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Deep Learning-Based Space Debris Tracking and Mitigation

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Abstract: - The increasing threat of space debris, whether deliberately generated or inadvertently produced, necessitates vigilant monitoring and forecasting to safeguard both crewed and uncrewed space missions. This study evaluates eight prevalent models for monitoring and predicting space debris: TLE-based SGP4, ORDEM, MASTER, Debrisat, SDebrisNet, SDTS, CARA, and SSN. A comprehensive strategy is used for each model, considering its diverse attributes, precision, complexity, data requirements, adaptability, dependability, and usability. This evaluation outlines the advantages and disadvantages of each technique in addressing the primary challenges of data, computing, and system building. The study moreover examines the advancement of tracking gadgets and current methods, together with potential enhancements to address real-time issues. The comparative evaluation of the models in this research will strategically enhance existing methods for space debris control equipment, hence promoting safety and sustainable operational practices in outer space. This research aims to develop techniques that align with the expanding and dynamic efforts of space exploration by monitoring debris with maximum efficiency and accuracy.

Index Terms- Space Debris, Tracking Models, SGP4, ORDEM, MASTER, Debris

INTRODUCTION

The rapid progression of space technology has led to a notable rise in the quantity of operating spacecraft, which presently confront substantial hazards from space debris. This debris predominantly originates from recurrent launch activities, resulting in an escalating threat to satellites and other space assets. As of March 2022, the U.S. Space Surveillance Network (SSN) has cataloged around 25,000 objects, including space debris, inactive spacecraft, and operational satellites, a figure expected to increase steadily. Collisions with substantial debris may utterly obliterate a spacecraft, although even little pieces moving at elevated speeds can inflict significant damage, resulting in performance deterioration or catastrophic failure. Consequently, the efficient monitoring and forecasting of space debris have become essential for protecting functioning spacecraft and maintaining the sustainability of space travel. Tracking space debris requires not only the detection of its presence but also the prediction of its course for collision avoidance. Space debris tracking systems may be categorized into ground-based and space-based systems, each possessing distinct benefits and limits. Ground-based systems use telescopes and radar situated on the Earth's surface, constrained by meteorological conditions and the planet's rotation. Space-based systems use sensors on satellites or spacecraft to detect space debris with greater reliability, free from atmospheric influence. Advanced algorithms and machine learning techniques, such as the spatial-temporal saliency network described by Tao et al. (2023), have shown significant potential in enhancing detection accuracy and efficiency in space debris tracking.

Consequently, the escalating issues of space debris render this study a compelling appeal for improved monitoring, tracking, and prediction systems to the World Environment Organization (WEO), aiming to contribute information and methodologies to this vital research area. Precise monitoring and forecasting of space debris is essential to Space Situational Awareness (SSA) since the space environment, especially Low Earth Orbit (LEO) and Geostationary Orbit (GEO), has become congested with a substantial quantity of space junk. The deployment of new satellites into orbit significantly heightens the risk of inadvertent collisions with operational satellites and space debris, potentially resulting in catastrophic failures and the destruction of costly space equipment. It also advocates for the development of effective monitoring technology to monitor and evaluate potential incidents, therefore accurately determining the likelihood of space collisions with other celestial bodies to ensure the sustainable future of space exploration. Furthermore, certain regulatory bodies are elevating the standards of space operations by mandating operators to demonstrate their strategies for preventing debris and safeguarding their assets and the space environment.

