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BILLIARDS: A DEMONSTRATION MISSION FOR HUNDRED-METER CLASS NEAR-EARTH ASTEROID DISRUPTION

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I. Introduction

Collisions from near-Earth asteroids (NEAs) have the potential to cause widespread harm to life on Earth. The hypervelocity nature of these collisions means that a relatively small asteroid (about a quarter-mile in diameter) could cause a global disaster. Proposed strategies for deflecting or disrupting such a threatening asteroid include detonation of a nuclear explosive device (NED) in close proximity to the asteroid, as well as intercepting the asteroid with a hypervelocity kinetic impactor[1]. NEDs allow for the delivery of large amounts of energy to a NEA for a given mass launched from the Earth, but have not yet been developed or tested for use in deep space. They also present safety and political complications, and therefore may only be used when absolutely necessary. Kinetic impactors require a relatively simple spacecraft compared to NEDs, but also deliver a much lower energy for a given launch mass. To date, no demonstration mission has been conducted for either case, and such a demonstration mission must be conducted prior to the need to utilize them during an actual scenario to ensure that an established, proven system is available for planetary defense when the need arises. One method that has been proposed to deliver a kinetic impactor with impact energy approaching that of an NED is the "billiard-ball" approach[2]. This approach would involve capturing an asteroid approximately ten meters in diameter with a relatively small spacecraft (compared to the launch mass of an equivalent direct kinetic impactor), and redirecting it into the path of an Earth-threatening asteroid. This would cause an impact which would disrupt the Earth-threatening asteroid or deflect it from its Earth-crossing trajectory. The BILLIARDS Project seeks to perform a demonstration of this mission concept in order to establish a protocol that can be used in the event of an impending Earth/asteroid collision. In order to accomplish this objective, the mission must (1) rendezvous with a small (<10m), NEA (hereinafter "Alpha"), (2) maneuver Alpha to a collision with a ~100 m NEA (hereinafter "Beta"), and (3) produce a detectable deflection or disruption of Beta. In addition to these primary objectives, the BILLIARDS project will contribute to the scientific understanding of the physical properties and collision dynamics of asteroids, and provide opportunities for international collaboration.

II. Asteroid Selection

In order to feasibly redirect Alpha, only NEAs less than 10 m in diameter were considered. Assuming an albedo of 0.14 and a density of 2 g/cm^3, this translates to a mass of about 10^6 kg and an absolute magnitude ≥ 27.5. The Orbit Condition Code (OCC) was limited to ≤1 in order to limit the amount of uncertainty in the NEA's ephemeris, which affects mission performance during rendezvous with the NEA. Table 1 summarizes the results for a Small-Body Database (SBDB) query. NEA 2011 MD was chosen because of its larger estimated diameter. At twice the diameter of 2009 BD and 2006 RH$_{120}$, 2011 MD likely has an order of magnitude higher mass, so it would deliver more kinetic energy to Beta, increasing the likelihood of disrupting it. Both 2009 BD and 2011 MD are suspected to be rubble piles[3]. Alpha is an Earth co-orbital asteroid, making rendezvous with it inexpensive compared to other NEAs. This property was also likely responsible for the discovery of the asteroid, since it is only 6 m in diameter and therefore must repeatedly pass close to the Earth to be discovered and

Table 1: Alpha Asteroid Candidates

Asteroid	OCC	Estimated Diameter (m)	Absolute Magnitude	a (AU)	e	i (degrees)
2006 RH$_{120}$	1	4	29.5	0.9986	0.0198	1.53
2009 BD	0	3-4	28.1	1.009	0.0408	0.39
2011 MD	1	6	28.0	1.06	0.00416	2.58

characterized.

Search for a Beta asteroid began with the full SBDB catalogue of roughly 11,500 NEAs. Asteroids that were classed as potentially hazardous to the Earth were eliminated from consideration for this demonstration to avoid the risk of causing a hazardous Earth impact. The OCC was limited to 0 to support observational success for orbit change determination, and to ensure that the position of the asteroid was known as accurately as possible well before terminal guidance. Beta must present a large enough target to ensure a collision, but small enough to produce an observable result of a successful collision. Therefore, the diameter was constrained to 100—500 m, yielding 250 potential candidates. A trajectory analysis was performed to find close approaches between these candidates and 2011 MD from the mid-2020's to the mid-2030's. Based on this analysis, 2010 PR_{10} was selected as the Beta asteroid. The close approach that occurs on January 26, 2029 is in the middle of the window considered. This is one of the closest approaches with 2011 MD of all asteroids considered, which reduces the amount of propellant required to redirect Alpha. Its closest natural approach to 2011 MD occurs at a distance of 9.329×10^{-3} AU (1.396×10^{6} km), with a relative velocity of 6.6 km/s. For analysis purposes, Alpha is assumed to have a density of 1.13 g/cm^3 and Beta was assumed to have a density of 2 g/cm^3.

