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APPLYING CENTRIFUGAL PROPULSION TO ENABLE ASTEROID DEFLECTION

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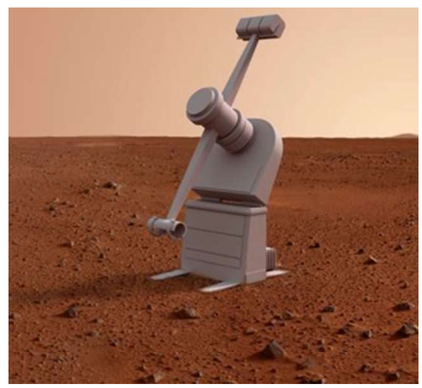
ABSTRACT

To date, asteroid trajectory modification techniques employ the “big bang” approach. An impulsive deflection is imparted by slamming one or more high-speed kinetic impactor spacecraft into the object or by detonation of a nuclear device in its proximity. This is a “hit it once and hope for the best” approach.



Instead of relying on this restrictive method, centrifugal propulsion offers an alternative, where a centrifuge and power supply land on a threatening asteroid to collect and incrementally project portions of the asteroid, using momentum transfer of the recoil to gradually adjust the trajectory away from Earth.

This process sequentially allows “ejection, measurement, and repetition” to gradually fine-tune the trajectory needed for course correction. This offers flexible operation parameters that can be varied for convenience and optimization, including the location of the landing site, weight of each ejected payload, launch speed, direction, cadence, timing of successive ejections, and the relationship to the asteroid’s velocity vector and spin axis. Once landed on an asteroid, the centrifugal system requires no consumables. Operating entirely on electrical power, it can operate indefinitely without additional support.

This approach addresses aspects of Goal 3 of the 2018 U.S. government’s “National Near-Earth Object (NEO) Preparedness Strategy and Action Plan”—“Develop Technologies for NEO Deflection and Disruption Missions.” The centrifuge approach adds a sustainable and repeatable slow-push tool to the planetary defense toolbox, mitigating the risk and uncertainty of single-impulse methods. An artist’s early concept is shown above.

An on-site centrifuge could deflect Chelyabinsk and Tunguska-sized asteroids to miss Earth within a few weeks’ operation. The asteroid Bennu could be deflected in a few years of continuous spinner operation, depending upon the parameters chosen, which would be sufficient to eliminate a potential collision with Earth in the late 22nd century.

The innovation of a self-contained power and kinetic launch capability without consumables opens new vistas for cost-effective asteroid deflection and other commercial, scientific, government, and international space missions.

Introduction

Missions to near-Earth asteroids (NEAs) are of interest due to the expected scientific return, planetary defense objectives, and utilization of their resources. A key aspect of planetary defense is redirection of hazardous asteroids away from Earth, while asteroid mining involves sending extracted materials back to an Earth orbit or processing them in situ [1]. The science and technology required to perform these operations are largely common.

Hazardous asteroids can be diverted to an Earth-miss trajectory either instantaneously or by slow push, given that sufficient time exists between their discovery and the time of potential impact. An impulsive deflection can slam one or more high-speed kinetic impactor spacecraft into the object or detonate a nuclear device in its proximity. Tether slingshot deflection techniques occurring over a small fraction of the asteroid orbit are example approximations of instantaneous impulsive deflection [2]. In most cases, small- to medium-size objects typically require several years before Earth impact for the deflection to successfully eliminate the threat. Risks and costs associated with some mitigation options are discussed in Reference [3].

This report looks at a new way of dealing with the asteroid problem—rather than diverting through an impact from an incoming spacecraft, a mechanism is landed that would "scoop up" asteroid material, over time, and eject it into space. The recoil from each ejection would slowly, but inexorably, change the asteroid's trajectory in a controllable and measurable manner. Figure 1 illustrates an example of this type of asteroid deflection.

