Ion Beam Shepherd for Asteroid Deflection

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1 Introduction

Asteroid deflection is becoming a key topic in astrodynamics. Although no asteroid has been deflected so far, altering the trajectory of a small-size asteroid to avoid a catastrophic impact with the Earth has been shown to be, in principle, technically feasible [1] and different techniques, ranging from nuclear detonation to kinetic impact and low-thrust methods, have been proposed [1], [2], [3]. Each of these methods shows advantages and drawbacks that in general depend on the mass and orbital characteristics of the particular asteroid to be deflected as well as its physical property (porosity, composition, surface reflectivity, etc.) and rotation state.

Among the low-thrust methods, in which the asteroid trajectory is altered by a small and continuous push, a very interesting solution was proposed in 2005 by Lu and Love[4]. The method, named “gravity tractor” or “gravity tugboat” exploits the gravitational interaction between an Earth-threatening asteroid and a spacecraft hovering above its surface to achieve a contactless deflection of the former. In the above article, it was shown that a 20-tonne spacecraft could deflect a typical asteroid of about 200-m diameter within one year of hovering time and given a lead time of 20 years. The possibility to predictably change the asteroid orbit with no need of physical attachment and irrespectively of the mechanical properties of the asteroid makes the gravity tractor concept one of the preferred deflection strategies for sub-kilometer asteroids whose orbit characteristics are known with sufficient time before the predicted impact. In addition, the gravity tractor can be used in conjunction to less accurate deflection methods (e.g. kinetic impactor or nuclear detonation) to provide a deflection trim capability and avoid secondary impacts.

However, while offering the undoubtable advantage of no physical attachment with the asteroid the gravity tractor concept suffers from at least two major drawbacks.

The first is the need for a massive spacecraft to physically produce the gravitational force required to slowly deflect the asteroid. As it will be shown in this article, in order to achieve a given gravitational pull a gravity tractor needs to carry a total mass which greatly exceeds the mass required (in terms of propellant and power system mass) to counteract such force with an optimized electric propulsion system. While the extra mass can be used for other spacecraft functions (e.g. scientific payloads), the need to deliver it up to the asteroid orbit will affect the total mission cost significantly.

The second is the need for a continuous control of the spacecraft hovering distance, which has to be fairly small (a fraction of the asteroid radius) if sufficient force is to be achieved. The instability associated with the hovering equilibrium position and the rotation of the generally irregularly-shaped asteroid poses collision risks and complicates the matter even further.

Recently, these authors have proposed a new propulsion concept [5] in which a highly collimated, high-velocity ion beam is produced by an ion thruster on board a shepherd spacecraft and pointed against a target to modify its orbit and/or attitude with no need for docking. If the ion beam is correctly pointed at the target

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Figure 1: Schematic of asteroid deflection with an Ion beam shepherd. The shepherd spacecraft directs a stream of accelerated ions towards the asteroid surface so that the momentum carried by the stream is transferred to the asteroid to be deflected. A second ion propulsion unit thrusting in the opposite direction is needed in order to keep a constant distance between the shepherd and the asteroid.

the momentum transmitted (ions have been accelerated up to 30 km/s and more on board spacecraft in past missions) can reach the same magnitude that would be obtained if the target object had the same ion thruster mounted on its own structure. The same concept can be advantageously applied to the contactless deorbiting of space debris in low Earth orbit [6] and Earth geostationary orbit [7], a theme that is gaining considerable interest in the field of space science and utilization. Note that the idea of accelerating a spacecraft with a flux of incident ions was also recently explored by Brown et al. [8] who propose a lunar-based ion-beam generator to remotely propel spacecraft in the Earth-Moon system.

As it will be shown in this article, this concept can be used to alter the trajectory of earth threatening asteroids with a much higher efficiency when compared to the gravity tractor concept.

