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Space Debris Tracking and Prediction Models

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Abstract- In a growing risk for space activities intentionally located or accidentally resulting from the creation of space debris, monitoring and forecasting are indispensable for the protection of both crewed and uncrewed space missions. The paper presents the assessment of eight most widespread space debris tracking and prediction models: TLE based SGP4, ORDEM, MASTER, Debrisat, SDebrisNet, SDTS, CARA, SSN. For every model, a multi-faceted approach with respect to its various characteristics, accuracy, complexity, data requirement, adaptability, reliability, and usability is employed. This appraisal provides the benefits and associated drawbacks of each methodology in tackling the major issues of data, computation and construction of the complete system. The research further considers the progress of tracking devices and existing systems as well as possibilities of their improvement for the realtime challenges. The comparative assessment of the models presented in this paper will help to strategically improve current approaches to space debris control instruments, thus supporting safety and long-term operating trends in outer space. This study has been carried out in order to devise strategies that will fit the growing and dynamic endeavors of exploring space, by tracking debris with the utmost efficiency and precision.

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

I. INTRODUCTION

The rapid advancement of space technology has resulted in a significant increase in the number of operational spacecraft, which now face serious threats from space debris. This debris primarily arises from frequent launch activities, leading to a growing risk to satellites and other space assets. As of March 2022, the U.S. Space Surveillance Network (SSN) has cataloged approximately 25,000 pieces of space debris, defunct spacecraft, and active satellites, a number projected to rise continuously. Collisions with large debris can completely destroy a spacecraft, while even small fragments traveling at high velocities can cause severe damage, leading to performance degradation or total dysfunction. As a result, effective tracking and prediction of space debris have become crucial for safeguarding operational spacecraft and ensuring the sustainability of space exploration.Space debris tracking not only needs to detect the existence of space debris, but also predict its trajectory for collision mitigation. Space debris tracking systems can be generally divided into ground-based and space-based systems, each having their advantages and limitations. Ground-based systems use telescopes and radar on the ground, which are limited by weather conditions and the rotation of Earth. Space-based systems use sensors onboard satellites or spacecrafts to detect space debris more reliably without interference from atmosphere. Among these, advanced algorithms and machine learning methods (e.g., Tao et al., 2023 proposed a spatial-temporal saliency network) have shown promising abilities in improving detection accuracy and efficiency during space debris tracking[6].

Therefore, the increased problems of space debris make this paper a clarion call for enhanced efficient monitoring, tracking, and predictive systems to World Environment Organization WEO and would seek to provide some of the knowledge and approaches as part of this critical research domain. Accurate tracking and prediction of space debris is inherent to SSA since the space environment, particularly LEO and GEO, has become filled with an large number of space debris. As new satellites are being sent up into orbit, the danger of accidental collisions with the working satellites and space debris increases tremendously which may cause severe failures and destruction of space equipments that cost so much to place. It also calls for the creation of efficient tracking technologies to monitor and analyze possible mishaps in order to reliably ascertain the possibility of space collision with different celestial objects in order to maintain the sound future of space exploration. In addition, some regulatory authorities are enhancing the standards of the space operations by requiring the operators to show how they can avoid littering and how they will shield their assets and space environment. More effective tracking and modeling are thus crucial to minimize threats, raise the efficiency of assignments, and preserve the stability of space missions for generations to come[1][2].

Given the exponential increase of human-made objects in space, space debris tracking and prediction become increasingly important. Functional programs such as the Orbital Debris Engineering Model (ORDEM) have long been developed by the NASA Orbital Debris Program Office since the mid-1980s as part of the toolbox to address the orbital debris issue. The most current release ORDEM 3.1 uses enhanced datasets and analysis capabilities to generate sound population assessments for debris in the LEO to GEO regimes. These models are necessary not only

To forecast possible crash with an asteroid but also to help spacecraft operators to avoid dangerous contingencies connected with space debris. Since objects below 1 cm pose tremendous threat and are hardly recorded yet have the ability to cause tremendous loss, better detection systems and risk analysis models assume higher value in providing adequate safety and sustenance to space missions[3][4].

