Modelling and Simulation of Autonomous CubeSats for Orbital Debris Mitigation

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Outline

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   Simulation
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   Orbital Debris Mitigation
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The Situation

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- The presence of orbital debris within Low Earth Orbit (LEO) is becoming increasingly prevalent.

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- Increasing the presence of objects within LEO leads to Kessler Syndrome [1].
- Kessler Syndrome leads to the decreased viability of maintaining satellites in LEO.

Figure: Debris objects within LEO [2]
Orbital Debris - Numbers

According to scientific models, orbiting around Earth, there are:

• Over 170 million debris objects smaller than 1 mm.
• 670,000 debris objects larger than 1 cm.
• 29,000 debris objects larger than 10 cm [2].
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Orbital Debris - Characterisation

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- Orbital planes change over time, resulting in global coverage, leading to Kessler syndrome.
- Collisions in LEO can occur from virtually any direction.
- Kessler syndrome entails the cascading of orbital debris collisions in LEO, such that space activities may one day become infeasible.

[2]
Orbital Debris - Sources

- Artificial satellites orbiting Earth, that have been abandoned or have become nonfunctional.

Figure: Vanguard I: the oldest surviving man made object remaining in orbit. [3]
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- Anti-satellite weapons.

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Orbital Debris - Dangers

For a typical satellite, a collision with a:

- 10 cm object may result in a catastrophic fragmentation.
- 1 cm object may result in a loss of function.
- 1 mm object may destroy its subsystems.
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- Debris as small as 1 cm can be detected.

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- Most debris cannot be directly observed.
- Radar and optical detectors are mainly used.

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Active Debris Removal - Current Efforts

Current efforts include:

- Electrodynamic tethers
- Laser brooms
- Solar Sails
- Nets
- And so on...
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CubeSats - Design

Reasons to use CubeSats:

• They’re economical.
• They can be deployed in multiples.
• They minimise risk to the rest of their launch vehicle.
• They are easily accommodated to preexisting payload capsules.
• They can utilise launch opportunities on short notice.
• Redundancy is not as big of a concern.

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Technicals

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Figure: 1-unit CubeSat. [7]
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- Provide 1 litre of useful volume, while weighing no more than 1.33 \text{ kg per unit}
- Size standardisation allows CubeSats to be launched by a common deployment system.
- Commercial-off-the-shelf hardware is readily accessible.

Figure: 1-unit CubeSat. [7]
CubeSats - Design

Classifications:

- Microsatellites are 10 - 100 kg
- Nanosatellites are 1 - 10 kg
- Picosatellite are 0.1 - 1 kg
- Femtosatellite are 0.01 - 0.1 kg

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• **Two-line elements** of the debris were obtained through CelesTrack.

• **Cross-sectional areas** of the debris were obtained through the satellite catalogue, *SatCat*, of CelesTrack.
Simulation - Road Map

- Enviromental Modelling
  - N-Body Problem
  - Ephemerides
  - Solar Radiation Pressure
  - Aerodynamic Drag

- Thruster Selection
  - High Impulse
  - Low Impulse

- Initial Orbit
  - Random Initial LEO Position
  - Random Initial Circular Velocity
  - Random Initial Direction

- Debris Selection
  - Proximity
  - ΔV Required
  - Priority

- Rendezvous
  - Hill-Clohessy-Wiltshire Equations
  - Global Optimisation

- Deorbitation
  - Passive Aerobreaking
  - Remaining Propulsive Resources
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Random Insertion

In order to test for robustness, a potential testing spacecraft should have random initial:

- Coordinates: $\theta$ and $\phi$.
- Altitude: $h$.
- Eccentricity within limits: $e$.
- Direction of velocity: $\hat{v}$.

**Definition**

Random initial longitude and latitude:

$\theta = 2\pi u$: $u \in (0, 1)$

$\phi = \cos^{-1}(2v - 1)$: $v \in (0, 1)$

**Definition**

Random initial velocity direction:

$\hat{v} = \frac{\vec{r}_{arb} - \vec{r}}{|\vec{r}_{arb} - \vec{r}|}$
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The relevant conservative forces must be accounted for:

\[
\vec{A}_n = -\mu^j_n (\vec{R}_n^j - \vec{R}_n^{sc}) \frac{1}{\left\| \vec{R}_n^j - \vec{R}_n^{sc} \right\|^3}
\]
Conservative Forces

The relevant conservative forces must be accounted for:
- Earth’s gravity.

Definition

Gravitational Acceleration:

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\vec{A}_n^j = -\mu_j \left( \frac{\vec{R}_n^j - \vec{R}_{scn}^j}{\| \vec{R}_n^j - \vec{R}_{scn}^j \|^3} \right)
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- Essentially an N-Body problem.

