

PDC
2021

Terminal guidance of small body impact using velocity increment corridor

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1. Introduction

With the deepening of human's observation and research on small near-Earth objects, the potential threat of small bodies impacting the Earth has received a large amount of attention, and planetary defense technology is under extensive discussion. With NASA's DART mission^[1] being around the corner years after the Deep Impact mission implemented successfully^[2], the kinetic impact scheme has become one of the main ideas in the defense of hazard near-Earth small bodies. Due to the limitation of rockets' carrying capacity, the kinetic impactor useable at present is relatively small in mass which cannot generate enough kinetic energy during the impact, resulting in a weak influence on the orbit state of the hazard small body.

In order to increase the impact kinetic energy, Marcus et al. designed a small body guided impact scheme, planning to capture a small near-Earth asteroid(α), and guide it to the target asteroid(β) for impact^[3]. However, the impactor with thousands of tons in mass has brought great challenges to the guidance and control system. In addition, because the target asteroid has a small volume with a diameter of only 100~200m, the terminal guidance needs to possess high precision. At present, the terminal guidance scheme for small body impact missions generally adopts prediction-correction guidance. Zhu et al. designed a high-speed impact GNC system based on the prediction-correction guidance, and studied the relationship between the maneuver time and fuel consumption with the impact accuracy^[4]. Zhu et al. also designed a predictive guidance law based on line of sight information. The impact deviation was controlled within 250m^[5]. Bhaskara et al. used prediction-correction guidance on the basis of autonomous optical navigation to simulate the impact of a small body with a diameter of 500m, and obtained extremely high hit rate^[6]. However, the terminal guidance performance has not been analyzed for the situation that the target small body is less than 200m in diameter and the impactor has a total mass greater than 10³kg.

In this paper, a predictive guidance scheme for real-time adjustment of maneuvering time and number was designed to improve the accuracy of impact. The Monte Carlo simulation shows that, with a specific impactor mass, this scheme can increase the hit rate from less than 80% to over 95%.

2. Dynamics

The impact dynamics is defined in the body plane (B-plane) coordinate system of the target small body, with its origin located at the center of mass. The B-plane is perpendicular to the impactor's approaching super-velocity V_∞ , which is align with the S-axis. The R-axis and T-axis are both within the B-plane. As is shown in Fig 1.

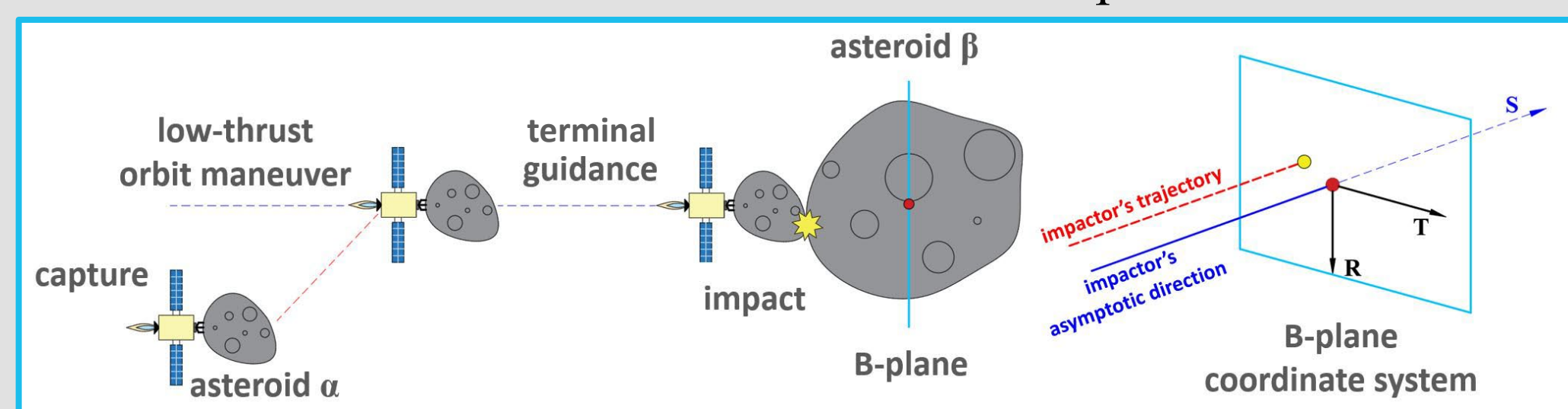


Fig 1. Guided impacting scheme and B-plane coordinate system

The multi-body dynamical equation is expressed as follows.

