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The optimal control for the tethered system formed by an asteroid and a solar sail

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Abstract

This paper focuses on a method of changing the orbit of an asteroid by attaching a solar sail to the asteroid. First, the dynamic model of the tethered system is derived. Legendre pseudospectral method is then used to discretize the system, and the sequence of two quadratic programming is utilized to obtain the optimal control law. Simulation results show that the tethered solar sail can efficiently change the asteroid's orbit. Moreover, the problem of the tether twining around the asteroid caused by the relative orbit motion between the solar sail and the asteroid can be avoided. Finally, the effectiveness of altering an asteroid's orbit by different solar sails is analyzed. Simulation results show that when the area of the solar sail is 10^6 m^2, the asteroid can be deflected at 1.227×10^8 m by the solar sail after about 20 years, which is better than the effect of a gravitational tractor.

Keywords: Solar sail; Asteroid; Tethered system; Legendre pseudospectral method; Optimal control

1. Introduction

The impact of near-Earth asteroids into the Earth demonstrates a small probability, but the possibility cannot be ignored. Many countries and institutions have taken active measures, and various methods have been proposed to defend against these dangerous asteroids (Koschny and Drolshagen, 2015). According to the defense results, these methods can be divided into two categories. One is destroying the asteroid or splitting it into smaller bodies, whereas the other is changing the orbits of the asteroids. The first method refers to nuclear explosion. A nuclear device is placed in the internal or surface of the asteroid and then triggered. The asteroid will then be divided into two parts or more, and the orbits of the small parts will be deflected (Ahrens and Harris, 1994; Holsapple, 2004). However, these small parts may not be completely harmless to the Earth. Even if the objects split from the asteroid are small enough, the important information about the origin and evolution of the solar system carried by the asteroid is destroyed simultaneously. Alternatively, the second method includes several ways to slowly change the asteroid's orbit, such as active collision, mass drivers, gasification promotion, Yarkovsky effect and gravitational tractors.

The concept of deflecting the orbit of an asteroid with the aid of a mass driver was first proposed by Snively and O'Neill (1983). Olds et al. (2007) suggested that the midget modular mass drivers are more suitable for dealing with the complexity of the task. McInnes (2004) and Dachwald et al. (2007) considered the use of a near-term solar sail to deliver an inert projectile onto a retrograde solar orbit to impact the asteroid. Zeng et al. (2011) suggested hitting the asteroid by a solar sail in a double H-reversal trajectory directly. Gong et al. analyzed the characteristics of altering an asteroid's trajectory by a collision with a solar sail running in an H-reversal trajectory (Gong et al., 2009, 2011). The counter force produced by

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the material gasification reaction can divert the asteroid from its original orbit (Campbell et al., 2002). Hughes et al. (2013) adopted the gasification promotion theory to introduce a planetary sighting system designed to manage planet threats. Spitale (2002) proposed a method to avoid the asteroid threat based on the Yarkovsky effect. Sasi and Visakh (2009) presented a method to deflect the asteroid from a gravitational keyhole by influencing the Yarkovsky effect with magnetic field. Lu and Love (2005) described the concept of gravitational tractor. The gravity between an asteroid and a spacecraft hovering around it can be used to change the asteroid's orbit. NASA's jet propulsion laboratory discussed the prevention of the asteroid into a gravitational keyhole with a gravitational tractor of 1000 kg (Yeomans et al., 2008). Gong et al. (2009) studied the control problem of gravitational tractors, in which their formations flew in a hover orbit. Gong and Li (2015) also proposed an approach enabling the capture of an asteroid by using the lunar flyby.

For the second method mentioned in the preceding paragraphs, a temporary change of the asteroid's orbit can only be ensured. French and Mazzoleni (2009), as well as Mashayekhi and Misra (2014) studied the attachment of a long tether and ballast mass to change the asteroid's orbit. A parametric study was conducted to determine the degree to which the trajectory of an asteroid or comet can be altered by attaching a tether and ballast. However, the present study does not include the control problem. The tether winding problem caused by the relative orbit motion between the ballast mass and the asteroid is also not considered.