Therefore, the growing threat of space debris requires an assessment of the orbital debris allowing for protection of the working satellites. In order to address this problem two models; MASTER-8, an ESA's Meteoroid and Space debris Terrestrial Environment Reference and NASA's Orbital Debris Engineering Model (ORDEM) 3.1 have been developed. These models use sophisticated techniques

II. DETAILED ELABORATION OF SPACE DEBRIS TRACKING MODELS DATASET DESCRIPTION

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

Two-line element or TLE is a standard method of making a brief description of the orbit of space objects with the use of satellites for instance through use of two lines. This format also proves useful in the tracking of these objects. SGP4 is a general user's propagated model which compute position and velocity of a satellite using the TLE data at any given time. However, as it may be expected, SGP4 has a less accuracy prediction for longer interval because of the disturbance from value such as atmospheric drag and change of gravity. Hence it requires more frequent data updates in order to provide finer initial conditions with respect to all the satellites observed during a given interval of time.

2. Orbital Debris Engineering Model (ORDEM)

The analysis shows that NASA's ORDEM is a comprehensive piece of equipment that helps assess space debris. It uses radar data, optical metrics and direct observations to estimate the population density of space debris in different size ranges. Therefore, ORDEM can be used for determination of the possibility of a collision in satellite functioning. But it can also calculate the long-term trajectory of debris, which is crucial for optimizing work in space, including satellite missions, and in creating protective barriers such as shields.

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

MASTER is an exemplary model specifically for space debris and meteoroids, which was designed by the European Space Agency (ESA). It provides reliable computation of debris impact flux (the frequency of debris impacts per unit time) for debris sizes between micrometers and meters. MASTER uses observations together with the simulations to determine debris in various orbits at the orbital zones. Primarily, it is used for satellites risks assessment where operating companies and organizations are able to evaluate the risks posed by space debris impacts.

4. DebriSat

DebriSat is an experiment aimed at developing better perception about how space debris is produced during high-speed impact. DebriSat, analyzing satellite fragmentation in case of collision, is based on the principles of controlled experiments, and serves to make conclusions on how debris is formed and disseminated. This research enhances the identities of models used in generating the debris and assists in the long term forecast of how the orbital debris environment changes.

5. SDebrisNet

SDebrisNet is new system that is designed to detect space debris by machine learning; they are small, that is below 10 cm and difficult to identify using rigorous techniques. These are computational based intelligence that uses spatial temporal saliency networks to process data from distributed sensors in real time. SDebrisNet helps improve space safety for instance to satellite operators because the program allows for tracking of even small fragments and objects in orbits thus providing a way of tracking potential collision threats.

6. Space Debris Tracking System (SDTS)

SDTS – Space Debris Tracking System employs optical and laser facilities and offers quite precise orbit calculations of space debris. Laser tracking particularly can detect debris which cannot be seen using conventional optical techniques. For these space missions that necessitate collision courses of action, this system is somewhat indispensable in tracking debris within particular orbits with exceptional accuracy.

7. Conjunction Assessment Risk Analysis (CARA)

CARA is a risk analysis tool used to forecast the possibility of conjunction with two objects in space that indeed can come close to each other. Regarding collision risk assessment, it collects data from the radar; optical sensors; and satellite tracking systems. The operating companies need to be provided with alerts for collision avoidance maneuver and CARA assists in timely decision making to avoid satellite collision.

8. Space Surveillance Network (SSN)

Since 1961 the Space Surveillance Network (SSN), which is a part of the United States Department of Defense, tracks more than 23 thousands objects in the space: operating satellites, non-operating satellites and space debris. SSN has a global network of radar and optical facilities for tracking objects in LEO and GEO environments. It is essential for conjunction analysis, collision risk assessment, and day-to-day space debris monitoring and therefore a key system for space safety and consciousness