$$\ddot{\mathbf{r}} = -\frac{\mu}{|\mathbf{r}|^3} \mathbf{r} - \sum_i \mu_i \left(\frac{\mathbf{r} - \mathbf{s}_i}{|\mathbf{r} - \mathbf{s}_i|^3} + \frac{\mathbf{s}_i}{|\mathbf{s}_i|^3} \right) + P \frac{A}{m} \frac{\mathbf{r} - \mathbf{s}_{\text{sun}}}{|\mathbf{r} - \mathbf{s}_{\text{sun}}|^3} + \frac{\mathbf{F}}{m} + \mathbf{n}$$

where \mathbf{r} is the impactor's position vector, m is the impactor's mass, μ represents the gravitational coefficient of the target small body, \mathbf{s}_i and μ_i are position and gravitational coefficient of other celestial bodies, P is the coefficient of sunlight pressure, A is the impactor's effective illuminated area, and \mathbf{F} is the control acceleration, \mathbf{n} is unmodeled disturbance.

3. Velocity increment guidance

Define the impactor's state vector as $\mathbf{X} = [r_s, r_T, r_R, v_s, v_T, v_R]^T$, which are the position and velocity in three axis. The dynamical equation can be rewritten as $\dot{\mathbf{X}} = f(\mathbf{X})$. Denote the real state as \mathbf{X}_n , the corrected state as \mathbf{X}_c , and $\Delta \mathbf{X} = \mathbf{X}_c - \mathbf{X}_n$. Then the deviation dynamics can be linearized as follows.

$$\Delta \dot{\mathbf{X}} = \mathbf{A} \Delta \mathbf{X}, \quad \mathbf{A} = \left. \frac{\partial f}{\partial \mathbf{X}} \right|_{\mathbf{X}=\mathbf{X}_n}$$

Recurse the formula to the terminal moment, it can be obtained that $\Delta \mathbf{X}_f = \Phi \Delta \mathbf{X}_0$, where $\dot{\Phi} = \mathbf{A} \Phi$, $\Phi(0) = \mathbf{I}_{6 \times 6}$, therefore the deviation of final state can be obtained by the present deviation.

$$\Delta \mathbf{r}_f = \Phi(1:3,1:3) \Delta \mathbf{r}_0 + \Phi(1:3,4:6) \Delta \mathbf{v}_0$$

where $\Delta \mathbf{r}$ is the impactor's deviation of position, $\Delta \mathbf{v}$ is the deviation of velocity, subscript f represents the final time, and subscript 0 represents the current moment. Because of the continuity of position vector, $\Delta \mathbf{r}_0$ equals 0. In order to realize the correction of final position $\Delta \mathbf{r}_f$, the current velocity increment should be

$$\Delta \mathbf{v}_0 = \Phi(1:3,4:6)^{-1} \Delta \mathbf{r}_f$$

Since the velocity correction maneuver will cause change to the initial state, the recursive should be performed repeatedly for the state after the maneuver until the predicted impact accuracy meets the requirement, and obtain the total velocity increment. To determine the timing and number of correction maneuvers, define the remaining time before impact as t_{go} , which can be approximated by the ratio of the impactor's position and velocity in S-axis $|r_s|/|v_s|$, the maximum velocity increment the engine can provide should be $\Delta v_{\text{max}} = t_{go} \cdot |F|/m$. Assuming that the current maneuver that should be applied is Δv_{real} . To ensure the impactor's state be within the controllable range, the predicted velocity increment should always be smaller than the maximum increment. Therefore, the startup criteria of the correction maneuver should be set as

$$\Delta v_{\text{real}} > \eta \Delta v_{\text{max}}$$

Where $0 < \eta < 1$ is the redundancy factor, and $\eta \Delta v_{\text{max}}$ is recorded as the alert velocity increment.

In the terminal guidance stage, Δv_{real} is estimated in a high frequency. When it exceeds the alert velocity increment, maneuver will be carried out. Then the state vector is controlled within a corridor formed by maximum and alert increment, as is shown in Fig 2.

