Modelling and Simulation of Autonomous CubeSats for Orbital Debris Mitigation

Rensselaer Polytechnic Institute

Christopher Iliffe Sprague

6^{th} International Conference on Astrodynamics Tools and Techniques

March 9, 2016

Outline

Next Subsection

The Situation

- Increasing space activity leads to an increased potential of generating orbital debris.

The Situation

- Increasing space activity leads to an increased potential of generating orbital debris.
- The presence of orbital debris within Low Earth Orbit (LEO) is becoming increasingly prevalent.

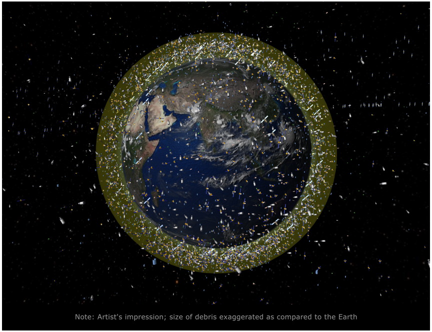


Figure: Debris objects within LEO [2]

The Situation

- Increasing space activity leads to an increased potential of generating orbital debris.
- The presence of orbital debris within Low Earth Orbit (LEO) is becoming increasingly prevalent.
- Increasing the presence of objects within LEO leads to Kessler Syndrome [1].

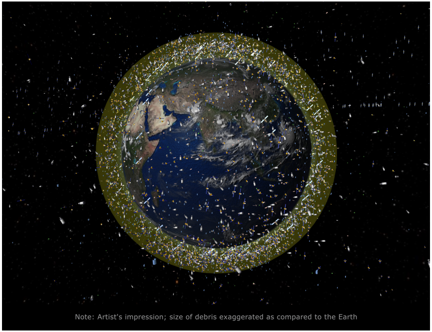


Figure: Debris objects within LEO [2]

The Situation

- Increasing space activity leads to an increased potential of generating orbital debris.
- The presence of orbital debris within Low Earth Orbit (LEO) is becoming increasingly prevalent.
- Increasing the presence of objects within LEO leads to Kessler Syndrome [1].
- Kessler Syndrome leads to the decreased viability of maintaining satellites in LEO.

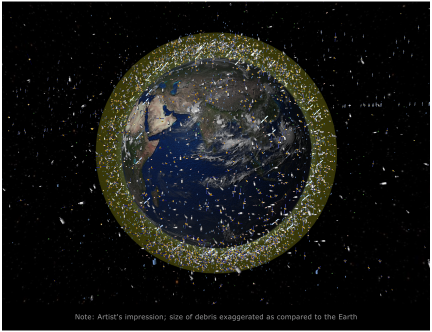


Figure: Debris objects within LEO [2]

Next Subsection

Orbital Debris - Numbers

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

Orbital Debris - Numbers

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

- Over 170 million debris objects smaller than 1 mm.

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.

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].

Orbital Debris - Characterisation

- Orbital debris within LEO are situated in various orbital planes.

[2]

Orbital Debris - Characterisation

- Orbital debris within LEO are situated in various orbital planes.
- Orbital planes change over time, resulting in global coverage, leading to Kessler syndrome.

[2]

Orbital Debris - Characterisation

- Orbital debris within LEO are situated in various orbital planes.
- Orbital planes change over time, resulting in global coverage, leading to Kessler syndrome.
- Collisions in LEO can occur from virtually any direction.

[2]

Orbital Debris - Characterisation

- Orbital debris within LEO are situated in various orbital planes.
- 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]

Orbital Debris - Sources

- Artificial satellites orbiting Earth, that have been abandoned or have become nonfunctional.
- Rocket upper stages that have been broken up by unburned fuel.

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

Orbital Debris - Sources

- Artificial satellites orbiting Earth, that have been abandoned or have become nonfunctional.
- Rocket upper stages that have been broken up by unburned fuel.
- Anti-satellite weapons.

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

Orbital Debris - Dangers

For a typical satellite, a collision with a:

Orbital Debris - Dangers

For a typical satellite, a collision with a:

- 10 cm object may result in a catastrophic fragmentation.

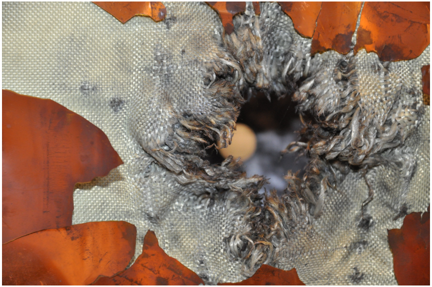


Figure: Exit hole through the Kevlar-Nextel fabric, used to shield the ISS; incurred by a 7.5 mm diameter aluminium bullet travelling at 7 km/s. [2]

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.