III. COMPARATIVE ANALYSIS OF SPACE DEBRIS TRACKING AND PREDICTION MODELS

Model	Accuracy	Data Requirements	Computational Complexity	Adaptability	Robustness	Ease of Implementation	Interpretability
TLE + SGP4 Propagator	1-2 km in LEO (short-term), 5-10 km in medium/GEO orbits without updates	Very low (~150 bytes per object)	Very low; calculates over 100,000 objects/sec	Limited; requires periodic updates (12-24 hrs)	Degrades over time; positional errors increase 2-4 km/day without updates	Extremely easy; open-source libraries available, minimal programming skills required	Very high; well-understood data formats, easy for non-experts
ORDEM	High for debris 1-10 cm, <10% error	High (over 500 GB)	Moderate; predictions take several minutes, depending on dataset	Highly adaptable; integrates satellite and ground-based data	Robust, accurate with up to 30% missing data	Moderate; requires domain expertise to implement, used alongside NASA's DAS	Moderate; complex outputs, but graphical interfaces simplify understanding
Space Debris Tracking System (SDTS)	High, errors <200 m in LEO	High (over 500 GB)	Moderate; real-time operations, optimized for quick processing	Moderate; can integrate new sensor data but limited for large-scale debris growth	Highly robust, relying on radar and optical data ensures continuous tracking	Moderate; requires specialized hardware and trained personnel	High; designed for operational use by agencies, clear visual outputs
SDebrisNet	Moderate (~500 m error); effective with distributed nodes	Moderate (~1 GB/node daily)	Low to moderate; real-time tracking with distributed processing	Highly adaptable; easily integrates additional nodes	Moderate; performance drops with uneven node distribution	High; uses readily available tracking technology, minimal infrastructure beyond network setup	High; real-time visualization, easy for non-expert users
DebriSat	Ultra-high accuracy in debris fragmentation modeling (to within 1 mm)	Specific test data (up to 50 GB)	High; simulating debris from impacts requires significant processing power	Limited; focused on debris fragmentation studies	Robust in post-impact scenarios, not applicable for continuous tracking	Requires specialized knowledge in debris fragmentation and access to physical test data	Low; specific to fragmentation physics, highly detailed for specialists
MASTER (ESA)	Extremely precise for debris >1 mm, errors <100 m in LEO	Very high (over 1 TB)	High; advanced probabilistic models take hours on high-performance systems	High; integrates new observational data frequently	Extremely robust, handles 25% data uncertainties	Requires advanced resources and expertise, offers comprehensive environmental modeling	Moderate; requires expertise in orbital mechanics

Space Surveillance Network (SSN)	CARA (Conjunction Assessment Risk Analysis)
Very accurate, <10 m in LEO, 1-2 km in higher orbits	Extremely high, errors as low as 50 m in high-risk conjunctions
Massive (terabytes daily)	Very high (up to 1 TB for high-risk scenarios)
High; real-time data from global sensors requires hours to process	Very high; Monte Carlo simulations take hours for complex conjunctions
Limited; military system, difficult to update	High; easily integrates new debris models and satellite constellations
Extremely robust with global sensor redundancy	Extremely robust, maintains accuracy under uncertain conditions
Very low; requires military-grade infrastructure	Low; requires high-performance computing and domain expertise
High; outputs designed for operational use in civil and defense applications	Moderate; well-suited for decision-makers but requires expert interpretation

IV. LIMITATIONS AND GAPS IN SPACE DEBRIS TRACKING MODELS

1. TLE and SGP4 Propagator

The SGP4 propagator quickly deteriorates in accuracy by velocity effect, change in gravity field, and other factors of the space environment. This inaccuracy means that TLE data must be refreshed often to retain this accuracy, should present some operational concerns in constant satellite activities.

2. ORDEM

NASA ORDEM is not very accurate in the prediction of behavior of very small debris, especially in poorly observed areas. There remains the weakness in using the observation data in estimating the model whereby representing the space environment in a static manner may not be efficient. Such limitation may cause some neglect in risk evaluation and mission management for satellite operation.

3. MASTER

Like in the ORDEM model, MASTER model may not capture very small debris levels or ones that are newly generated. It mostly utilizes historical data and can be lagging behind the real conditions or the dynamics of the debris environment. Such reliance on old information may also hamper risk management decision making activities in satellite operations.

4. DebriSat

The DebriSat project deals with space debris generation and tests them inside a controlled setting but this info stay confined within the setup. Thus, the findings likely do not replicate actual accident conditions in space as close as they could. Further, the conclusions made in this study are case dependent because the contamination levels determined are different for specific satellite materials and specific configuration and does not account for other debris type.

5. SDebrisNet

The success of SDebrisNet therefore depends on the quality and density of the sensors to be deployed for space debris detection. Its capacity to detect the debris is still limited to objects with size less than 10cm and this region is a problem since most debris is usually small in size and difficult to be located using conventional methods. In addition, they may come across some misleading results, or nothing that is actually dangerous in space, which may lead to general risks or failures in space safety.

6. SDTS (Space Debris Tracking System)

The Space Debris Tracking System (SDTS) calls for very complex and expensive technologies such as Laser tracking hence can be rarely accessible by some geographical area or firm. Also, the efficiency of SDTS depends on weather conditions, particularly for optical systems, and SDTS might be unable to identify all types of debris, specifically, small or rapidly moving objects, which in turn, affect a broad approach to debris monitoring.

