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Satsafe-Ai: Ai-Based Satellite Collision Prediction and Anomaly Detection System

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Abstract - The increasing population of operational satellites, inactive spacecraft, and orbital debris has intensified the need for continuous space-object monitoring and collision-risk assessment. This paper presents SATSAFE-AI, a real-data-based satellite safety monitoring system that integrates orbital data collection, orbit propagation, close-approach analysis, statistical anomaly detection, visualization, and simulated collision avoidance decision support. The system retrieves Two-line Element (TLE) records from CelesTrak and applies the Simplified General Perturbations 4 (SGP4) model to estimate satellite and debris positions and velocities at selected times. Relative position and separation-distance analysis is used to identify close approaches, while a ZScore-based method highlights observations that differ significantly from the measured orbital-data distribution. A web application developed using Python and Flask provides data management and monitoring functions, with MySQL used for persistence and CesiumJS and Plotly supporting orbital and analytical visualization. The system presents risk information and simulated orbit-adjustment recommendations for user examination; it does not command real spacecraft or execute manoeuvres. SATSAFE-AI therefore provides an integrated prototype for understanding orbital movement, investigating unusual behaviour, and supporting preliminary satellite-safety analysis. The paper describes the system design and methodology; quantitative performance claims are not made without validated experimental measurements.

Keywords—Satellite collision monitoring, space debris, TLE, SGP4, anomaly detection, Z-score, orbital analysis, collision-avoidance simulation.

I. INTRODUCTION

Satellites support essential services such as communication, navigation, weather forecasting, remote sensing, and scientific research. The growth in the number of active satellites, inactive spacecraft, discarded launchvehicle components, and debris fragments has increased congestion in Earth orbit. Orbital objects move at high relative speeds, and a collision involving even a small fragment may damage or disable an operational spacecraft. Monitoring orbital motion and identifying potentially hazardous close approaches are consequently important elements of space safety.

Satellite monitoring relies on orbital information and mathematical models to estimate the positions and velocities of space objects. Two-Line Element (TLE) data provides a standardized representation of orbital parameters, while the Simplified General Perturbations 4 (SGP4) model propagates those parameters to estimate an object's state at a selected time. Analysing multiple objects requires repeated propagation and comparison of their relative positions. In addition to close-approach analysis, unusual changes in orbital parameters may warrant further investigation.

SATSAFE-AI is developed as an integrated monitoring prototype that combines TLE collection, SGP4-based propagation, relative-motion analysis, close-approach identification, Z-score anomaly detection, and trajectory visualization. It provides a web-based interface through which users can inspect orbital data, view analysis outputs, and explore simulated avoidance recommendations. The recommendations are decision-support simulations only and are not transmitted to or executed by real satellites.

A. Problem Statement

The increasing number of satellites and space debris in orbit raises the risk of collisions that can damage satellites and disrupt missions. Existing systems mainly predict collisions but lack effective anomaly detection and trajectory analysis for early risk identification

B. Objectives

- To predict potential collisions between satellites and space debris using trajectory data with orbital parameters and Machine Learning techniques.
- To detect anomalies in satellite trajectories that may indicate abnormal movement or potential risk.
- To visualize satellite trajectories and orbital movement for better monitoring and analysis.
- To suggest possible avoidance maneuvers to reduce the risk of satellite collisions.

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II. LITERATURE SURVEY

Research in satellite safety spans orbital mechanics, debris tracking, collision-risk estimation, anomaly identification, and automated maneuvers planning. Conventional approaches use orbital data and mathematical propagation to estimate object states and compare their relative motion. These methods provide a physical basis for trajectory analysis, but large object populations and continuous updates make data handling and interpretation challenging.

Recent work explores artificial-intelligence methods for decision support and prediction. Reinforcement learning (RL) models learn actions from interaction with a simulated environment and have been investigated for collision-avoidance planning. Deep reinforcement learning (DRL) extends this approach using neural networks to handle more complex state and action spaces. Recurrent architectures, including gated recurrent units (GRUs), can represent sequential data. Physicsinformed neural networks (PINNs) incorporate physical constraints into learning and have been explored for estimating the motion of debris that is difficult to track directly.

The reviewed approaches address important but often specialized tasks. A practical monitoring interface can benefit from integrating data acquisition, propagation, close-approach screening, anomaly flagging, and visualization. SATSAFE-AI focuses on this integration rather than claiming a new orbital-dynamics model or a validated autonomous avoidance algorithm.

