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Estimation of necessary laser power to deflect near-Earth asteroid using conceptual variable-laser-power ablation

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ABSTRACT

In this research, the necessary laser power to deflect a near-Earth asteroid (NEA) is estimated using a future conceptual variable-laser-power ablation technique. The required necessary laser power is approximated by the established system dynamics that considers a conceptual on-board laser tool, which can vary the laser power output within a certain range to ablate an object's surface. Using established system dynamics, the necessary laser power (both the maximum and minimum values), action direction and action duration with respect to various action start times are successfully estimated. These estimates are significantly lower than those assumed in previous studies. In addition, the effectiveness of deflections using a time-varying laser power within a certain range by controlling both laser action directions is discussed. The method described in this work is expected to be useful in approximating the necessary laser power with regard to various operation start times for future deflection missions with space-based laser ablation tools provided by any type of power source.

1. Introduction

Despite being an improbable event, the possibilities of impact by hazardous Earth-crossing objects (ECOs) should not be ignored. Therefore, many scientists and engineers have proposed various methods to deflect such objects: kinetic energy impacts, nuclear explosions, mass drivers, laser ablations, solar sails, solar collectors and gravity tractors [1,2]. Among these methods, kinetic energy impact is an effective approach to divert small, solid objects. However, for larger objects, the momentum change imparted could potentially shatter the object into fragments; if these fragments are large, they could themselves become Earth-threating objects. Regardless of the fragmentation of the object, recent analyses have again focused on using a nuclear explosion and concluded that the use of a nuclear explosion is an efficient method to deflect or disrupt an object's trajectory based on a short warning time [3–5].

Among the numerous, fascinating deflection methods proposed, the effectiveness of different asteroid deflection methods have been determined, which have concluded that ablation might be another efficient method [6]. Ablation methods alter an object's trajectory with continuous momentum changes by irradiating the object with different laser light sources, i.e., either collected solar radiation or driven by internal power. A sufficiently intense laser ablates the ECO's surface by causing a plasma blow-off, which generates a small thrust in the direction opposite to the applied laser that changes the object's orbit [7]. The ablation technique could overcome the mass penalties associated with other non-disruptive approaches because the object's own material is the propellant source. Additionally, this method is effective against a wide range of surface materials and does not require any landing or physical attachment to the object [7]. Actually, laser-ablating methods can be categorized as either ground- or space-based concepts. ECO deflection methods using ground-based laser facilities have been proposed [8–10], and the concept of a lunar-based laser station to prevent Earth collisions has also been suggested [11]. However, to mitigate distant ECOs, the power and optics requirements of a laser ablation system on the ground or near Earth may be too extreme to realize. One solution to this method would be to permit a spacecraft to carry a laser tool as a payload to a particular celestial body and perform a given mission task. The concept of a solar collector, which uses sunlight collected by large onboard mirrors to evaporate material from the object's surface and gener-

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ate continuous propulsive forces, has also been proposed [1] and has been extensively studied [12–16]. Although extensive research has been performed using the solar sublimating concept, this concept still requires rather complex control strategies to maximize the collected solar power at a stable level.

As an alternative approach, a conceptual deflection scenario using a spacecraft with variable specific impulse magnetoplasma rocket (VASIMR) engines designed to deliver a laser ablation payload to ablate the object's surface has been presented [7,17–19]. In Refs. [7,17–19], the assumption is that a powerful propulsion system, which is activated by a nuclear reactor, is first used for rapid rendezvous with the objects. After a successful rendezvous, the required power for an onboard laser system to ablate an ECO's surface is assumed to be supported by the same nuclear reactor that provided power to the spacecraft's main propulsion system. Such a mission could solve the rapid rendezvous problem with detected hazardous ECOs and also ease the problem of supporting a stable level of power to oscillate the onboard laser system. Indeed, a rapid rendezvous capability to reach target ECOs using future conceptual spacecraft with a VASIMR engine has also been analyzed [20,21]. In previous studies, the required deflection energy was estimated with first-order approximations under the assumption that the cumulative energy generated by the laser is applied as equivalent impulsive ΔV levels [7,17] or formulated as a constrained optimization problem. However, these studies used pre-defined constant laser powers that supplied several tens of MW of power and assumed full-power operations throughout laser actions within a planar motion of the given object's heliocentric motion [18,19]. When investigating the feasibility of such a future conceptual deflection mission, one of the key parameters to estimate is the necessary laser power with the appropriate operating directions; operating lasers over an extended period of time at several tens of MW at full power significantly burdens the thermal control system, which includes the spacecraft's bus and also the onboard laser tool.