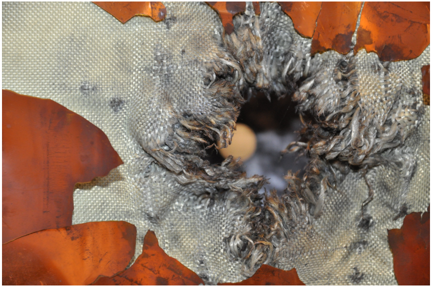


Figure: Exit hole through the Kevlar-Nextel fabric, used to shield the ISS; incurred by a 7.5 mm diameter aluminium bullet travelling at 7 km/s. [2]

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.

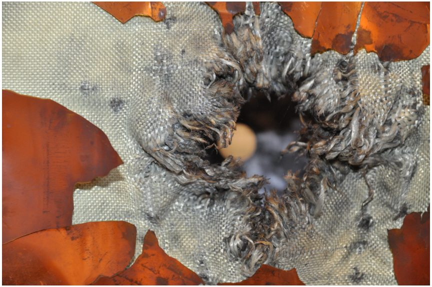


Figure: Exit hole through the Kevlar-Nextel fabric, used to shield the ISS; incurred by a 7.5 mm diameter aluminium bullet travelling at 7 km/s. [2]

Orbital Debris - Detectability

- Debris as small as 1 cm can be detected.

Figure: Goldstone Antenna [4]

Orbital Debris - Detectability

- Debris as small as 1 cm can be detected.
- Most debris cannot be directly observed.

Figure: Goldstone Antenna [4]

Orbital Debris - Detectability

- Debris as small as 1 cm can be detected.
- Most debris cannot be directly observed.
- Radar and optical detectors are mainly used.

Figure: Goldstone Antenna [4]

Next Subsection

Active Debris Removal - Current Efforts

Current efforts include:

Active Debris Removal - Current Efforts

Current efforts include:

- Electrodynamic tethers

Active Debris Removal - Current Efforts

Current efforts include:

- Electrodynamic tethers
- Laser brooms

Figure: An artistic representation of a laser broom's implementation. [5]

Active Debris Removal - Current Efforts

Current efforts include:

- Electrodynamic tethers
- Laser brooms
- Solar Sails

Figure: An artistic representation of a laser broom's implementation. [5]

Active Debris Removal - Current Efforts

Current efforts include:

- Electrodynamic tethers
- Laser brooms
- Solar Sails
- Nets

Figure: An artistic representation of a laser broom's implementation. [5]

Active Debris Removal - Current Efforts

Current efforts include:

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

Figure: An artistic representation of a laser broom's implementation. [5]

CubeSats - Design

Reasons to use CubeSats:

Figure: A CubeSat being deployed from the ISS. [6]

CubeSats - Design

Reasons to use CubeSats:

- They're economical.

Figure: A CubeSat being deployed from the ISS. [6]

CubeSats - Design

Reasons to use CubeSats:

- They're economical.
- They can be deployed in multiples.

Figure: A CubeSat being deployed from the ISS. [6]

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.

Figure: A CubeSat being deployed from the ISS. [6]

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.

Figure: A CubeSat being deployed from the ISS. [6]

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.

Figure: A CubeSat being deployed from the ISS. [6]

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.

Figure: A CubeSat being deployed from the ISS. [6]

CubeSats - Design

Technicals

- Standard CubeSats are made up of 10x10x11.35 cm units

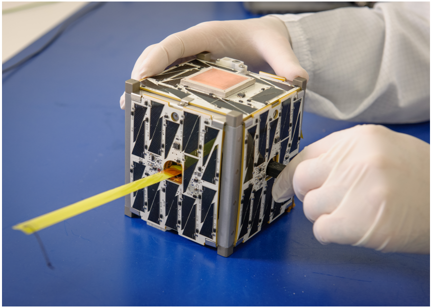


Figure: 1-unit CubeSat. [7]

CubeSats - Design

Technicals

- Standard CubeSats are made up of 10x10x11.35 cm units
- Provide 1 litre of useful volume, while weighing no more than 1.33 kg per unit.

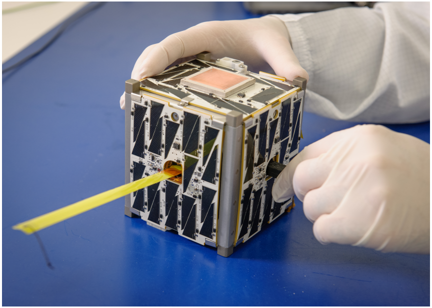


Figure: 1-unit CubeSat. [7]

CubeSats - Design

Technicals

- Standard CubeSats are made up of 10x10x11.35 cm units
- Provide 1 litre of useful volume, while weighing no more than 1.33 kg per unit.
- Size standardisation allows CubeSats to be launched by a common deployment system.

