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Comparative analysis of redirection methods for asteroid resource exploitation

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ABSTRACT

An in-depth analysis and systematic comparison of asteroid redirection methods are performed within a resource exploitation framework using different assessment mechanisms. Through this framework, mission objectives and constraints are specified for the redirection of an asteroid from a near-Earth orbit to a stable orbit in the Earth–Moon system. The paper provides a detailed investigation of five redirection methods, i.e., ion beam, tugboat, gravity tractor, laser sublimation, and mass ejector, with respect to their capabilities for a redirection mission. A set of mission level criteria are utilized to assess the performance of each redirection method, and the means of assigning attributes to each criterion is discussed in detail. In addition, the uncertainty in physical characteristics of the asteroid population is quantified through the use of Monte Carlo analysis. The Monte Carlo simulation provides insight into the performance robustness of the redirection methods with respect to the targeted asteroid range. Lastly, the attributes for each redirection method are aggregated using three different multicriteria assessment approaches, i.e., the Analytical Hierarchy Process, a utility-based approach, and a fuzzy aggregation mechanism. The results of each assessment approach as well as recommendations for further studies are discussed in detail.

1. Introduction

Asteroids are small celestial bodies that have great potentials to provide insight into the nature of the early solar system, expedite human space activities, as well as cause incredible devastation to Earth through an impact. The incentives for investigating asteroids are numerous and varied, and both the public and private sectors have recently taken interest. In particular, NASA currently has three programs focused on asteroids: OSIRIS-REx, [1] Robotic Asteroid Prospector [2] and the Asteroid Redirect Mission [3]. Further, JAXA's Hayabusa mission to collect samples from Itokawa [4] as well as ESA's Rosetta mission to explore 67P/Churyumov–Gerasimenko [5] were historical steps towards the ultimate goal of exploiting and utilizing resources of celestial bodies in our solar system. Moreover, several private corporations are seeking means to profitably exploit asteroid resources [6]. Now, more than ever, a systematic assessment of asteroid redirection methods is of value, particularly with respect to resource exploitation.

The vast majority of current research into asteroids investigates the deflection of large asteroids over long time periods. Contrastingly, this paper focuses on the redirection of asteroids from a near-Earth orbit, i.e., orbits with a perihelion distance less than 1.3 Astronomical Unit (AU), to a stable and easily accessible orbit in the Earth–Moon system (EMS) for the purpose of resource exploitation. This work will investigate methods primarily studied for

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asteroid deflection within the context of a redirection and exploitation framework, and will expand upon previous work in [7]. The following sections outline the major mission constraints, the assessment criteria, the redirection methods considered, and the selected assessment approaches. Lastly, the performance of each redirection method with regard to the various criteria and assessment approaches will be discussed in detail in light of the quantified results.

2. Problem formulation

The scope of an asteroid redirection mission for resource exploitation provides clear constraints on both the target range of asteroids and on the employable redirection methods. In particular, the asteroid population considered will be constrained with respect to taxonomic type, density, capture delta-v, diameter, and spin rate. Since the goal is to redirect the asteroid for resource exploitation, the target asteroids will be restricted to the most suitable taxonomic types, i.e., carbonaceous (C-Type) and metallic (M-Type) asteroids. C-Type asteroids contain volatile materials useful for the production of propellants and supporting life support systems. Moreover, M-Type asteroids contain high concentrations of metals for in-situ construction. Given the taxonomic types, the range of asteroid densities considered reflect a Gaussian distribution about the calculated average densities for each type, namely, 1380 kg/m^3 and 5320 kg/m^3 for C-Type and M-Type asteroid, respectively [8]. The asteroid diameters are also constrained to a range of small to medium size asteroids between 20 m and 150 m in diameter. The upper limit is set to represent the largest diameter considered safe with regard to planetary protection. In particular, a near-Earth asteroid (NEA) with a diameter greater than 150 m and a minimum orbital intersection distance less than 0.05 AU is termed a potentially hazardous object (PHO) [9]. Moreover, the lower limit of 20 m represents a bound for the smallest asteroids considered economically valuable, and also eliminates the prospect of utilizing envelopment redirection methods that are viable for very small diameter asteroids [2,10]. The spin rate of the asteroids is also of particular importance for asteroid redirection, and is seen to have considerable variability especially with regard to small asteroids [11]. The spin rate has also been shown to be related to asteroid diameter [11], and as a result, will be constrained relative to the selected diameter according to a relation described in Section 3.1.

The redirection methods considered are also constrained with regard to number of spacecraft, system mass, system volume, timeframe for redirection, and Technology Readiness Level (TRL) in order to ensure their viability for a redirection mission and to provide a valid baseline for comparison. Although several redirection methods have been considered with respect to formation design [12], this assessment focuses on the simplest practical spacecraft configuration for each method, namely consisting of one or two spacecraft systems. The maximum mass and volume for the system will also be constrained to the payload specifications of an Atlas V launch vehicle. Each redirection method will have a system mass less than 6800 kg and stowed system volume less than a payload envelope of 4.572 m in diameter and 12.192 m in length [13]. The redirection timeframe will also be constrained to 4 years from rendezvous to capture in order to ensure economic feasibility [14]. Lastly, the redirection method will have a minimum of TRL 2, i.e. “Technology concept and/or application formulated” [15]. The restriction of the Technology Readiness Level guarantees the redirection methods considered have been sufficiently researched, such that attributes can be readily assigned to the assessment criteria.

In addition, the mission design assumes a simple circular capture orbit, and focuses on the redirection methods applicability from rendezvous to capture. It should be noted that this work considers monolithic asteroids, and does not study rubble-pile or highly porous asteroid structures. Lastly, since the orbital paths of the target asteroids are intersecting or closely approaching the Earth's orbit, the Earth's orbital path is taken as a reference for defining the environmental constraints. The environmental constraints imposed on the asteroids and redirection techniques are standard values, and as such all redirection methods are assumed to satisfy these constraints.

3. Assessment criteria

The assessment criteria represent a combination of standard mission parameters and criteria specific to an asteroid redirection mission. The criteria are defined in Table 1, and a detailed methodology for each criterion is provided in the subsequent sections. It is important to note that mass and volume have been omitted from the assessment criteria. As it will be seen in Section 4, all the redirection methods benefit from maximizing the system mass to the constrained upper bound, and as a result comparing the mass would be inconsequential. Further, since the mass is maximized, there is very little value in comparing system volume. The advantage of a smaller stowed configuration would normally imply additional payload capacity; however, in this case payload limits have already been reached. The selected criteria are most valuable in assessing an asteroid redirection mission from the perspective of economic viability and performance efficacy.

A discussion of the method for assigning attributes to each criterion is discussed for delta-v, performance robustness, asteroid alteration, system cost, technology readiness and risk, mission risk, and long-term value. The average required power will be determined directly from the redirection method specifications in Section 4.

3.1. Delta-v, performance robustness and asteroid alteration

The delta-v for each redirection method is determined through the method's specific formulae that will be presented in Section 4. The formulae for calculating delta-v are included in the Monte Carlo simulation, since they are