To determine if Beta will be disrupted as a result of the collision, the specific energy, Q, of the collision must be considered, where Q is the kinetic energy of Alpha divided by the mass of Beta. If Q is greater than the critical specific dispersal energy, Q^*_d, then Beta is disrupted. While there are no direct measurements of asteroid collisions, for an asteroid of 100 m, Q^*_d would be approximately 100 J/kg.[4] For the collision considered in this analysis, the predicted value of Q/Q* is 9.0, so a disruption is expected. As a result, this mission will provide a unique opportunity for a priori knowledge of a "natural" collision event, providing an unprecedented opportunity to observe dynamics of the collision debris, which could include coalescence of a portion of the debris into a new object.

III. Mission Design

The BILLIARDS mission comprises two modules; an Instrumentation Module (IM) and a Terminal Guidance Module (TGM). The IM houses most scientific and navigational instruments, as well a high specific impulse solar electric propulsion (SEP) system. After launch, the IM performs low thrust maneuvers to rendezvous with Alpha. The asteroid is then captured with a mechanism on the TGM, and the SEP system is used to modify its orbit, placing it on a collision course with Beta. This is similar to the concept of operations proposed for option A of NASA's asteroid redirect mission[9]. Shortly before the collision, the IM separates from the TGM, maneuvering away from the TGM and Alpha to monitor the collision and relay data to Earth. The TGM spins up Alpha to a slow rotation rate, and performs correction maneuvers as necessary to ensure that it is on a collision course with Beta. There is also an option to send a second spacecraft to Beta prior to the collision. This spacecraft would characterize the asteroid's properties prior to the collision, and would remain in the vicinity of Beta (or remaining debris thereof) to observe the long-term evolution of the environment as a result of the collision. An in depth analysis of this spacecraft was not performed as part of this study. The full design and implementation of this spacecraft can be conducted by a different agency or country, which would promote international collaboration. This would be similar to AIDA, another proposed multi-spacecraft cooperative mission, where one spacecraft is first characterizes and lands on the target asteroid and the second acts as a kinetic impactor[5].

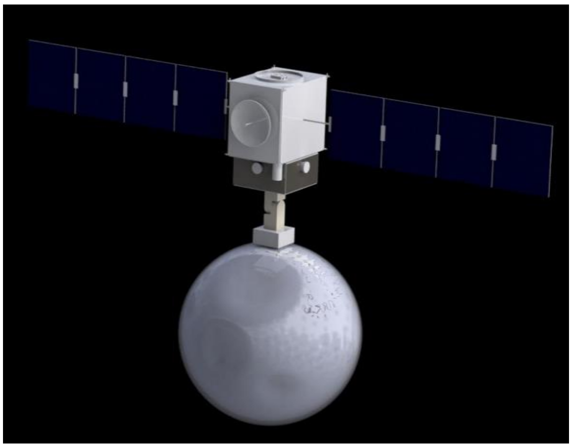

Fig. 1: BILLIARDS Spacecraft, with IM (top, between solar panels), TGM (middle) and captured Alpha asteroid (bottom)

The mission begins with the launch of the spacecraft on a Falcon 9 v1.1 from Cape Canaveral Air Force Station, with a C_3 of 5.225 km^2/s^2 and a declination of launch asymptote (DLA) of -29.5°. The SEP system is activated to maneuver the spacecraft to a rendezvous with 2011 MD three and a half years after launch. The trajectory from Earth to Alpha was computed using the Evolutionary Mission Trajectory Generator[6] (EMTG). Only a single BPT-4000 hall thruster is used in the solution, requiring approximately 5 kW of power, and generating approximately 0.25 N of thrust, with a specific impulse of 2011 s. The mass delivered to Alpha is 2500 kg according to this trajectory solution, with 200 kg of propellant required. The required propellant would be slightly higher, due to the mass of the spacecraft being closer to 3000 kg in the current iteration. However, this is within available propellant margin and the capabilities of the selected launch vehicle, the Falcon 9 v1.1.

The spacecraft will spend approximately one month imaging and characterizing 2011 MD after rendezvous, prior to capturing it. Capture would be accomplished with a capture mechanism based on the capture bag currently proposed for Option A of ARM. The operation occurs while the asteroid is still spinning, with the spacecraft approaching along the asteroid's axis of rotation after matching rotation rates, and nulling this rotation after capture using onboard attitude control thrusters. In order to troubleshoot any issues that may occur with asteroid capture and spin-down, fifty days are allotted for this capture operation. An additional two months of margin are built into the timeline to allow for further analysis and troubleshooting before the Alpha redirection maneuver begins in the middle of May, 2025.