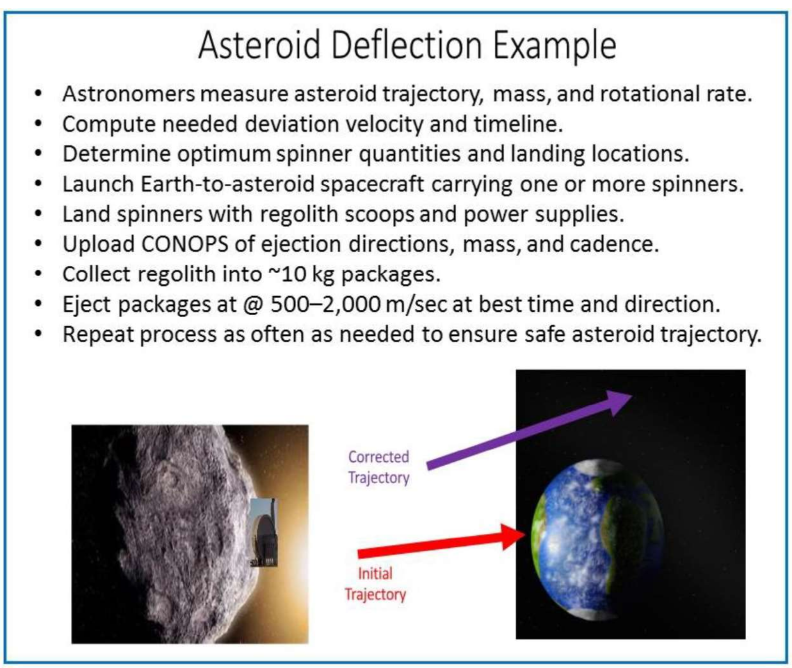


Figure 1. Asteroid deflection concept using a spinner(s).

Slow-push techniques apply a small force to the object to alter its trajectory, typically over years or decades, depending on mass and orbit [4]. Examples of proposed slow-push concepts are ion beam deflection, enhanced gravity tractor, laser ablation, and mass-driver redirection. If it can be shown that the time of slow-push procedures occupies a small fraction of the asteroid's orbit, then the operation can be approximated as an impulsive deflection and simplify mission design.

The mass-driver redirection slow-push method involves the ejection of asteroidal materials off the surface faster than the escape velocity and, as a result, propelling the asteroid [1]. Mass drivers may be thought of as "propellantless" rocket engines that could offer advantages for sustained application of thrust versus standard chemical rockets in terms of increased mission flexibility, lower manufacturing costs, reduced individual launch mass, improved overall mission reliability, and higher duty cycle surface operations [5]. Moreover, the technique does not require the proliferation of nuclear weapons into space, offers a controlled, metered application of perturbing force, and removes uncertainties in impact location and timing, asteroid internal structure and mass distribution, and cratering physics associated with impact deflection [5].

Reference [5] examined the use of multiple mass driver-equipped landers to rendezvous and attach to a threatening asteroid, drill into its surface, and eject small amounts of the asteroid material away from the object at high velocity using a mass driver, such as a rail gun or electromagnetic launcher.

Propellantless Asteroid Deflection Using Spinners

This study proposes a novel approach to deflect an asteroid using an electromagnetic centrifugal mass driver launcher, compares it with the kinetic impact and nuclear detonation impulsive methods, and examines whether this slow-push technique can approximate impulsive deflection. The kinetic impact and nuclear deflection impulses used for comparison are estimated using the JPL/Aerospace-developed physics-based tool, NEO Deflection App, utilizing orbital mechanics and launch vehicle performance [6]. The NEO Deflection App models the orbits of various simulated NEAs on a collision course with Earth and estimates the largest kinetic impactor mass the launch vehicle can lift from Earth's surface to the asteroid for a specific deflection scenario. Two fictitious asteroids designated as "2019 PDC" and "2021 PDC," used in the 2019 and 2021 Planetary Defense Conference (PDC) hypothetical asteroid impact scenario exercises, respectively, were selected as case study objects in this work [7][9].

The orbit of 2019 PDC is maintained, but the object size is adjusted to 30 and 60 meters to create two study cases corresponding to a range of small asteroids that could collide with Earth in the next decades to centuries. The orbit of 2021 PDC is also maintained and the object size is adjusted to that of Bennu to represent long-term collision risk by large, potentially hazardous asteroids.

To defend Earth from an inbound asteroid, one or more centrifugal systems deployed on the threatening object would, at a fast pace, eject small projectiles dug from the surface to generate the cumulative push required to prevent Earth impact. The projectiles must be propelled along the asteroid's velocity vector for the push to be most effective. Consequently, although asteroid rotation limits a single launcher's ejections to once per complete turn, several such ejector systems could be dispersed along the asteroid's surface to increase the push along the velocity vector. Alternatively, a capability could be explored for a sole spinner to eject projectiles along the velocity vector from a single location.

