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FUEL-OPTIMAL TRAJECTORY PLANNING FOR MULTI-DEBRIS ACTIVE REMOVAL MISSIONS USING HIERARCHICAL REINFORCEMENT LEARNING

Abstract

The rapid development of space activities has brought numerous conveniences to humanity, but it has also led to the continuous deterioration of the space environment. Among the most serious issues is the problem of the space debris. Currently, a substantial amount of debris has accumulated in space, posing a significant threat to the safety of spacecraft. Therefore, the need for active space debris removal missions is becoming increasingly urgent. When a mission targets only one piece of debris, the cost is high and the removal efficiency is low. Therefore, this paper proposes a multi-objective trajectory planning algorithm based on hierarchical reinforcement learning, which enables the removal of multiple pieces of orbital debris in a single mission while minimizing fuel consumption. In the designed mission scenario, the working spacecraft captures one piece of debris, transfers it to a disposal orbit, and then proceeds to remove the next piece of debris. The process is repeated until all debris has been cleared. The multi-debris removal mission involves both outer and inner layer optimizations. The outer layer optimization determines the sequence in which debris should be removed, while the inner layer optimization focuses on optimizing the transfer trajectory for capturing each target debris and moving it to a disposal orbit. Traditional optimization algorithms face challenges such as high computational demand and slow optimization speeds when addressing this problem. Using hierarchical reinforcement learning not only enables rapid online planning but also allows for intelligent adjustments based on observed states, significantly enhancing the autonomy and adaptability of spacecraft. In constructing the neural network, this paper employs a transformer network to extract the intrinsic relationships between the orbital elements of debris and the spacecraft's own state, thereby determining the optimal removal sequence and transfer trajectory at any given moment. Additionally, we introduce a dynamic multi-attention mechanism that adaptively adjusts the action space dimension according to the number of debris, greatly improving the algorithm's generalization performance. In the experimental section, we compare our proposed algorithm with the Particle Swarm Optimization (PSO) algorithm, demonstrating its effectiveness through empirical validation.