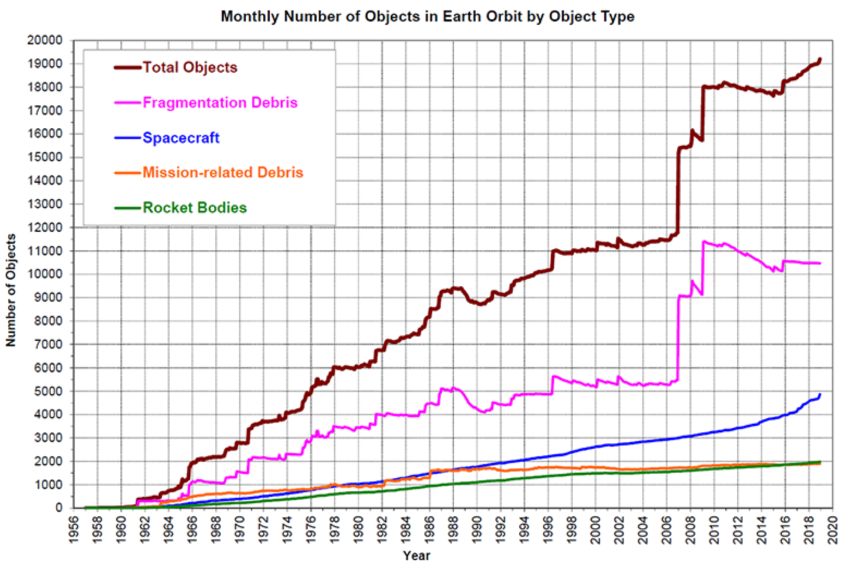
More efficient monitoring and modeling are therefore necessary to minimize dangers, enhance the efficiency of assignments, and preserve the stability of space missions for centuries to come[1][2]. Due to the exponential

[1,2,3,4] International School of Technology and Sciences for Women

proliferation of anthropogenic objects in space, the surveillance and prediction of space debris have become growing significance. The NASA Orbital Debris Program Office has been developing functional projects, like the Orbital Debris Engineering Model (ORDEM), since the mid-1980s to tackle the problem of orbital debris. The latest version, ORDEM 3.1, employs improved datasets and analytical capabilities to provide accurate population estimates of debris in the LEO to GEO regimes. These models are essential not just for predicting potential asteroid collisions but also for assisting spacecraft operators in avoiding hazardous situations associated with space debris. Objects smaller than 1 cm present significant hazards and are seldom documented, although they may result in substantial damage; hence, enhanced detection systems and risk analysis models are crucial for ensuring proper safety and support for space missions. [4].
Consequently, the escalating menace of space junk necessitates an evaluation of orbital debris to safeguard operational satellites. To tackle this issue, two models have been developed: MASTER-8, an ESA Meteoroid and Space Debris Terrestrial Environment Reference, and NASA's Orbital Debris Engineering Model (ORDEM) 3.1. These models use advanced methodologies.

Current Scenario of Space Debris

The existing situation regarding space debris presents a considerable risk to the space sector and necessitates immediate action. Space debris denotes artificial objects in orbit that have ceased to serve a purpose, including derelict spacecraft, rocket stages, paint fragments, hardened fluids, unburned residues, and debris generated by erosion, collisions, or malfunctions. As of November 2021, the US Space Surveillance Network documented around 27,000 manmade objects in Earth's orbit, a figure that pertains only to the bigger debris bits that are detectable. In actuality, millions of minuscule debris bits provide a considerable threat to spacecraft. The shards measure under 1 centimeter and exceed 128 million in quantity. As of January 2019, there are over 900,000 trash particles measuring between 1 and 10 cm and approximately 34,000 chunks exceeding 10 cm in Earth's orbit. The impact of space debris on spacecraft should not be underestimated. Even little debris bits may inflict damage akin to sandblasting, especially on solar panels and optical instruments like as telescopes or star trackers, which are challenging to protect with ballistic shielding. This presents a considerable threat to the safety and sustainability of space operations. Certain stakeholders in the space sector are undertaking the measurement, mitigation, and prospective removal of debris to solve this problem. Nonetheless, considering the magnitude of the issue, much effort need to be undertaken. The space industry must collaborate to devise effective strategies for managing the increasing volume of space debris and ensuring the safety and sustainability of space operations.



Related work.

