National Aeronautics and Space Administration

Closed Loop Terminal Guidance Navigation for a Kinetic 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 with a spacecraft
  - Not primary goal of mission, but it did demonstrate that such an impact could be accomplished with current technologies and relatively modest budget
- 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)
- AutoNav successfully used on all recent comet missions to date
  - DS1 flyby of Borrelly (2001)
  - Stardust flyby of Wild 2 (2004)
  - DI flyby and impact of Tempel 1 (2005)
  - EPOXI flyby of Hartley 2 (2010)
  - Stardust NExT flyby of Tempel 1 (2011)
- All missions required onboard closed loop target relative orbit knowledge and pointing control to sub-km level accuracy. DI required additional closed loop orbit control to impact location to sub-km level accuracy
- Technology well understood, robust, and mature, having performed successfully on 4 different spacecraft and 5 missions

Introduction (cont.)

- 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

	DI	**Asteroid Deflection**
Approach velocity	10.5 km/s	~3 - > 20 km/s
Approach phase angle	62 deg	0 to 180 deg
Target diameter	~ 6 km	~100 to ~300 m

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

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 1st 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

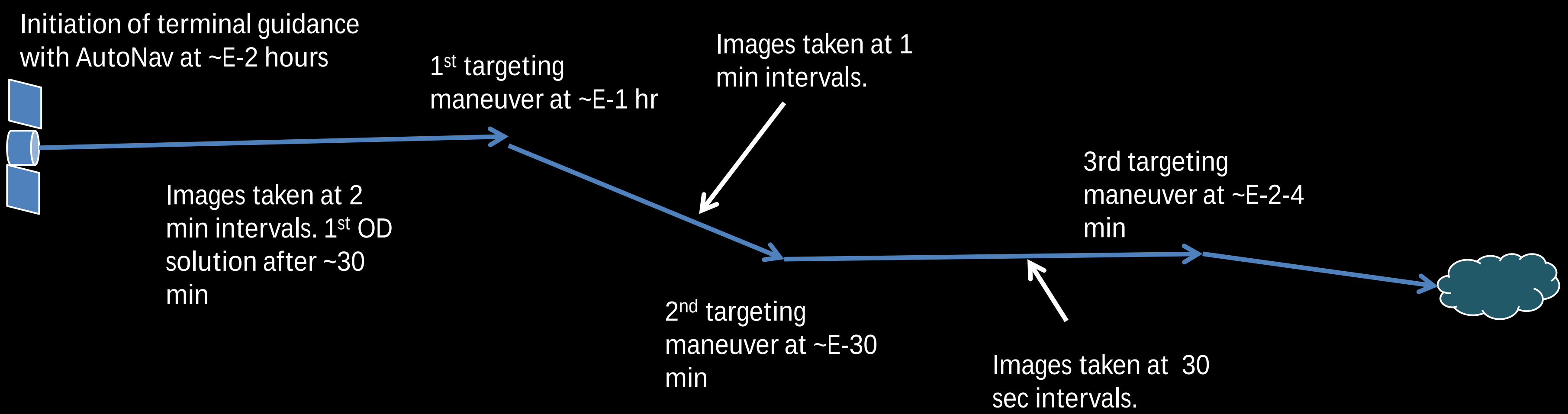
