Performance Analysis of the OBB-TM Algorithm for LIDAR-based Pose Estimation of Non-Cooperative Space Targets

Keywords:

« Non-Cooperative Pose Estimation », « LiDAR Point Cloud Registration », « Ambiguity Reduction »

Abstract

1. Analysis of scenario

The increasing congestion of near-Earth orbital environment and the proliferation of space debris have made autonomous proximity operations a strategic priority for future missions. On-Orbit Servicing (OOS) and Active Debris Removal (ADR) require robust pose estimation capabilities for non-cooperative targets—satellites or debris lacking fiducial markers or communication systems. LiDAR sensors have emerged as the primary technology for acquiring 3D point clouds in space, offering superior robustness to extreme lighting conditions compared to passive sensors. However, significant challenges remain: point cloud sparsity at operational ranges (20-120 m), structural symmetries in spacecraft geometries causing pose ambiguities, and computational constraints of onboard processors. Recent literature has proposed a novel model-based approach, Oriented Bounding Box – Template Matching, to reduce the pose search space from 3-DOF to 1-DOF, substantially decreasing computational burden, to resolve pose ambiguities and operate efficiently with low-resolution 3D data, paving the way for reliable autonomous proximity operations.

2. Statement of the problem

This thesis implements and validates the Oriented Bounding Box - Template Matching (OBB-TM) algorithm for autonomous pose acquisition of non-cooperative space targets from sparse LiDAR data. Research objectives are: (1) implement an efficient 1-DOF template matching pipeline leveraging PCA-based alignment; (2) integrate and validate the Ambiguity Reduction strategy for resolving orientation ambiguities in symmetric targets; (3) characterize performance across varying distances (20-120 m), angular resolutions (0.1°-0.2°-0.5°-1.0°), and target geometries (Envisat, TDRS, Dawn).

3. Adopted methodology

The OBB-TM algorithm, implemented in MATLAB, employs a model-based pipeline for pose estimation. It features an offline phase where a 1-DOF template database is generated by rotating the target model around its principal axis derived via Principal Component Analysis. Online, the measured point cloud is aligned using PCA to define a local reference frame, matched against the templates for coarse estimation, and refined via ICP. An Ambiguity Reduction module resolves symmetry-induced errors by evaluating 180°-rotated candidate poses, selecting the solution that minimizes the ICP residual error.

4. Main results

Monte Carlo simulations validated the algorithm on three targets (Envisat, TDRS, Dawn). As shown in Figure 2, the OBB-TM pipeline proved highly effective on the asymmetric Envisat, achieving >95% Success Rate (SR) at fine resolutions, although performance decreased at <30 m due to Field-of-View occlusions. For the symmetric TDRS, the algorithm showed optimal results (Fig.1) but required the Ambiguity Reduction module to resolve 180° orientation errors, slightly increasing SR (Fig.1). Conversely, on Dawn, the method reached a performance ceiling (SR 82-87%) even with finer resolutions and at medium distances; this was due to the target's geometry characterized by thin solar panels and a small central bus, which limited PCA alignment accuracy. Computational analysis in MATLAB environment confirmed execution times between 1.0-5.7 s. Finally, resolution tests identified 0.5° as a critical threshold: the algorithm achieves saturation performance at finer resolutions, while 1.0° proved insufficient for reliable acquisition.

