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Asteroid rotation and orbit control via laser ablation

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Abstract

This paper presents an approach to control the rotational motion of an asteroid while a spacecraft is deflecting its trajectory through laser ablation. During the deflection, the proximity motion of the spacecraft is coupled with the orbital and rotational motion of the asteroid. The combination of the deflection acceleration, solar radiation pressure, gravity field and plume impingement will force the spacecraft to drift away from the asteroid. In turn, a variation of the motion of the spacecraft produces a change in the modulus and direction of the deflection action which modifies the rotational and orbital motion of the asteroid. An on-board state estimation and control algorithm is then presented that simultaneously provides an optimal proximity control and a control of the rotational motion of the asteroid. It will be shown that the simultaneous control of the rotational and proximity motions of asteroid and spacecraft has a significant impact on the required deflection time.

Keywords: Asteroid rotation control; Asteroid deflection; Proximity operation; Spacecraft control; Rotational dynamics

1. Introduction

Near Earth objects (NEOs) have been generating a growing scientific interest because, as primordial remnants of our solar system, they preserve precious information on its formation, composition and evolution. Besides, their collision with the early Earth would have influenced the shape and composition of our planet. Some NEOs are especially attractive targets for low-cost missions, because of their orbital accessibility with current technologies. This easy accessibility suggests the possibility to use them as source of raw materials and for the settlement of future human outposts (Seboldt et al., 2000). At the same time, NEO collisions with the Earth represent a possible threat to mankind. In particular, small size asteroids pose a concrete threat on the short term, with significant expected damages at regional level. Advances in orbit determination and theoretical studies on hazard characterisation have increased the capability of predicting potential impacts (Chapman and Morrison, 1994). The manipulation of asteroid, instead, still remains an open problem. Increasing our capabilities in asteroid orbit and attitude manipulation is therefore required, both for reducing the collision hazard and for future asteroid exploitation.

In the past two decades, different techniques for asteroid manipulation have been studied and compared; among them, surface ablation was shown to be theoretically one of the most promising methods (Sanchez et al., 2009). Ablation is achieved by irradiating the asteroid with a high intensity light source. Within the illuminated spot area, the absorbed energy increases the temperature of the asteroid, enabling it to sublimate. The ablated material then expands to form an ejecta plume. The resulting thrust induced by

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the ejecta plume pushes the asteroid away from its original trajectory.

In a recent study, supported by the European Space Agency (ESA), the Light Touch^2 concept was proposed as technology demonstrator to validate this concept (Vasile et al., 2013a). The main specifications of this study were to impart a minimum variation of velocity of 1 m/s over the course of one year operations to a small asteroid 2–4 m in diameter or equivalently 130 tons in mass, considering an average density of a silicate asteroid. Further constraints limited the target asteroid's orbital elements to have a perihelion larger than 0.7 AU, an aphelion smaller than 1.4 AU and an inclination smaller than 5°. Light Touch^2 employs a laser beam, focused on the surface of the asteroid, to generate a controllable thrust via surface ablation.

This paper presents an approach to control the rotational motion of an asteroid, while the spacecraft deflects the asteroid's trajectory through laser ablation.

During the deflection, the proximity motion of the spacecraft is coupled with the orbital and rotational motion of the asteroid. In fact, a change in the angular velocity of the asteroid induces a variation of the ablation rate that, in turns, affects both the orbital and rotational motion of the asteroid. At the same time a change in the ablation rate, orbital and rotational motion affects the proximity motion of the spacecraft as it changes the perturbations due to the impingement with the plume of gas, the gravity of the asteroid and the relative acceleration between asteroid and spacecraft. Since the spot size of the laser beam needs to be kept below an acceptable limit to guarantee constant ablation, the spacecraft needs to manoeuvre to maintain its relative distance under the effect of perturbations that are a function of the ablation process. Since, as shown in Sanchez et al. (2009) and Vasile et al. (2014), the lower is the angular velocity of the asteroid the higher is the thrust generated by the ablation process, the simultaneous control of both the spacecraft relative position and asteroid's angular velocity is paramount.

The asteroid is modelled as a tumbling ellipsoid with a random initial angular velocity vector and the characteristics of the reference asteroid used in the Light Touch^2 study. The rotational motion of the asteroid is then controlled by off-setting the thrust vector, induced by the laser, with respect to the centre of mass. The spacecraft proximity motion and the instantaneous rotational velocity of the asteroid are estimated through two filters: an augmented Unscented Kalman Filter that determines the spacecraft trajectory from optical and laser ranging measurements, and a batch filter which processes optical flow measurements from the camera to reconstruct the rotational velocity of the asteroid.

It will be shown that, through the proposed control method, the time required to achieve a given variation of velocity can be substantially decreased and the displacement of the asteroid from its nominal unperturbed orbit maximised.

This paper is organised as follows. Section 2 briefly introduces the thrust and contamination models. Then, Section 3 describes the spacecraft dynamics and control during proximity operations. Section 4 presents the asteroid rotational dynamics and the control to decrease the angular velocity. Section 5 focuses on the proximity and rotational motion reconstruction. Finally, Section 6 shows some results for the proposed mission scenario.

2. Ablation model

This section outlines the ablation model used to predict the torque and force acting on the asteroid and the spacecraft. A more complete description, including some experimental results can be found in Vasile et al. (2014, 2013a,b) and Gibbings et al. (2013).

The force acting on the asteroid F_L is given by the product of the velocity of the ejected gas $\bar{v}$ and the mass flow rate of the ablated material $\dot{m}$:

$$F_L = \lambda \bar{v} \dot{m} \tag{1}$$

where $\lambda = 0.88$ is a constant scatter factor used to account for the non-unidirectional expansion of the ejecta. The mass flow rate is given by the integral, over the area illuminated by the laser where ablation occurs, of the mass flow rate per unit area $\dot{\mu}$:

$$\dot{m} = 2V_{rot} \int_0^{y_{max}} \int_{t_{in}}^{t_{out}} \dot{\mu}\, dtdy \tag{2}$$

where V_{rot} is the speed at which the surface of the asteroid is moving under the spotlight, y_{max} is the maximum width of the spot. The time t_{in} identifies the point under the spotlight at which the ablation starts while t_{out} is the time at which a point of the surface moving with velocity V_{rot} exits from the spotlight. The assumptions are that locally the surface is flat and the spot is a circle, and that the temperature of a point under the spot light progressively increases but with negligible or no vaporisation till time t_{in}. In this case, an approximated solution for the temperature T after an exposure time t can be derived assuming that radiation loss Q_{rad} is small compared to the absorbed laser power per unit area P_{in} (see Anisimov and Khokhlov, 1995) and is given by:

$$T = \frac{2P_{in}}{\pi \kappa_A} \sqrt{\frac{\kappa_A t}{C_v \rho_A}} \tag{3}$$

From which one can estimate t_{in} as:

$$t_{in} = \frac{\pi^2}{4} \left(\frac{\sqrt{C_v \kappa_A \rho_A} T_S}{P_{in}} \right)^2 \tag{4}$$

The mass flow rate $\dot{\mu}$ per unit area is expressed as:

$$E_v^* \dot{\mu} = P_{in} - Q_{RAD} - Q_{COND} \tag{5}$$

where E_v^* is an augmented enthalpy of complete vaporisation, Q_{COND} the conduction and Q_{RAD} the radiation loss per unit area. The augmented enthalpy $E_v^* = E_v^*(T_0, T_S,$