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DYNAMIC TOPOLOGY AND RISK-AWARE ATTENTION OF SPACE DEBRIS PREDICTION FOR MEGA-CONSTELLATION NETWORKS

Abstract

The rapid and large-scale deployment of multiple Mega-constellations in the low-Earth orbit (LEO) environment is facing critical space safety challenges. The number of LEO satellites, exemplified by the SpaceX's Starlink constellation, has exceeded 6,000 and is projected to form a mega-constellation network exceeding 100,000 satellites by 2030. Against this backdrop, the exponential growth of space debris has led to a nonlinear escalation trend on the risk of Kessler syndrome. To address the limitations of traditional collision warning systems in dynamic correlation modeling and real-time responsiveness, this study proposes the STGA (Satellite Spatio-Temporal Graph Attention) model, integrating a spatio-temporal graph neural network (T-GNN) with a multi-level attention mechanism. By constructing a three-dimensional spatio-temporal graph encompassing orbital dynamics parameters, debris evolution characteristics, and space environmental factors, the model achieves comprehensive characterization of complex collision scenarios in LEO space. The dataset combines outputs from CARDC's Spacecraft Breakup Model (CSBM) and NASA's breakup model to ensure spatio-temporal coverage and statistical significance. The innovation lies in two dimensions: 1) Dynamic topology handling: The T-GNN component employs a dynamic neighborhood node sampling algorithm to address topological evolution caused by high-speed orbital object motion; 2) Risk-aware attention: A dual-channel (spatial-temporal) feature extraction mechanism incorporating risk cascade propagation weights enables intelligent identification of critical collision pathways. Compared to traditional Monte Carlo simulations, the STGA model attains enhanced spatio-temporal resolution and computational efficiency in the collision probability predictions. Numerical results indicate high prediction accuracy and real-time responsiveness when processing large-scale orbital debris datasets. Retrospective analysis of historical collision events further validates the effectiveness and reliability of the model proposed. The trinary coupling framework, i.e., integrating debris evolution, constellation operations, and environmental perturbations, establishes a novel paradigm for the prediction of complex space system. This can also be extended to the scenarios such as MEO, GEO or even cislunar space with minor modification.