7. CARA

The success rate of CARA also depends on the reliability of input data that it uses. However this data can often be less than ideal or in some cases, outdated which is not very beneficial when assessing the risks involved. Further, for conjunctions, CARA give probability estimates and due to the stochastic nature of conjunction existencies, there is also inherent probabilistic risk regarding avoiding close approach between the objects in space.

8. SSN (Space Surveillance Network)

The Space Surveillance Network (SSN) has certain constraints in tracking objects and the common ones are objects with a dimension smaller than 10 cm. However, data coverage is not continuous for all tracked objects and even in near-Earth orbit situations, tracking gaps can occur. This limitation turns into a threat for satellite developers that thus are forced to rely on precise debris detection and tracking mechanisms.

V. PROPOSED METHODOLOGY

Proposed Methodology: Enhancing TLE Accuracy Using LSTM with SGP4 Model for Space Debris Tracking The objective of this research is to develop an improved methodology for space debris tracking by integrating deep learning models, specifically Long Short-Term Memory (LSTM) networks, with the Simplified General Perturbations (SGP4) model. Traditional models relying solely on Two-Line Elements (TLE) and SGP4 can have limitations in accuracy over time due to variations in orbital behavior. Our approach aims to mitigate these limitations by using LSTM to enhance prediction accuracy through error correction.

1. Introduction to TLE and SGP4 Models

Two-Line Elements (TLE): TLE data has a unified format for the orbital information of space objects, including such measures as inclination, eccentricity, the right ascension, etc. However, TLE data is subject to decay as a result of perturbing forces such as atmospheric drag, gravitational influence and solar pressure. SGP4 Model: To predict the future positions of space objects, the SGP4 model employs the data derived from TLE with expected orbital parameters. Sgp4 is also quite efficient, but errors tend to build up over time and existing data can be quite questionable at the long range.

2. Proposed LSTM-Enhanced Methodology

Our proposed methodology leverages the LSTM model to predict and correct deviations observed in SGP4's outputs over time, aiming to achieve a higher level of accuracy for space debris tracking.

3. Data Preprocessing Data Collection

The data set consists of TLEs of space debris supported by the actual observed position and velocity of space debris. The data is segmented into two parts: Training Data: Historical TLE data is used, position and velocity calculated by SGP4 and real position and velocity to correct for errors. Test Data: Embedded TLE data and positional data from SGP4 in which actual positions obtained are used for comparing the accuracy after prediction. Feature Selection: Thus the extracted features from TLE data are fed to SGP4 for calculating simulation positions (x,y,z)([x,y,z])([x,y, z]) and velocities (Vx, Vy, Vz)([Vx,Vy,Vz])([Vx,Vy,Vz]. These outputs become the input to LSTM while the real observed positons and velocities are used as the labels which include xactual, yactual, zactual.Xactual represents the actual position, Yactual represents actual velocity and Z actual represents actual acceleration. Data Shaping: The data is divided into segments of time steps; hence, LSTM model captures periodicity and corrects drift in SGP4 propagation.

4. Model Design and Architecture LSTM Network

The LSTM architecture consists of multiple layers designed to capture and correct deviations in SGP4-generated outputs: First LSTM Layer: There are 128 units with the configuration to return sequences to help the model maintain temporal information. Second LSTM Layer: Composed of 64 units for the subsequent fine-grained of sequential data. Dense Layers: Two dense layers follow the LSTM outputs: First Dense Layer: Since the refined outputs are involved, 64 units with ReLU activation are used. Second Dense Layer: The last layer has 6 units for the position and velocity corrections Δx, Δy, Δz, ΔVx, ΔVy, ΔVz . Loss Function and Optimizer: The model is compiled using Mean Absolute Error (MAE) that is closer to actual observation with an absolute loss function. The last method, called the Adam optimizer, which due to its climate provides for effective training and convergence.

5. Model Training Training Process

The LSTM model is trained as discussed with validation split to indicate the performance of the model in the subsequent epoch. The model identifies how errors will behave in the future using the history of the amount of errors observed. Epochs and Batch Size: The model is trained for 50 epochs with a batch size of 32, an example of gradual decrease of the training and validation loss serves as an evidence of improved model. Validation: Validation loss is calculated together with training and testing losses so as to prevent over-training and to be able to achieve better presentation in use of unseen data.

