Detecting Anomalies in Satellite Orbit Data

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Feburary 22, 2025

1 Introduction

The increasing number of objects in Earth's orbit necessitates accurate tracking to ensure collision avoidance and satellite functionality. The 18th Space Defense Squadron publishes daily orbital data in the Two-Line Element (TLE) format, which records the trajectory of thousands of orbiting objects. Detecting anomalies in this data is critical for identifying potential satellite maneuvers and unexpected events. This project aims to apply time-series anomaly detection techniques to identify such anomalies in the TLE dataset.

2 Background

Satellite maneuvers are intentional or unintentional changes in their orbits. These can result from station-keeping maneuvers, collision avoidance, or malfunctions. Identifying these maneuvers from TLE updates is a challenge, as the data contains both normal and anomalous orbital updates. Traditional anomaly detection techniques in time-series data, such as statistical forecasting models and machine learning-based approaches, can help uncover these anomalies. Prior research suggests that forecasting deviations in orbital elements can be indicative of maneuvers.

3 Methods

To detect anomalies in the TLE dataset, we propose implementing two anomaly detection techniques:

1. **ARIMA-Based Forecasting:**
   - ARIMA (AutoRegressive Integrated Moving Average) is a statistical model that predicts future values based on past observations.
   - The model will forecast the orbital elements for the next timestamp, and deviations between the predicted and observed values will be analyzed for anomalies.
2. **Gradient Boosted Trees (XGBoost, CatBoost, LightGBM):**
   - These machine learning models use ensemble techniques to improve prediction accuracy.
   - The models will be trained on past orbital data to predict future states, and anomalies will be flagged where residuals exceed a threshold.

The dataset will require preprocessing, including cleaning the maneuver timestamp data and handling format inconsistencies between different satellite groups (e.g., Fengyun vs. non-Fengyun satellites). The evaluation will compare detected anomalies against ground-truth maneuver timestamps using precision, recall, and F1-score.

4 Data Analysis and Initial Findings

The dataset consists of orbital elements recorded at various time points, along with labeled maneuver timestamps. Initial readings suggest that anomalies manifest as abrupt deviations in parameters such as semi-major axis, eccentricity, and inclination. These deviations must be systematically analyzed to differentiate between normal orbital perturbations and actual maneuvers.

Additional literature on anomaly detection in satellite tracking suggests that hybrid approaches combining statistical and machine learning methods may improve detection accuracy.

4.1 Implementation Plan

1. **Data Preprocessing:**
   - Standardize the TLE format and clean maneuver timestamp data.
   - Handle missing values and format inconsistencies.
2. **Model Development and Training:**
   - Implement ARIMA for time-series forecasting and residual-based anomaly detection.
   - Develop gradient boosted trees for anomaly classification.
3. **Evaluation and Comparison:**
   - Compare detected anomalies against ground-truth maneuvers.
   - Compute precision, recall, and F1-score for performance assessment.
4. **Refinement and Finalization:**
   - Optimize models based on evaluation results.
   - Perform comparative analysis to determine the best approach.

5 References

Relevant literature and data sources will be reviewed to refine the methodology. Further exploration of anomaly detection algorithms beyond the suggested techniques may be considered to enhance performance.

This proposal outlines the preliminary steps toward detecting anomalies in satellite orbit data. The project will iteratively refine the methodology based on findings and evaluation results.