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Rapid design and optimization of low-thrust rendezvous/interception trajectory for asteroid deflection missions

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Abstract

Asteroid deflection techniques are essential in order to protect the Earth from catastrophic impacts by hazardous asteroids. Rapid design and optimization of low-thrust rendezvous/interception trajectories is considered as one of the key technologies to successfully deflect potentially hazardous asteroids. In this paper, we address a general framework for the rapid design and optimization of low-thrust rendezvous/interception trajectories for future asteroid deflection missions. The design and optimization process includes three closely associated steps. Firstly, shape-based approaches and genetic algorithm (GA) are adopted to perform preliminary design, which provides a reasonable initial guess for subsequent accurate optimization. Secondly, Radau pseudospectral method is utilized to transcribe the low-thrust trajectory optimization problem into a discrete nonlinear programming (NLP) problem. Finally, sequential quadratic programming (SQP) is used to efficiently solve the nonlinear programming problem and obtain the optimal low-thrust rendezvous/interception trajectories. The rapid design and optimization algorithms developed in this paper are validated by three simulation cases with different performance indexes and boundary constraints.

Keywords: Asteroid deflection; Low-thrust trajectory optimization; Shape based approaches; Radau pseudospectral method

1. Introduction

Near-Earth Asteroids (NEAs) represent both opportunities and risks for mankind. Asteroids are considered to be the most primitive residue in the solar system with unique geological structures and physical properties that can provide us with important information about the early information of the Solar system. It is significantly important to explore various asteroids, which helps humans understand the origin and evolution of the solar system, and uncover the origin of life. Asteroids can also be utilized as the resource base of mankind to perform further deep-space exploration (Radovich et al., 1992). At the same time, numerous Earth-crossing asteroids pose a huge potential threat to human being (Ivan, 2009). It is well documented from geological records that the Earth has been struck by NEAs many times throughout its history. The largest one of these impacts happened 65 million years ago and resulted in the disappearance of the dinosaurs and mass life extinctions. The spectacular collision of the Shoemaker–Levy 9 asteroid with Jupiter in July 1994 was a dramatic reminder that the Earth has also experienced and will continue to experience such catastrophic events. To date, there are nearly 9,000 known near-Earth asteroids, and approximately 1,000 of them were discovered in the last year. Considering the number of known NEAs and their current discovery rate, it is inevitable that we will stumble upon many small bodies that pass very close to Earth, and even some that might be on impact trajectories

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toward Earth (Ivan, 2009; Matloff, 2012; Grebow et al., 2011). If an asteroid is discovered to be on an impact trajectory, it is imperative that we develop tested and reliable technologies for deflecting the asteroid's course safely away from Earth (Smith et al., 2004).

The issue of asteroid threat and deflection has aroused widespread concern since the 1990s. Scientists, engineers and space agencies around the world have discussed and developed various strategies and methods to alter the path of an asteroid in a collision trajectory with the Earth. Generally speaking, the proposed deflection methods in the literature mainly fall into two categories, kinetic deflection methods and low-thrust deflection methods (Ivan, 2009; Matloff, 2012). Kinetic impactor and nuclear interceptor are considered part of the kinetic deflection methods. On the other hand, gravity tractor, laser ablation, low-thrust propulsion, solar collector and mass driver can be classified as low-thrust deflection methods (Wie, 2005; Gennery, 2004; Lu and Love, 2005; Wie, 2008; Vasile and Maddock, 2012; Scheeres and Schweickart, 2004; Matloff, 2013). Because potentially hazardous asteroids have significantly different physical characteristics, elements and sizes, none of the deflection methods mentioned above is suitable for effectively deflecting all kinds of dangerous asteroids heading towards Earth, and the exact methods adopted will vary depending on the type of asteroid that is targeted (Ivan, 2009; Matloff, 2012). For example, some asteroids, known as rubble piles, are composed of rocks and ice. A spacecraft with a relative velocity of about 60 km/s would impart a kinetic energy of 1.8 billion Joules per kilogram and could fragment these kind of asteroids, which might just make things worse (Matloff, 2012). In this case, the low-thrust deflection methods can be utilized to gradually alter the orbit of a hazardous asteroid without fragmentation.