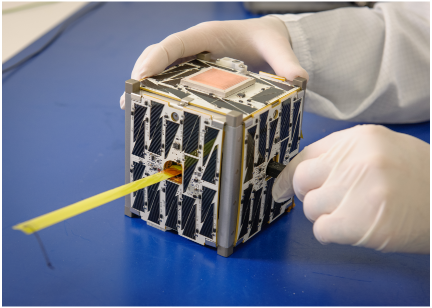


Figure: 1-unit CubeSat. [7]

CubeSats - Design

Technicals

- Standard CubeSats are made up of 10x10x11.35 cm units
- Provide 1 litre of useful volume, while weighing no more than 1.33 kg per unit.
- Size standardisation allows CubeSats to be launched by a common deployment system.
- Commercial-off-the-shelf hardware is readily accessible.

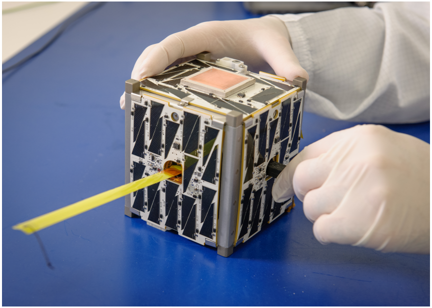


Figure: 1-unit CubeSat. [7]

CubeSats - Design

Classifications:

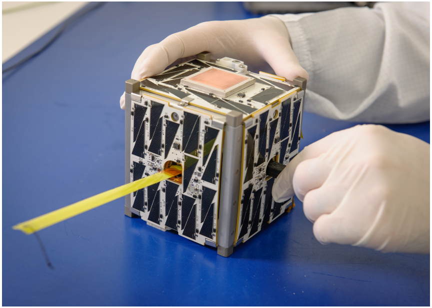


Figure: 1-unit CubeSat. [7]

CubeSats - Design

Classifications:

- Microsatellites are 10 - 100 kg

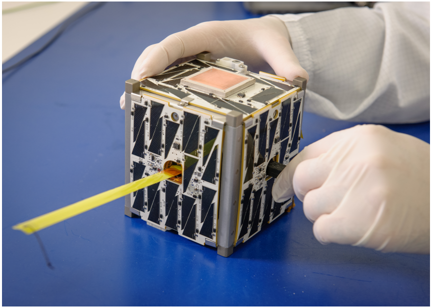


Figure: 1-unit CubeSat. [7]

CubeSats - Design

Classifications:

- Microsatellites are 10 - 100 kg
- Nanosatellites are 1 - 10 kg

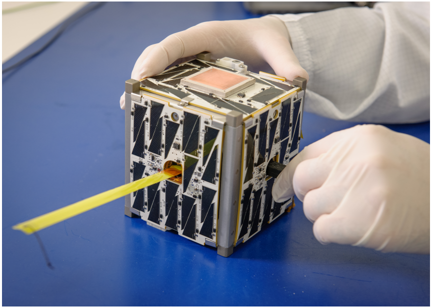


Figure: 1-unit CubeSat. [7]

CubeSats - Design

Classifications:

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

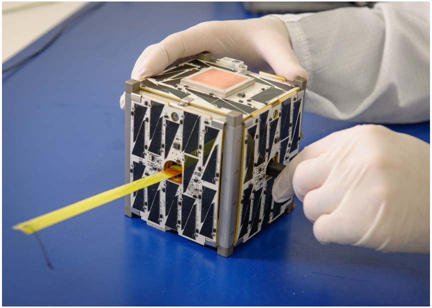


Figure: 1-unit CubeSat. [7]

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

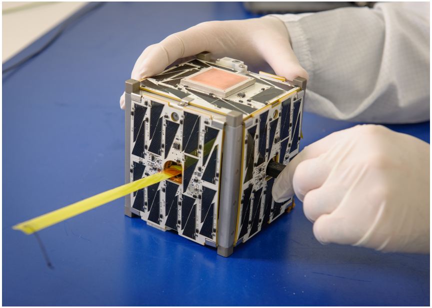


Figure: 1-unit CubeSat. [7]

Next Subsection

Simulation - Development

- Python 2.7 was chosen as the programming language.

Simulation - Development

- Python 2.7 was chosen as the programming language.
- Ephemerides were obtained through NASA's Jet Propulsion Laboratory Development Ephemeris, *DE423*, by use of the Python module, *jplephem 1.2*.

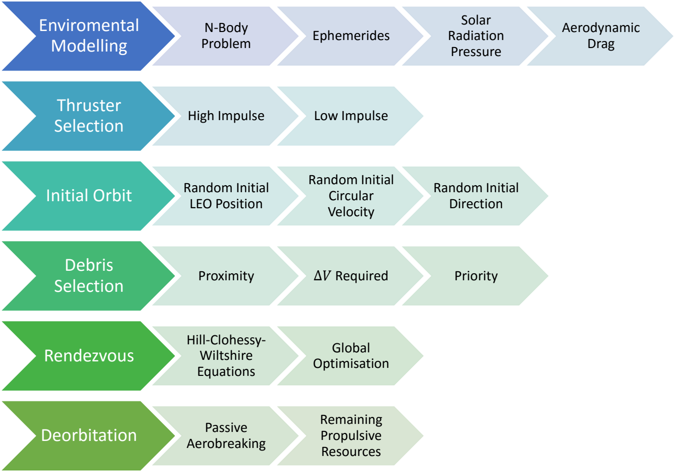
Simulation - Development

- Python 2.7 was chosen as the programming language.
- Ephemerides were obtained through NASA's Jet Propulsion Laboratory Development Ephemeris, *DE423*, by use of the Python module, *jplephem 1.2*.
- Two-line elements of the debris were obtained through CelesTrack.