2 Ion Beam Shepherd Satellite

The concept of Ion Beam Shepherd (IBS) applied to asteroid deflection is schematized in Fig.1. The shepherd spacecraft is located not too far from the asteroid and pointing one of its ion thrusters directly at the asteroid surface. The high-velocity ions of the quasi-neutral plasma emitted by the thruster reach the asteroid surface transmitting their momentum. Assuming the collision is predominantly inelastic and that the beam fully intercepts the surface of the asteroid, the latter will undergo a force roughly equal and opposite to the one experienced by the spacecraft. It will then be necessary to have a second ion thruster mounted on the spacecraft to cancel out the total force and keep constant the distance with respect to the asteroid.

In the real case, secondary ions and neutrals are sputtered back from the surface increasing, in principle, the net momentum transmitted to the asteroid. Yet their ejection velocities are generally small compared to the ones of the impinging ions [9] so that in the end the effect on the transmitted force is negligible. On the other hand, a decrease in the total transmitted momentum occurs when part of the ions miss the target due to ion beam divergence effects and possible beam pointing errors. In order for the beam to fully intercept the asteroid surface the hovering distance of the spacecraft must not exceed the value:

\[
d_{\text{max}} \leq \frac{s}{2 \sin \varphi},
\]

where \( s \) denotes the smaller asteroid dimension and \( \varphi \) is the divergence angle of the beam (Figure 1).

State of the art ion thruster can reach half-cone divergence angles as low as 15 degrees [10] which would allow, for example, to fully intercept a spherical asteroid at a distance of about twice its diameter. At such distances the risk of collision is greatly reduced when compared to the case of a closely hovering gravity tractor. At the same time, as it will be shown later in the article, the resulting gravitational pull would be negligible.

\[\text{As it is always the case in electric propulsion technology the plasma leaving the propulsion system is neutralized in order to avoid a net charge to accumulate on the spacecraft.}\]
compared with the force provided by the thruster, hence greatly reducing the instability of the hovering motion, but still large enough to be detected by onboard measurement systems so that it can be used for estimating the distance between the asteroid and the spacecraft.

If one assumes, for simplicity, that the asteroid orbit is quasi-circular, the force needed to produce a velocity change $\Delta V$ after a hovering time $\Delta t$ for a spherical asteroid of diameter $d_{ast}$ and density $\rho$ is [4]:

$$F_{th} = 2 \times \frac{\Delta V}{\Delta t} \times \frac{4}{3} \rho \pi (d_{ast}/2)^3,$$

The total propellant mass spent after the hovering time $\Delta t$ is:

$$m_{fuel} = \frac{2F_{th} \Delta t}{v_E},$$

where $v_E$ is the ion ejection velocity and the initial factor of 2 takes into account the need for a second thruster to bring to zero the net thrust force on the spacecraft [4].

The mass of the spacecraft power plant needed to produce the force $2F_{th}$ is:

$$m_{pp} = \frac{2F_{th} \alpha v_E}{2 \eta},$$

where $\eta$ is the thruster efficiency and $\alpha$ the inverse specific power (kg/W) of the power plant feeding the electric propulsion system.

The total spacecraft mass needed to accomplish the deflection is obtained by adding to the latter two terms the structure mass $m_{str}$:

$$m_{IBS} = m_{fuel} + m_{pp} + m_{str} = \pi \rho d_{ast}^3 \frac{\Delta V}{6} \left( \frac{2}{v_E} + \frac{\alpha v_E}{\eta \Delta t} \right) + m_{str}$$

The latter equation can be used to find the optimum value of the ion thruster exhaust velocity which turns out to be the Irving-Stuhlinger characteristic velocity [11]:

$$v_{E, opt}^2 = \frac{2\eta \Delta t}{\alpha}$$

The IBS mass has to be compared with the one of a gravity tractor achieving the same deflection $\Delta V$ after a hovering time $\Delta t$ which is [4]:

$$m_{GT} = \frac{\Delta V (kd_{ast}/2)^2}{G \Delta t}$$

where $G$ is the gravitational constant and $k$ is the hovering distance measured in asteroid radii.

