Blockchain-Enabled Predictive Tool for Satellite Management

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Abstract

The growing complexity of satellite operations requires an advanced and secure monitoring system to ensure data integrity, system reliability, and operational efficiency. Traditional satellite monitoring frameworks rely on centralized data management, which is vulnerable to cyber threats, data loss, and unauthorized modifications. This study presents a Blockchain-Enabled Prediction System that acts as a supporting tool for existing satellite monitoring infrastructures. The proposed system utilizes Hyperledger fabric to establish a tamper-proof ledger for storing satellite telemetry data, ensuring data security and traceability. Unlike conventional models, the blockchain architecture guarantees immutability, enabling secure and verifiable satellite performance monitoring. A web-based dashboard is integrated to facilitate real-time alerts and parameter visualization. The implementation of smart contracts allows for automated validation and alert generation when anomalies are detected in satellite parameters. The performance of the system is evaluated in terms of transaction efficiency, security validation, and integrity assurance, demonstrating its feasibility for scalable and secure satellite operations.

Keywords: Satellite Management, Downtime Prediction, Hyperledger Fabric, Supervised Learning.

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1. Introduction

Satellite management involves the continuous monitoring and control of satellite systems to ensure optimal performance and mission success in space environments. Modern satellite networks face challenges related to data security, real-time monitoring, and anomaly detection. Traditional monitoring systems often suffer from centralized vulnerabilities, where unauthorized access or single-point failures can compromise the integrity of satellite telemetry data. Additionally, existing systems lack transparent traceability, making it difficult to verify historical logs in case of discrepancies. cyber threats, such as data interception and tampering, further threaten the reliability of satellite communications.

This study introduces a blockchain-enabled monitoring system to enhance security and transparency in satellite network operations. By analysing historical datasets to detect the anomalies, the system can predict potential satellite failures allowing operators to take preventive actions. The Hyperledger Fabric platform is used to create an immutable ledger, ensuring that all telemetry logs remain unaltered. Unlike traditional models, which rely on centralized data storage, the proposed system uses decentralized verification mechanisms to ensure data authenticity.

- Development of a Web-Based Dashboard for monitoring and enabling satellite operators to access telemetry data securely.
- Integration of supervised learning algorithm for satellite health monitoring, enabling detection of anomalies and potential failures based on historical dataset.
- Design and Implementation of a blockchain-based satellite monitoring system that integrates hyperledger fabric for secure and tamper-proof data logging.
- Evaluation of performance metrics, including transaction speed, and blockchain scalability for satellite telemetry data.

By comparing the performance of this tool with traditional satellite monitoring systems, we demonstrate how the addition of blockchain not only improves predictive accuracy but also enhances data integrity and verifiability. This innovative solution is ideal for applications where the reliability and integrity of satellite data are paramount, such as in government, military, and corporate environments.

2. Related Work

The integration of blockchain technology in satellite monitoring is an emerging field that addresses concerns related to data security, transparency, and predictive maintenance. Previous research has explored multiple approaches to ensuring satellite data integrity, fault tolerance, and predictive analytics for anomaly detection.

A. N. Bikos et al [1] explores how blockchain enhances space security, focusing on secure data storage and access control. Its approach aligns with the proposed sudy by utilizign the blockchain for encrypted file management and tamper-proof key sharing using cryptographic methods. Meanwhile, A. Baliga et al [2] takes an experimental approach, where they study the throughput and latency characteristics of fabric by subjecting it to different sets of workloads. V. Okanovic et al [3] investigates the development of dynamic web application using web frameworks based on web components. The study considers several existing open-source Java web component frameworks. Blockchain technology has gained attention as a solution for ensuring data immutability and security. Androulaki et al. [4] provided a foundational overview of Hyperledger Fabric, highlighting its role as a permissioned blockchain framework capable of supporting secure and tamper-proof data storage. Sentencing Commission [5] discussed the relevance of blockchain in emerging technologies, emphasizing the benefits of decentralized architectures in secure data management. Similarly, Torky, M.et al. [6] uses Proof of Space Transactions (POST), using Ethereum to secure and authenticate peer-to-peer satellite communications within constellations, utilizing Space Digital Tokens (SDT). It demonstrates the protocol's efficiency and security through performance metrics like latency, throughput, and accuracy.