Simulation - Development

- Python 2.7 was chosen as the programming language.
- Ephemerides were obtained through NASA's Jet Propulsion Laboratory Development Ephemeris, *DE423*, by use of the Python module, *jplephem 1.2*.
- 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



Next Subsection

Random Insertion

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

Random Insertion

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

- Coordinates: θ and ϕ.

Definition

Random initial longitude and latitude:

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

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

Random Insertion

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

- Coordinates: θ and ϕ.
- Altitude: h.

Definition

Random initial longitude and latitude:

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

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

Random Insertion

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

- Coordinates: θ and ϕ.
- Altitude: h.
- Eccentricity within limits: e.

Definition

Random initial longitude and latitude:

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

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

Random Insertion

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

- Coordinates: θ and ϕ.
- 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:

$$\hat{v} = \frac{\vec{r}_{arb} - \vec{r}}{\|\vec{r}_{arb} - \vec{r}\|}$$

Next Subsection

Conservative Forces

The relevant conservative forces must be accounted for:

Definition

Gravitational Acceleration:

$$\vec{A}_n^j = -\frac{\mu^j(\vec{R}_n^j - \vec{R}_n^{sc})}{\|\vec{R}_n^j - \vec{R}_n^{sc}\|^3}$$

Conservative Forces

The relevant conservative forces must be accounted for:

- Earth's gravity.

Definition

Gravitational Acceleration:

$$\vec{A}_n^j = -\frac{\mu^j(\vec{R}_n^j - \vec{R}_n^{sc})}{\|\vec{R}_n^j - \vec{R}_n^{sc}\|^3}$$

Conservative Forces

The relevant conservative forces must be accounted for:

- Earth's gravity.
- The Sun's gravity.

Definition

Gravitational Acceleration:

$$\vec{A}_n^j = -\frac{\mu^j(\vec{R}_n^j - \vec{R}_n^{sc})}{\|\vec{R}_n^j - \vec{R}_n^{sc}\|^3}$$

Conservative Forces

The relevant conservative forces must be accounted for:

- Earth's gravity.
- The Sun's gravity.
- The Moon's gravity

Definition

Gravitational Acceleration:

$$\vec{A}_n^j = -\frac{\mu^j(\vec{R}_n^j - \vec{R}_n^{sc})}{\|\vec{R}_n^j - \vec{R}_n^{sc}\|^3}$$

Conservative Forces

The relevant conservative forces must be accounted for:

- Earth's gravity.
- The Sun's gravity.
- The Moon's gravity
- Essentially an N-Body problem.

Definition

Gravitational Acceleration:

$$\vec{A}^j_n = -\frac{\mu^j(\vec{R}^j_n - \vec{R}^{sc}_n)}{\|\vec{R}^j_n - \vec{R}^{sc}_n\|^3}$$

Definition

N-Body Problem:

$$\vec{A}_{i,n} = \sum_{j=0, i\neq j}^{N} \vec{A}^j_{i,n}$$

Barycentric Perspective

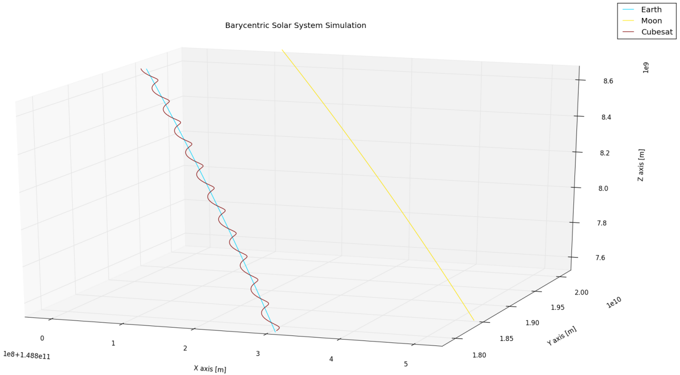


Figure: A barycentric view of a CubeSat in Low Earth Orbit with the Moon in view.

Non-Conservative Forces

The non-conservative perturbations must be accounted for:

Non-Conservative Forces

The non-conservative perturbations must be accounted for:

- Atmospheric Drag.

Non-Conservative Forces

The non-conservative perturbations must be accounted for:

- Atmospheric Drag.
- Atmospheric Scale Model.

