In the evolving landscape of space operations, the increasing prevalence of space debris presents a formidable challenge, threatening the safety and integrity of both manned and unmanned space missions. To mitigate this hazard, the development of sophisticated predictive models and the implementation of effective collision avoidance strategies are imperative. This research delineates a groundbreaking approach that capitalizes on the synergistic potential of the Simplified General Perturbations models (SGP4/SDP4) for accurate orbital mechanics calculations, in conjunction with cutting-edge machine learning algorithms—namely, Deep Learning Long Short-Term Memory (DL LSTM) networks and Graph Neural Networks (GNN). This combination is employed to enhance the prediction of potential space debris collisions and to formulate efficient avoidance maneuvers.

Introduction: The escalating density of space debris in Earth’s orbit significantly escalates the risk to satellite operations and space exploration endeavors. Traditional debris tracking and avoidance methodologies, often reliant on oversimplified models, inadequately address the intricate dynamics of space objects. This study leverages the robustness of SGP4/SDP4 models, acclaimed for their precision in calculating satellite orbits from Two-Line Element (TLE) data, supplemented by advanced machine learning techniques. This fusion aims to accurately interpret and predict space debris trajectories with unparalleled precision.

Methods: The core of our methodology is the integration of SGP4/SDP4 models with DL LSTM and GNN algorithms, establishing a comprehensive framework for calculating the orbital paths of space debris and satellites. The SGP4/SDP4 models lay the groundwork for our predictive analysis, while DL LSTM networks, adept at processing sequential data, are tasked with forecasting the future positions of debris, considering their temporal patterns. Furthermore, GNNs are utilized to capture the complex spatial interactions among debris objects, thereby refining the system’s predictive capability for potential collision scenarios. This holistic approach, developed and validated using MATLAB and Simulink, and supported by AWS for high-performance simulations, incorporates additional tools such as Visual Studio Code (VSCode) and Spacecraft Trajectory Analyzer tools like GMAT or SPARTN for a thorough development and testing framework.

Results: Integrating SGP4/SDP4 models with DL LSTM and GNN algorithms has markedly enhanced the accuracy of space debris trajectory predictions, enabling the early identification of collision threats up to 7 days in advance. Importantly, the study incorporates a detailed risk analysis, quantifying collision probabilities and evaluating risk levels, thereby informing the strategic planning and execution of optimal avoidance maneuvers. This advancement significantly diminishes the likelihood of collisions.

Discussion: This study’s fusion of precise orbital mechanics models with state-of-the-art machine learning algorithms emerges as a formidable tool for bolstering space safety. Through accurate collision predictions and the efficient planning of avoidance maneuvers, the proposed system advocates for the sustainable utilization of space, safeguarding both current and future space missions. The research accentuates the viability of integrating traditional aerospace models with contemporary AI methodologies to surmount the challenges posed by space debris management, highlighting a significant stride toward mitigating spaceborne hazards.