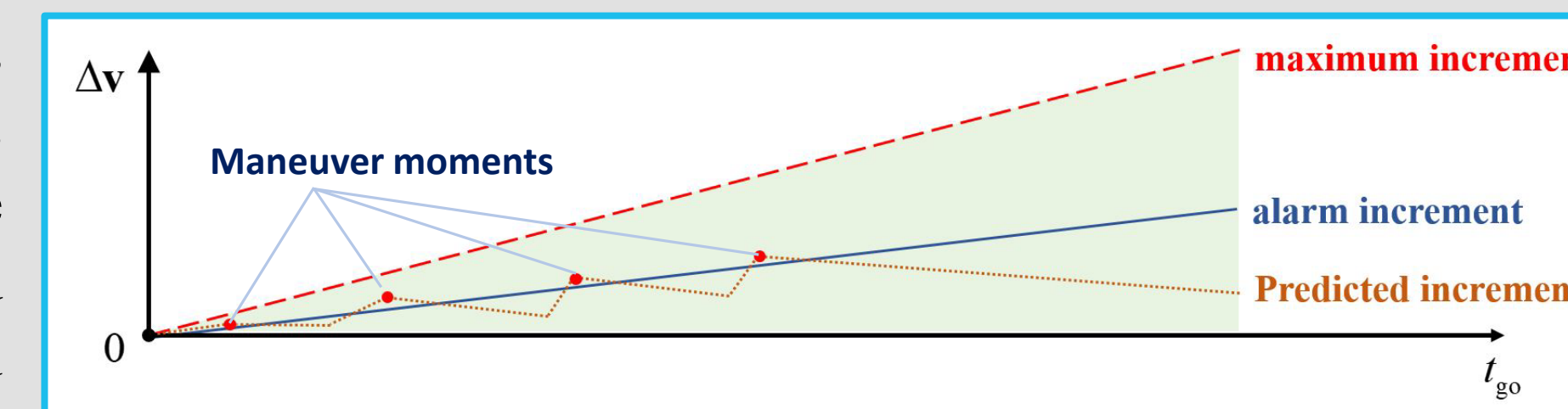


Fig 2. Velocity increment corridor

4. Simulations

Firstly, the influence of the impactor's mass on the terminal guidance accuracy is studied. The initial position is [73440 0 0]km, and initial velocity is [-10.2 0 0]km/s with proper navigation errors exist.

Suppose that the density of asteroid $\rho = 2\text{g/cm}^3$, given the diameter of asteroid α be 1m, 3m, and 5m (which means 8378kg, 226195kg, and 1047198kg in mass), the terminal impacting trajectory in the S-T plane and maneuver situation is shown in Fig 3. The maximum control force is set to be 88N. When the impactor's mass is large enough, the maneuver time will become unacceptable, and the correction can not be finished. For the current example, it is reasonable to set the upper limit of the asteroid α 's diameter to be 3m.

