Terminal Guidance Navigation for an Asteroid Impactor Spacecraft

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Introduction

- On July 4, 2005, the Deep Impact impactor spacecraft successfully collided with comet 9P/Tempel 1, while the main spacecraft flew by and shuttered images which captured the impact
  - 1st hypervelocity impact of a primitive Solar System body
  - Not primary goal of mission, but it did demonstrate that such an impact could be accomplished with current technologies and relatively modest budget
- Increased concerns have been raised in recent years about the hazard posed to the Earth from impacts by Near Earth Objects
- Recent NASA report outlined mitigation strategies should a NEO be found that poses a hazard to Earth
- For relatively small asteroids and short turnaround times from detection to impact, kinetic energy technique recommended as the most practical and cost effective technique for deflection
Introduction (cont)

- DI impact made possible by onboard closed-loop autonomous navigation system (AutoNav)
- Parameter settings and sequence of events performed by AutoNav determined through simulations to optimize probability of impact for DI and Tempel 1 approach scenario
- Key differences in scenarios between DI and potential asteroid deflection

<table>
<thead>
<tr>
<th></th>
<th>DI</th>
<th>Asteroid Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach velocity</td>
<td>10.5 km/s</td>
<td>~3 - &gt; 20 km/s</td>
</tr>
<tr>
<td>Approach phase angle</td>
<td>62 deg</td>
<td>0 to 180 deg</td>
</tr>
<tr>
<td>Target diameter</td>
<td>~ 6 km</td>
<td>&lt; 100 to &gt; 300 m</td>
</tr>
</tbody>
</table>
Introduction (cont)

• In this paper, we broaden the experience base of AutoNav for use on the asteroid deflection scenario.
• Use Monte Carlo simulations to assess performance for a wide range of scenarios:
  – Determine range of parameters from literature.
  – Vary key parameters to test their sensitivity.
• Simulations include:
  – Generation of photorealistic images using triaxial shape model for asteroid.
  – Orbit determination and maneuver targeting using AutoNav.
Deep Space Navigation

- Step 1: design trajectory to intercept asteroid
  - Details of how this is done out of scope for this paper
  - Use other studies, in particular one by Hernandez and Barbee (2012), that found a candidate set of reference trajectories

- Step 2: navigate reference trajectory from launch to impact
  - General techniques of navigation from launch, cruise, and early approach out of scope of this study
  - Main focus of this paper is the terminal guidance, defined here as point when AutoNav takes control.
  - As for DI, we assume this takes place approximately 2 hours prior to impact
Asteroid Ephemeris

- Knowledge of precise target asteroid location an important consideration for deflection
- Asteroid orbits obtained from ground observations, primarily optical from telescopes, but also from radar for a limited number of cases
- Accuracy of ground-based asteroid ephemeris at time of deflection dependent on several factors (density, quality, geometry, types of observations, and length of time from last observation to the time of deflection)
- Generally, we can say it is good to the tens of km level
  - Good enough for targeting to general vicinity during deep space cruise
  - Not good enough for precision targeting of small asteroids
- Only way to achieve extremely high accuracy is to perform target relative navigation using onboard camera
Optical Navigation

• Optical navigation (OpNav) is the science of using onboard camera as navigation device
• Images of target object against star background
  – Stars provide accurate inertial orientation of image
  – Centroiding on target body provides angular measurement relative to spacecraft
  – Accuracy increases as distance decreases
  – Provides only target-relative navigation information (ground-based radiometric data provides Earth-referenced navigation information)
Camera

• Opnav images provided by onboard camera
  – Generally use framing camera CCDs with long focal lengths

• Key parameters for camera include IFOV (angular resolution of single pixel), sensitivity
  • IFOV set by focal length, pixel size, and determines angular accuracy of measurement
  • Sensitivity determined by CCD and electronics, and determines S/N of light source, and hence ability to detect objects
Camera (cont.)

• “Unresolved” objects
  – Angular extent of target body less than 1 pixel
  – Stars always unresolved
  – Light spread to multiple pixels due to diffraction and lens defocusing
  – Centerfind using Gaussian function

• “Resolved” objects
  – Angular extent of target body greater than 1 pixel
  – Shape becomes apparent as object increases in size
  – Use COB to do centerfinding
    • Offset of COB from true center of object can be large due to shape and lighting effects

• Note that for the deflection scenarios we are examining, the target object will almost always be unresolved at start of terminal guidance, and may remain so until < 5 minutes to impact
Camera (cont.)