Definition

Scaling atmospheric density model:

$$\rho_n = \rho_0 e^{\frac{-h_n}{H}}$$

Non-Conservative Forces

The non-conservative perturbations must be accounted for:

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

Definition

Acceleration due to solar-radiation pressure:

$$\vec{A}_n^{Solar} = -\frac{p_n^s C_n^R A_n^{\perp \hat{s}} \hat{s}_n}{m_n}$$

Definition

Scaling atmospheric density model:

$$\rho_n = \rho_0 e^{\frac{-h_n}{H}}$$

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:

$$\rho_n = \rho_0 e^{\frac{-h_n}{H}}$$

Definition

Acceleration due to solar-radiation pressure:

$$\vec{A}_n^{Solar} = -\frac{p_n^s C_n^R A_n^{\perp \hat{s}} \hat{s}_n}{m_n}$$

Definition

Eclipse determination:

$$\tau = \frac{\vec{r} \cdot \vec{r} - \vec{s}_E}{|\vec{r} - \vec{s}_E|^2}$$

Atmospheric Drag

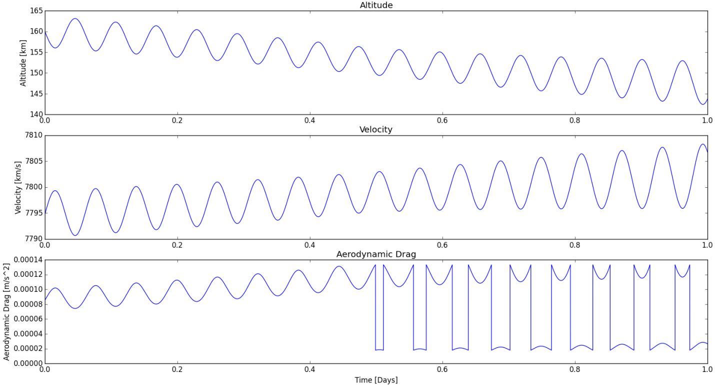


Figure: Atmospheric drag with scale model implemented.

Solar-Radiation Pressure

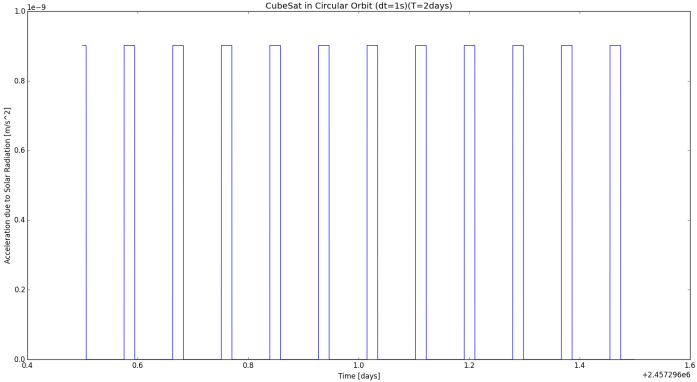


Figure: Solar-radiation pressure model with eclipse model implemented.

Next Subsection

Numerical Propagation

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

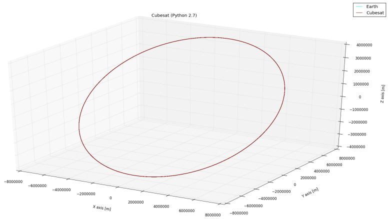


Figure: Simple Low Earth Orbit motion, as propagated by the RKF45 method.

Numerical Propagation

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

- Forward Euler method.

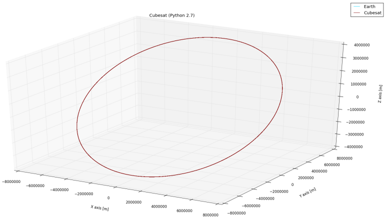


Figure: Simple Low Earth Orbit motion, as propagated by the RKF45 method.

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.

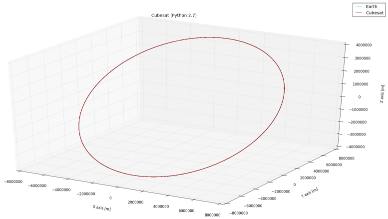


Figure: Simple Low Earth Orbit motion, as propagated by the RKF45 method.

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.

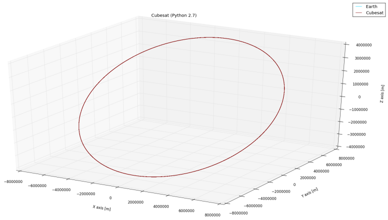


Figure: Simple Low Earth Orbit motion, as propagated by the RKF45 method.

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.

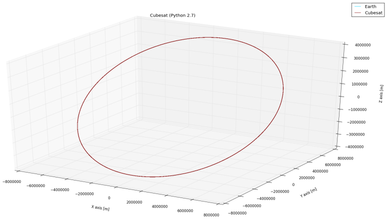


Figure: Simple Low Earth Orbit motion, as propagated by the RKF45 method.

