Removing Space Debris and Deflecting Asteroids with Ion Beams

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Annotation

The tasks of actively removing space debris and deflecting asteroids are greatly simplified by the use of contactless actuation, in which linear and angular momentum is transferred to a target without a direct mechanical interaction. The recently proposed ion beam shepherd (IBS) concept enables contactless actuation in a very efficient way by using the beam momentum of an ion engine or space plasma thruster pointed towards the surface of a target. This article summarizes the main aspects of the IBS technology and its applicability to the space debris removal and asteroid deflection problems.

Keywords

ion beam shepherd; asteroid deflection; space debris

Introduction

Contactless actuation, i.e., the transmission of forces and torques to a target body without any mechanical interaction, is highly desirable when facing challenging tasks in space such as active space debris removal and asteroid deflection. Removing space debris implies the need to transfer a deorbiting (or reorbiting) force to a non-cooperative space object whose dynamical state can be problematic. Much space debris are thought to be tumbling or even spinning at relatively high angular rate, which complicates mechanical docking/capturing. In addition, they may be fragile or deteriorated after years or decades of exposure to the harsh space environment, which raises the concern of possible generation of extra debris material (or even explosion in some cases) following a direct mechanical interaction.

Deflecting an asteroid from its collision course with our planet poses similar challenges. In virtually all cases asteroids are spinning bodies whose material and mechanical properties are not known in advance. Many asteroids, even relatively small ones like Itokawa, are thought to be unconsolidated bodies held together by gravity and friction alone (rubble piles). These problematic dynamical and physical properties greatly complicate the task of landing on the asteroid surface with a spacecraft to transfer a continuous deflecting acceleration. For these reasons alternative methods not requiring mechanical contact have been proposed.

Laser beams are perhaps the most popular contactless actuation method [1], having being explored since the 70's. Material ablations induced by a laser beam, and to a lesser extent the photon pressure of the laser, give rise to a continuous acceleration of the target body eventually modifying its orbit. Unfortunately though, lasers are not very efficient and require high power to produce relatively low actuation forces, not large enough to significantly deflect even small asteroids or deorbit low Earth orbit satellites or upper stages in a reasonable amount of time.

Electrostatic actuation [2] has also been proposed with applications to formation flying and space debris removal. The problem with this method comes from the need for high charges (i.e. high potentials) on the surface of all interactive bodies in order to produce reasonable attraction/repulsion forces. Charge accumulation on a spacecraft can create discharge effects damaging critical hardware and software components.

A new contactless actuation method, named ion beam shepherd (IBS) has been recently proposed by the Technical University of Madrid [3, 4]. The method employs the momentum of plasma ions produced by an electric propulsion system on board a spacecraft to modify the orbit of space debris and asteroids with a much higher efficiency compared with the techniques described above. This paper describes the IBS technique and its application as an asteroid deflection and space debris removal concept.

The Ion Beam Shepherd Concept (IBS)

The ion beam shepherd (IBS) concept proposes a novel use of space electric propulsion in which the ions accelerated by an ion thruster (or similar electric propulsion device) are directed against the surface of a target object to exert a force (and a torque) from a distance of a few times the target size (Figure 1). This will eventually modify the orbit and/or the attitude of the target for a variety of purposes. In typical IBS application the «shepherd spacecraft» rendezvous with the target and position itself at a safe distance from the target surface, towards which one (or multiple) electric propulsion thruster(s) are aimed. As long as the ion beam emitted by the thruster(s) is correctly pointed a deflection force arises from the variation of momentum of the plasma ions (typically xenon) impacting against the surface of the object and penetrating its outermost layers before being stopped. An essential element of the IBS is then the presence of a secondary propulsion system that compensates for the reaction force that the ion beam exerts on the shepherd and that would make it accelerate away from the asteroid.

