Mission Design and Optimal Asteroid Deflection for Planetary Defense

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NAVIGATION & MISSION DESIGN BRANCH

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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

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

![Graph showing close approach deflection versus time to close approach with labels for 1st and 2nd peaks.]

1st peak
2nd peak

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## 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>Atlas V (551)</td>
<td>Single</td>
<td>Rendezvous</td>
<td>Nuclear</td>
</tr>
<tr>
<td>Delta IV Heavy</td>
<td>Double</td>
<td>Flyby</td>
<td>Kinetic</td>
</tr>
<tr>
<td>- Min dry mass: 1900 kg</td>
<td></td>
<td>Combined with EGA</td>
<td></td>
</tr>
<tr>
<td>- Max. mass 5000 kg</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Propulsion system**
  - Ballistic
  - SEP: Number of thrusters: 2
  - Chemical: 1 DSM

- **Engine**
  - NEXT TT11
    - Duty cycle: 90%
    - Power at BOL: 20 kW
    - S/C power: 0.8 kW
    - Throttle logic: min. number of thrusters
Mission Design Solutions

**Single S/C**
- Survey + Deflection

**Double S/C**
- Survey
- Deflection

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**Before 1st peak**
- Event 1: launch Earth 8/1/2019
- \( v_i = 100.000 \text{ km/s} \)
- DEC = 3.5°
- \( m = 1045 \text{ kg} \)

**1st peak**
- Event #1: launch Earth 10/14/2020
- \( c_i = 76.33 \text{ km/s} \)
- DLA = 7.5°
- \( m = 2680 \text{ kg} \)

**Before 2nd peak**
- Event #1: launch Earth 8/2/2019
- \( v_i = 7.003 \text{ km/s} \)
- DEC = 8.0°
- \( m = 1963 \text{ kg} \)

**Two flybys**

**After 2nd peak**
- Event #2: launch Earth 6/11/2023
- \( v_i = 1900 \text{ km/s} \)

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**Double S/C**
- Survey + Deflection

- Event #2: launch Earth 6/11/2023
- \( v_i = 7.003 \text{ km/s} \)
- DEC = 8.0°
- \( m = 1963 \text{ kg} \)

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**Survey**
- Event #2: intercept 2017 PDC 3/11/2024
- \( v_n = 7.105 \text{ km/s} \)
- DEC = 8.0°
- \( m = 1963 \text{ kg} \)

**Deflection**
- Event #2: intercept 2017 PDC 10/29/2022
- \( v_n = 5.115 \text{ km/s} \)
- DEC = 8.3°
- \( m = 1963 \text{ kg} \)

**Survey + Deflection**
- Event #2: intercept 2017 PDC 3/11/2024
- \( v_n = 6.046 \text{ km/s} \)
- DEC = 6.4°
- \( m = 1900 \text{ kg} \)

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**Rendezvous**
- Event #1: launch Earth 8/2/2019
- \( c_i = 76.33 \text{ km/s} \)
- DLA = 10.9°
- \( m = 2468 \text{ kg} \)