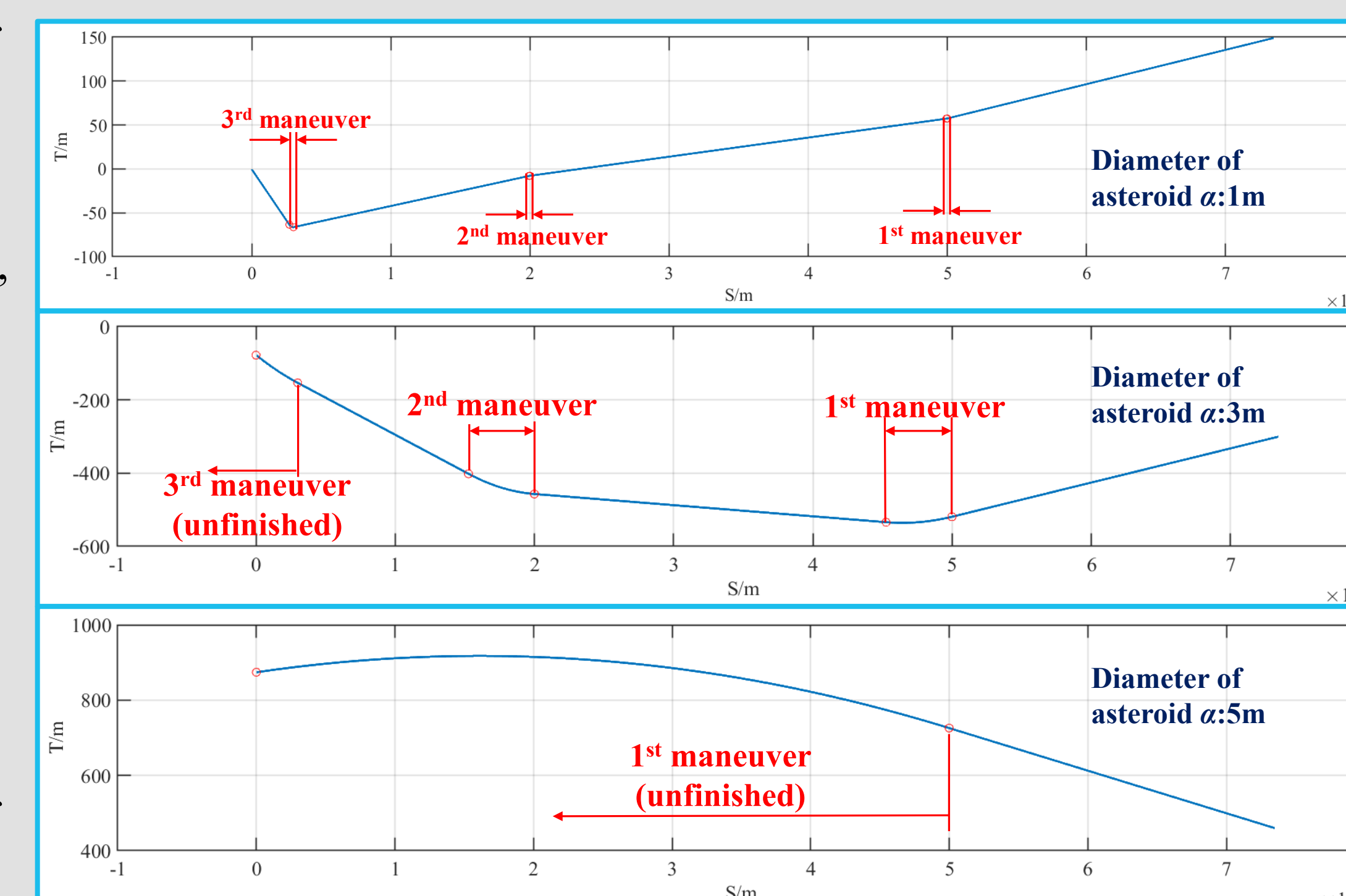


Fig 3. Terminal guidance situation with different impactor size

Then the performance of terminal guidance strategy with velocity increment corridor is carried out under the situation that asteroid α has a diameter of 3m and is 226195kg in mass. Suppose the diameter of asteroid β (target asteroid) is 160m. If the final position deviation is under 80m, it can be considered as a successful impact. One impact trajectory obtained using the proposed guidance strategy is shown in Fig 4. The mark points from right to left on the trajectory in Fig 4 are the start and shutdown points of the four correction maneuvers. The total maneuver time is 2069.10s, the fuel consumption is 61.93kg, and the final impact deviation is 11.31m, which is a successful impact.

A Monte Carlo simulation was carried out using the speed incremental corridor guidance method, and the distribution map of 500 impact points on the B plane was obtained. Compared with tradition prediction-correction guidance method, the hit rate has increased from 75% to 99.6%, with the average fuel consumption also increased from 43.84kg to 59.86kg. As is shown in Fig 5.

