EUCASS 2017

Systematic space debris collection using Cubesat constellation

Romain Lucken
Co-founder of Share My Space
PhD student at LPP, CNRS/Ecole polytechnique

Damien Giolito

July 4th 2017, Politecnico Milano
Outline

- Introduction
- Mission requirements
- Cubesat maneuvers
- Technical solutions
- Constellation management
Introduction

• Motivation: The **Rise of LEO economy**
  – Overcrowded SSO and polar orbits due to legacy
  – Cubesat and nanosats for technology testing
  – Megaconstelations
    10 000+ smallsats deployment expected within 10 years

• Opportunity: **Standardization** of Cubesat parts
  – Design
  – Recycling and servicing

• Solution of Cubesat constellation for ADR is addressed
Introduction

Space debris are localized in orbit space

Unclassified data from www.space-track.org
Introduction

Space debris forecasts

Business as usual  Compliance with Law of space

Each curve represents a prediction scenario
Mission requirements

• Multiple **debris collection and release**
  – Debris tracking
  – On-orbit rendez-vous with non-collaborative target
  – **High Δv** maneuvers

• Docking on **inflatable mothership**
  – Debris temporary storage
  – End-of-life
Technical solutions

• Off-the shelf parts
  – Attitude control
  – Solar panels ~ 120 W
  – Antennas
  – On-board electronics

• Plasma propulsion
  – Cathode-less RF ion thruster
  – Iodine for compact storage under solid state
  – Specific impulse > 3000 s
Technical solutions

• Grabbing device
  – Expandable loops
  – 3 electric motors + 3 for redundancy

• Tracking
  – 3D viewing using stereoscopic cameras
  – Low power LIDAR

Structure Core Occipital 3D camera
Cubesat maneuver

Phase angle

<table>
<thead>
<tr>
<th>Description</th>
<th>Variable</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC mass</td>
<td>$M$</td>
<td>8.0</td>
<td>kg</td>
</tr>
<tr>
<td>Propellant mass</td>
<td>$m_p$</td>
<td>1.0</td>
<td>kg</td>
</tr>
<tr>
<td>Electric power for propulsion</td>
<td>$P_{elec}$</td>
<td>120</td>
<td>W</td>
</tr>
<tr>
<td>Thrust to power ratio</td>
<td>$t_w$</td>
<td>$3.0 \times 10^{-5}$</td>
<td>N/W</td>
</tr>
<tr>
<td>Specific impulse</td>
<td>$I_{sp}$</td>
<td>3000</td>
<td>s</td>
</tr>
<tr>
<td>Thrust</td>
<td>$T$</td>
<td>3.6</td>
<td>mN</td>
</tr>
<tr>
<td>Thruster mass flow rate</td>
<td>$\dot{m}$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>g/s</td>
</tr>
<tr>
<td>Angular velocity variation</td>
<td>$\Delta \omega$</td>
<td>$1.2 \times 10^{-6}$</td>
<td>rad/s</td>
</tr>
</tbody>
</table>

\[
\Delta h = \frac{2}{3\sqrt{GM_T}}(R_T + h)^{5/2} \Delta \omega
\]

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit altitude</td>
<td>[km]</td>
</tr>
<tr>
<td>Altitude shift</td>
<td>[km]</td>
</tr>
<tr>
<td>Required pulse</td>
<td>[Ns]</td>
</tr>
<tr>
<td>Time to shift orbit</td>
<td>[hours]</td>
</tr>
<tr>
<td>Used propellant mass</td>
<td>[kg]</td>
</tr>
</tbody>
</table>

\[
\Delta h \ll h \\
\Delta m_p \ll M + m_p \\
\Delta t \ll 1 \text{ month}
\]

\[
\Delta \omega = \frac{\pi}{1 \text{ month}}
\]
Cubesat maneuver

Orbit raising

• Vis-viva equation

\[ \Delta v = \sqrt{\frac{GM_T}{r_1 r_2}} \left( \sqrt{\frac{2}{r_1 + r_2}} (r_2 - r_1) - \sqrt{r_2} + \sqrt{r_1} \right) \]

