>
<td>61.79</td>
</tr>
<tr>
<td>EDDE</td>
<td>0.45</td>
</tr>
</tbody>
</table>

### De-orbiters - Utility v Cost

<table>
<thead>
<tr>
<th>Design</th>
<th>Utility/Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflatables</td>
<td>0.55</td>
</tr>
<tr>
<td>Propulsion</td>
<td>4.66</td>
</tr>
<tr>
<td>EDDE</td>
<td>0.45</td>
</tr>
<tr>
<td>Infl.+Prop.</td>
<td>1.20</td>
</tr>
</tbody>
</table>
Results [3]

Choose the highest utility per cost design from each stage and aggregate into an overall debris remediation system

<table>
<thead>
<tr>
<th>Design:</th>
<th>Recommended:</th>
<th>Cost:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch and Rendezvous</td>
<td>Falcon 9</td>
<td>$61.2M</td>
</tr>
<tr>
<td>Grapple</td>
<td>Harpoon</td>
<td>$7.96M</td>
</tr>
<tr>
<td>De-orbit</td>
<td>Propulsion</td>
<td>$40M</td>
</tr>
<tr>
<td>Total:</td>
<td></td>
<td>$109.16M</td>
</tr>
</tbody>
</table>
Recommendations

• Some designs, including EDDE, increase in efficiency the longer they are deployed
• Further research and development is required to bring electromagnetic designs to a reasonable TRL for implementation
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Market Size

- 385 satellite owners operating over 1200 satellites
- The goal is to capture 36% of this market over the next 20 years
- Pessimistic estimate of 13%
- Optimistic estimate of 99%
Competitors and Roadblocks

• No current competitors
• Business model relies on regulatory acceptance of the harpoon ADR design
• Changes in the political atmosphere have serious impact on the feasibility of implementation
• The Tragedy of the Commons decreases incentive for any single purchaser
Costs

Non-recurring:
• Design improvement, testing, and finalization: $7,500,000 over 2 years

Recurring:
• Salaries: 5 employees at $75,000 = $375,000
• Overhead modifier of 2.0: $750,000
• ADR design purchase: ~$270,000 for the harpoon from Astrium Stevenage
• Launch cost: 325 kilogram design at $4109/kg = $1,335,425 per launch
• Maneuvering fuel cost: $1716-17,160
• Total Cost: $1,337,141-$1,352,585
Sales Profile

• Charge cost plus 10% fee: $1,487,843
• Total Market Value: 385*$1,623,102 = $572.8 billion
• Market Share Value: TMV*36%=$206.2 billion
• Annual Revenue: MSV*2%=$4,124,302
Return on Investment

- Pessimistic 10 year ROI:
  - $6,567,652, 88%

- Expected 10 year ROI:
  - $36,324,522, 484%

- Optimistic 10 year ROI:
  - $125,595,132, 1675%

- Stock Market over 10 years (5% annually):
  - $12,216,709, 163%
Breakeven Point

Revenue and Breakeven

- Pess. Balance
- Exp. Balance
- Opt. Balance
- Stock Market (5%)
BACKUP SLIDES
Our Solution

• Mission control for debris remediation services
• Deployment of an ADR design according to specific customer needs
Track Two Diplomacy
Debris Risk

- Risk = Probability x Severity
  - Space Debris Risk = Collision Probability x Mass
  - Mass has an effect on damage caused and creation of debris
- Large number of small objects vs small number of large objects

Source: D. McKnight, 2009
Gap Analysis

Without remediation, the number of objects and collisions will continue to climb, even without additional launches.

Source: J. C. Liou, 2011

Source: AAS, 2010
Gap Analysis

- 90% Post Mission Disposal (PMD) does not halt growth of population
- 90% PMD along with 2 high-risk objects removed per year slows but does not halt growth
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Source: J. C. Liou, 2011