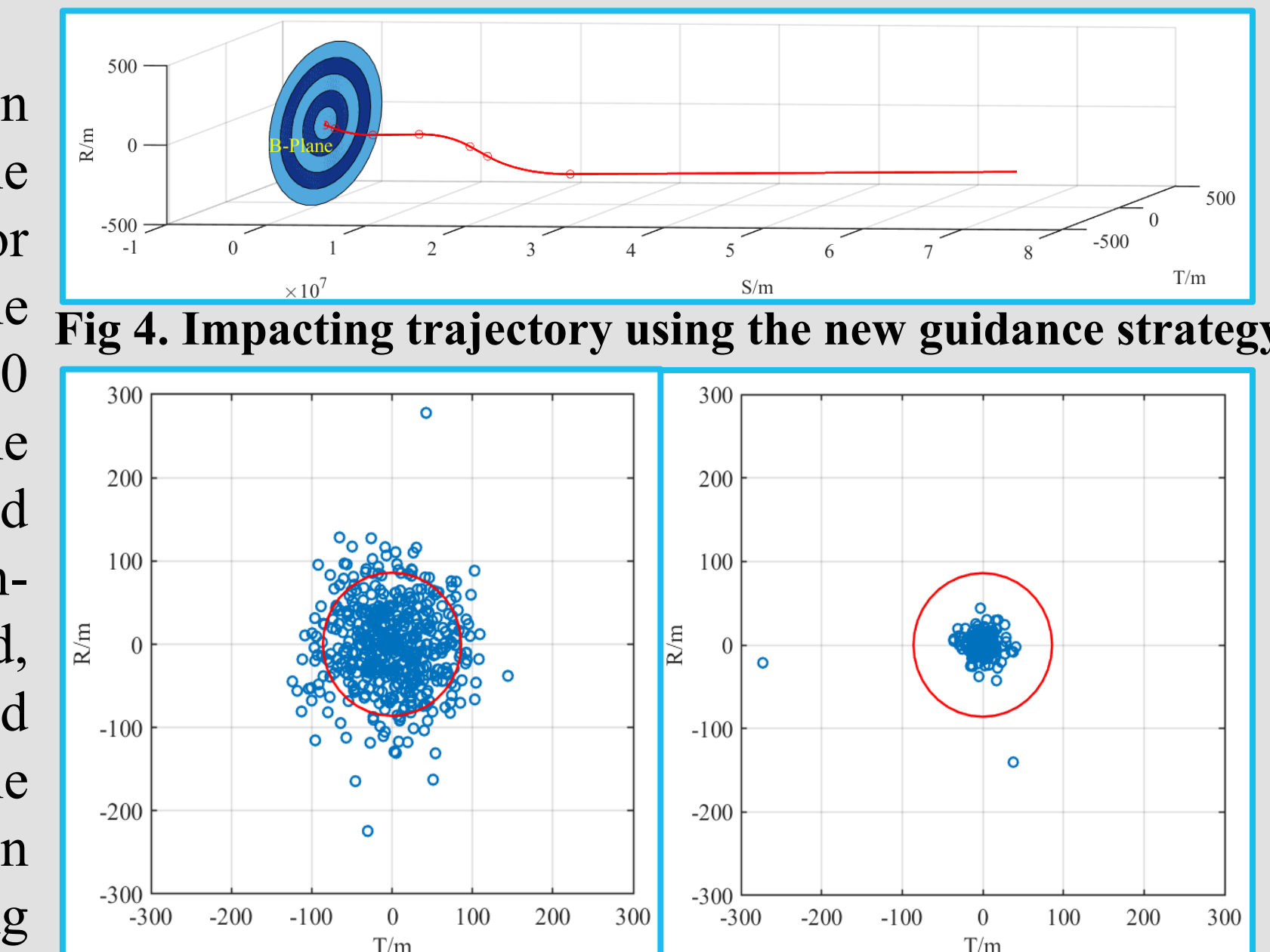


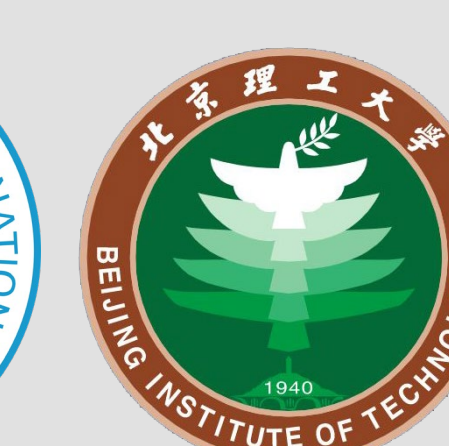
Fig 5. Distribution of impact points under traditional guidance(left) and new guidance strategy(right)

5. Conclusion

Aiming at improving the terminal accuracy of the planetary defense scheme of small body guided impact, this paper studies the trajectory characteristics of the terminal guidance when the impactor carries a large mass small body, and analyzes the upper limit of the impactor mass. In addition, an adaptive prediction-correction guidance method with velocity increment corridor is proposed, and numerical simulation has verified that this method can significantly increase the hit rate under a specific impactor mass.

Reference

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