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Statistical multi-criteria evaluation of non-nuclear asteroid deflection methods

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ABSTRACT

In this paper we assess and compare the effectiveness of four classes of non-nuclear asteroid deflection methods applied to a wide range of virtual collision scenarios. We consider the kinetic impactor, laser ablation, the ion beaming technique and two variants of the gravity tractor. A simple but realistic model of each deflection method was integrated within a systematic approach to size the spacecraft and predict the achievable deflection for a given mission and a given maximum mass at launch. A sample of 100 synthetic asteroids was then created from the current distribution of NEAs and global optimisation methods were used to identify the optimal solution in each case according to two criteria: the minimum duration between the departure date and the time of virtual impact required to deflect the NEA by more than two Earth radii and the maximum miss-distance achieved within a total duration of 10 years. Our results provide an interesting insight into the range of applicability of individual deflection methods and argue the need to develop multiple methods in parallel for a global mitigation of all possible threats.

1. Introduction

Near Earth Asteroids (NEA) are defined as asteroids with perihelia lower than 1.3 astronomical units (AU). Potentially hazardous asteroids (PHA) represent a portion of the NEAs whose current orbits has a Minimum Orbit Interception Distance (MOID) with the Earth's orbit which is less than 0.05 AU and whose diameter is at least 100 m. PHAs are deemed to represent a risk as they could come into a collision course with the Earth due to perturbations affecting their orbits Chapman [1].

Several deflection methods have been proposed over the years to mitigate the risk of an impact of a PHA with the Earth. Most of the strategies proposed fall into two categories: impulsive and slow-push. Impulsive strategies are usually modelled with an instantaneous change of momentum given by, for example, a nuclear explosion (nuclear interceptor) or the hypervelocity impact of a spacecraft (kinetic impactor) with the asteroid. Slow-push methods, on the other hand, allow for a more controllable deflection manoeuvre by exerting a small continuous and controllable force on the asteroid over an extended period of time. In Sanchez et al. [2]; the authors proposed a comparative analysis of several deflection methods considering thousands of mission scenarios and a number of representative PHAs.

Following the same idea, this paper proposes a new comparative assessment of four classes of asteroid deflection methods for a wide range of collision scenarios. The classes selected for this comparison are: the kinetic impactor [3], the laser ablation [4], the ion beaming technique [5] and the gravity tractor [6]. For the kinetic impactor we will put to the test the simplest variant with highest technology readiness level but will discuss the potentiality of a version using low-thrust transfers introduced by Conway [7]. For the gravity tractor we will analyse two different configurations.

The laser ablation and the ion beaming were not part of the methods analysed by Sanchez et al. [2]. Furthermore, in this paper, a sample of 100 synthetic PHAs are created from the current distribution of known NEAs and used to build a set of mission scenarios for each deflection method. In all cases, the argument of perigee of the orbit of the PHA is modified so that the virtual asteroid crosses the ecliptic plane at a distance of 1AU from the Sun. A fixed asteroid mass of 4×10^9 kg is considered throughout this study (unless otherwise stated), which corresponds to an estimated diameter of 156 identical the size of asteroid 2011AG5 which was previously considered by NEOSHIELD [8] and is also comparable to the size of Didymoon which will be the target of the AIDA demonstrator mission.

The methodology in this paper also differs from Sanchez et al. [2] in that the deflection models are integrated with a revised system sizing

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approach to quantify the mass of the spacecraft at launch and predict the achievable deflection for a given epoch. Furthermore it is assumed that all methods fully exploit the maximum interplanetary launch capability of 10 mt (for a $c_3 = 0\ \mathrm{km}^2/\mathrm{s}^2$), equivalent to that of Delta 4 Heavy RS-68A upgrade version.

The available system mass after the transfer to the target asteroid is used to evaluate the achievable deflection. For the case of the kinetic impactor, a direct injection using a multiple-revolution Lambert arc is considered. For the case of slow-push methods, a low-thrust transfer is retained in order to take advantage of the large electrical power available which would otherwise remain unused during the transfer phase.