• Sensitivity of camera determines time of initial detection and ability to have both stars and target object visible in single frame

• Initial detection
  – Early detection (> E-1 day) - initial OD and 1\textsuperscript{st} targeting maneuver can be done with ground in the loop
  – Detection < E-1 day – all OD/maneuvers done onboard

• Stars and object in single camera frame
  – May be difficult because target brightness will vary considerably from initial detection to last image used for targeting
  – If possible – precise attitude knowledge available, which greatly improves OD performance
  – If not possible – rely on star tracker/IMU for attitude knowledge. Errors in this one of the largest contributors to targeting errors
  – Can use some techniques to mimic single star/target frames
AutoNav Description

• Entirely self-contained system uses onboard camera to take images of target body to compute target relative navigation solution
  – Does not require radio link to other s/c or the Earth
• 3 main components of AutoNav
  – Image processing element to extract target center-of-figure information
  – Orbit determination element to combine set of target centroid information in least-squares filter estimate of s/c trajectory
  – Maneuver planning and execution element to compute delta-V needed to hit target
Targeting Scenario

Initiation of terminal guidance with AutoNav at \( \sim E-2 \) hours

1st targeting maneuver at \( \sim E-1 \) hr

Images taken at 30 sec intervals. 1st OD solution after xx min

1st OD solution after xx min

2nd targeting maneuver at \( \sim E-30 \) min

3rd targeting maneuver at \( \sim E-2-4 \) min

Spacecraft Trajectory

B-plane intercept

Incoming Asymptote

R

T

B-plane
Case Study Scenarios

Monte Carlo Simulations

• Impactor targeting accuracy assessed through Monte Carlo simulations
• Methodology of simulations
  – “Truth” trajectory generated by taking random samples from a normal distribution of parameters which describe the trajectory.
  – At varying intervals, truth trajectory and attitude used to create photorealistic image of target
  – Image data fed to AutoNav to perform image processing and orbit determination using least-squares batch filter
  – At predetermined maneuver times, maneuver to target impact computed based on filtered OD solution
  – As the truth trajectory either crosses surface of triaxial ellipsoid or is determined to have passed by without impacting, simulation stopped and relevant parameters describing hit or miss stored
  – DI MRI camera, with 10 microrad IFOV, used in the sims
### Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial asteroid-relative state error</td>
<td>Position: 30 km&lt;br&gt;Velocity: 5 cm/s</td>
</tr>
<tr>
<td>Gates model maneuver execution error</td>
<td>Fixed magnitude: 4.3 mm/s&lt;br&gt;Proportional magnitude: 10%&lt;br&gt;Fixed direction: 4 mm/s&lt;br&gt;Proportional direction: 3.1%</td>
</tr>
<tr>
<td>Gyro errors (MIMU class)</td>
<td>Rate bias: 0.005 deg&lt;br&gt;Angle random walk: 0.005 deg/sqrt(hr)</td>
</tr>
<tr>
<td>Gyro errors (SSIRU class)</td>
<td>Rate bias: 0.0005 deg&lt;br&gt;Angle random walk: 0.0005 deg/sqrt(hr)</td>
</tr>
<tr>
<td>Asteroid size</td>
<td>130 x 90 x 90 m&lt;br&gt;390 x 260 x 260 m</td>
</tr>
<tr>
<td>Asteroid pole orientation</td>
<td>RA: 0 to 360 deg, uniform&lt;br&gt;Dec: -90 to 90 deg, uniform</td>
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All errors values are 1 sigma unless otherwise noted.
Simulation Results – Effects of Attitude Knowledge Mode

In this setup:
- No scene generated – observables were simulated with no errors to eliminate phase effects
- No maneuver execution errors

Results show that MIMU level gyro inadequate for objects < ~ 300 m.
## Simulation Results – All Inclusive

<table>
<thead>
<tr>
<th>Case</th>
<th>Vinf (km/s)</th>
<th>Phase angle (deg)</th>
<th>Stellar reference</th>
<th>SSIRU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>100 m</td>
<td>300 m</td>
</tr>
<tr>
<td>1</td>
<td>7.5</td>
<td>30</td>
<td>98.8%</td>
<td>100.0%</td>
</tr>
<tr>
<td>2</td>
<td>7.5</td>
<td>80</td>
<td>96.5%</td>
<td>100.0%</td>
</tr>
<tr>
<td>3</td>
<td>12.5</td>
<td>140</td>
<td>56.6%</td>
<td>99.4%</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>5</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
Example of Phase Effects in Final Image

Phase = 5 deg
Phase = 80 deg
Phase = 140 deg
Histogram of Miss Distances for Case 3
Conclusion and Recommendations

• Attitude knowledge mode is the single biggest factor in determining impact success
  – With stellar reference, probability of success fairly high
  – Otherwise, must have very stable IMU

• Phase angle second largest effect
  – High value in designing reference trajectories which lower approach phase angle

• Higher V-infinity not concern if phase angle is low

• Still need to examine
  – Improving filter performance for IMU cases
  – More complex shape models
  – Finite duration burns