Recent years have seen increasing apprehension over the instability of the orbital debris population in low Earth orbit (LEO), exemplified by the collision of Iridium 33 and Cosmos 2251. Consequently, there has been a resurgence of interest in active debris removal (ADR) to aid with environmental remediation. The execution of economically feasible ADR encounters several problems, including technological, resource-related, operational, legal, and political aspects. A comprehensive evaluation of the efficacy of ADR must be undertaken prior to achieving agreement on its need. A sensitivity analysis has been performed to assess the use of Active Debris Removal (ADR) for stabilizing the future Low Earth Orbit (LEO) debris environment. The research used NASA's long-term orbital debris evolutionary model, LEGEND, to assess the influence of several factors, including target selection criteria and the time of Active Debris Removal (ADR) execution. The research further examines several operational alternatives to optimize the benefit-to-cost ratio. A system has been developed for the removal of medium-sized orbital debris in low Earth orbits. The system comprises a transfer vehicle and a netting vehicle that operate in conjunction to collect the debris. The system is situated near a functioning space station at an angle of 28.5 degrees and a height of 400 kilometers. Ground-based tracking is used to ascertain the position of satellite disintegration or debris formations, which is then sent to the transfer vehicle. The transfer vehicle thereafter proceeds to the debris's position in a lower altitude parking orbit. The netting apparatus is thereafter deployed to monitor and ensnare the designated waste. Upon depleting the existing nets, the netting vehicle returns to the transfer vehicle to acquire a new netting module and resumes capturing further trash in the designated region. Upon depleting all netting modules, the transfer vehicle returns to the orbit of the space station, where it is replenished with fresh netting modules from a space shuttle cargo. The fresh modules are deployed from the ground, while the used modules are retrieved to Earth for debris extraction, refueling, and net repacking. The restored nets are then sent to orbit for reutilization. The device may catch up to 50 pieces of orbital debris, with an average duration of around six months. The system is designed to provide a 30-degree inclination alteration throughout both the outbound and inbound journeys of the transfer vehicle.

DETAILED ELABORATION OF SPACE DEBRIS TRACKING MODELS DATASET DESCRIPTION

1. Two-Line Elements (TLE) and SGP4 Propagator

A two-line element (TLE) is a standardized approach for succinctly describing the orbits of space objects, such as satellites, using two lines of data. This style is equally effective for tracking these items. SGP4 is a generic user-propagated model that calculates the location and velocity of a satellite using TLE data at any specified moment. Nonetheless, as anticipated, SGP4 exhibits diminished predictive accuracy over extended intervals due to perturbations from factors such as air drag and variations in gravitational forces. Consequently, it necessitates more regular data updates to provide more precise beginning circumstances concerning all satellites monitored within a certain time span.

2. Orbital Debris Engineering Model (ORDEM)

The investigation indicates that NASA's ORDEM is an extensive apparatus designed to evaluate space debris. It employs radar data, optical measurements, and direct observations to assess the population density of space debris across several size categories.

Consequently, ORDEM may be used to assess the likelihood of a collision in satellite operations. Additionally, it can compute the long-term trajectory of debris, which is essential for optimizing operations in space, including satellite missions, and for constructing protective barriers such as shields.

3. MASTER (Meteoroid and Space Debris Terrestrial Environment Reference)

MASTER is a distinguished model particularly developed for space debris and meteoroids by the European Space Agency (ESA). It offers dependable calculations of debris impact flux (the rate of debris impacts per unit time) for debris sizes ranging from micrometers to meters. MASTER uses observations in conjunction with simulations to identify debris in diverse orbits inside the orbital zones. It is mostly used for assessing hazards associated with satellites, enabling operational corporations and organizations to analyze the threats presented by impacts from space debris.

4. DebriSat

DebriSat is an experiment designed to enhance understanding of the generation of space debris resulting from high-velocity impacts. DebriSat, which examines satellite fragmentation resulting from collisions, is based on controlled experimental methods and aims to draw conclusions on the formation and distribution of debris. This study improves the models used in debris generation and aids in the long-term prediction of changes in the orbital debris environment.