Assuming the centrifugal systems accomplish the desired deflection over a small fraction of the asteroid's orbit allows approximating the cumulative deflection as impulsive and utilizing the JPL/Aerospace NEO Deflection App to compare the results with purely impulsive kinetic and nuclear methods of deflections of the same object [6].

The NEO Deflection App was also used to estimate the yield of a nuclear deflection device detonating at an optimal standoff distance from 2019 PDC 750 days before its impact with Earth. The same two asteroids used in the above kinetic deflection examples require 160 KT and 700 KT, respectively, to achieve a 2 Earth radius (R_E) Earth miss distance.

The last row in Table 1 shows that the spinners operate over a small fraction of the asteroid's orbit in the examples shown. Thus, cumulative deflection by one or more centrifugal launch systems operating sequentially over a small part of the asteroid's orbit can be approximated as impulsive deflection and compared with kinetic impact deflection using the NEO Deflection App [6]. The spinner approach is broken down to a series of small impulses that are imparted to the example asteroids and accumulate to a miss distance of 2 R_E. The number of pulses needed by the systems depends on the parameters and is shown in Table 1. The power requirements are on the order of 10 kW, compatible with NASA's plan for a nuclear lunar power supply.

Table 1. System Mission Design Parameters

Case	**1**	**2**	**3**	**4**
Asteroid diameter [m]	30	60	60	60
Asteroid density [g/cm^3]	3	3	3	3
Asteroid mass [kg]	4.24E+7	3.39E+8	3.39E+8	3.39E+8
Asteroid orbital period [d]	971	971	971	971
Asteroid spin rate [rev/d]	3	3	3	2
Time before impact [d]	750	750	750	750
Earth miss distance [R_E]	1	1	1	1
Projectile mass [kg]	10	10	10	10
Projectile ejection relative velocity [km/sec]	2	2	2	2
Number of systems	2	2	6	6
Part of asteroid orbit [%]	1.4	12.1	4.1	6.1

Table 1 shows that several percentage points of the asteroid orbit are required to achieve a 1 R_E miss distance with centrifugal deflection under the four representative, but not comprehensive, example cases. The NEO Deflection App is used to compare the spinner approach with the high-speed kinetic deflection and nuclear standoff deflection. See Figure 2 for a case example and Figure 3 for a NEO Deflection App model output.

