Paper ID: 100066
student

23rd IAA SYMPOSIUM ON SPACE DEBRIS (A6)
Interactive Presentations - 23rd IAA SYMPOSIUM ON SPACE DEBRIS (IP)

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NEURAL NETWORK-BASED ATTITUDE ESTIMATION OF SPACE DEBRIS USING A MONOCULAR OPTICAL CAMERA

Abstract

The increasing amount of space debris poses significant risks to satellite operations and long-term space sustainability. To mitigate these risks, active debris removal (ADR) is crucial. One of the key challenges in ADR is the rendezvous and capture of uncooperative targets, which requires precise attitude estimation. Existing methods, such as LiDAR-based 3D matching, contour-based matching, and infrared image-based matching, still face challenges.

LiDAR-based 3D matching enables precise shape analysis and model comparison. However, it demands substantial computational resources and is sensitive to surface reflectivity. Contour-based matching relies solely on contour information, making it difficult to distinguish the correct orientation of symmetric objects. Infrared image matching relies on thermal patterns, enabling observation in low-light environments, but is influenced by temperature variations and material properties. These methods primarily rely on external contours or thermal distributions, which can lead to inaccuracies under complex conditions.

To overcome these challenges, this research proposes a monocular optical camera-based attitude estimation system utilizing a neural network. Our approach first integrates local sun time as prior information to estimate possible illumination conditions and constrain the range of likely orientations. The neural network then analyzes texture information and shading variations to determine the attitude, leading to improved accuracy and fewer misclassifications. Additionally, obtaining a large dataset of real space images is costly and challenging, making it impractical for extensive training. To overcome this, we developed a synthetic dataset by tuning CG images using real images captured in ground-simulated space conditions as a reference. This dataset was designed to replicate key physical characteristics observed in real environments, incorporating variations in illumination, rotation, and sensor noise to enhance its realism. By training on this dataset, our AI-driven approach surpasses existing techniques by leveraging detailed surface characteristics and illumination patterns for more reliable estimation.

The system is evaluated through simulations using a 3D CG model of the H-IIA upper-stage rocket. The model replicates realistic shape characteristics, surface textures, and rotational behaviors. We evaluate accuracy and robustness under different lighting conditions, rotation speeds, and observation angles using ground truth values.

Results demonstrate the feasibility of using a monocular optical camera and a neural network for space debris attitude estimation. This approach offers a lightweight, cost-effective, and scalable alternative to LiDAR and traditional matching methods. It effectively reduces computational costs while maintaining robust performance, providing an efficient solution for space debris attitude estimation.