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Definition

N-Body Problem:

$$\vec{A}_{i,n} = \sum_{j=0, i \neq j}^{N} \vec{A}_{i,n}^j$$
Figure: A barycentric view of a CubeSat in Low Earth Orbit with the Moon in view.
Non-Conservative Forces

The non-conservative perturbations must be accounted for:

- Atmospheric Drag.
- Atmospheric Scale Model.
- Solar-Radiation Pressure.
- Eclipse Model.

Definition: Scaling atmospheric density model:

\[ \rho_n = \rho_0 e^{-hn/H} \]

Definition: Acceleration due to solar-radiation pressure:

\[ \vec{A}_{\text{Solar}} = -p_{\text{s}} C_{\text{R}} A_{\perp} \hat{s}_n m_n \]

Definition: Eclipse determination:

\[ \tau = \vec{r} \cdot \vec{r} - \vec{s}_E \left| \vec{r} - \vec{s}_E \right|^2 \]
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Figure: Atmospheric drag with scale model implemented.
Figure: Solar-radiation pressure model with eclipse model implemented.
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Numerical Propagation

In order to accurately simulate the test spacecraft’s motion, one must choose a numerical integrator:

- **Forward Euler method.**
  - Simple, but may not be accurate.
- **Runge-Kutta-Fehlberg method with an adaptive time-step.**
  - Complex, but more accurate and accommodating.

**Figure:** Simple Low Earth Orbit motion, as propagated by the RKF45 method.
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Mechanism of Action

The steps to efficient orbital debris mitigation:

- Rendezvous using Aerojet Rocketdyne’s MPS-120 (CHAMPS) with $\Delta V = 200 \text{ m/s}$.
- Capture with ejected net.
- Passively deorbit with aerodynamic drag, utilising Clyde Space’s (AEOLDOS) with $A = 3 \text{ m}^2$.
- Utilise remaining propellant.

**Figure:** MERiDIUS passively deorbiting captured debris. [10]
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Fengyun-1C

Attention will be brought to Fengyun–1C, the Chinese weather satellite that was destroyed on January 11th, 2007, as a result of an anti-satellite missile test.

- Polar orbit satellite of the Fengyun series.
- Mass of 750 kg.
- Created more dangerous orbital debris than any other space mission in history [11].

Figure: Fengyun–1C debris scattering, 5 minutes after its collision. [12]
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Now to dispose of the debris...

Figure: The trajectory of every trackable debris fragment of Fengyun-1C as of January 1st, 2016.
Relative Motion

In order to simulate the relative motion of a spacecraft to its target, the closed-form solution of the Hill-Clohessy-Wiltshire equations can be implemented for rendezvous.

Definition

The HCW equations:

\[
\begin{align*}
\delta \ddot{x} - 3n^2 \delta x - 2n \delta \dot{y} &= \frac{T_x}{m} \\
\delta \ddot{y} + 2n \delta \dot{x} &= \frac{T_y}{m} \\
\delta \ddot{z} + n^2 \delta z &= \frac{T_z}{m}
\end{align*}
\]

Closed-form solution:

\[
\begin{align*}
\delta \vec{r}(\delta t) &= \Phi_{rr}(\delta t)\delta \vec{r}_0 + \Phi_{rv}(\delta t)\delta \vec{v}_0 \\
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- Computationally inexpensive.
- Real-time control enables autonomy.
- Spacecraft must be in the vicinity of the target debris and the target.

Definition

The HCW equations:

\[ \delta \ddot{x} - 3n^2 \delta x - 2n \delta \dot{y} = \frac{T_x}{m} \]

\[ \delta \ddot{y} + 2n \delta \dot{x} = \frac{T_y}{m} \]

\[ \delta \ddot{z} + n^2 \delta z = \frac{T_z}{m} \]

Closed-form solution:

\[ \delta \vec{r}(\delta t) = \Phi_{rr}(\delta t)\delta \vec{r}_0 + \Phi_{rv}(\delta t)\delta \vec{v}_0 \]

\[ \delta \vec{v}(\delta t) = \Phi_{vr}(\delta t)\delta \vec{r}_0 + \Phi_{vv}(\delta t)\delta \vec{v}_0 \]
Relative Motion

In order to simulate the relative motion of a spacecraft to its target, the closed-form solution of the Hill-Clohessy-Wiltshire equations can be implemented for rendezvous.

- Computationally inexpensive.
- Real-time control enables autonomy.
- Spacecraft must be in the vicinity of the target debris and the target.
- Target must be in a nearly circular orbit.