Next Subsection

Mechanism of Action

The steps to efficient orbital debris mitigation:

Figure: MERiDIUS passively deorbiting captured debris. [10]

Mechanism of Action

The steps to efficient orbital debris mitigation:

- Rendezvous using Aerojet Rocketdyne's *MPS-120 (CHAMPS)* [8] with $\Delta V = 200\ m/s$.

Figure: MERiDIUS passively deorbiting captured debris. [10]

Mechanism of Action

The steps to efficient orbital debris mitigation:

- Rendezvous using Aerojet Rocketdyne's *MPS-120 (CHAMPS)* [8] with $\Delta V = 200\ m/s$.
- Capture with ejected net.

Figure: MERiDIUS passively deorbiting captured debris. [10]

Mechanism of Action

The steps to efficient orbital debris mitigation:

- Rendezvous using Aerojet Rocketdyne's *MPS-120 (CHAMPS)* [8] with $\Delta V = 200\ m/s$.
- Capture with ejected net.
- Passively deorbit with aerodynamic drag, utilising Clyde Space's *(AEOLDOS)* [9] with $A = 3\ m^2$.

Figure: MERiDIUS passively deorbiting captured debris. [10]

Mechanism of Action

The steps to efficient orbital debris mitigation:

- Rendezvous using Aerojet Rocketdyne's *MPS-120 (CHAMPS)* [8] with $\Delta V = 200\ m/s$.
- Capture with ejected net.
- Passively deorbit with aerodynamic drag, utilising Clyde Space's *(AEOLDOS)* [9] with $A = 3\ m^2$.
- Utilise remaining propellant.

Figure: MERiDIUS passively deorbiting captured debris. [10]

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].

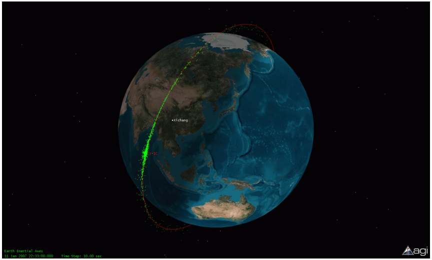


Figure: Fengyun−1C debris scattering, 5 minutes after its collision. [12]

Next Subsection

Now to dispose of the debris...

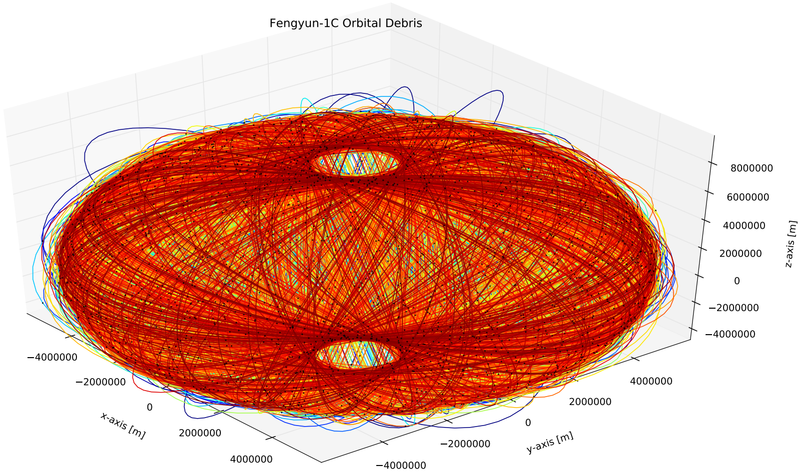


Figure: The trajectory of every trackable debris fragment of Fengyun−1C as of January 1^{st}, 2016.

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:

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

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

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

Closed-form solution:

$$\delta\vec{r}(\delta t) = \mathbf{\Phi}_{rr}(\delta t)\delta\vec{r}_0 + \mathbf{\Phi}_{rv}(\delta t)\delta\vec{v}_0$$

$$\delta\vec{v}(\delta t) = \mathbf{\Phi}_{vr}(\delta t)\delta\vec{r}_0 + \mathbf{\Phi}_{vv}(\delta t)\delta\vec{v}_0$$

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.

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:

$$\delta\vec{r}(\delta t) = \mathbf{\Phi}_{rr}(\delta t)\delta\vec{r}_0 + \mathbf{\Phi}_{rv}(\delta t)\delta\vec{v}_0$$

$$\delta\vec{v}(\delta t) = \mathbf{\Phi}_{vr}(\delta t)\delta\vec{r}_0 + \mathbf{\Phi}_{vv}(\delta t)\delta\vec{v}_0$$

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.

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:

$$\delta\vec{r}(\delta t) = \mathbf{\Phi}_{rr}(\delta t)\delta\vec{r}_0 + \mathbf{\Phi}_{rv}(\delta t)\delta\vec{v}_0$$

$$\delta\vec{v}(\delta t) = \mathbf{\Phi}_{vr}(\delta t)\delta\vec{r}_0 + \mathbf{\Phi}_{vv}(\delta t)\delta\vec{v}_0$$

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.