Attitude Knowledge

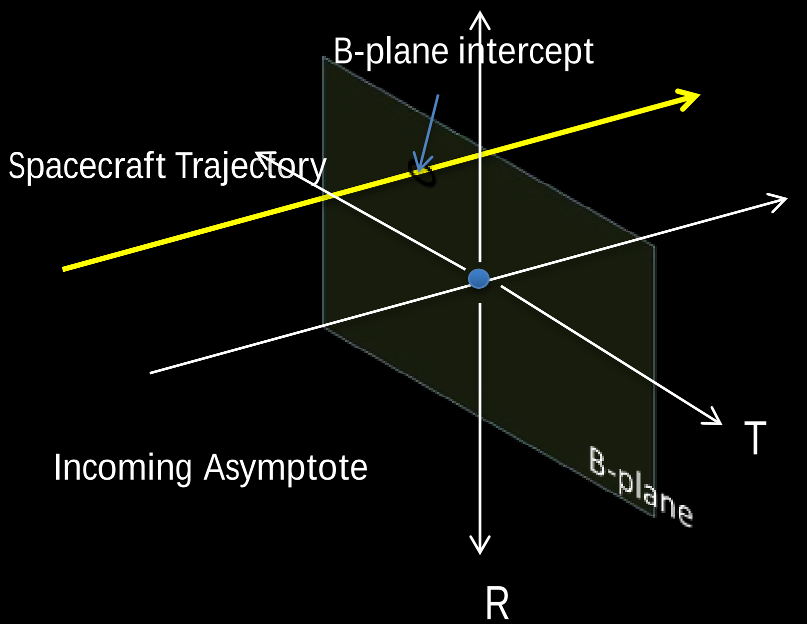
- Errors in attitude knowledge directly affects accuracy of OD
  - Must estimate attitude error as part of filter which degrades strength of target relative angular information
- “Stellar mode” attitude knowledge
  - Stars available in navigation camera, attitude knowledge near perfect
- Star tracker/IMU
  - Degraded attitude knowledge depending on Star tracker/IMU information
  - Past experience suggests using IMU propagation only
  - Use 2 general classes of IMU capability for this study (MIMU, SSIRU)
    - MIMU found to be inadequate for current scenarios, so simulations only used SSIRU

AutoNav Description

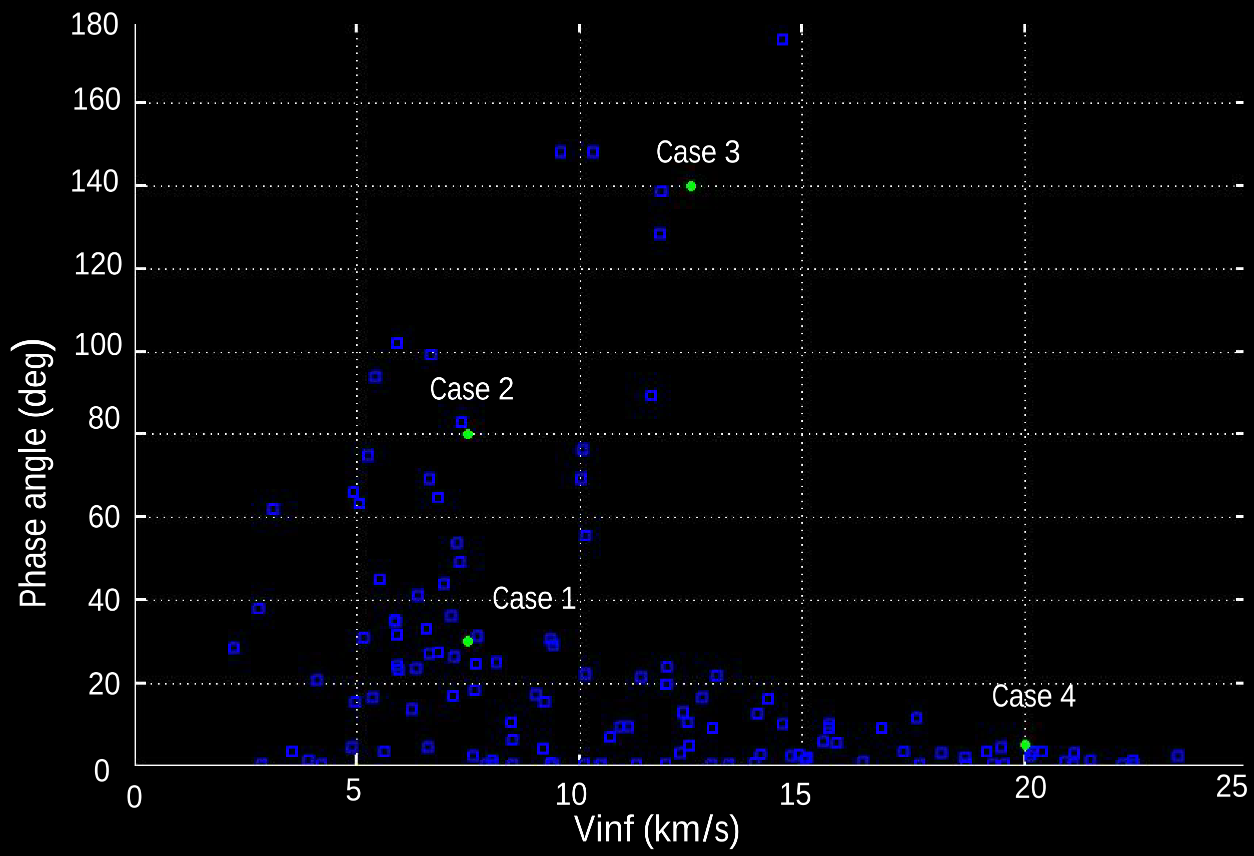
- Entirely self-contained system uses onboard camera to take images of target body to perform guidance and navigation to impact target
  - Does not require radio link to other s/c or the Earth
- 3 main components of AutoNav
  - Image processing element to extract target center-of-figure information
  - Orbit determination element to combine set of target centroid information in batch least-squares filter estimate of s/c trajectory
  - Guidance maneuver planning and execution element to compute delta-V needed to hit target
- AutoNav initialized with ground-based information of spacecraft's orbit relative to asteroid
- 3 maneuver guidance strategy for robustness

