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Advances in Space Research xxx (2018) xxx–xxx

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Advances in Space Research (a COSPAR publication)

www.elsevier.com/locate/asr

Formation of multiple landers for asteroid detumbling

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Received 18 January 2018; received in revised form 8 May 2018; accepted 8 May 2018

Abstract

This work develops a method for ascertaining the landing locations and thruster orientations of a formation of multiple spacecraft on an irregular asteroid for discrete time optimal detumbling control, as a prerequisite to asteroid redirection. Asteroid geometries are known to be extremely irregular, especially for small asteroids, which are the typical targets for redirection missions. The method entails the modelling of asteroids as convex polyhedra with triangular facets, and computing the mass and inertial properties through the divergence theorem and Green's theorem. Given the asteroid geometry, mass, and inertial properties, the feasible lander locations and thruster orientations are determined. The model ensures full attitude control of the asteroid, using multiple spacecraft with fixed-orientation, low-thrust modules, through measures imposed on the location and orientation of each thruster. A linear control scheme is employed to assess the time and fuel requirements of the asteroid detumbling maneuver, given feasible spacecraft formation configurations and thruster orientations. The method then assesses the detumbling time performance of each formation configuration to determine the discrete optimal landed formation configuration for a given asteroid. Simulations are performed to demonstrate the method using an irregular asteroid with characteristics derived from available asteroid data. Extensions of the method are further discussed in light of the results.

Keywords: Asteroid redirection; Detumbling; Landed formation design; Spacecraft formation

1. Introduction

Asteroid redirection and capture has been an opportunity on the horizon for many years, and has recently gained significant traction due to significant interest from the private sector and publicly funded space missions (Chesley et al., 2013; Tsuda et al., 2013). Researchers have proposed many creative and innovative approaches for redirecting and detumbling an asteroid, many of which require the landing of multiple spacecraft on the asteroid surface to complete detumbling and transfer maneuvers, e.g., mass ejectors (Olds et al., 2007), and landed thrusters (or "tugboats") (Sanchez and McInnes, 2012; Schweickart et al., 2006). Amongst these methods, the most promising approaches are those considering configurations of landed low-thrust spacecraft (Bazzocchi and Emami, 2016). The landed thruster configurations tend to fall into two main approaches, landed thrusters that are positioned on an asteroid's primary spin axis (Schweickart et al., 2006), or thrusters positioned equatorially on the asteroid surface (Sanchez and McInnes, 2012). In the first approach, the thruster must first align the asteroid's spin axis with the redirection vector of the transfer maneuver, and then must apply a continuous thrusting force. However, in this case, if the asteroid is not in a primary axis rotation, the thruster action required to control the asteroid's spin rate and subsequently realign the spin axis may not be feasible. In the second approach, the transfer maneuver is accomplished by intermittently firing the thrusters as they align with the redirection vector. In this approach, if the asteroid is

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https://doi.org/10.1016/j.asr.2018.05.011
0273-1177/

Please cite this article in press as: Bazzocchi, M.C.F., Emami, M.R. Formation of multiple landers for asteroid detumbling. Adv. Space Res. (2018), https://doi.org/10.1016/j.asr.2018.05.011

tumbling, with a large configuration the redirection maneuver can still be accomplished; albeit somewhat inefficiently. It should be further noted, that these approaches tend to assume simplistic asteroid landed configurations, such as, two antipodal thrusters, or equally spaced thrusters about the equator (Bazzocchi and Emami, 2017). Similarly, the asteroid bodies considered tend to be spherical or ellipsoidal, which allow for the spacecraft configurations to be easily distributed over the surface. While these configurations provide the basis for assessing the feasibility of asteroid low-thrust transfers, they fail to adequately consider the complexity of realistic asteroid geometries and tumbling rates. In practice, small near-Earth asteroids (NEAs) tend to be of irregular geometry, that is, not necessarily spherical or ellipsoidal. Moreover, these asteroids are often rotating or tumbling at higher rates than larger NEAs (Pravec et al., 2008). As such, it is often more efficient for asteroid redirection missions to be divided into two phases, first, detumbling, and second, orbital transfer (Vetrisano et al., 2016). This work considers a redirection mission that employs five landed thrusters and a mothership. First, the mothership deploys four thruster spacecraft to detumble the asteroid, and then once the asteroid is detumbled, the fifth spacecraft is deployed and the attitude of the asteroid is aligned to the redirection thrust vector throughout the transfer. Since the redirection of the asteroid and thrust directions have been studied in previous works for orbital transfer (Bazzocchi et al., 2017), this work focuses on the necessary perquisite of efficiently detumbling the asteroid using the landed four spacecraft formation.