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:

$$\delta\vec{r}(\delta t) = \mathbf{\Phi}_{rr}(\delta t)\delta\vec{r}_0 + \mathbf{\Phi}_{rv}(\delta t)\delta\vec{v}_0$$

$$\delta\vec{v}(\delta t) = \mathbf{\Phi}_{vr}(\delta t)\delta\vec{r}_0 + \mathbf{\Phi}_{vv}(\delta t)\delta\vec{v}_0$$

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.

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:

$$\delta\vec{r}(\delta t) = \mathbf{\Phi}_{rr}(\delta t)\delta\vec{r}_0 + \mathbf{\Phi}_{rv}(\delta t)\delta\vec{v}_0$$

$$\delta\vec{v}(\delta t) = \mathbf{\Phi}_{vr}(\delta t)\delta\vec{r}_0 + \mathbf{\Phi}_{vv}(\delta t)\delta\vec{v}_0$$

Dynamic Greedy Travelling Salesperson

The spacecraft is to:

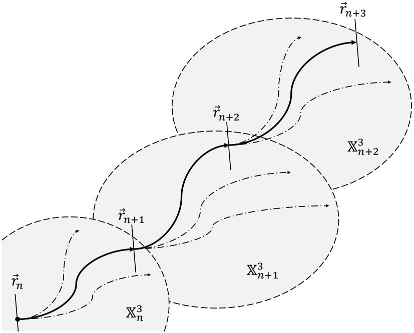


Figure: An illustration of the method by which the spacecraft is to capture debris efficiently.

Dynamic Greedy Travelling Salesperson

The spacecraft is to:

- Determine the permissible HCW space $\mathbb{X}^3$: **HCW Space**.

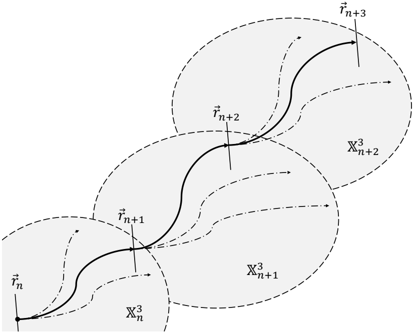


Figure: An illustration of the method by which the spacecraft is to capture debris efficiently.

Dynamic Greedy Travelling Salesperson

The spacecraft is to:

- Determine the permissible HCW space $\mathbb{X}^3$: **HCW Space**.
- Search within that space for possible debris targets: **NNS**.

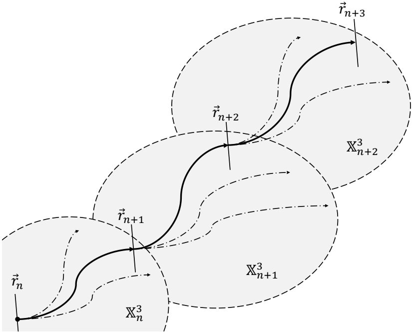


Figure: An illustration of the method by which the spacecraft is to capture debris efficiently.

Dynamic Greedy Travelling Salesperson

The spacecraft is to:

- Determine the permissible HCW space $\mathbb{X}^3$: **HCW Space**.
- Search within that space for possible debris targets: **NNS**.
- Compute the cost to rendezvous with each feasible debris: **MCW2I**.

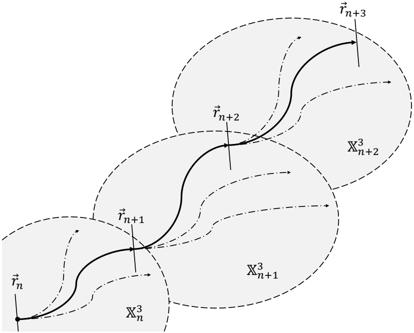


Figure: An illustration of the method by which the spacecraft is to capture debris efficiently.

Dynamic Greedy Travelling Salesperson

The spacecraft is to:

- Determine the permissible HCW space $\mathbb{X}^3$: **HCW Space**.
- 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 ΔV.

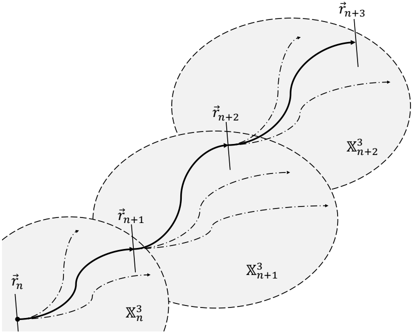


Figure: An illustration of the method by which the spacecraft is to capture debris efficiently.

Dynamic Greedy Travelling Salesperson

The spacecraft is to:

- Determine the permissible HCW space $\mathbb{X}^3$: **HCW Space**.
- 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 ΔV.
- Repeat for each subsequent debris until all propellant is expended.

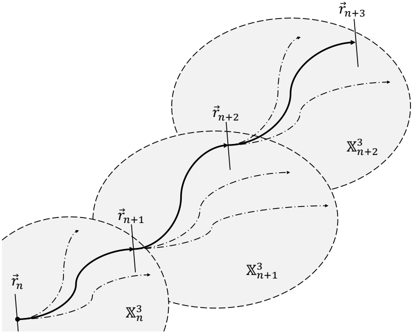


Figure: An illustration of the method by which the spacecraft is to capture debris efficiently.