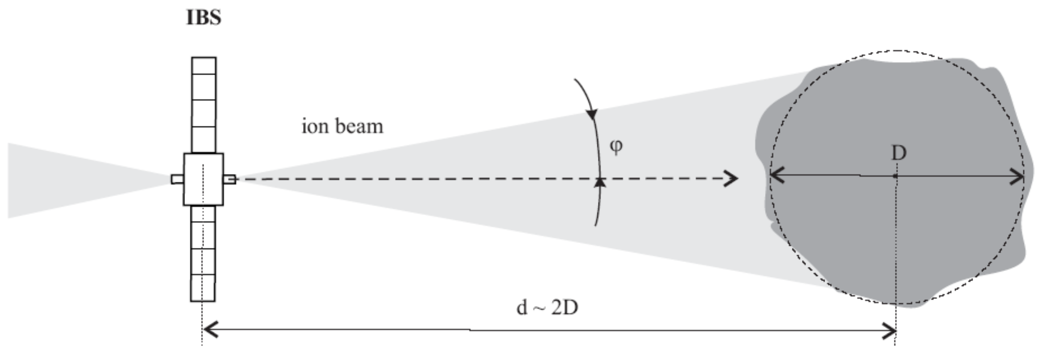

Figure 1 - Asteroid Ion Beam Shepherd Concept

This simple idea can be used to remotely maneuver objects in space without physical contact (docking) and has been proposed for the active removal of space debris [3] and the deflection of asteroids [4].

Asteroid Deflection

The deflection of an asteroid from its collision course with our planet is, in principle, technically feasible and can be carried out in different ways. The basic idea is to transmit to the asteroid an impulsive or continuous acceleration, which will results into a shift of the asteroid intersection point on the Earth encounter b-plane. If this shift is sufficiently large (say at least 2 Earth radii) the impact with our planet can be ruled out with a high enough degree of confidence. Transferring such acceleration in a continuous «slow-push» manner offers the benefit of an accurate and controllable deflection and can be done in a contactless manner with an IBS hovering at a distance of a few asteroid radii above the asteroid surface (Figure 1).

If for simplicity we assume the applied force F is constant and the primary and secondary propulsion systems are equal, the total mass m_{IBS} needed for such a slow-push campaign of duration Δt can be divided into fuel, power plant and structure:

$$m_{IBS} = 2F\left[\frac{\Delta t}{I_{sp}g} + \frac{\alpha I_{sp}g}{2\eta}\right] + m_{str},$$

where I_{sp} is the (constant) thruster specific impulse, g is the see-level gravity, η is the thruster efficiency, m_{str} is the structural mass and α is the inverse specific power, also considered constant.

Figure 2 plots the achievable constant deflecting force for an IBS system of given mass (1, 5 and 10 tons) as a function of the desired push time and for two different values of the specific impulse.

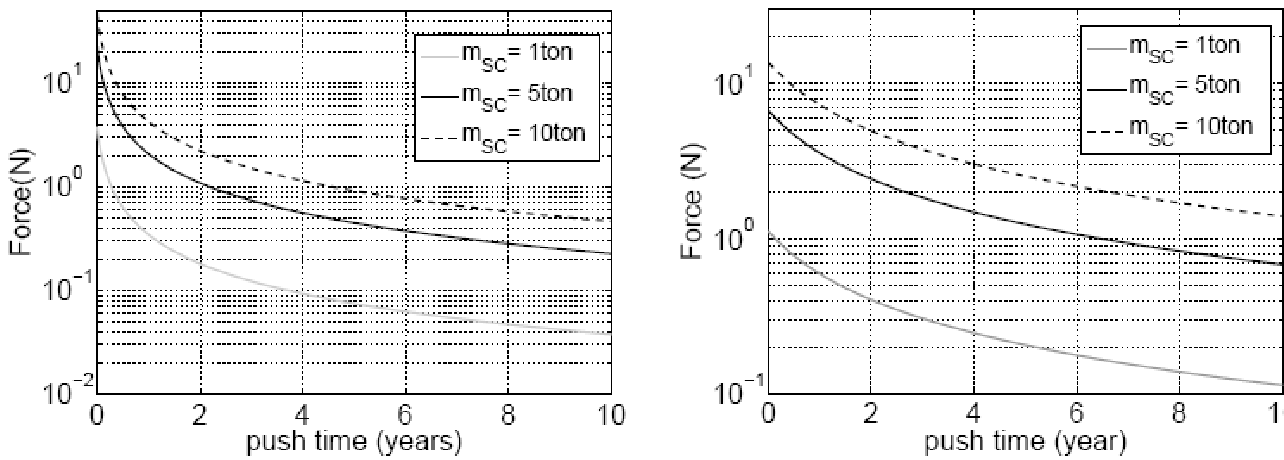

Figure 2 - Deflection Force Achievable as a Function of the Push Time for Different IBS Masses and Considering a Specific Impulse of 3000 s (Left) and 10000 s (Right). Thruster efficiency is set to 70 %, inverse specific power to 5 kg/kW, and structural mass to 150 kg

Figure 3 plots the achievable b-plane deflection for two target asteroids considering a continuous 1 N tangential force applied starting from a given time before the predicted impact. The chosen target asteroid are 2007VK184 and 2011AG5 the only two known asteroids having level 1 in the Torino scale. Asteroid 2011AG5, with a chance of 1 over 500 of hitting the Earth in 2040 is currently the most dangerous known asteroid. Note that the highest collision probability for 99942 Apophis (in 2036) is currently less than 1 in 100000.