A comparison of the total mass required to deflect asteroids of different diameters using the IBS and the gravity tractor concept is shown in Figure 2 in which the two deflection systems provide during one year a velocity change of $1.9 \times 10^{-3} \text{ms}^{-1}$, which is enough to deflect a typical asteroid of 200 m given a 20 years lead time [4]. The IBS allows more than one order of magnitude mass savings when compared to the gravity tractor concept with the difference increasing the smaller the asteroid diameter.

Two different propulsion systems are considered for the IBS concept: an advanced propulsion and power system (IBS1) with 80% efficiency and providing 10000 s specific impulse (which corresponds to the optimum value for a thrust time of one year) and 5 kW/kg power density, as well as a state-of-the-art system [12] (IBS2) with 60% efficiency, 3100-s specific impulse and 10 kW/kg power density. Note that assuming a constant power

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2The additional force needed to deflect the beam shepherd satellite from its original orbit (by the same amount as the asteroid) is clearly negligible.

3Note that in Stuhlinger book the thruster efficiency is not accounted for in the formula and that the specific power, rather than the inverse specific power, is employed.
Figure 2: Total spacecraft mass required for deflecting asteroids of different size using the gravity tractor vs ion beam shepherd approaches. The deflection velocity change is set to $1.9 \times 10^{-3} \text{ms}^{-1}$ after a hovering time of one year. The asteroid is assumed spherical with mass density of 2000 kg m$^{-3}$\cite{4}. The gravity tractor is kept at constant hovering distance equal to 1.5 asteroid radii. Two different configurations of IBS spacecraft are considered. A “near-future” design (IBS1) employs an ion thruster with 80% thrust efficiency and 10000 s specific impulse ($v_E \sim 100 \text{km/s}$) and a power plant with $\alpha = 5 \text{kg/kW}$. A “state-of-the-art” design (IBS2) employs an ion thruster with 60% thrust efficiency and 3100 s specific impulse ($v_E \sim 30 \text{km/s}$) and $\alpha = 10 \text{kg/kW}$. Structural mass is set, as a preliminary value, to 300 kg in both cases.

In particular, the deflection of a 200-m diameter asteroid, which would require a 20-tonne gravity tractor, can be accomplished with an ion-beam shepherd spacecraft weighting less than 1 tonne employing high-efficiency and high-specific impulse ion thrusters available in the near future, or less than 2 tonne with state-of-the-art hardware.

Additional plots (Fig. 3,4) compare the value of the ion beam thrust force on the asteroid with the (negligible) mutual gravitational attraction between the latter and an IBS spacecraft hovering at two asteroid diameters from the center (providing full beam interception with a 15 degree half-cone divergence) and provide the values for the power level and total propellant consumption throughout the mission.

3 Conclusions and Recommendations

A new concept for low-thrust asteroid deflection has been presented that exploits the momentum transmitted by a low-divergence accelerated ion beam flux from the propulsion system of a nearby spacecraft. The concept, which shares with the gravity tractor the ability of deflecting an asteroid without any physical contact, allows more than one order of magnitude mass savings when compared with the former and does not require close hovering hence greatly simplifying the spacecraft control problem. Given these improvements and because low-divergence ion beams are routinely employed in spacecraft technology, an asteroid deflection demonstration mission may be in reach in the near future. Future studies will be needed to evaluate the actual deflection performance of the system for different asteroid orbits and to compare it with other short-term deflection methods such as the kinetic impactor.
Figure 3: Comparison between the thrust force $F_{th}$ exerted on the IBS by the asteroid and the mutual gravitational force $F_g$ as a function of the asteroid diameter. The deflection magnitude, asteroid density and IBS design are the same as in Fig. 2. A hovering distance of two asteroid diameters from the center is assumed.

Figure 4: Power and total propellant consumption for the two IBS designs considered in Fig. 2 and using the same asteroid deflection magnitude and density.

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