A single objective global optimisation technique is then used to find an optimal solution for each scenario within a limited mission duration. A memetic multi-objective optimiser is then also used to identify solutions that are optimal with respect to two criteria: the minimum duration between the departure date and the time of virtual impact required to deflect the PHA by more than 2 Earth radii or the miss-distance achieved within a maximum duration of 10 years.

2. Fundamentals of deflection astrodynamics

In this section we briefly recall the formulas to calculate the deflection and the associated impact parameter given either an impulsive or a slow-push deflection action. A more extensive treatment can be found in Vasile and Colombo [9]; Colombo et al. [10].

2.1. Impulsive deflection

The effect of an impulsive change in the velocity of the asteroid induces a variation of its orbit and related orbital elements. The assumption is that this variation is small compared to the asteroid-Sun distance, thus the modified orbit remains in close proximity to the undeflected one. In this case, given the instantaneous change in the asteroid velocity vector $\delta\mathbf{v} = [\delta v_t, \delta v_n, \delta v_h]^T$ in a tangential, normal, out-of-plane reference frame, the position of the deflected asteroid with respect to the undeflected one at true anomaly θ_{MOID} along the orbit of the undeflected asteroid is:

$$\begin{aligned} \delta x_r &= \frac{r}{a}\delta a + \frac{ae\sin\theta_{\mathrm{MOID}}}{\sqrt{1-e^2}}\delta M - a\cos\theta_{\mathrm{MOID}}\,\delta e \\ \delta y_\theta &= \frac{r}{(1-e^2)^{3/2}}(1+e\cos\theta_{\mathrm{MOID}})^2\delta M + r\delta\omega \\ &\quad + \frac{r\sin\theta_{\mathrm{MOID}}}{(1-e^2)}(2+e\cos\theta_{\mathrm{MOID}})\delta e + r\cos i\,\delta\Omega \\ \delta z_h &= r\left(\sin\theta^*_{\mathrm{MOID}}\delta i - \cos\theta^*_{\mathrm{MOID}}\sin i\,\delta\Omega\right) \end{aligned} \tag{1}$$

where $\delta\mathbf{r} = [\delta x_r, \delta y_\theta, \delta z_h]^T$ is the displacement vector in a radial, transversal, out-of-plane reference frame attached to the undeflected asteroid, θ_{MOID} is the true anomaly of the point of Minimum Orbit Intersection Distance (MOID), $\theta^*_{\mathrm{MOID}} = \theta_{\mathrm{MOID}} + \omega$, r, a, e, i and ω are respectively the radius, semi-major axis, eccentricity, inclination, argument of the pricentre of the orbit of the undeflected asteroid, and δa, δe, δi, $\delta\Omega$, $\delta\omega$, δM are the variations of the orbital parameters due to $\delta\mathbf{v}$. The variation of the orbital elements are given by:

$$\begin{aligned} \delta a &= \frac{2a^2V}{\mu}\delta v_t \\ \delta e &= \frac{1}{V}\left(2(e+\cos\theta_d)\delta v_t - \frac{r}{a}\sin\theta_d\,\delta v_h\right) \\ \delta I &= \frac{r\cos\varpi_d}{h}\delta v_h \\ \delta\Omega &= \frac{r\sin\varpi_d}{h\sin I}\delta v_h \\ \delta\omega &= \frac{1}{eV}\left(2\sin\theta_d\,\delta v_t + \left(2e + \frac{r}{a}\cos\theta_d\right)\delta v_n\right) - \frac{r\sin\varpi_d\cos I}{h\sin I}\delta v_h \\ \delta M &= \delta M_n - \frac{b}{eaV}\left(2\left(1+\frac{e^2r}{p}\right)\sin\theta_d\,\delta v_t + \frac{r}{a}\cos\theta_d\,\delta v_n\right) \end{aligned} \tag{2}$$