Merikallio and Janhunen (2010) proposed the idea of attaching an electric solar wind sail to an asteroid to move it. This idea is explored further in the current study by constituting a tethered system with a traditional solar sail. The asteroid's orbit will be changed by the force generated from the tethered solar sail. As such, the threat of asteroids to the Earth can be mitigated. Meanwhile, the structure and composition of asteroids will not be destroyed. Furthermore, Earth-threatening asteroids can be controlled to run in an expected state on a designed orbit and in a more economical way.

First, the dynamic model of the tethered system formed by an asteroid and a solar sail (TSASS) is established. The solution of the open-loop optimal control law and state constraints is then studied by adopting the nonlinear optimal control theory. The method is verified and analyzed by simulation. The results show that the TSASS can effectively control the asteroid and tow it to an appropriate destination.

2. The dynamic model

2.1. The dynamic model of the tethered system

The TSASS consists of a solar sail and an asteroid, which are both connected by a tether. This system is illustrated in Fig. 1. The solar sail and the asteroid are regarded as mass points in the modeling process. The mass and elasticity of the tether are also ignored. Due to the small mass of the solar sail, the gravity between the solar sail and the asteroid is also ignored.

The forces on the asteroid and solar sail are illustrated in Fig. 2. The dynamical equations of motion for a tethered system are expressed as follows (French and Mazzoleni, 2009):

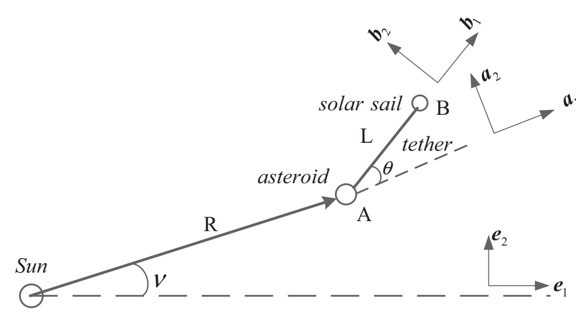

Fig. 1. Diagram of the TSASS.

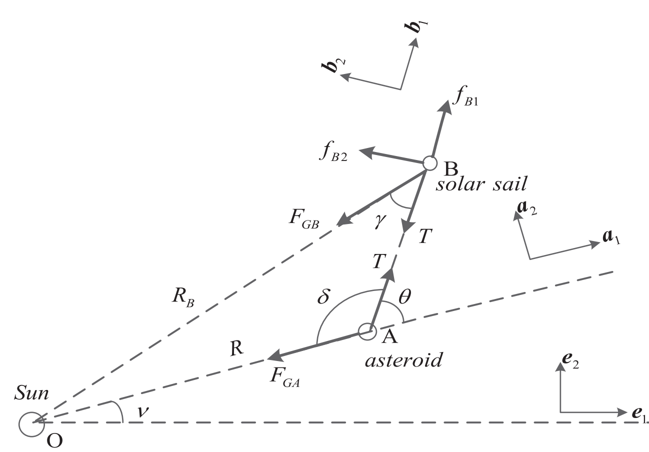

Fig. 2. Diagram of system forces.

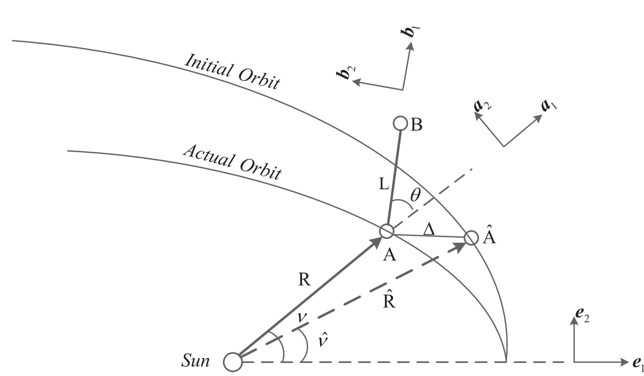

Fig. 3. Diagram of deflection distance.