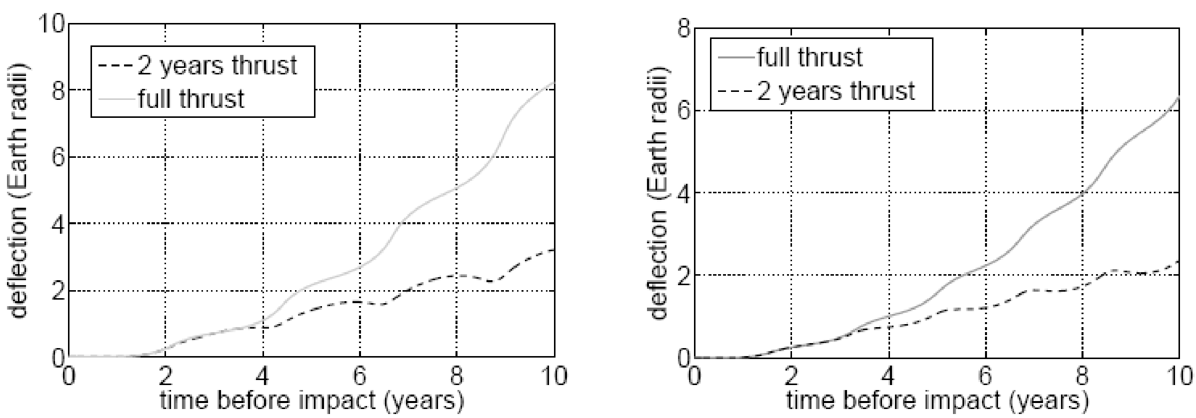

Figure 3 - Achievable b-plane Deflection for Constant Tangential Thrust Acceleration (F=1 N) Applied to the Asteroid 2007VK184 (Left) and 2011AG5 (Right) as a Function of the Time before Impact. Two strategies are considered: one in which the thrust is applied during two years and followed by a coast phase, another in which the thrust is applied all the time

Altogether figures (2, 3) show that both asteroids can be deflected by more than 2 Earth radii with an IBS of less than 5 tons provided a warning time of 10 years. Note that in order to build up the same deflection with a gravity tractor spacecraft more than 50 tons would be needed.

Space Debris Removal

The other fundamental IBS application is the active removal of space debris in Low Earth orbit (LEO) as well as at geostationary altitude (GEO). Studies have shown that even in the extreme hypothesis that no new satellites were launched, the number of objects in LEO would continue to increase due to collisions and explosions between resident space objects [5]. This means that actively removing space debris that are already in orbit will be a necessary step for the preservation of the LEO (and to a less extent the GEO) environment.

An IBS spacecraft allows to deorbit or reorbit multiple space debris in a contactless way with high efficiency. Figure 4 shows that LEO debris can be deorbited with an optimized IBS weighting about 5 % of the debris mass.

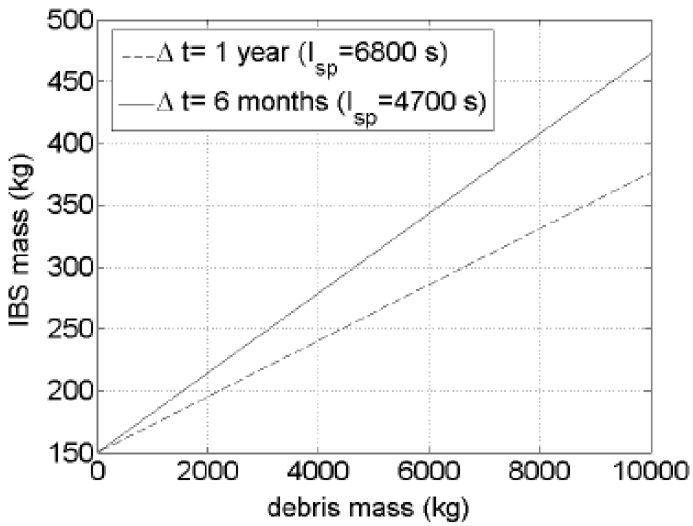

Figure 4 - IBS Mass Needed for Deorbiting Space Debris from 1000 km to 500 km Altitude. A constant tangential thrust, 70 % efficiency and 10 kg/kW specific power are assumed

Acknowledgments

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