Dynamic Greedy Travelling Salesperson

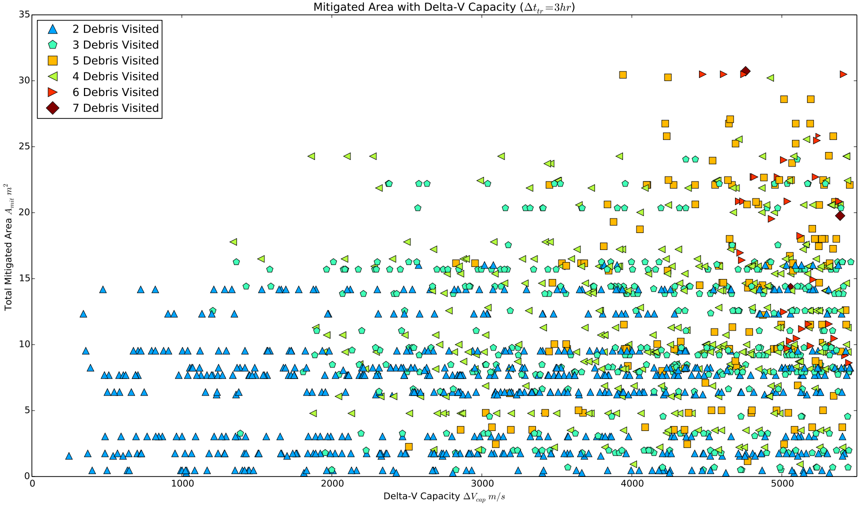


Figure: Unconstrained NN tours. $\Delta V_{cap} = 5000\ m/s$ & $\Delta t_{tr} = 3\ hrs$

Dynamic Greedy Travelling Salesperson

1^{st} Debris	2^{nd} Debris	ΔV_{spent} $[m/s]$	A_{deb} $[m^2]$
1999-025AY	1999-025BMF	159.8777	1.752
1999-025BQ	1999-025ANC	206.9559	1.752
1999-025AEF	1999-025BXU	132.8574	1.752
1999-025AJX	1999-025BRF	197.5427	1.752
1999-025AZV	1999-025ZM	142.8967	0.277
1999-025BLJ	1999-025CT	182.6922	7.688
1999-025BMF	1999-025AY	199.7687	1.752
1999-025CAH	1999-025BLV	213.9889	7.688
1999-025CBT	1999-025ALT	99.7949	6.402
1999-025CFR	1999-025DLT	105.7221	14.185
1999-025DDV	1999-025DYC	126.0361	16.031
1999-025DVV	1999-025AZB	129.6952	8.249

Table: Feasible HCW Rendezvous Tours. $\Delta V_{cap} = 220 m/s$ & $\Delta t = 3 hrs$

Dynamic Greedy Travelling Salesperson

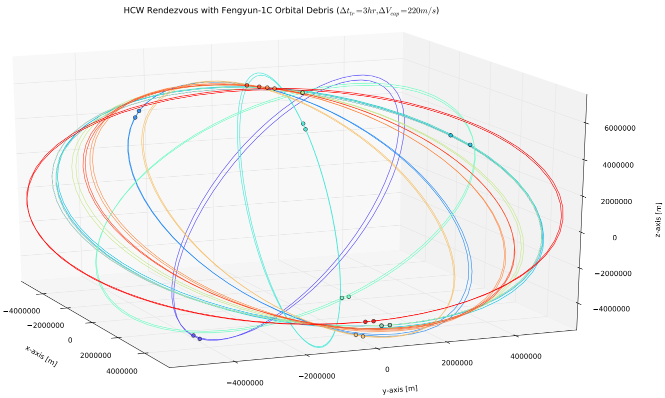


Figure: Optimal NN tours with $\Delta V_{cap} = 200$ m/s and $\Delta t_{tr} = 3$ hrs.

Next Subsection

Passive Deorbitation

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

	$A_D = 0.01\ [m^2]$	$A_D = 3\ [m^2]$
Altitude [*km*]	Time to Deorbit T_D [*hrs*]	
200	136.56	2.42
250	1185.61	7.24
300	21806.44	21.36
350	80219.76	79.23
400	275637.64	275.76
450	275637.62	928.84
500	887488.56	2968.56

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

Next Subsection

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.

Next Subsection

Future Work

To be included in future renditions of this project:

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

Citations

Donald J Kessler, Nicholas L Johnson, J.-C Liou, and Mark Matney,
"The Kessler Syndrome: Implications to Future Space operations,"
.

Esa,
"Technologies for space debris remediation," .

Alice Gorman,
"Humanity's next giant leap: our heritage in space is our future too," .

OrbitalHub,
"Goldstone Antenna," .

"Laser broom," jan 2016.