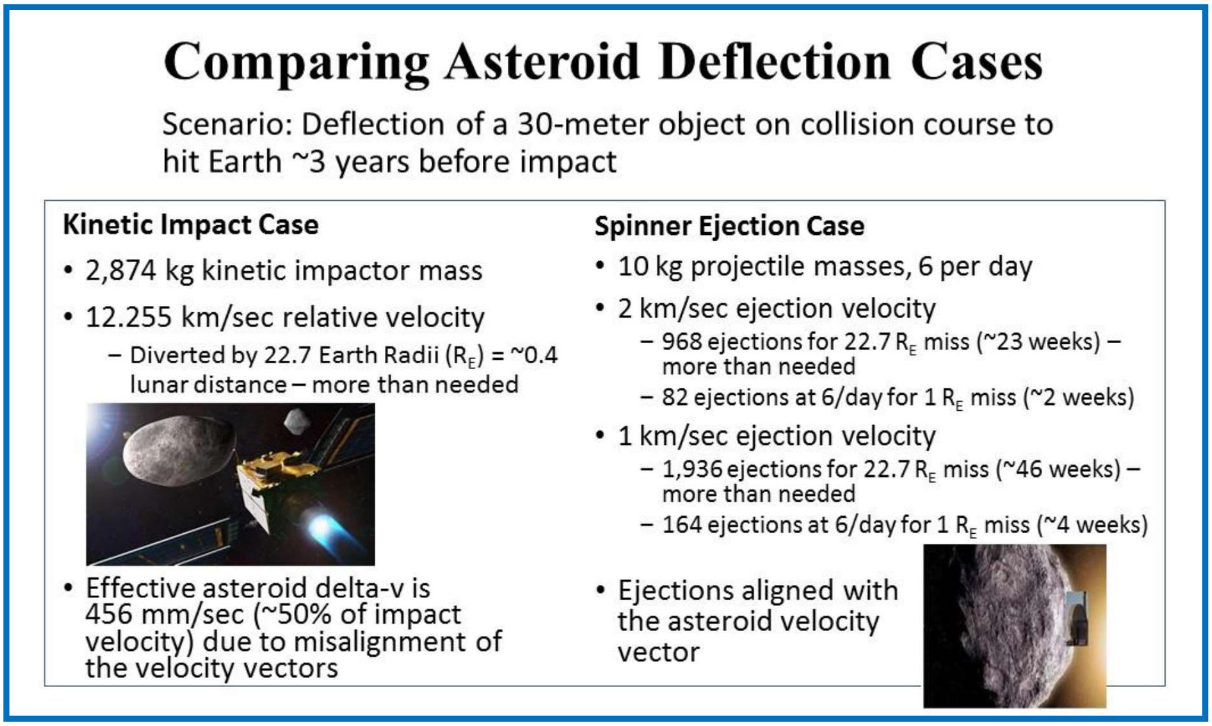


Figure 2. Asteroid deflection example.

Figure 3. Asteroid kinetic impact deflection model [6][7].

Figure 4, Figure 5, and Figure 6 are parametric examinations of 10 kg ejections at 2 km/sec using state-of-the-art carbon fiber cable. The centrifuge cable is designed to sustain the 2 km/sec projectile launch velocity referenced above. The size and mass of the centrifuge suggest that a mission to land such a system on an asteroid might be feasible.

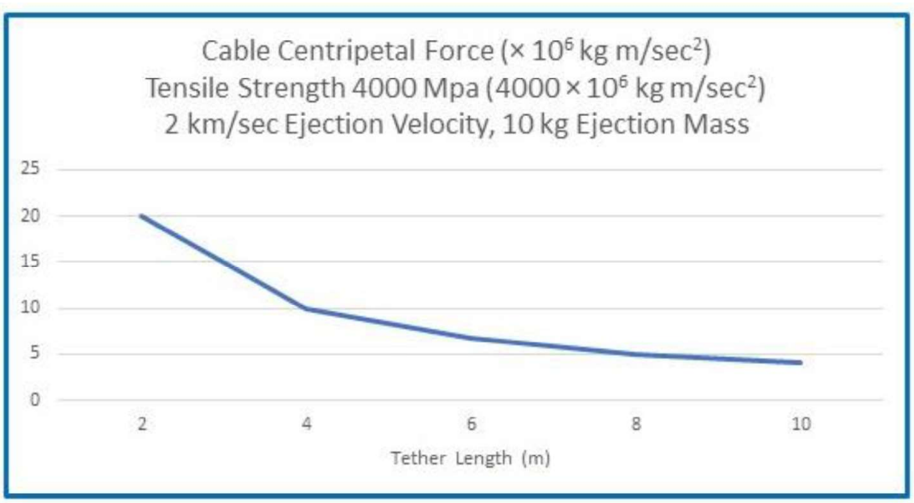


Figure 4. Cable centripetal force.

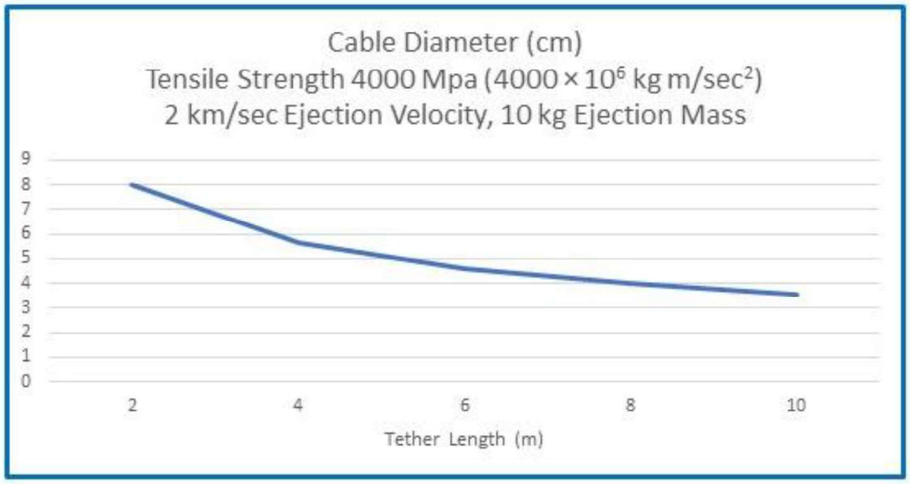


Figure 5. Minimum cable diameter.