All complete asteroid deflection missions should include the following two consecutive phases: rendezvous or interception phase and deflection phase. There are a lot of published papers in the area of asteroid deflection techniques and missions, but most of them are focused on deflection strategies and mitigation effectiveness analysis (Gennery, 2004; Lu and Love, 2005; Wie, 2008; Vasile and Maddock, 2012; Scheeres and Schweickart, 2004; Matloff, 2013; Sanchez et al., 2009; Vasile and Colombo, 2008; Park and Mazanek, 2003; Holsapple, 2004; Sanchez, 2009; Colombo et al., 2009). Little attention has been paid on the rapid design and optimization of the low-thrust rendezvous/interception trajectory for potentially hazardous asteroid deflection, which is considered as a prerequisite for successfully implementing the following asteroid deflection operations. Conway successfully solved the problem of minimum-time low-thrust trajectories for the interception of Earth-approaching asteroids by virtue of collocation and nonlinear programming. The use of low-thrust propulsion after Earth escape is shown to dramatically decrease the mass of the interceptor vehicle at launch (Conway, 1997). Park and Choi presented the optimal trajectories that intercept and rendezvous with Earth-crossing objects (ECO) by using an advanced magneto-plasma spacecraft with variable low-thrust capability. They used an indirect optimization method for the mitigation trajectories. For various types of ECO, the characteristics of the intercept and rendezvous trajectories are analyzed with respect to spacecraft departure time before collisions (Park and Choi, 2005). Based on differential dynamic programming, Colombo addressed the optimization problem of rendezvous and fly-by trajectories to near-Earth objects. Differential dynamic programming is a successive approximation technique that computes a feedback control law in correspondence of a fixed number of decision times. In this way, the high dimensional problem characteristic of low-thrust optimization is reduced into several small dimensional problems (Colombo et al., 2009). Mengali and Quarta investigated the solar-sail-based rendezvous trajectories toward asteroid 99942 Apophis. They showed that a realistic near-term mission option, with a transfer time of about 300 days, requires a solar sail with a characteristic acceleration of 0.5 mm/s^2 (Mengali and Quarta, 2009).

The rapid design and optimization of low-thrust rendezvous/interception trajectories for asteroid deflection missions has always been a challenging task. In fact, the design of low-thrust rendezvous or interception trajectories generally requires the solution of an optimal control problem, which has no general closed form solution. At the same time, different deflection strategies correspond to apparently different performance indexes and boundary constraints. The aim of this paper is to develop a general framework for rapid design and optimization of the low-thrust rendezvous/interception trajectory for future asteroid deflection missions, which can be widely applied to various deflection missions with least modification. The flowchart of the general framework proposed in this paper is depicted in Fig. 1. The integrated design and optimization process involves the closely associated three steps. Firstly, shape-based approaches, in combination with genetic algorithm (GA), are adopted to perform preliminary design, which provides a suitable initial guess for subsequent accurate optimization. Secondly, Radau pseudospectral method is utilized to transcribe the low-thrust trajectory optimization problem into a discrete nonlinear programming problem, which be easily solved by the well-developed nonlinear optimization (NLP) algorithms. Finally, sequential quadratic programming (SQP) is used to solve the nonlinear programming problem, and obtain the optimal low-thrust rendezvous and interception trajectories.

The rest of this paper is organized as follows. Section 2 presents the low-thrust dynamic model, various performance indexes, and boundary constraints. Section 3 briefly describes the two popular preliminary design methods of low-thrust trajectories, the 6th inverse polynomial and the exponential sinusoid. Radau Pseudospectral Method based accurate optimization design of low-thrust trajectories is defined in Section 4. In Section 5, three simulation