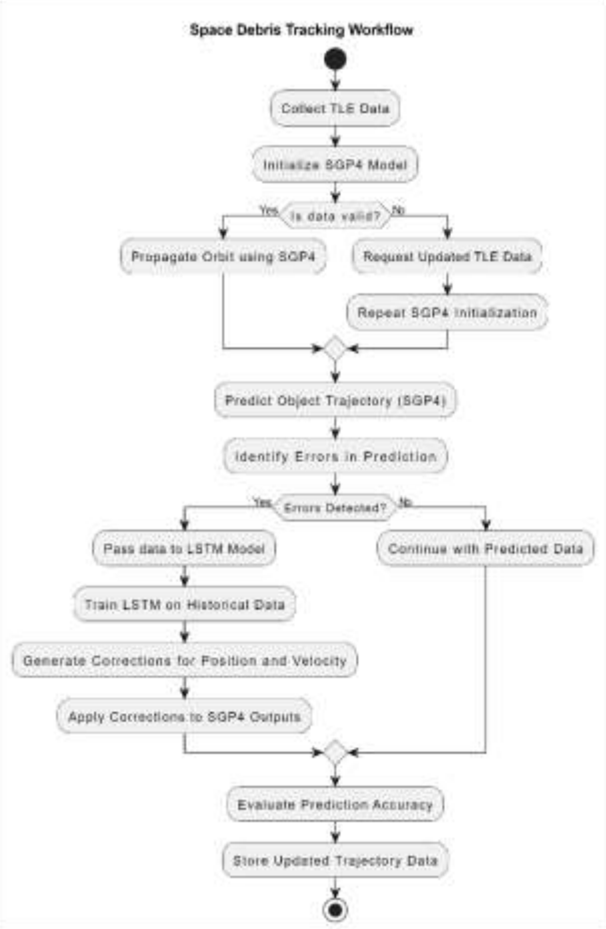

Figure 1: Work Flow Diagram

6. Action plan of Before Predicting and After Predicting and Correction Process Predictions Using LSTM

They are untimately used for predicting deviations in a model after undergoing through training from new test inputs. These deviations are then used to build corrections leading to improvements in the predicted positions and velocities generated by the SGP4. Correction Mechanism: The corrections (Δx,Δy,Δz,ΔVx,ΔVy,ΔVz) estimated by an LSTM are then added to the actual position and velocities produced by SGP4 providing more accurate estimates of the space debris' trajectory.

7. Evaluation Performance Metrics

The effectiveness of the enhanced model is tested through typical performance indices including Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE), between corrected prediction and observed data. Visualization: Scatter plots, line plots and 3D trajectory projections are created to compare predictions by SGP4 and predictions from the proposed LSTM model by highlighting regions where accuracy has improved. Error Analysis: An error histogram and distribution plot help understand how accurately the model removes the deviations over time to improve the reliability of the presented methodology.

8. Conclusion and Future Work Performance Summary

Interacting LSTM networks with the conventional SGP4 model thus performs enhanced trajectory prediction of space debris. The learning ability from historical data and ability to correct deviations from it guarantees better long-term tracking performance.

Future Enhancements: Other future studies can try to improve the conventional LSTM structure in a variety of ways; such as using deeper networks; trying out different types of activation functions; using more sophisticated recurrent architectures such as GRU etc. However,, it is possible to include other factors like external drag coefficients, solar refection coefficients, and gravitation pull values that will increase the prediction chances, thereby making the model even more versatile to real life situations.

