Guided asteroid deflection by kinetic impact: Mapping keyholes to an asteroid's surface

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The kinetic impactor deflection approach is likely to be the optimal deflection strategy in most real-world cases, given the likelihood of decades of warning time provided by asteroid search programs and the probable small size of the next confirmed asteroid impact that would require deflection. However, despite its straightforward implementation, the kinetic impactor approach can have its effectiveness limited by the astrodynamics that govern the impactor spacecraft trajectory. First, the deflection from an impact is maximized when the asteroid is at perihelion, while an impact near perihelion can in some cases be energetically difficult to implement. Additionally, the asteroid change in velocity ΔV should aligned with the target's heliocentric velocity vector in order to maximize the deflection at a potential impact some years in the future. Thus the relative velocity should be aligned with or against the heliocentric velocity, which implies that the impactor and asteroid orbits should be tangent at the point of impact. However, for natural bodies such as meteorites colliding with the Earth, the relative velocity vectors tend to cluster near the sunward or anti- sunward directions, far from the desired direction. This is because there is generally a significant crossing angle between the orbits of the impactor and target and an impact at tangency is unusual. The point is that hitting the asteroid is not enough, but rather we desire to hit the asteroid at a point when the asteroid and spacecraft orbits are nearly tangent and when the asteroid is near perihelion.

However, complicating the analysis is the fact that the impact of a spacecraft on an asteroid would create an ejecta plume that is roughly normal to the surface at the point of impact. This escaping ejecta provides additional momentum transfer that generally adds to the effectiveness of a kinetic deflection. The ratio β between the ejecta momentum and the total momentum (ejecta plus spacecraft) can range from around 1 for a porous, compressible body producing negligible ejecta, to 2 when the ejecta momentum matches the spacecraft momentum, and as high as 5–10 for rocky bodies that produce large, high-velocity ejecta fragments.

If the impactor hits the centerpoint of a spherical asteroid the momentum of the escaping ejecta directly adds to the momentum of the impacting asteroid, but if the impact is oblique then the ejecta and spacecraft momenta are added to the asteroid in vector sum. This suggests the possibility that for a given intercept trajectory the asteroid deflection could include guidance by targeting an oblique impact that could steer the asteroid ΔV to a more optimal direction that is different from the relative velocity direction of the spacecraft. An oblique impact decreases the net ΔV magnitude, and yet could significantly increase the net deflection at the time of the threatening Earth encounter.

We use asteroid (101955) Bennu, which is the target of the OSIRIS-REx asteroid sample return mission and which has a series of potential Earth impacts in the years from 2175–2196, as an example to demonstrate the effectiveness of the oblique impact. These future potential impacts will occur if the asteroid passes through one of a series of keyholes when the asteroid passes the Earth at roughly the lunar distance from the Earth in 2135. To study the Bennu deflection problem we simulate a hypervelocity spacecraft impact on Bennu in March 2021, after the OSIRIS-REx mission is complete. In our example, the spacecraft arrives from approximately the sunward direction, and targeting ahead or behind the center of the asteroid allows non-negligible transverse accelerations for modest values of β. A given impact location on the asteroid surface yields a given ΔV vector, and our approach starts by mapping the net ΔV components on the surface for an assumed value of β. Knowing the mapping from impact location to ΔV and also the mapping from ΔV to the future Earth miss distance allows us to map the surface locations where a spacecraft impact would lead to an Earth impact 150–200 years later. In effect, we are able to project Earth impact trajectories, or keyholes, onto the asteroid surface and, for a given value of β, we can target our impactor spacecraft for an area on the surface that avoids potential Earth impacts.

Of course, at the present time we have little information on what is the appropriate value or range of values for β in the case of asteroid Bennu, or any other asteroid for that matter. However, if this information is made known, either through a precursor mission or better inferences as to its nature we can develop a distribution of β that can be used to better design an impact deflection strategy. Specifically, we can compute a map of Earth impact probability density on the surface of the asteroid based on an assumed probability density function for β. If we target the lowest impact probability density regions then we maximize the chance of a successful deflection. This approach has the potential to allow more efficient kinetic impactor deflection, and therefore the deflection of larger bodies than would otherwise be possible.