Hassanien A. E et al.[7] A blockchain-based protocol using Space Digital Tokens (SDTs) to securely authenticate satellite transactions. The Ethereum-based implementation demonstrates post’s efficiency through performance metrics like latency, throughput, and transaction cost, ensuring secure and reliable satellite communications. The increasing role of blockchain in space operations is also emphasized by Razzaq, Abdul et al. [8], it explores secure big data management in remote sensing using blockchain, ensuring decentralized storage by using blockchain for encrypted file storage, hidden data management, and secure key retrieval mechanisms. Samira Gholizadeh et al. [9] deals with python libraries that effectively simplify many important processes such as analysing and visualizing data, retrieving unstructured data from the web and textual information. In the domain of predictive analytics, Yihan Jing et al [10] analyses satellite operator's sales strategies and finds that blockchain technology can enhance profits and consumer utility, especially in SataaS and dual-channel models. Gorenflo et al. [11] introduced fast fabric, a system designed to scale Hyperledger Fabric to process up to 20,000 transactions per second, making it a practical option for high-frequency telemetry logging.

Similarly, Hussein A. Ibrahim et al [12] used blockchain in satellite swarms to enhance reliability and availability by distributing data across nodes, showing significant improvements compared to traditional networks. Recent work by Quan Zou et al [13] proposes a multi-level blockchain architecture for secure remote sensing data management, integrating IPFS for decentralized storage and Ethereum for public query access. This approach enhances data security, traceability, and efficiency, addressing challenges in handling large-scale remote sensing datasets.

Zyskind et al. [14] introduced a decentralized approach to protecting sensitive data using blockchain, a concept that aligns well with the security needs of satellite telemetry systems. Several studies have investigated the role of blockchain in securing space-based communications . Ochuba, N. A et al [15] used predictive analytics in real-time data and AI to forecast failures in satellite telecommunications, enabling proactive maintenance and reducing downtime. It enhances reliability by analyzing sensor data to optimize operations, though it requires addressing data security and integration challenges. The overall existing literature demonstrates the significance of blockchain technology in securing satellite telemetry data while also highlighting the growing role of prediction in satellite maintenance.

3. Proposed Work

The predictive tool for satellite downtime management is designed to enhance the monitoring, forecasting, and management of satellite operations. By utilizing Hyperledger Fabric, preventing unauthorized modifications and enhancing trust in satellite telemetry data. The tool integrates supervised learning to predict potential failures and anomalies, allowing proactive maintenance and operational adjustments.

3.1 System Components and Functionality

1. Prediction Module

- Analyses historical satellite telemetry data to identify patterns and trends.
- Forecasts potential system downtimes using a supervised learning approach, specifically utilizing a linear regression algorithm.
- Facilitates proactive decision-making by enabling pre-emptive measures to mitigate operational failures.

2. Data Logging Mechanism

- Maintains a comprehensive, immutable record of all predictions and operational events.
- Ensures tamper-proof data storage and enables historical traceability through blockchain-based logging.

3. Secure Data Retrieval

- Provides authorized operators with access to verified and unaltered telemetry records.
- Enhances data integrity and security by utilizing blockchain technology to prevent unauthorized modifications.

3.2 Application Interface

3.2.1 Satellite Data Collection

The process begins by analysing satellite operational data, which is a historical dataset. The operational data includes parameters like battery level, signal strength, and temperature (Table 1). Using a Python-based approach, the system applies predefined conditions to assess the satellite's health and predict possible downtime.

Table 1. Sample Historical Logs

Satellite_ID	Battery_Level	Signal_Strength	Temperature
sat1	100	20	60
satid122	45	100	60
sat3	100	100	60
sat4	50	60	40
sat5	75	80	55
Id765	30	40	70
Id924	90	70	65
Id149	60	90	50
Id367	85	50	45
Id146	40	30	75

i. **Battery Level**: Monitors power availability and ensures satellites have sufficient charge for operation.

ii. **Signal Strength**: Evaluates communication stability between the satellite and ground stations.

iii. **Temperature**: Assesses internal system health and potential overheating risks.