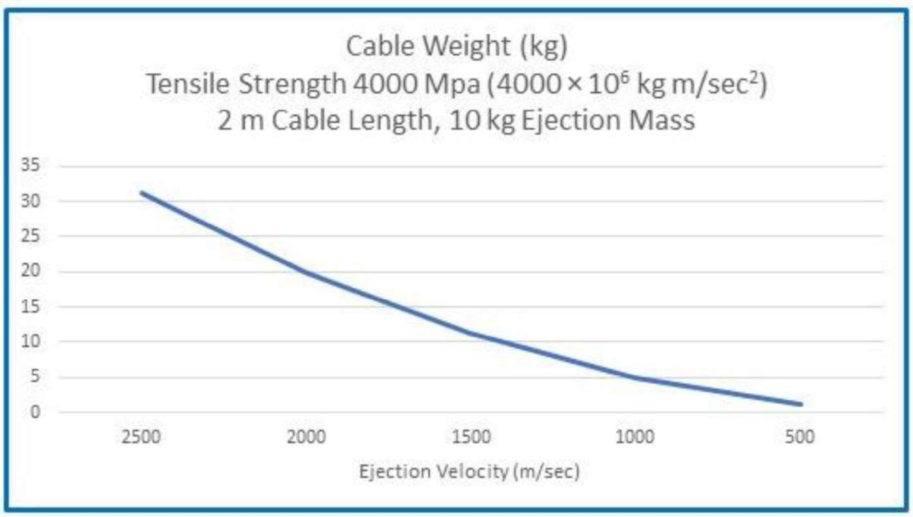


Figure 6. Minimum cable weight.

Success of the recent Double Asteroid Redirection Test (DART) mission gives insight into how large kinetic impactors can divert incoming asteroids. Instead of colliding large spacecraft with an approaching asteroid, it might be possible to use a "lunar-launched kinetic deflector" process, in coordination with a lunar manufacturing site, as follows: A permanent lunar facility capable of manufacturing and storing small printable spacecraft would be created using mostly lunar materials. The facility would act as a logistics hub capable of quicky spin-launching flotillas of small spacecraft to execute reconnaissance or make kinetic intercepts of asteroids. For example (see Figure 7), using a 10 kg spacecraft with 90 percent lunar materials, 60 such spacecraft are the equivalent of one DART impactor using only 60 kg of materials brought from Earth. Future research will examine whether storing many such microinterceptors adjacent to a lunar spin-launcher could improve preparedness to react to eventualities more rapidly and economically than might be attainable from Earth. Figure 8 depicts the many rock fragments scattered on the surface of the asteroid impacted during the DART mission, suggesting that spinner operation on that and similar rubble-pile bodies may be feasible.