III. METHODOLOGY

SATSAFE-AI follows a sequential workflow. TLE records are retrieved from CelesTrak, validated and processed, and stored for subsequent analysis. The SGP4 model propagates selected objects to common timestamps. Their positions and velocities are compared to estimate relative separation and identify close approaches. Orbital observations are also examined using a Z-score threshold to flag statistical deviations. The outputs are stored or presented through the web dashboard, including visual trajectory displays and simulated avoidance decision support.

A. TLE Data Collection and Preprocessing

The system uses publicly available Two-Line Element records from CelesTrak. TLE records contain the orbital parameters and epoch required by the propagation model. Before processing, records are checked for availability and expected structure. The selected object information and orbital records are managed by the application and database. TLE freshness and consistency are important because propagation accuracy depends on the input record and its epoch.

B. SGP4 Orbit Propagation

SGP4 is used to estimate the position and velocity of an orbital object at a specified time from its TLE data. For each selected object, the application supplies the orbital record and target time to the SGP4 implementation. The resulting state vectors are used for trajectory display and relative-motion analysis. To compare two objects meaningfully, their states must be evaluated at compatible timestamps and in a consistent coordinate representation.

C. Close-Approach and Collision-Risk Screening

For two objects A and B propagated to the same time, the relative position is obtained from their state vectors. The separation distance can be represented as: $d(t) = \| r_A(t) - r_B(t) \|$ where $r_A(t)$ and $r_B(t)$ are the position vectors of the two objects. The system examines separation over the analysis interval and identifies the minimum observed distance as a close-approach indicator. Relative velocity can also be calculated from the difference between the velocity vectors. The resulting distance and relative-motion information are used to flag potential risk situations for review. This screening is not equivalent to a validated collision-probability calculation, which would require additional uncertainty and covariance information. **D. Z-Score-Based Anomaly Detection**

A statistical Z-score method is used to identify observations that differ substantially from the distribution of a monitored parameter. For an observation x, mean μ, and standard deviation σ, the score is:

$$Z = (x - \mu) / \sigma$$

The project report specifies a default threshold of 3.0. An observation whose absolute Z-score exceeds the threshold is flagged as an anomaly for further examination. Parameters described in the project include altitude, position, velocity, and speed. The method provides statistical alerts and does not, by itself, establish the cause of an unusual observation or confirm a satellite malfunction. A zero or near-zero standard deviation must be handled to avoid undefined or unstable scores.

E. Visualization and Decision Support

CesiumJS is used to present orbital objects and trajectories in a geospatial/three-dimensional view, while Plotly supports analytical plots. The dashboard presents satellite and debris information, close-approach indicators, anomaly outputs, and related monitoring results. The avoidance-support component enables examination of simulated orbit-adjustment options, including timing shifts along the track as described in the project. These are illustrative simulations; no command is sent to a spacecraft.

IV. TOOLS AND TECHNOLOGIES

The SATSAFE-AI system is developed using Python and Flask, with HTML, CSS, and JavaScript for the frontend and MySQL for database management. Pandas and NumPy are used for data processing, while Scikit-learn supports machine learning operations. SGP4 and Skyfield are used for orbital data processing and satellite trajectory analysis. CesiumJS and Plotly provide interactive visualization of satellite trajectories and orbital data. Satellite and space debris data are obtained from CelesTrak. Visual Studio Code, XAMPP, and phpMyAdmin are used as development and database management tools.

V. IMPLEMENTATION

The proposed SATSAFE-AI system follows a systematic approach for satellite safety monitoring and collision-risk assessment. Real-time Two-Line Element (TLE) data of satellites and space debris are collected from CelesTrak and periodically updated. The collected data are processed and validated to extract NORAD IDs and essential orbital parameters, which are stored in a MySQL database for further

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analysis. Satellite positions and velocities are calculated using the SGP4 orbital propagation model at the required timestamps, enabling trajectory analysis. Potential close approaches between satellites and space debris are identified through orbital and spatial screening, followed by detailed analysis of closest approach distance and relative velocity to assess collision risk. Statistical analysis of orbital parameters is performed to identify unusual variations in satellite position, velocity, and orbital behavior. The system provides interactive visualization of satellite positions, trajectories, and encounter information through CesiumJS and Plotly. Additionally, decision-support simulations evaluate possible along-track timing adjustments for highrisk encounters by comparing original and modified trajectories to examine improvements in separation distance.