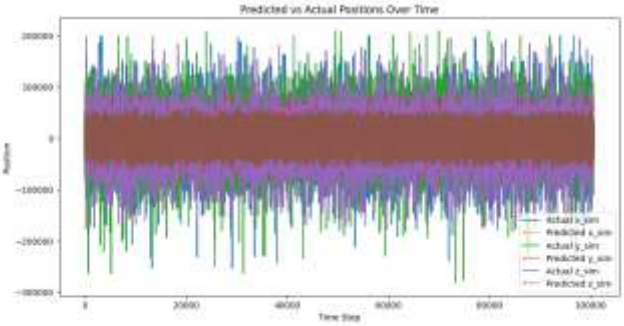

Figure 2: Time vs Position Graph

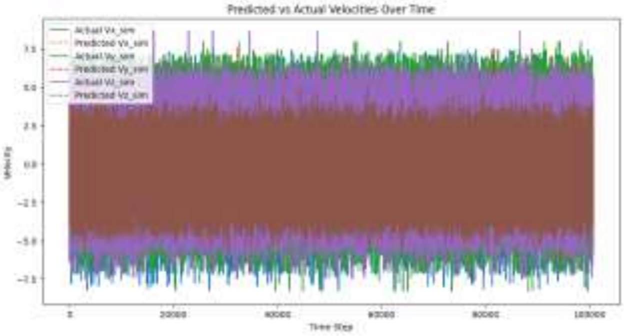

Figure 3: Time vs Velocity Graph

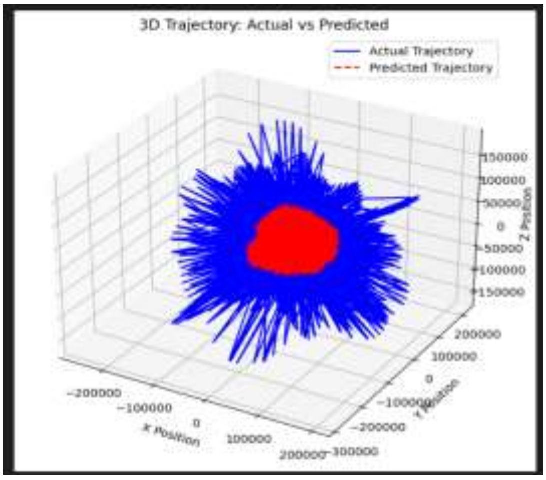

Figure 4: Actual vs Predicted Trajectory

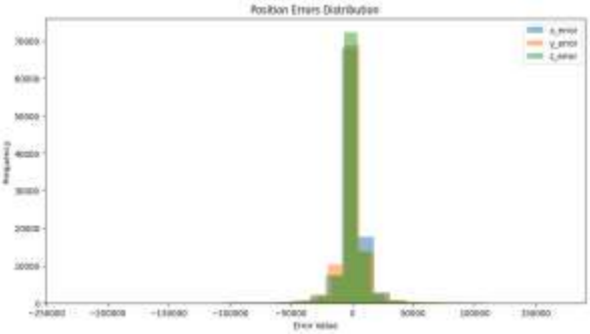

Figure 5: Position Errors Distribution

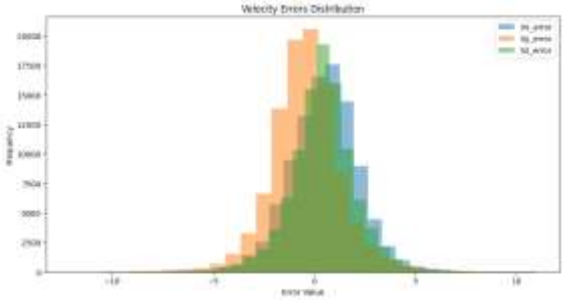

Figure 6: Velocity Error Distribution

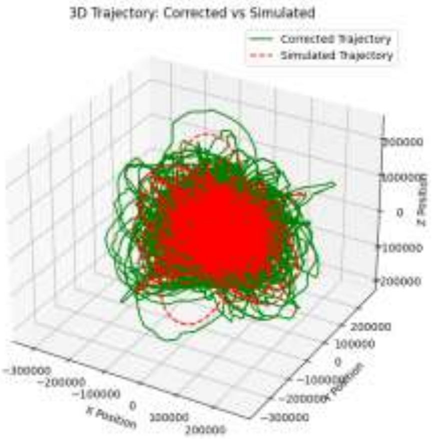

Figure 7: 3D Trajectory

VI. CONCLUSION

Space debris has become a threat to satellite operations, manned flights, and to future endeavors into space because any attempts at sustaining human activities in space are uncertain. Each of the models on the above include; TLE and SGP4, ORDEM, MASTER, DebriSat, SDebrisNet, SDTS CARA, and SSN describes the various approaches and models of tracking and disposal of space debris. But they also reveal quite a serious vulnerability or a gap that hinders their correct operation. Therefore, these limitations must be surmounted to enhance the current conception and attrition of space debris. This includes improving credible and timely collection and dissemination, probable integration of utilization of the advanced technology such as machine learning for the small debris identification and prediction, and sufficient surveying of the orbital area. Besides, interaction with other states and the establishment of a single system for tracking debris lead to the development of effective measures to address the issue. Therefore, stakeholders should look for ways to close these gaps for better further investigations of the last frontier without necessarily the shadow of space debris. Last but not least, the combination of the best options from the described models is going to be essential to provide an opportunity to adequately monitor, assess, and prevent

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