Targeting Scenario





Case Study Scenarios



	Vinf (km/s)	Phase angle (deg)
1	7.5	30
2	7.5	80
3	12.5	140
4	20	5

Reference for data: Hernandez, S. and Barbee, B. "Design of Spacecraft Missions to Test Kinetic Impact for Asteroid Deflection", Paper AAS 12-129, presented at the AAS/AIAA Spaceflight Mechanics Meeting, Feb. 2012.

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
  - Maneuver execution errors added to truth for propagation
  - 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

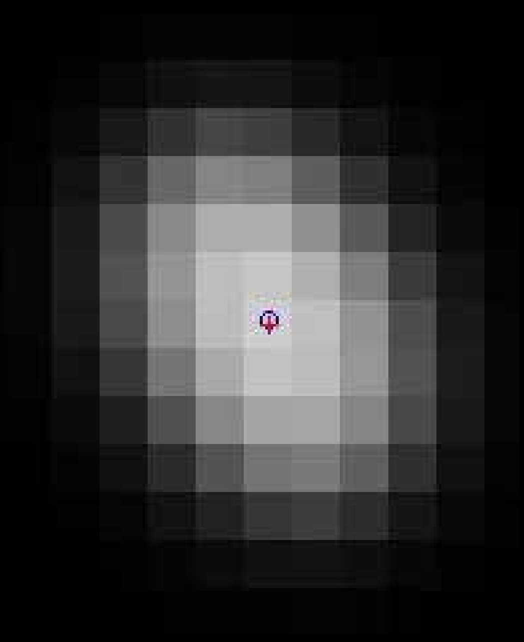
Initial asteroid-relative state error	Position: 30 km Velocity: 5 cm/s
Gates model maneuver execution error	Fixed magnitude: 4.3 mm/s Proportional magnitude: 10% Fixed direction: 4 mm/s Proportional direction: 3.1%
Gyro errors (MIMU class)	Rate bias: 0.005 deg Angle random walk: 0.005 deg/sqrt(hr)
Gyro errors (SSIRU class)	Rate bias: 0.0005 deg Angle random walk: 0.0005 deg/sqrt(hr)
Asteroid size	130 x 90 x 90 m 390 x 260 x 260 m
Asteroid pole orientation	RA: 0 to 360 deg, uniform Dec: -90 to 90 deg, uniform

All errors values are 1 sigma unless otherwise noted

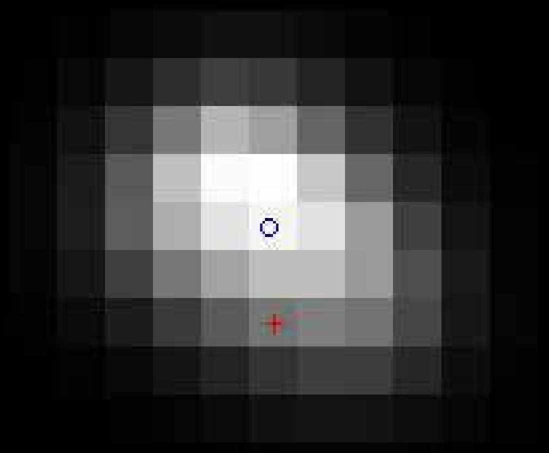
Simulation Results

Case	Vinf (km/s)	Phase angle (deg)	Stellar reference		SSIRU	
			100 m	300 m	100 m	300 m
1	7.5	30	98.8%	100.0%	85.5%	100.0%
2	7.5	80	96.5%	100.0%	73.8%	99.2%
3	12.5	140	56.6%	99.4%	53.8%	90.6%
4	20	5	100.0%	100.0%	75.4%	99.6%