where θ_d is the true anomaly at the deflection epoch, $\varpi_d = \theta_d + \omega$ is the argument of latitude $p = a(1-e^2)$ is the semilatus rectum, $h = \sqrt{\mu a(1-e^2)}$ is the angular momentum, $r = p/(1+e\cos\theta)$ is the orbital radius, and V is the instantaneous asteroid velocity modulus. The time dependent variation of the mean anomaly δM_n is given by:

$$\delta M_n = \frac{3}{2}\frac{\sqrt{\mu}}{a^{5/2}}\Delta t\ \delta a \tag{3}$$

From the deflection $\delta\mathbf{r}$ the impact parameter b on the impact plane at the time of the MOID can be computed. The impact plane can be defined as the plane centered in the Earth and perpendicular to the velocity vector of the undeviated asteroid with respect to the Earth, $\mathbf{U}_{\mathrm{neo}}$, at the time of the impact (see Fig. 1 where $\mathbf{v}_E$ is the velocity of the Earth). The simplifying assumption is that the velocity vector of the deflected asteroid remains parallel to the one of the undeflected asteroid at the MOID. The deflection vector $\mathbf{x}_b$ in the b-plane coordinates can be expressed as:

$$\mathbf{x}_b(t_{\mathrm{MOID}}) = [\xi \quad \eta \quad \zeta]^T = \left[\hat{\xi} \quad \hat{\eta} \quad \hat{\zeta}\right]^T\delta\mathbf{r} = \mathbf{B}\delta\,\mathbf{r} \tag{4}$$

where

$$\hat{\eta} = \frac{\mathbf{U}_{NEO}}{U_{NEO}}, \quad \hat{\xi} = \frac{\mathbf{v}_E \wedge \hat{\eta}}{\|\mathbf{v}_E \wedge \hat{\eta}\|}, \quad \hat{\zeta} = \hat{\xi}\wedge\hat{\eta}$$

If one then calls $\delta\boldsymbol{\alpha} = [\delta a, \delta e, \delta I, \delta\omega, \delta\Omega, \delta M]^T$ the vector of the variations of the parameters, and $\mathbf{A}$ and $\mathbf{G}$ the two matrices such that $\delta\boldsymbol{\alpha} = \mathbf{G}\delta\mathbf{v}$ and $\delta\mathbf{r}(t_{\mathrm{MOID}}) = \mathbf{A}\delta\boldsymbol{\alpha}$ then we have:

$$\mathbf{x}_b(t_{\mathrm{MOID}}) = \mathbf{BAG}\delta\mathbf{v} \tag{5}$$

with the impact parameter b:

$$b = \sqrt{\xi^2 + \zeta^2} \tag{6}$$

Note that other deflection formulas can be derived from Eq. (8) by assuming for example that the deflection is not introducing any geometric variation on the b-plane but only a temporal variation δM_n. However, retaining only the temporal variation precludes the possibility to study deflection actions with short warning times or leading to

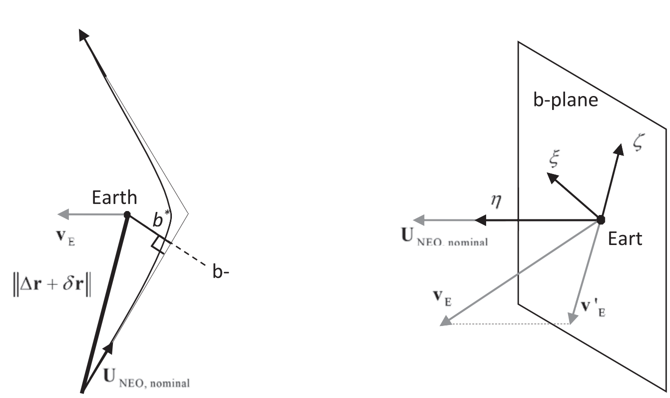

Fig. 1. The b-plane and the impact parameter b.