LIMITATIONS AND GAPS IN SPACE DEBRIS TRACKING MODELS

1. TLE and SGP4 Propagator

The SGP4 propagator rapidly declines in precision due to velocity effects, variations in the gravitational field, and other environmental conditions in space. The inaccuracy necessitates frequent updates of TLE data to maintain precision, which may provide operational challenges in ongoing satellite operations.

2. ORDEM

NASA ORDEM has limited accuracy in predicting the behavior of minute debris, particularly in inadequately monitored regions. The limitation in using observational data for model estimation lies in the potentially inefficient representation of the spatial environment in a static fashion. This constraint may result in negligence in risk assessment and mission management for satellite operations.

3. MASTER

Similar to the ORDEM model, the MASTER model may fail to detect minimal debris levels or those that are recently produced. It mostly relies on historical data and may not accurately reflect current circumstances or the dynamics of the debris environment.
This dependence on outdated information may hinder risk management decision-making processes in satellite operations.

4. DebriSat

The DebriSat project addresses the development of space debris and conducts experiments inside a controlled environment; nevertheless, this information remains restricted to the experimental framework. Consequently, the results probably do not accurately simulate genuine accident circumstances in space to the fullest extent possible. The findings of this research are contingent upon individual cases, since the contamination levels identified vary for certain satellite materials and configurations, without considering other types of debris.

5. SDebrisNet

The efficacy of SDebrisNet is contingent upon the caliber and concentration of the sensors used for space debris detection. The capability to identify debris remains limited to particles smaller than 10 cm, presenting a challenge since the majority of debris is often little and difficult to discover using traditional approaches. Furthermore, they may encounter deceptive outcomes or find no genuine threats in space, perhaps resulting in overarching hazards or failures in space safety.

PROPOSED METHODOLOGY

Proposed Methodology: Improving TLE Precision by LSTM Integration with the SGP4 Model for Space Debris Monitoring This project aims to enhance space debris tracking methodologies by merging deep learning models, particularly Long Short-Term Memory (LSTM) networks, with the Simplified General Perturbations (SGP4) model. Conventional models that depend only on Two-Line Elements (TLE) and SGP4 may exhibit accuracy limits over time owing to fluctuations in orbital dynamics. Our methodology seeks to alleviate these constraints by using LSTM to improve predictive accuracy via error correction.
Two-Line Element Set (TLE): TLE data has a standardized format for the orbital parameters of celestial objects, including metrics such as inclination, eccentricity, and right ascension, among others.
TLE data experiences degradation due to perturbative influences like air drag, gravitational effect, and solar pressure. SGP4 Model: The SGP4 model utilizes data obtained from TLE to forecast the future locations of space objects, using anticipated orbital characteristics. Sgp4 is efficient; nonetheless, faults accumulate over time, rendering current data potentially unreliable over extended ranges.
Our suggested technique utilizes the LSTM model to forecast and rectify discrepancies seen in SGP4's outputs over time, with the objective of attaining enhanced accuracy in space debris tracking.
The data set comprises TLEs of space debris, corroborated by the actual observed location and velocity of the debris. The data is divided into two segments: Training Dataset: Historical TLE data is used, with position and velocity computed by SGP4, and actual position and velocity employed to rectify discrepancies. Test Data: Embedded TLE data and positional data from SGP4, whereby real locations collected are used to assess accuracy

post-prediction. Feature Selection: The collected features from TLE data are input into SGP4 to compute simulation locations (x, y, z) and velocities (Vx, Vy, Vz). The outputs serve as inputs to the LSTM, while the actual observed positions and velocities, denoted as xactual, yactual, and zactual, function as the labels. Xactual denotes the actual position, Yactual signifies actual velocity, and Zactual indicates actual acceleration. Data Shaping: The data is segmented into time intervals, allowing the LSTM model to capture periodicity and rectify drift in SGP4 propagation.

