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OPTIMAL DESIGN OF KINETIC ENERGY IMPACT ASTEROID ORBIT BASED ON MULTIPLE SPACECRAFT

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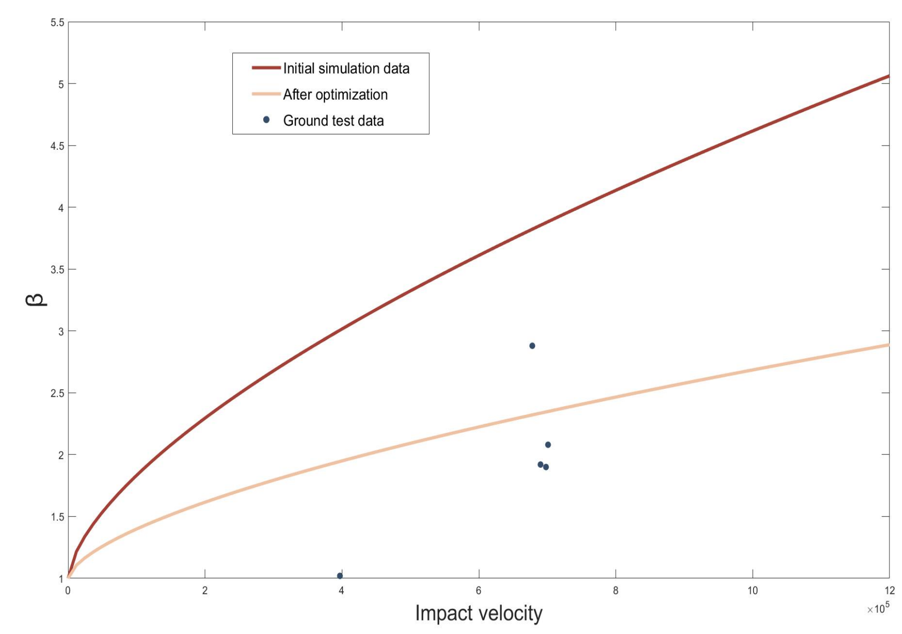
1.Introduction

Among all asteroid defense methods, the kinetic energy impact technology has the highest maturity, which is the only asteroid defense method that has been actually used. The Deep Impact mission conducted by NASA in 2005 facilitated the use of this technology to understand the internal structure and composition of comets, and the Dart mission in 2022 is to demonstrate the technology's effectiveness, which involves deflecting an asteroid (Dimorphs) off its course by colliding with it at approximately 6.2km/s. However, the impact to Dimorphs can only bring a speed change of approximately 0.4 millimeters per second. In future planetary defense missions, such a small speed change may not be sufficient to withstand asteroid threats. Therefore, this paper first studies the impact model based on momentum enhancement factor β and the optimal Kinetic-Impact Geometry method so as to analyze the impact of the ejectors generated by the collision on the amount of velocity change and the effect of planetary deflection. In addition, this paper proposes a multi spacecraft interception trajectory optimization strategy based on the kinetic energy impact method, and takes Apophis as an example to demonstrate the effectiveness of this strategy.