The trajectory needed to deflect Alpha to collide with Beta was solved for using a multi-revolution Lambert solver.[7] A collision on January 26, 2029, the date of the natural close approach, was found to minimize the ΔV required for Alpha redirection. Fig. 2 shows the optimal time to perform the Alpha redirect maneuver. Here, the maneuver date ranges up to the collision date, while the collision date is limited to be within several days of the close approach. This plot shows that the optimum times for performing maneuvers occur at integer multiples of Alpha's orbital period (400 days), counting back from the collision time. The optimal points are also assumed to be efficient times to perform midcourse corrections (MCCs). The planned times for the Alpha redirect maneuver and MCCs are labelled on this plot. The ΔV budget for the mission is presented below in Table 2. It should be noted that while the ΔV required for Alpha rendezvous is two orders of magnitude greater than that required for all other low thrust operations, the propellant required is approximately equal, since all other low thrust maneuvers are performed while attached to Alpha. The first option for performing the Alpha-to-Beta redirection maneuver following this date occurs on August 12, 2025. Two MCCs are scheduled to be performed at the following minimum ΔV nodes found in Fig. 3, and a third MCC will be performed 100 days before the collision.

The final phase of the primary mission begins with acquisition of Beta by the terminal guidance imager, approximately 42 hours before the collision, at a distance of one million kilometers. The IM separates from the TGM 36 hours before the collision, positioning itself closer to the sun and well behind the TGM relative to Beta. This location allows it to observe the sunlit side of both asteroids, providing navigational data to the TGM throughout this mission phase, and allowing the IM several seconds to record the collision before passing the collision hypocenter. The TGM performs a terminal guidance initiation burn 24 hours before collision, which places Alpha on a collision trajectory based on updated positional information from visual tracking of Beta. The TGM is oriented with imagers pointed at Beta. Following the terminal guidance initiation burn, the TGM spins up Alpha to a rotation period of 3 minutes. The plane of this rotation is normal to the relative position vector from Alpha to Beta ($\hat{z}$). This allows the TGM to null out the component of velocity normal to $\hat{z}$ using its bipropellant thrusters, keeping Alpha on a collision course with Beta. Since Alpha is ideally on a collision course with Beta, the relative velocity between the two is assumed to be primarily in the $\hat{z}$ direction, so the terminal guidance maneuvers are comparatively small. After passing the collision hypocenter, the IM then slews 180° to continue observing the aftermath of the collision until approximately two days after the collision, at which point Beta (or its remains) are expected to be beyond the observable range of the IM, approximately one million km.

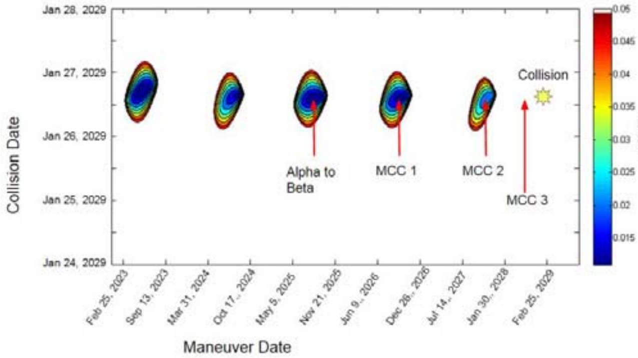

Fig. 4: Alpha Redirection Maneuver Contour Plot

IV. Spacecraft Design

A. *Instrumentation Module*

The instrumentation array for the IM was based on the instruments used on the Dawn and Deep Impact missions, and the electrical power system was assumed to be identical to that used for the Dawn mission[8], due to the similar beginning-of-life power requirements. The instrumentation module is designed with SEP provided by four BPT-4000 hall thrusters operating at 0.25 N thrust, although currently only one thruster is required to operate at a time for the planned maneuvers. IM mass estimates are given below in Table 3.

Table 3: Instrumentation Module Mass Budget

Subsystem	Mass (kg)
Structural	240
Propulsion (dry)	120
SEP Propellant	750
RCS Propellant	50
Power System	401
Thermal	44
Data Processing	61
Attitude Control	64
Science Instrumentation	70

Table 2: Mission ΔV Budget

Maneuver Type	Maneuver	Start Date	ΔV
Launch	Launch	July 4, 2021	C_3 = 5.225 km^2/s^2
Low-Thrust	Alpha Rendezvous	July 11, 2021	1600 m/s
Low-Thrust	Alpha Redirect	August 12, 2025	12 m/s
Low-Thrust	Midcourse Corrections		19 m/s
High-Thrust	Terminal Guidance Maneuvers	January 25, 2029	8 m/s

Total Dry	1000
Total	1800

B. Terminal Guidance Module

The TGM features five R-4D bipropellant N_2O_4/N_2H_4 thrusters for terminal guidance. The body of the module is connected to the asteroid capture mechanism by a two axis gimbal, which is used to ensure that the thrust vector from the main thruster and SEP points through Alpha's center of mass. The fine details of the capture mechanism are relegated to future work, with the current plan being to utilize a capture mechanism based on the one used by option A of NASA's Asteroid Redirect Mission[9]. Mass estimates for the TGM are given in Table 4.