The LSTM architecture has many layers intended to identify and rectify discrepancies in SGP4-generated outputs. Initial LSTM Layer: Comprising 128 units configured to return sequences, hence enabling the model to preserve temporal information. Second LSTM Layer: Consists of 64 units for the future detailed analysis of sequential data. Fully Connected Layers:

Subsequent to the LSTM outputs, there are two thick layers. Initial Dense Layer: Given the incorporation of refined outputs, 64 units with ReLU activation are employed. Second Dense Layer: The last layer has 6 units for the position and velocity adjustments Δx, Δy, Δz, ΔVx, ΔVy, ΔVz. The model is created using Mean Absolute Error (MAE), which aligns closely with real observations via an absolute loss function.

The last approach, known as the Adam optimizer, facilitates efficient training and convergence owing to its characteristics.

The LSTM model is trained as stated with validation split to reflect the performance of the model in the subsequent epoch. The model predicts future error behavior based on historical error data.

The model undergoes training for 50 epochs with a batch size of 32, and a steady reduction in training and validation loss exemplifies enhanced model performance. Validation: Validation loss is computed alongside training and testing losses to mitigate overfitting and enhance performance on unseen data.

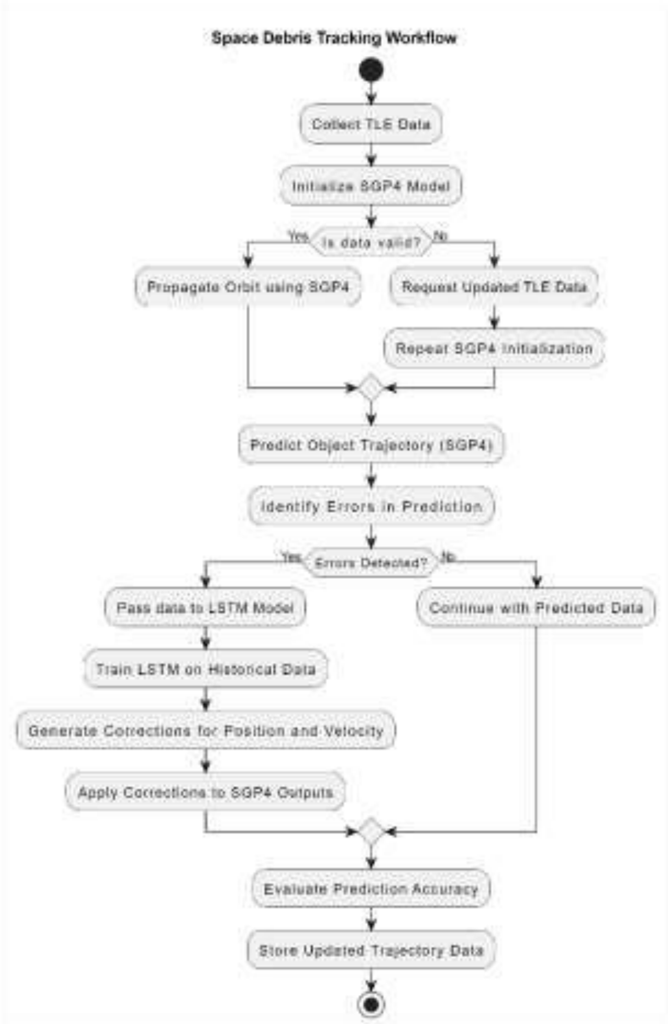


Figure 1: Work Flow Diagram

CONCLUSION

Space debris poses a significant risk to satellite operations, crewed missions, and future space exploration, since the viability of supporting human activities in space remains questionable. The aforementioned models include TLE, SGP4, ORDEM, MASTER, DebriSat, SDebrisNet, SDTS CARA, and SSN, which represent diverse methodologies for monitoring and managing space debris. However, they also disclose a significant weakness or deficiency that obstructs their proper functioning. Consequently, these constraints must be overcome to improve the existing understanding and management of space debris.

This includes enhancing reliable and prompt collection and distribution, potential integration of modern technologies like as machine learning for tiny debris detection and prediction, and adequate surveying of the orbital region. Moreover, collaboration with other jurisdictions and the creation of a unified system for monitoring debris facilitate the formulation of effective strategies to tackle the problem.

