Neural-based Pose Estimation and 3D Reconstruction for Non-Cooperative Maneuvering Space Target

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***Abstract*—Pose estimation and 3D reconstruction for Non-Cooperative Maneuvering Space Target (NCMST) are vital for enhancing spacecraft intelligence sensing capabilities. However, the challenges posed by unpredictable movements and the extreme space environment often complicate such processes. Therefore, this letter addresses the hurdles associated with reconstructing high-quality 3D models and achieves near-real-time parallel pose estimation for NCMST under limited viewing constraints. To address this issue, several contributions are proposed. First, a novel Neural Radiance Fields (NeRF) framework specifically designed for NCMST is suggested, enabling simultaneous pose estimation and 3D reconstruction. Second, to enhance the network's expressive capacity within constrained views, the integration of image encoding into the neural network's input is planned. Lastly, a simulator utilizing Unreal Engine 5 (UE5) is developed to replicate space's characteristics, thus creating a comprehensive RGB-D NCMST dataset and ensuring scalability for future navigation and control tasks. The achieved experiments validate the efficacy of the proposed NeRF framework, demonstrating its superior ability to achieve 3D reconstruction and simultaneous pose estimation for NCMST.**

***Index Terms*—Non-Cooperative Maneuvering Space Target, Neural Radiance Fields, simultaneous pose estimation and 3D reconstruction, constrained views, RGB-D dataset.**

I. INTRODUCTION

THE increasing accumulation of space debris poses significant risks to the safety of in-orbit spacecraft. For the debris incapable of performing orbital maneuvers, it requires close-proximity operations by servicer spacecraft. The main challenge is that the target objects are often uncooperative [1], lacking available pose and geometric information [2]. To ensure the safety of servicer spacecraft, pose estimation and 3D reconstruction are essential before close-proximity operation. Furthermore, Non-Cooperative Space Target (NCST) typically lacks active communication links, relying solely on data from non-contact sensors like cameras and radars.

Several image-based navigation systems have been proposed to enable rapid pose estimation and 3D reconstruction at close range [3]–[6]. These systems often represent the target's geometry by using point-based models. This approach is feasible because projecting a point cloud onto the 2D camera plane is differentiable, allowing for optimization of the pose and the shape of the point cloud. However, point-based representation has inherent limitations as a discrete method for modeling geometric shapes. Sparse surface textures and strong reflections often result in insufficient feature points for satellites, and unobserved areas may contain significant gaps. These limitations make point-based representations unsuitable for high-precision reconstruction, necessitating reliance on space teleoperation technologies for complex operations. This dependency restricts the broader application of Active Debris Removal (ADR) and On-Orbit Servicing (OOS).

Recently, advancements in representing the geometry of target for terrestrial applications have relied on Neural Radiance Fields (NeRF) representation [7]. Like point-based representation, NeRF relies on a differentiable rendering process, making it suitable for pose estimation and 3D reconstruction. Unlike point-based representation, NeRF has been proven to produce photorealistic renderings through its continuous and implicit representation of targets. This capability makes NeRF a promising tool for refining operations and navigation in space environments. However, because of the differences in imaging principles, NeRF-based method bypassing traditional pose estimation and 3D reconstruction pipeline, the application in such harsh space conditions requires improvements in both efficiency and reliability.

With the computational and fuel constraints of servicer spacecraft, real-time pose estimation and 3D reconstruction are essential. In NeRF-based approaches, computation time primarily depends on the network size and the number of sampling points. Combining implicit and explicit representations is useful to reduce network parameters [8]–[10]. Studios like Plenoxels [11] and Gaussian Splatting [12] discard network structures, but neural-based representations align better with other visual tasks, guiding our focus. Instant-NGP [13] incorporates aspects of explicit representations by encoding positions using a multi-resolution hash table. This encoding method has significantly influenced subsequent work [14]–[16].

In addition, because feature-point-based approaches do not rely on geometry models, most on-orbit experiments perform pose estimation and 3D reconstruction as separate tasks. However, this sequential process requires significant computation and cannot use the 3D model to optimize the pose, as methods like the Iterated Closest Point (ICP) algorithm do. Therefore,

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