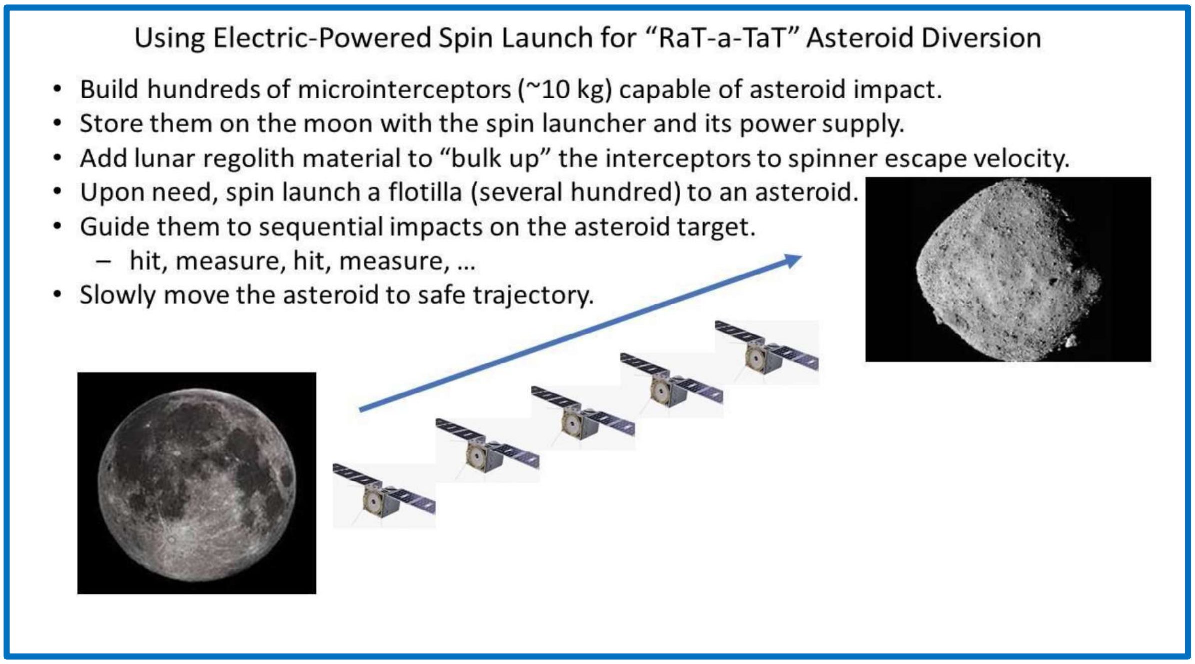


Figure 7. "RaT-a-TaT" asteroid diversion example.

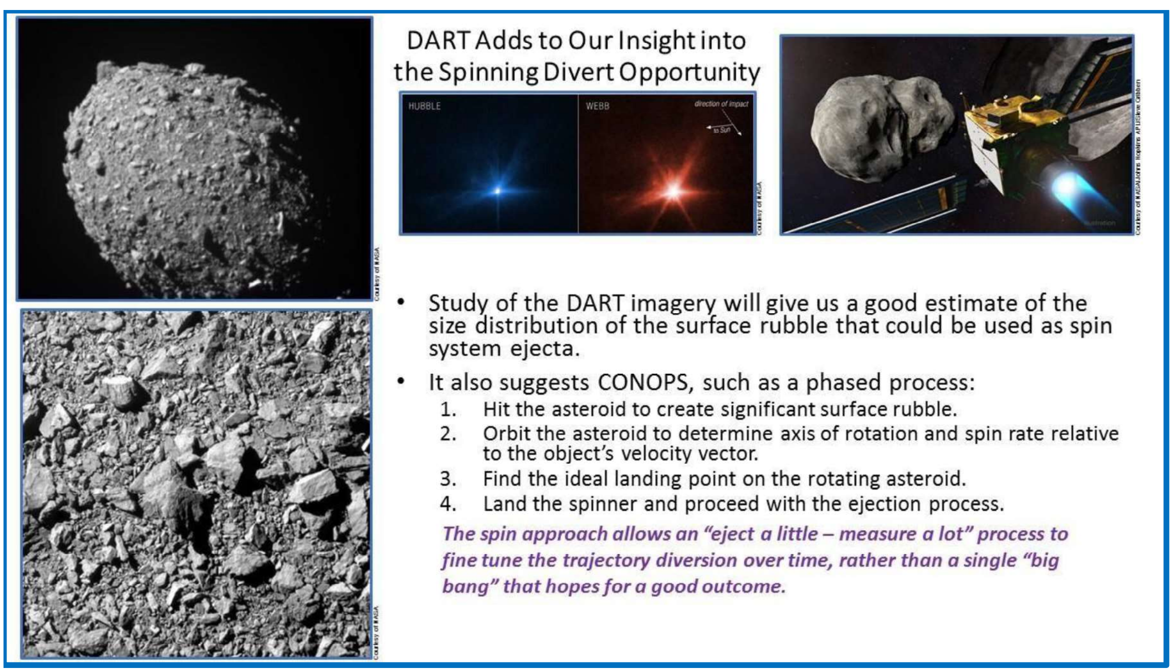


Figure 8. DART insight to spinning divert opportunity.

Examples of Small Asteroid Deflection Using Spinners

The NEO Deflection App in Figure 3 is the basis for comparison of the spinner approach with high-speed kinetic deflection of a fictitious asteroid designed to impact with Earth in the future. Solid rock asteroids of spherical shape and density of 3 g/cm^3 are assumed. Two asteroid sizes of 30 and 60 meters correspond to masses of 4.24E+07 and 1.13E+11 kg, respectively. The orbital period of asteroid 2019 PDC is 971 days and the time before impact with Earth is 750 days. The NEO Deflection App calculates that one Atlas V rocket can launch a kinetic impactor spacecraft of 2,873 kg that will fly for 370 days before colliding with 2019 PDC 750 days before Earth impact.