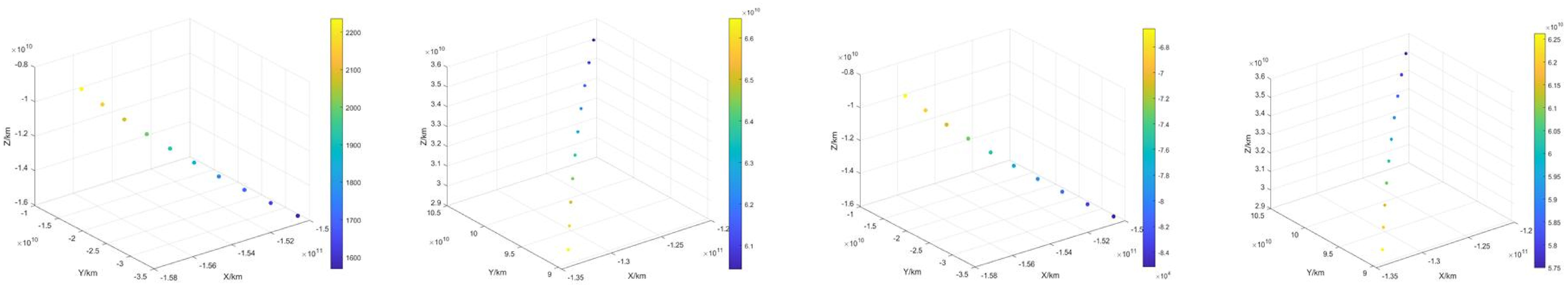
2.Impact Model

The concept of β, a measure of momentum transfer efficiency in kinetic impact scenarios, was first proposed by Housen and Holsapple in 2011. Their work included a groundbreaking sputtering scaling law theory, which leveraged point source theory and dimensionless analysis to provide a detailed theoretical description of the mass, velocity, and position distribution of sputtering objects.[14] Building on this foundation, Holsapple further refined the calculation method for β in 2012, focusing specifically on the impact of small celestial bodies. This work helped to shed light on the complex interactions that occur during kinetic impact scenarios, and has proven invaluable for designing and planning future missions in this area. Our team has estimated β of an M-type asteroid with a diameter of about 100 meters based on ground tests and numerical simulation experiments. The preliminary findings of the momentum enhancement curve for M-type asteroids, as derived from fitting analyses, are presented as follows:

$$\beta = 1 + (5.374 \times 10^{-4})U^{0.638}, initial\ data\ fitting$$
$$\beta = 1 + (2.955 \times 10^{-4})U^{0.626}, after\ optimization$$



Relationship between β obtained from simulation test and impact velocity

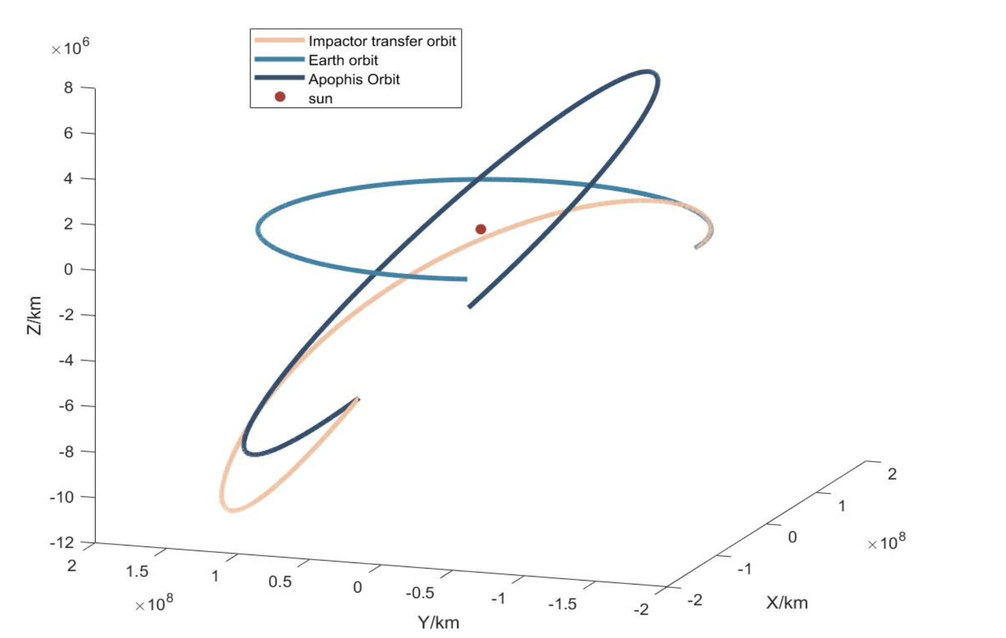


Offset distance increase on April 10, 2029 and May 5, 2036 under two interception schemes single spacecraft and multiple spacecrafts

3. Orbit Design for Multiple Spacecraft Interception

Given the launch time, transfer time, and the time of collision or closest approach between the asteroid and Earth, the velocity change Δv required by the spacecraft to deflect the asteroid can be calculated using the impact model, which yields the absolute velocity range at which the spacecraft will intercept the asteroid. When determining the transfer time and terminal velocity of a designated spacecraft, minimizing fuel consumption leads to a higher residual mass, greater momentum, and improved deflection effect. Therefore, the orbit optimization problem with maximum momentum at collision is thus reduced to an optimization problem of minimizing the spacecraft's fuel consumption subject to special constraints and fixed time intervals.

Programming simulation based on the above ideas.The results of numerical simulation test show that the multi spacecraft interception strategy can greatly improve the asteroid deflection effect when the warning time is short. Under the impact of 25 spacecraft, the orbital offset increased by about 31 times in April 2029.In the case of short warning time and large target asteroid size, implementing the multi spacecraft interception strategy can more effectively protect the Earth's homeland.



Three-dimensional diagram of interception and transfer trajectory of Apophis