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Dynamic Greedy Travelling Salesperson

The spacecraft is to:

- Determine the permissible HCW space $X^3$.
- Search within that space for possible debris targets $NNS$.
- Compute the cost to rendezvous with each feasible debris $MCW2I$.
- Rendezvous with the debris requiring the least $\Delta V$.
- Repeat for each subsequent debris until all propellant is expended.

**Figure:** An illustration of the method by which the spacecraft is to capture debris efficiently.
Dynamic Greedy Travelling Salesperson

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**Figure**: An illustration of the method by which the spacecraft is to capture debris efficiently.
Dynamic Greedy Travelling Salesperson

Figure: Unconstrained NN tours. $\Delta V_{cap} = 5000 \text{ m/s} & \Delta t_{tr} = 3 \text{ hrs}$
**Dynamic Greedy Travelling Salesperson**

<table>
<thead>
<tr>
<th>1ˢᵗ Debris</th>
<th>2ⁿᵈ Debris</th>
<th>$\Delta V_{spent} ,[\text{m/s}]$</th>
<th>$A_{deb} ,[\text{m}^2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999-025AY</td>
<td>1999-025BMF</td>
<td>159.8777</td>
<td>1.752</td>
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<tr>
<td>1999-025BQ</td>
<td>1999-025ANC</td>
<td>206.9559</td>
<td>1.752</td>
</tr>
<tr>
<td>1999-025AEF</td>
<td>1999-025BXU</td>
<td>132.8574</td>
<td>1.752</td>
</tr>
<tr>
<td>1999-025AJX</td>
<td>1999-025BRF</td>
<td>197.5427</td>
<td>1.752</td>
</tr>
<tr>
<td>1999-025AZV</td>
<td>1999-025ZM</td>
<td>142.8967</td>
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<tr>
<td>1999-025BLJ</td>
<td>1999-025CT</td>
<td>182.6922</td>
<td>7.688</td>
</tr>
<tr>
<td>1999-025BMF</td>
<td>1999-025AY</td>
<td>199.7687</td>
<td>1.752</td>
</tr>
<tr>
<td>1999-025CAH</td>
<td>1999-025BLV</td>
<td>213.9889</td>
<td>7.688</td>
</tr>
<tr>
<td>1999-025DDV</td>
<td>1999-025DYC</td>
<td>126.0361</td>
<td>16.031</td>
</tr>
<tr>
<td>1999-025DVV</td>
<td>1999-025AZB</td>
<td>129.6952</td>
<td>8.249</td>
</tr>
</tbody>
</table>

**Table:** Feasible HCW Rendezvous Tours. $\Delta V_{cap} = 220 \text{m/s} \& \Delta t = 3 \text{hrs}$
Figure: Optimal NN tours with $\Delta V_{cap} = 200 \, m/s$ and $\Delta t_{tr} = 3 \, hrs$. 
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Passive Deorbitation

Once the debris objects are captured, the drag sail is deployed, and the time to deorbit decreases significantly.

\[
A_D = 0.01 \text{ [m}^2\text{]} \\
A_D = 3 \text{ [m}^2\text{]}
\]

<table>
<thead>
<tr>
<th>Altitude [km]</th>
<th>(A_D = 0.01 \text{ [m}^2\text{]})</th>
<th>(A_D = 3 \text{ [m}^2\text{]})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time to Deorbit (T_D) [hrs]</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>136.56</td>
<td>2.42</td>
</tr>
<tr>
<td>250</td>
<td>1185.61</td>
<td>7.24</td>
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<tr>
<td>300</td>
<td>21806.44</td>
<td>21.36</td>
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<tr>
<td>350</td>
<td>80219.76</td>
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<tr>
<td>400</td>
<td>275637.64</td>
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<tr>
<td>450</td>
<td>275637.62</td>
<td>928.84</td>
</tr>
<tr>
<td>500</td>
<td>887488.56</td>
<td>2968.56</td>
</tr>
</tbody>
</table>

Table: Orbital decay comparison from various altitudes for a 5 kg cubesat, with and without a deployed drag sail.
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Conclusions

The method of deorbiting space debris with CubeSats through computationally inexpensive means and passive aerodynamic drag has herewith been conceptually proven. Some conclusions:

- Aerodynamic drag sails are currently the most efficient way to deorbit debris once they’ve been captured.
- The use the HCW equations may prove feasible in opportunistic debris removal.
- Instead of targeting debris, the debris should come to the spacecraft.
- CubeSats are a prime candidates for simultaneous, large-scale, economical active debris removal.
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Future Work

To be included in future renditions of this project:

- Global optimisation.
- Continuous thrust.
- Heuristic sampling methods.
- Parallelisation.
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