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Nuclear cycler: An incremental approach to the deflection of asteroids

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Abstract

This paper introduces a novel deflection approach based on nuclear explosions: the nuclear cycler. The idea is to combine the effectiveness of nuclear explosions with the controllability and redundancy offered by slow push methods within an incremental deflection strategy. The paper will present an extended model for single nuclear stand-off explosions in the proximity of elongated ellipsoidal asteroids, and a family of natural formation orbits that allows the spacecraft to deploy multiple bombs while being shielded by the asteroid during the detonation.

Keywords: Asteroid deflection; Planetary defence; Nuclear interceptor

1. Introduction

Deflection methods are commonly divided into two main categories, impulsive and slow push, depending on whether the modification of the orbit of the asteroid is, respectively, quasi-instantaneous or modified over a longer period of time. Examples of impulsive methods include the nuclear interceptor (Hammerling and Remo, 1995) and the kinetic impactor (Jutzi and Michel, 2014), while slow-push methods include, among others, the gravity tractor (Lu and Love, 2005), laser ablation (Vasile and Maddock, 2012), ion-beam shepherd (Bombardelli and Peláez, 2011) and mass driver (Olds et al., 2004).

The nuclear interceptor can nudge the asteroid off of its collision course with the Earth even when the warning time is low, but a single explosion represents a single point of failure and does not allow any control over the evolution of the trajectory of the asteroid. On the other hand, slow-push methods allow for a more precise control of the deflection manoeuvre but typically require a longer warning time, additional propellant in order to maintain a hovering position in the vicinity of the asteroid, the ability to operate autonomously and are dependent on the distance from the Sun (Bombardelli and Peláez, 2011; Cuartielles et al., 2009; Vasile and Maddock, 2012).

Nuclear methods carry the highest energy density among all currently proposed mitigation strategies. As there is no atmosphere in space, the efficiency of nuclear methods is based on the amount of asteroid material that can be blasted away following the explosion. In a report to Congress, NASA (2007) argued that using a stand-off nuclear detonation would be ten to a hundred times more effective than any other alternative. While a subterranean explosion would, in principle, further increase the amount of material that can be expelled, a stand-off configuration does not require landing and digging and is thus more manageable with current technology.

The theoretical efficiency of nuclear-based approaches must be balanced with the difficulty in controlling the outcome of the explosion. This lack of control can lead to three main problems. The high level of energy released during the single detonation introduces the potential risk of an

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unwanted fragmentation. If the asteroid breaks up into several pieces following the explosion, it may be that some of the larger pieces will impact the Earth and the probability of causing damages may never go to zero (Sanchez Cuartielles et al., 2010); the risk of fragmentation is already reduced however due to the choice of the stand-off configuration.

Another problem arises from the precise detonation at the required location. Choosing such a location could actually require the addition of an observer spacecraft, as it is the case for the kinetic impactor. Last but not least, the current epistemic uncertainty on the properties of the asteroid translates into a significant variance on the expected deflection. In particular, as will be shown in this paper, the efficiency of the nuclear interceptor relies strongly on the amount of energy required to vaporize the asteroid material, which itself is not so well characterized in the available literature. Hence, relying on a single interceptor is a rather risky strategy.

The idea proposed in this paper partially overcomes these difficulties by fractionating a single explosion into a number of smaller and better controlled ones. A single spacecraft, carrying a number of bombs, is placed on a formation orbit with the asteroid and incrementally releases the bombs so that each of them explodes at an optimal position with respect to the surface of the asteroid. As will be shown, careful choices in the firing time and orbital trajectory can allow for the incremental deflection of the asteroid while ensuring an appropriate radiation shielding to the carrier.

The paper is structured as follows: first by a review of the model of a single nuclear interceptor method considering both spherical and elongated asteroids. The idea of the nuclear cycler is then explained, illustrating the concept with a possible choice of mission configuration. The following section shows the results of a comparison for the deflection of an elongated Apophis-like asteroid using a single interceptor and an incremental deflection using the nuclear cycler idea. Lastly is a discussion on the strategy and plans for future work.

2. Single detonator model

This section introduces a model to calculate the change in linear momentum of the asteroid due to a stand-off nuclear explosion. The first subsection presents a slightly modified version of the model presented by Cuartielles et al. (2009) applicable to the case of a spherical asteroid. The model is then extended to the case of an elongated body with an ellipsoidal shape. The semi-analytical model presented in this section is only an approximation of the complex phenomena that occur during a stand-off explosion. A number of effects are not considered here and there are strong assumptions on the absorption of radiation and on the vaporisation process. In particular, we assume that the surface of the asteroid is composed of hard rock with low porosity. As in Solem (1993), we assume a linear relationship between the mass of the nuclear bomb and total yield, with all the energy absorbed by the material going into the vaporisation process, where only vaporisation is considered rather than melting and vaporisation. Furthermore, no shockwave propagation, reflection and diffraction are modelled. More accurate results can be found in the work of Plesko et al. (2010) who used a full numerical simulation. As with Shubin et al. (1995), and Meshcheryakov (2014), the model in this section is sufficient to get an estimation of the δv imparted to the asteroid and serves the main scope of this paper, which is to compare a single detonation with a fractionated approach.

2.1. Spherical asteroid

The energy released during the explosion is carried by the debris of the exploded spacecraft and by the radiations produced. Table 1 shows the fraction f_i (with $i \in \{1, 2, 3, 4, 5\}$) of energy associated to each of the products of the explosion for the case of a fusion and fission devices (Glasstone, 1962; Hammerling and Remo, 1995).

The energy delivered during the explosion, Y_0, is computed from the yield-to-mass ratio and is conservatively assumed to have a value $YTW = 0.75$ ktons/kg for fusion devices and $YTW = 0.075$ ktons/kg for fission devices.[1]

$$Y_0 = YTW\, m_{wh} \tag{1}$$

where m_{wh} is the mass of the bomb. This assumption is more conservative than the one of Solem (1993). In this paper, no buried or surface detonation are considered due to the added difficulty of landing and digging on an asteroid.

With reference to Fig. 1, the explosion is assumed to happen at a distance H from the surface of the asteroid, therefore, only a portion m_{debris} of the total mass of debris m_d will hit the surface:

$$m_{debris} = S m_d \tag{2}$$

If one assumes that the exploding device sees a spherical cap with radius R_A, then the fraction S can be expressed as:

$$S = \frac{1}{2} - \frac{\sqrt{H}}{2} \frac{\sqrt{H + 2R_A}}{R_A + H} \tag{3}$$

The ejection velocity of the debris v_{debris} is then computed from the fraction $f_4 = 0.2$ (see Table 1) of the total energy Y_0 released during the blast:

$$v_{debris} = \sqrt{\frac{2 f_4 Y_0}{m_d}} \tag{4}$$

The variation of velocity δv_{debris} due solely to the debris cloud is then given by:

$$\delta v_{debris} = \beta S_{sc} \frac{m_{debris} v_{debris}}{m_A} \tag{5}$$

[1] Based on data available online at nuclearweaponarchive.org.