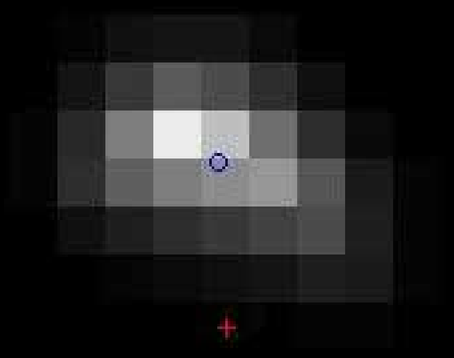
Example of Phase Effects in Final Image



Phase = 5 deg



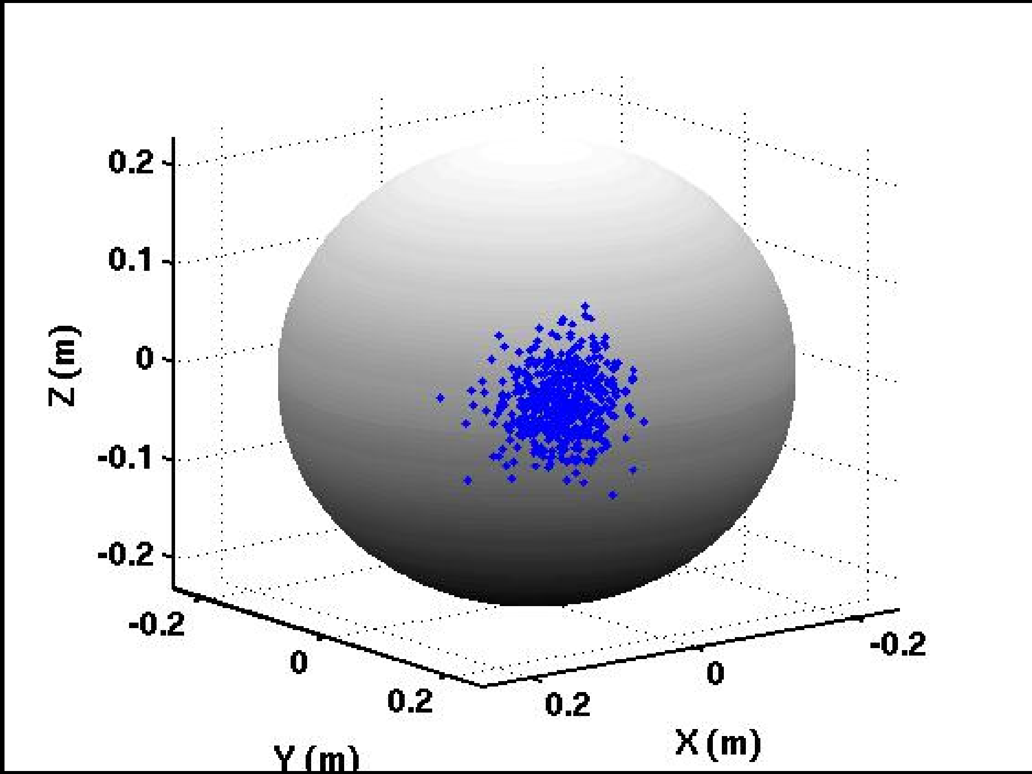
Phase = 80 deg



Phase = 140 deg

ISIS Example

- Vinf = 13.4 km/s
- Approach phase = 9 deg
- 1999RQ36 modeled as triaxial ellipsoid with dimensions:
    - 517 x 500 x 460 m
- Pole orientation fixed
- Rotation rate of 4.2 hours
- Attitude knowledge using SSIRU class gyro
- Results indicate 100% impact success rate, with all impact points within 100 m radius
- More detailed sims as spacecraft hardware matures



Conclusions

- 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
- With only modest enhancements, AutoNav, can be used to perform asteroid deflection for asteroids down to 100 m or less