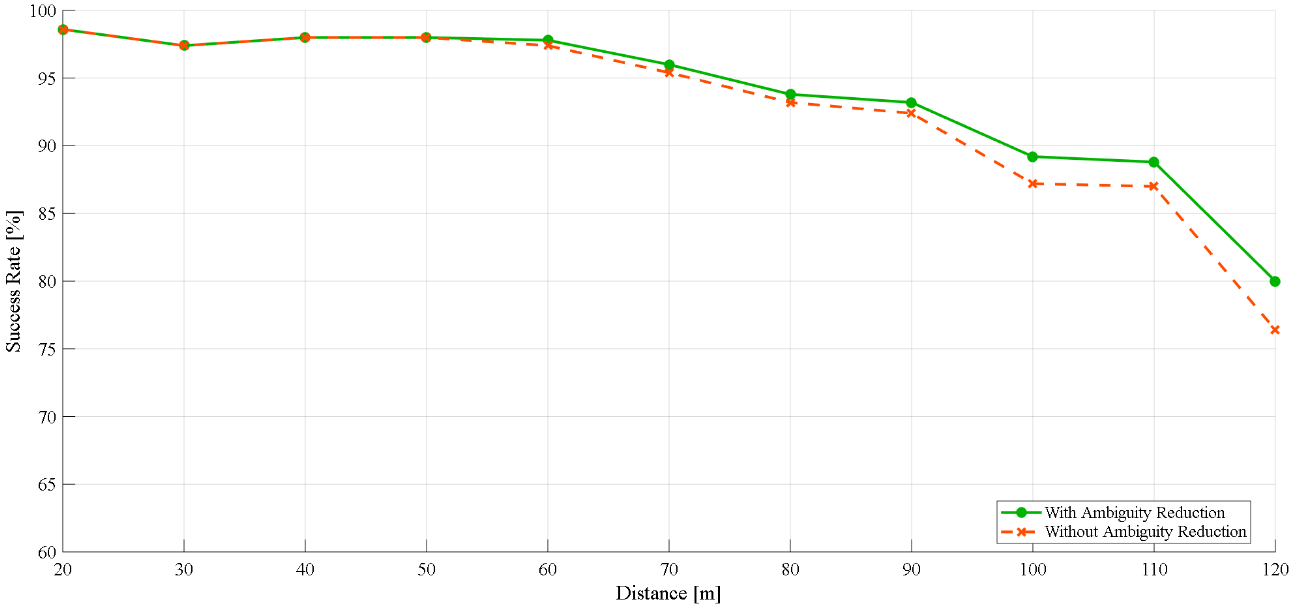

Fig. 1: Impact of the Ambiguity Reduction module on Success Rate for TDRS target at 0.5° sensor's resolution.

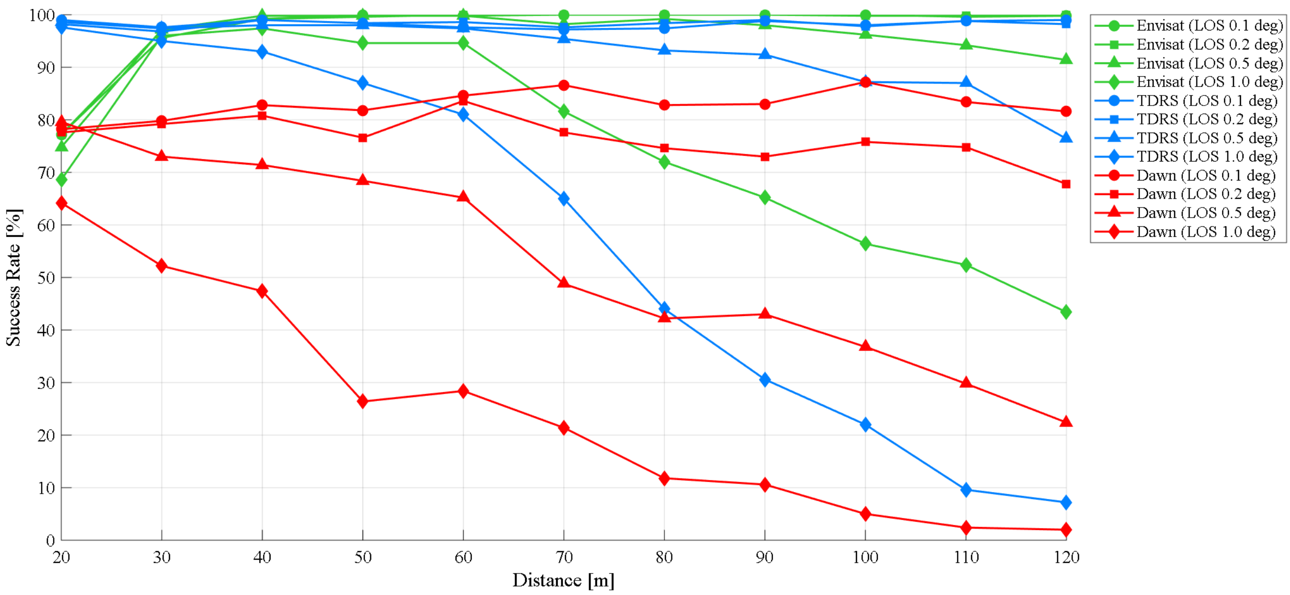

Fig. 2: Performance degradation, in terms of Success Rate, due to point cloud sparsity at lower angular resolutions for tested target.