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FUEL-OPTIMAL APPROACH PLANNING STRATEGY FOR HIGH-SPEED HYPERBOLIC AND PARABOLIC NEAR-EARTH ASTEROIDS

Abstract

With the growing number of bolide events (e.g., the 2013 Chelyabinsk meteor) observed and the near-Earth asteroids (NEAs) discovered, the threats of the NEAs have been drawing more and more attention as potential hazards to lives on the Earth. Current defensive measures like kinetic impact (NASA. 2021) and gravity tractor (Jeff. 2017) are designed and conducted on the estimation that the NEAs are approaching the Earth at a relative velocity lower than the critical escaping velocity, e.g., 5.99 km/s of Didymos in the DART mission recently in 2022. However, in the future, there will be high-speed NEAs approaching the Earth at a parabolic or hyperbolic velocity (e.g., 15.62 km/s of Didymos in 2041), where the aforementioned defense strategies can no longer be applied due to the non-periodic trajectories and shortened defense time. Therefore, this paper develops a general approach planning strategy for NEAs at parabolic and hyperbolic trajectories near the Earth. The defense spacecraft in this paper are applicable for current defensive measures propelled by ion thrust and our strategy analytically guarantees the fuel-optimal index.

First, we refine the key dynamical problem of the defense spacecraft and the NEA by two scenarios, i.e., interception (zero relative position) and rendezvous (zero relative position and velocity). In particular, the two scenarios can be described in the framework of the relative dynamics between the defense spacecraft and the NEA. Based on the assumption of close distance, we adopt the Tschauner-Hempel (T-H) equations to generalize the reference trajectory of the NEA as parabola and hyperbola. Using Pontryagin's maximum principle, the first-order necessary condition is analytically derived guaranteeing the optimal fuel consumption of the defense spacecraft in the two scenarios (interception and rendezvous). In order to shorten the defense time, we abandon the classic numerical method but develop the guidance law analytically by combining the general state transition matrix of the T-H equations with the variation of parameters (VOP) method. Our preliminary estimations show that this analytical method accelerates the computational efficiency by 5-20 times faster than the classic numerical method, which is of significance for fast automatic defense. Finally, the developed approach planning strategy is applied to kinetic impact in the DART mission but the binary asteroids are assumed to approach the Earth at parabolic or hyperbolic velocity. The fuel consumption of the defense spacecraft and the feedback efficiency of the guidance law are evaluated and compared with previous results of DART.