VI. RESULTS AND DISCUSSION A. Satellite Orbital Data Analysis

The system collects real satellite and space-debris Two-Line Element (TLE) data from CelesTrak. The collected orbital information is processed to extract the required parameters for satellite monitoring and trajectory analysis. The data provides the foundation for identifying orbital positions and monitoring satellite movement.

B. Satellite Trajectory Prediction

Satellite positions, velocities, and orbital trajectories are generated using the SGP4 propagation model. The propagated orbital data supports trajectory analysis and helps determine the relative positions of satellites and space debris at selected timestamps.

C. Collision Risk Assessment

Potential collision risks are evaluated by analyzing the closest approach distance and relative velocity between satellite and space-debris objects. The calculated encounter parameters are used to assess collision risk and identify potentially close orbital encounters.

D. Satellite Anomaly Detection

Z-Score statistical analysis is applied to identify unusual variations in satellite orbital parameters. Changes in position, velocity, and orbital behavior are analyzed to identify potential anomalies and support satellite monitoring.

E. Orbital Trajectory Visualization

Satellite and space-debris positions and trajectories are visualized using CesiumJS and Plotly. The visualization provides a graphical representation of orbital movement and encounter information, supporting the analysis of satellite trajectories and potential close approaches.

F. Collision Avoidance Decision Support

Possible avoidance maneuvers are simulated for potentially high-risk encounters by introducing along-track timing adjustments. The original and modified trajectories are compared to evaluate changes in separation distance and examine the effectiveness of the simulated avoidance approach.

VII. CONCLUSION

SATSAFE-AI presents an integrated prototype for satellite and space-debris monitoring using publicly available orbital data. By combining TLE retrieval, SGP4 orbit propagation, relative-motion analysis, close-approach screening, Z-score-based anomaly detection, and interactive visualization, the system supports the examination of orbital movement and potentially hazardous situations. The Flask and MySQL-based application provides a consolidated interface for managing and reviewing the analysis, while CesiumJS and Plotly support graphical interpretation.

The system is intended as a monitoring and decision-support prototype. Its close-approach indicators should not be interpreted as validated collision probabilities, and its avoidance recommendations are simulations rather than real spacecraft commands. Future work identified in the project includes expanding the orbital data sources and dataset, improving collision prediction, enhancing anomaly detection, improving visualization, refining avoidance simulation, and enabling more continuous monitoring. Further evaluation could also incorporate uncertainty-aware conjunction assessment, larger-scale processing, and documented quantitative testing, subject to the availability of suitable data and validation.

VIII. FUTURE SCOPE

The SATSAFE-AI system can be further enhanced through the following improvements: **A. Integration of Additional Satellite Data:**

Incorporating more satellite and space-debris data from multiple sources can improve orbital coverage and monitoring capabilities. **B. Improved Collision Prediction:**

Advanced prediction techniques can be explored to improve collision-risk assessment and identify potential close approaches more accurately.

C. Enhanced Anomaly Detection:

Advanced machine learning and statistical methods can be integrated to improve the detection of abnormal satellite orbital behavior. **D. Advanced 3D Visualization:**

The visualization module can be enhanced with more detailed 3D orbital representations, interactive trajectory analysis, and improved monitoring interfaces. **E. Improved Collision Avoidance Simulation:**

More advanced maneuver simulation techniques can be explored to evaluate alternative avoidance strategies and improve separation between objects. **F. Scalability and Performance Optimization:**

The system can be optimized to support a larger number of satellites and space-debris objects while improving data processing and monitoring efficiency.

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REFERENCES

[1] Tracking an Untracked Space Debris after an Inelastic Collision using Physics-Informed Neural Network (2024) https://doi.org/10.1038/s41598-024-51897-9

[2] Predictive Modelling for Assessing Collision Risk of Space Debris with Operational Satellites (2024) https://link.springer.com

[3] An On-Orbit Servicing Framework for Satellite Collision Avoidance: Towards Autonomous Mission Planning with Reinforcement Learning (2025) https://www.sciencedirect.com

[4] Spacecraft Autonomous Collision Avoidance and Maneuverer Based on Deep Reinforcement Learning (2025) https://arxiv.org

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