A representative asteroid velocity of 20 km/sec is assumed at the time of collision with the kinetic impactor spacecraft. The NEO Deflection App calculates a relative velocity of 12.255 km/sec between the spacecraft and the asteroid, resulting in a total of a –830.11 mm/sec change to the asteroid velocity. Only –456.46 mm/sec of the total velocity change is applied along the velocity vector and contributes to the asteroid deflection with efficiency of 55 percent.

The kinetic impactor deflects the 30-meter asteroid to a perigee distance of 23.67 R_E at the time of predicted impact with Earth, and the 60-meter asteroid is deflected to a perigee distance of 2.74 R_E. These distances correspond to a miss distance with Earth of 22.67 and 1.74 R_E, respectively.

In this study, deflection to a perigee distance of 2 R_E, or 1 R_E of miss distance, is assumed adequate. To achieve a miss distance of 1 R_E, the spinner system must apply a total deflection of –38.58 mm/sec to the 30-meter asteroid, and –41.68 mm/sec to the 60-meter asteroid.

Assuming projectile mass of 10 kg and –2 km/sec ejection velocity relative to the asteroid, 82 ejections are required to achieve the required deflection of the 30-meter asteroid, and 707 ejections are required to achieve the required deflection of the 60-meter asteroid.

Assuming an asteroid spin rate of 3 rev/day and operation of 2 spinners on its surface allows for 6 ejections per day along the asteroid velocity vector. To accomplish a deflection to 1 R_E of miss distance, 14 days of spinner operation are required on the 30-meter asteroid, and 59 days on the 60-meter asteroid. This amounts to spinner operation in 1.4 percent of the 30-meter asteroid orbital period of 971 days, and 12.1 percent of the 60-meter asteroid.

The spinner is seen to operate in small portions of the asteroid orbit in the above two examples, suggesting that impulsive approximation of the spinner operation is valid. The validity of the approximation might be increased if mission design allows a larger number of spinner systems and smaller portions of the asteroid orbit. Additionally, if spinner design allows projectile ejection along the asteroid velocity vector from a single location, fewer systems might be required. High-precision simulations will be required to assert the validity of these results in future work.

Example of Large Asteroid Deflection Using Spinners

Bennu is a 565-meter carbonaceous asteroid formed over 4.5 billion years ago that may contain elements such as metals and water that could be used industrially to get breathable air and rocket fuel [8]. The Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-REx) spacecraft studying of this asteroid may answer whether asteroid mining during deep space exploration and travel is feasible.

Bennu is a potentially hazardous asteroid because sunlight can change its orbit over time and create a small chance it will impact Earth in the late 22nd Century [8]. Given this long timescale, can 2 continuously operating spinner systems deflect the 565-meter Bennu from an impact with Earth to a 1 R_E miss distance? Fictional asteroid 2021 PDC was assigned the size and density of Bennu to estimate the capability to deflect it from Earth with spinners.

Representing Bennu, the velocity of 2021 PDC is about 28 km/sec. As was done in the small asteroid examples above, 10 kg projectiles ejected at 2 km/sec are also assumed in this example. Bennu spins at 5.6 rev/day so continuous operation of two spinner systems on its surface allows for about 11 ejections per day. Continuously operating for 6.4 years accumulates to the desired 1 R_E miss distance. If spinner operation is pulsed at 6 percent of Bennu's orbit, a cumulative deflection to 1 R_E miss distance is estimated after 106 years. This operational timeframe should be adequate given that the small chance that Bennu will impact Earth will occur between the years 2175 and 2199 [8].

Conclusions

This study proposes a method whereby a centrifuge and power supply would be landed on a threatening asteroid, collect material from the object, and sequentially spin it away to gradually adjust the trajectory to prevent endangering Earth. Once landed on an asteroid, the centrifugal system operates indefinitely entirely on electrical power, requiring no consumables. The innovation of a self-contained power and kinetic launch capability without consumables opens new vistas for cost-effective asteroid deflection and other commercial, scientific, government, and international space missions.

An on-site centrifuge can deflect 30–60-meter size asteroids to an Earth miss distance of 1 R_E within a few weeks of operation. The few weeks of spinner deflection is approximated as impulsive because it occurs over a small fraction of the orbit. The 565-meter asteroid Bennu can be deflected to a 1 R_E miss distance in a few years of continuous spinner operation, or in about 100 years of periodic operation, sufficient to eliminate a potential collision with Earth in the late 22nd century. Future work will use high-precision simulation tools to check the validity of these approximations.

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