Table 4: Terminal Guidance Mass Budget

Subsystem	Mass (kg)
Structural	240
Propulsion (dry)	26
Propellant	600
Power System	53
Thermal	32
Data Processing	16
Science Instrumentation	70
Capture Mechanism	310
Total Dry	687
Total	1287

Based on the uncertainties of Beta's orbit, we expect to know its position within 524,000 km before the asteroid is detected by the imagers. Errors in the intercept trajectory are corrected by the TGM's first burn, performed 24 hours before collision. Accounting for additional ΔV needed to adjust for remaining errors in the trajectory after this burn, a total of 8 m/s ΔV budgeted for the terminal guidance, requiring approximately 600 kg of propellant.

V. Cost Analysis

In order to produce a reasonable cost estimate for the BILLIARDS mission, a cost model for missions to small solar system bodies was created. This model is based on the development and production costs of previous and current missions that physically interacted with small bodies. When applying this cost model, the IM and TGM were considered separate spacecraft. The capture mechanism was modeled as a scientific instrument, due to its low maturity and added complexity, and its cost was determined using the Spacecraft/Vehicle Level Cost Model[10]. The mass of the capture mechanism was also included in the dry mass of the TGM for cost analysis.

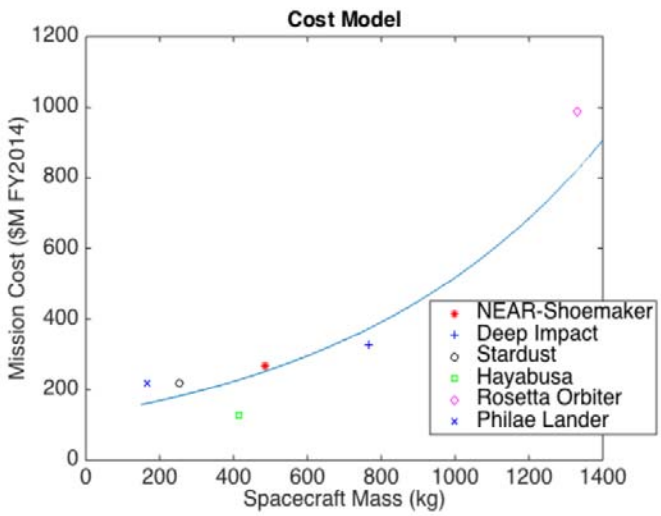

Fig. 5: Small Bodies Mission Cost Model

Table 5: BILLIARDS Cost Breakdown

IM Development and Production	\$518M
TGM Development and Production	\$334M
Capture Mechanism Development	\$64M
Launch Vehicle (Falcon 9 v1.1)	\$84M
Total Mission Cost	\$1001M

VI. Conclusion

A design has been presented for a planetary defense demonstration mission. The proposed system has the potential to deflect or destroy city-killer asteroids by redirecting smaller asteroids, less than 10 m in diameter, that already have a natural close approach with the hazardous asteroids, to collide with them. For this demonstration, 2011 MD was selected as the impactor, and 2010 PR10, a city-killer sized asteroid which poses no threat to the Earth, was selected as the safe proxy for a hazardous asteroid. The collision, occurring in early 2029, will involve a kinetic energy on the order of 10^{12} joules. Launching an equivalent kinetic impactor from the Earth would not be possible with any current launch vehicle. The mission will give scientists the opportunity to study the composition and geometry of both asteroids, providing valuable information for updating current asteroid models. If the collision can be observed by other observatories, then the mission will also provide an unprecedented opportunity to observe and study a collision between asteroids in deep space with a priori knowledge of the event. In the event of disruption of 2010 PR_{10}, which is expected, the mission will also allow the dynamics resulting from small body destruction, including possible new body formation dynamics, to be studied. In conclusion, this mission provides valuable scientific insight into the properties of small bodies of the same class as those that may threaten the Earth. Perhaps most importantly, conducting this mission will provide an opportunity to demonstrate a capability to deflect or destroy asteroids that threaten life on Earth before such a capability is required.

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