The method developed in this work systematically determines the discrete time-optimal spacecraft formation landing locations and thruster orientations for detumbling of an asteroid with irregular geometry and unique angular velocities. The method utilizes a triangularly faceted convex polyhedral model to create a practical representation of the target asteroid. The polyhedral model is subsequently assessed to determine its total mass, centre of mass, and inertial properties. The potential landing locations on the asteroid model are determined and a set of feasible thrust orientations are proposed, such that they comply with spacecraft and thruster limitations, as well as ensure non-intersection of the thrust lines with the asteroid surface. The feasible spacecraft configurations and thrust orientations are then combined to create sets under strict controllability conditions for full attitude control. The performance of each of the resulting combinations is assessed through a closed-loop servo control scheme and the time-optimal configuration is determined. It is important to note that the best performing configuration is not necessarily the optimal configuration for a given asteroid, but rather, a discrete optimal solution determined from a finite set of lander locations and orientations found through an exhaustive search. This work begins by outlining the details of the proposed method (Section 2). Subsequently, specifications for the simulations used to validate the method are introduced (Section 3), and the results of the simulation are shown and discussed along with further extensions to the work (Section 4). Lastly, some concluding remarks are presented (Section 5).

2. Method

This section outlines the method developed in this work for determining landing locations of a spacecraft formation on an irregular asteroid for attitude control. The presentation of the method is partitioned into five subsections in order to facilitate comprehension of its various components; namely, the subsections are asteroid modelling, thruster locations and orientations, control allocation, detumbling control, and performance measures.

2.1. Asteroid modelling

The modelling of the asteroid is divided into two main aspects, namely, approximating the geometry, and determining the mass properties. As mentioned previously, asteroid geometries tend to be quite irregular and as such, the placement of specific thrusters and spacecraft may not be intuitive. Asteroids tend to be modelled in three-dimensions through three different techniques, i.e., light-curve inversion (Kaasalainen and Torppa, 2001), radar imaging (Hudson, 1994), and spacecraft imaging (Fujiwara et al., 2006). Typically, through using one or more of these techniques a three-dimensional model of a target asteroid can be established; with the resolution dependent on the quality and quantity of the available data. A common representation structure for these three-dimensional models is a triangular faceted polyhedron (Viikinkoski et al., 2015). Fig. 1 provides an example of an asteroid modelled using triangular facets. These polyhedra are usually defined in cartesian coordinates by a series of vertices on the asteroid surface which are subsequently connected through the use of triangular surface facets. In

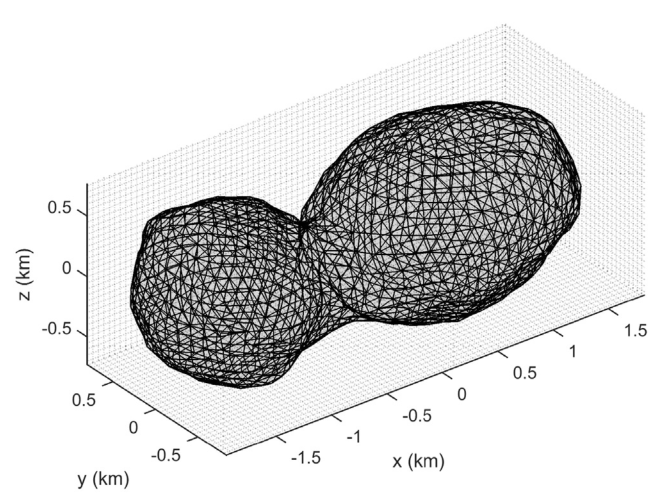

Fig. 1. Asteroid (8567) 1996 HW1 shape model determined from optical data (Hanus et al., 2016).