Mission Design and Optimal Asteroid Deflection for Planetary Defense

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Outline

- Optimal solutions for PD
- Problem Structure and Modeling
- Correctors
- The 2017 PDC scenario
- Peak Solutions for 2017 PDC
- Mission Constraints
- Mission Trade Study Options
- Mission Design Solutions
Optimal solutions for PD

• Simulation time and precision are key factors for PD missions
  – Asteroid post impact orbit (change in the order of cm/s)
  – Mission design trade (thousand optimizations)
• Previous research:
  – Analytical approximations on the close encounter conditions; or
  – Heavy n-body propagation of the asteroid's orbit
• This method: incorporates the trajectory design of the spacecraft with a simple set of two-body propagations to define the asteroid's post-deflection path. This provides a fast and cheap approximation with medium accuracy, suitable for preliminary mission design.
  – Kinetic impactor
  – Nuclear deflection

<table>
<thead>
<tr>
<th>Target orbit</th>
<th>Calculation</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real ephemerids (fully propagated model)</td>
<td>No analytical approximations</td>
<td>Fast</td>
</tr>
</tbody>
</table>
Problem Structure and Modeling

• This structure:
  – Leverages the optimization code structure
  – Gives direct control over the objective function

\[ \Delta v = X_M^- - X_M^+ \]

\[ F = \frac{\vec{X}_{Match}^- - \vec{X}_{Match}^+}{\|v_\infty \| r_{SOI}} \]

\[ v_\infty \cdot r_{SOI} \]

\[ \begin{bmatrix} \Delta \vec{v} \\ |v_\infty| \\ \theta_{r_{SOI}} \\ \delta_{r_{SOI}} \end{bmatrix} \]

\[ X = \begin{bmatrix} \vec{X}_{Match}^- - \vec{X}_{Match}^+ \\ v_\infty \cdot r_{SOI} \end{bmatrix} \]

\[ r_p = -a(1 - e) \]
Correctors

• A Kepler propagation of the asteroid’s orbit is NOT representative for PD
  – Lambert fit on the asteroid’s velocity at the point of deflection
• The new time of the SOI crossing is unknown
  – Single shoot search combine with a bisection to find the deflected orbit crossing time
• Radius of the perigee of the corrected orbit is different from the ephemerids
  – Lambert fit on Earth’s velocity at the SOI crossing
The 2017 PDC Scenario

• The 2017 PDC
  – Hypothetical asteroid impact scenario developed by NASA CNEOS

• The impact scenario:
  – An asteroid has been discovered on March 6, 2017.
  – First estimate of an Earthly impact is about 1 out of 40,000.
  – After an observation campaign the impact probability rose to 1%.
  – Latter confirmation of a Earth impact on July 21, 2027.

• Physical characteristics:
  – Asteroid is assumed to have 385 m in diameter with a density of the 2.6 g/cm$^3$ (mass is 7.768804e$^{10}$ kg)
Peak Solutions for 2017 PDC

The graph shows the close approach deflection relative to Earth radii over time in days. There are two peaks indicated:

1. **1st peak**: This peak occurs closer to the start of the timeline. The deflection value is about 3 Earth radii.

2. **2nd peak**: This peak is further along in the timeline and has a higher deflection value of about 4 Earth radii.

The x-axis represents the time to close approach in days, ranging from 500 to 3000 days.
### Mission Constraints

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Value</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch date</td>
<td>after Aug. 1, 2019</td>
<td>2 years after the asteroid’s probability of Earth impact rises to 10%.</td>
</tr>
<tr>
<td>Launch declination</td>
<td>±28.5</td>
<td>Declination bounds for the Kennedy launch complex.</td>
</tr>
<tr>
<td>Asteroid encounter phase angle</td>
<td>≤ 120</td>
<td>Upper limit to have enough of the asteroid illuminated for the spacecraft’s terminal guidance system.</td>
</tr>
<tr>
<td>Sun minimum distance</td>
<td>0.7 A.U.</td>
<td>Lower limit for the spacecraft design to handle the more aggressive thermal and radiation environments.</td>
</tr>
<tr>
<td>Sun maximum distance</td>
<td>3.5 A.U.</td>
<td>Upper limit to design a large spacecraft (complicated) enough to handle power generation and Earth communications at greater distances.</td>
</tr>
<tr>
<td>Earth Angle at asteroid encounter</td>
<td>≥ 3</td>
<td>Lower limit for the Deep Space Network to guarantee a viable RF link with the spacecraft.</td>
</tr>
</tbody>
</table>
# Mission Trade Study Options

<table>
<thead>
<tr>
<th>Launcher</th>
<th>Number of S/C</th>
<th>Encounter type</th>
<th>Deflection type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atlas V (551)</strong></td>
<td>Single</td>
<td>Rendezvous</td>
<td>Nuclear</td>
</tr>
<tr>
<td>- Min dry mass: 1900 kg</td>
<td></td>
<td>Flyby</td>
<td>- $</td>
</tr>
<tr>
<td>- Max. mass 5000 kg</td>
<td>Double</td>
<td>Combined with EGA</td>
<td>Kinetic</td>
</tr>
<tr>
<td><strong>Delta IV Heavy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Min dry mass: 1900 kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Max. mass 5000 kg</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Propulsion system</th>
<th>Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ballistic</strong></td>
<td>NEXT TT11</td>
</tr>
<tr>
<td><strong>SEP</strong></td>
<td>- Duty cycle: 90%</td>
</tr>
<tr>
<td>- Number of thrusters: 2</td>
<td>- Power at BOL: 20 kW</td>
</tr>
<tr>
<td></td>
<td>- S/C power: 0.8 kW</td>
</tr>
<tr>
<td><strong>Chemical</strong></td>
<td>- Throttle logic: min. number of thrusters</td>
</tr>
<tr>
<td>- 1 DSM</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- **Min dry mass:** Minimum dry mass of the vehicle.
- **Max. mass:** Maximum mass the vehicle can carry.
Mission Design Solutions

Single S/C - Survey + Deflection

Double S/C - Survey - Deflection