• Tsiolkovski equation

\[ \frac{\Delta m}{m} = \exp \left( \frac{\Delta v}{v_{ex}} \right) - 1 \]

• From 500 km:

<table>
<thead>
<tr>
<th>( h ) [km]</th>
<th>800</th>
<th>1200</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta m ) [g]</td>
<td>21</td>
<td>47</td>
<td>97</td>
</tr>
<tr>
<td>( T_{OR} ) [days]</td>
<td>47</td>
<td>107</td>
<td>220</td>
</tr>
</tbody>
</table>

\[
m = 10 \text{ kg} \\
T = 3.6 \text{ mN} \\
P_{elec} = 120 \text{ W} \\
\dot{m} = 1.2 \times 10^{-4} \text{ g/s} \\
I_{sp} = 3000 \text{ s}
\]
Cubesat maneuver

Orbit plane

Angle shift

\[ \alpha = \int d\alpha = \int \sqrt{d\theta^2 + \cos^2 \theta d\phi^2} \]

\[ \Delta v = 2v \sin \left( \frac{\alpha}{2} \right) \]

\[ \alpha = \frac{v_{ex}}{v} \ln \left( 1 + \frac{m_p}{m_0} \right) \]

- Very high propellant requirements
- Iodine plasma propulsion with high specific impulse and high storage density lead to a total angle over the mission:

\[ \alpha \approx 0.9\pi \]
Cubesat maneuver

Low thrust orbit transfer
Edelbaum’s equation for circular orbits:

\[ \Delta v^2 = v_1^2 + v_2^2 - 2v_1 v_2 \cos \left( \frac{\pi \alpha}{2} \right) \]

- Accounts for altitude and orbit plane variations

SMART-1 mission design (ESA)
Geometry of the constellation

\( n \): number of debris removed by each Cubesat

\( p \): number of Cubesats in the constellation

\[ p \leftrightarrow n \]
Constellation management

Multiple debris collection

Storage orbit

1 satellite

$n$ debris

$a$
Constellation management

Simplified model for mission design requirements

• Assumptions
  – Only orbit plane variation maneuvers are included
  – $N$ debris spread uniformly in a square-like domain of solid angle $\Omega$

• Result
  – Number of SC required:

\[
p = 0.83 \times \left( \frac{Nv}{v_{ex} \ln \left( 1 + \frac{m_p}{m_0} \right)} \right)^{2/3} \Omega^{1/3}
\]
Application to SSO debris

SSO debris spread in phase space

Sat. 1 Sat. 2 Sat. 3 etc.

1937 debris
Constellation management

Application to SSO debris
  – Inclination between 98° and 99.5°
  – Altitude between 750 km and 850 km

Constellation of 38 Cubesats
• Low-thrust orbit transfer with optimized domains
  – 1075 removed debris
• Global formula
  – 1937 removed debris

Approximate formula provides a fair order of magnitude
Conclusion

Achievements

• First guidelines for **multiple debris removal** using a **constellation** of
  • Cubesats
  • Propulsion requirements and technical solutions
  • Return of experience from debris removal demonstrators (e.deorbit, RemoveDebris...)
  • **Low-cost** approach
    – Standard parts
    – Terrestrial technologies

Future work

• **Collision modeling** for long-term risk prediction
• **Database merging**
• Subsystem validation (visualization, attitude control, communication)
• System integration
Acknowledgement

is grateful to

C. Bonnal (CNES)
V. Croes, F. Marmuse, A. Bourdon, P. Chabert (LPP)
EUCASS 2017 organizing committee

Thank you for your attention!

Questions?
Atmosphere density

Density as a function of the altitude

 ALTITUDE [km] [0 200 400 600 800 1000]
 DENSITY [kg/m^3] [10^-15 10^-14 10^-13 10^-12 10^-11 10^-10 10^-9 10^-8 10^-7 10^-6 10^-5]
Cubesat maneuver
Cubesat maneuver
Cubesat maneuver