Therefore, the primary focus of this paper is to approximate the necessary laser power required to divert Earth-threating objects; in previous studies, the necessary laser power was fixed to a certain pre-defined value (MW class) [18,19]. The system dynamics, which considers a conceptual laser tool that can vary the laser power output within a certain range to ablate the object's surface, is established to approximate the necessary laser power (both the minimum and maximum values) and the laser action duration with different action start times. In addition, the effectiveness of deflections using a time-varying laser power within a certain range by controlling both laser action directions is analyzed by comparing solutions derived in Refs. [18,19]. After approximating the necessary laser power, more detailed system specifications for the onboard laser tool could then be determined based on the technology readiness levels, i.e., the total number of laser oscillators required on a single platform to satisfy the required deflection energy and a station-keeping strategy using the redundant power from a hypothetical nuclear reactor. Although the current results are simulated under several assumptions, the current study attempts to build upon research previously performed on proposed conceptual deflection missions. The presented method could easily be modified and applied to other deflection missions using space-based lasers driven by other sources, which are expected further advance initial conceptual studies. The method used to formulate the proposed nonlinear deflection problem is explained in detail in Section 2, and the simulation pre-setup conditions and assumptions made for the current work are discussed in Section 3. The numerical simulation results are provided in Section 4, which includes a detailed analysis, and the conclusions are provided in Section 5.

2. Deflection problem statements

2.1. Equations of motion

For the proposed conceptual deflection mission, the fictitious ECO's states can be expressed in terms of modified equinoctial orbital elements, as shown in Eq. (1) [22].

$$\boldsymbol{y}^T = [p, f, g, h, k, L] \tag{1a}$$

$$\dot{\boldsymbol{y}} = \boldsymbol{A}(\boldsymbol{y})\boldsymbol{\Delta} + \boldsymbol{b} \tag{1b}$$

where $\boldsymbol{y}$ and $\dot{\boldsymbol{y}}$ are the set of ECO's state vectors and their derivatives expressed with modified equinoctial orbital elements, respectively, and p, f, g, h, k, and L are the components of the modified equinoctial orbital elements, which are all expressed in a heliocentric ecliptic coordinate system. Additionally, the term $\boldsymbol{\Delta}$ contains the disturbing acceleration forces applied to the ECO. The two vectors $\boldsymbol{A}$ and $\boldsymbol{b}$ in Eq. (1) are defined by the matrices below [22]:

$$\boldsymbol{A} = \begin{bmatrix} 0 & \frac{2p}{q}\sqrt{\frac{p}{\mu_\odot}} & 0 \\ \sqrt{\frac{p}{\mu_\odot}}\sin L & \sqrt{\frac{p}{\mu_\odot}}\frac{1}{q}\{(q+1)\cos L + f\} & -\sqrt{\frac{p}{\mu_\odot}}\frac{g}{q}\{h\sin L - k\cos L\} \\ -\sqrt{\frac{p}{\mu_\odot}}\cos L & \sqrt{\frac{p}{\mu_\odot}}\{(q+1)\sin L + g\} & \sqrt{\frac{p}{\mu_\odot}}\frac{f}{q}\{h\sin L - k\cos L\} \\ 0 & 0 & \sqrt{\frac{p}{\mu_\odot}}\frac{s^2\cos L}{2q} \\ 0 & 0 & \sqrt{\frac{p}{\mu_\odot}}\frac{s^2\sin L}{2q} \\ 0 & 0 & \sqrt{\frac{p}{\mu_\odot}}\frac{1}{q}\{h\sin L - k\cos L\} \end{bmatrix} \tag{2}$$

and

$$\boldsymbol{b}^T = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \sqrt{\mu_\odot p}\left(\frac{q}{p}\right)^2 \end{bmatrix} \tag{3}$$

where

$$q = 1 + f\cos L + g\sin L \tag{4a}$$

$$s^2 = 1 + h^2 + k^2 \tag{4b}$$

and $\mu_\odot$ is the Sun's gravitational constant. The acceleration due to the laser ablation jets $\boldsymbol{\Delta}_{Acc}$ can be included in the $\boldsymbol{\Delta}$ terms in Eq. (1) as follows:

$$\boldsymbol{\Delta} = \boldsymbol{\Delta}_{Acc} \tag{5}$$

$\boldsymbol{\Delta}_{Acc}$ can be expressed in terms of the defined in-plane, α, and out-of-plane, β, acceleration direction angles, as shown in Eq. (6).

$$\boldsymbol{\Delta}_{Acc} = \Delta_{Acc}\sin(\alpha)\cos(\beta)\hat{\mathbf{i}}_r + \Delta_{Acc}\cos(\alpha)\cos(\beta)\hat{\mathbf{i}}_t + \Delta_{Acc}\sin(\beta)\hat{\mathbf{i}}_n \tag{6}$$

where Δ_{Acc} is the magnitude of acceleration due to the ablation jets, and $\hat{\mathbf{i}}_r$, $\hat{\mathbf{i}}_t$, and $\hat{\mathbf{i}}_n$ are the unit vectors in the radial, tangential, and normal directions, respectively. The unit vectors are defined as follows: $\hat{\mathbf{i}}_r$ is the radius unit vector, which always points from the Sun's center along the radius vector to the ECO; $\hat{\mathbf{i}}_n$ is the unit orbital angular momentum vector, which is fixed along the direction normal to the orbital plane; and $\hat{\mathbf{i}}_t$ is the tangential velocity direction unit vector, which is always perpendicular to the radius vector. Additionally, angle α is measured from the tangential velocity direction unit vector $\hat{\mathbf{i}}_t$ to the projected acceleration vector onto the instantaneous orbit plane, and angle β is measured from