Consequently, stakeholders must seek methods to bridge these gaps to provide improved research of the last frontier, free from the encumbrance of space junk. Finally, the amalgamation of the optimal choices from the aforementioned models will be crucial for effectively monitoring, evaluating, and preventing.

REFERENCES

[1] Wright, Richard J. "Orbital debris mitigation system and method." U.S. Patent No. 8,567,725, 29 Oct. 2013.

[2] Missel, William,J., "Active space debris removal using capture and ejection." PhD diss., 2013.

[3] H Choi, Sang, and Richard S Pappa, "Assessment study of small space debris removal by laser satellites." Recent Patents on Space Technology 2, pp. 116.122, Issue. 2, 2012.

[4] Ishige, Y., Kawamoto, S. and Kibe, S., “Study on electrodynamic tether system for space debris removal”, Acta Astronautica, vol. 55, Issue 11, pp. 917-929, 2004.

[5] R.I. Samanta Roy, D.E. Hastings, E. Ahedo, “System Analysis of Electrodynamic Tethers, Journal of Spacecraft and Rockets”, vol. 29, Issue. 3, 1992.

[6] Ohkawa, Y., et al. "Preparation for on-orbit demonstration of electrodynamic tether on htv." Proceedings of the Joint Conference of 30th International Symposium on Space Technology and Science, 34th International Electric Propulsion Conference and 6th Nano-Satellite Symposium, pp.4-10, 2015.

[7] Wormnes, Kjetil, et al. "ESA technologies for space debris remediation." 6th European Conference on Space Debris, vol. 1. ESTEC, Noordwijk, The Netherlands: ESA Communications, 2013.

[8] Williams, P., “Optimal orbit transfer with electrodynamic tether”, Journal of Guidance, Control, and Dynamics, vol. 28, Issue 3, pp. 69–372, 2005.

[9] Missel, Jonathan, and Daniele Mortari. "Path optimization for Space Sweeper with Sling-Sat: A method of active space debris 43 emoval" Advances in Space Research, vol. 52, Issue.7, pp. 1339-1348, 2013.

[10] Gregory, D., Mergen, J., & Ridley, A., “Space debris elimination (spade) phase final report, “The National Aeronautics and Space Administration, www. nasa. gov/pdf/716066main_Gregory_2011_PhI_SpaDE. pdf (accessed September 15, 2013).

[11] Wright, R.,Orbital debris mitigation system and method. US Patent 8,567,725, 2013.

[12] Okada, N. "Active debris removal using carrier and multiple deorbiting kits", 3rd European Workshop on Space Debris Modelling and Remendiation, 2014.

[13] Missel, Jonathan, and Daniele Mortari. "Removing space debris through sequential captures and ejections." Journal of Guidance, Control, and Dynamics, vol.

[14] Issue 3, pp. 743-752, 2013. 36. N. Zinner, A. Williamson, K. Brenner, J.B. Curran, A. Isaak, M. Knoch, et al., “Junk hunter: autonomous rendezvous, capture, and de-orbit of orbital debris”, AIAA SPACE 2011 Conference & Exposition, Long Beach, CA, USA, 2011.

[15] Gregory, D. and J. Mergen, “Space debris removal using upper atmosphere and vortex generator” US Patent, 8,657,235, 2014. 38. V. Lappas, N. Adeli, L. Visagie, J. Fernandez, T. Theodorou, W. Steyn, and M. Perren, “CubeSail: A low cost CubeSat based solar sail demonstration mission,” Advances in Space Research, vol. 48, Issue 11, pp. 1890–1901, 2011.

[16] Bomabardelli C, Peleaz J. Ion beam shepherd for contactless space debris removal. Journal of Guidance, Control and Dynamics. 34(3):916-920 2011.

[17] Retat, B. Bischof, et al., “Net capture system: a potential orbital space debris removal system”, 2nd European Workshop on Active Debris Removal, CNES Headquarters, Paris, France, 201