Anomaly is predicted based on this predefined condition,

- If the signal strength drops below 30%, a weak signal alert is generated.
- If the temperature exceeds 75°C or drops below 10°C, a temperature out-of-range alert is issued.
- If radiation levels detected by the satellite exceed safe operating limits (e.g., 500 rads), a radiation alert is triggered.
- If solar panel efficiency falls below 60%, a low power generation alert is triggered.

- If Thruster Fuel Level for the satellite's thrusters falls below 15%, the system raises a low fuel alert.

This anomaly detection conditions were predefined based on domain-specific knowledge and operational thresholds. These established as part of this study, ensure real-time identification of potential satellite failures and facilitate proactive maintenance measures.

3.2.2 Blockchain Integration (Hyperledger Fabric Network)

Each satellite status check is securely logged using Hyperledger Fabric's blockchain network, ensuring data integrity and traceability. After the analysis, the results are recorded on the blockchain ledger.

Each block in the blockchain contains:

i. **Blockchain ledger**: A secure, tamper-proof storage system that maintains a sequential chain of blocks, storing every satellite telemetry record and anomaly prediction.

ii. **Timestamp:** Records the time of the satellite status check.

iii. **Satellite Data:** Contains the analysed satellite data, such as battery level, signal strength, and temperature. Figure .1 shows the pseudocode of the sample node structure for each data stored in the ledger and Table 2 shows the technical stack of the hyperledger fabric used.


```
{
 "Satellite_ID": "sat123",
 "Battery_Level": 85,
 "Signal_Strength": 75,
 "Temperature": 60,
 "Predicted_Status": "Stable",
 "Anomaly_Detected": "No",
 "Time_Stamp": "2025-03-08T12:30:00Z"
}
```


Figure 1. Sample Node Structure for Each Data Stored in Ledger

Table 2. Technical Stack of Hyperledger Fabric Used

Component	**Technology Used**	**Purpose**
Blockchain Framework	Hyperledger Fabric	Secure, permissioned blockchain network
Smart Contracts	Chaincode	Defines logic for telemetry validation & anomaly detection
Event Handling	SetEvent() API	Triggers alerts when anomalies occur
Backend API	Flask (Python)	Interfaces with the blockchain to query data
Data Processing	Pandas, NumPy	Formats telemetry data for storage
Prediction Model	Scikit-learn(Linear Regression)	Analyzes historical telemetry data for failure prediction

iv. Hashing Predicted Results

Equation: $H=SHA256(B(t)+S(t)+T(t))$

where:

- H is the hashed value,
- B(t),S(t),T(t) are telemetry parameters at time t
- SHA256 prevents unauthorized alterations

This generates a unique hash for each telemetry record before storing it into Hyperledger Fabric, making it immutable. Any unauthorized modification changes the hash, enabling anomaly detection and security verification using smart contracts. The role of the hyperledger fabric is illustrated in Figure 2.

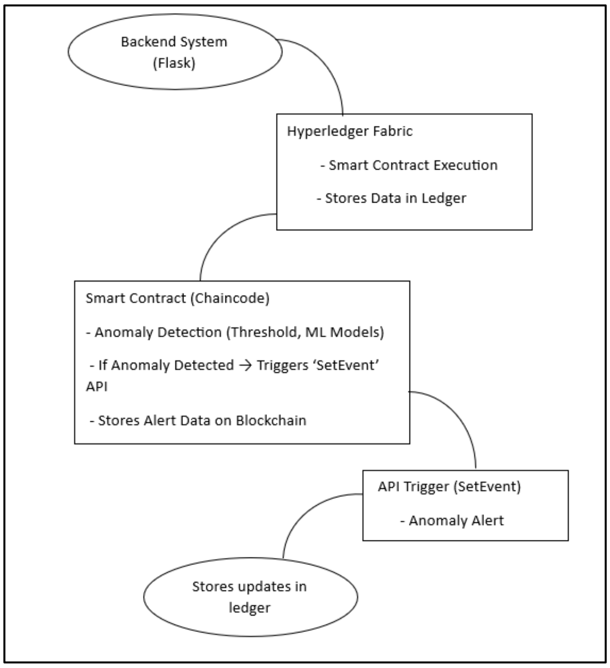

Figure 2. Role of Hyperledger Fabric in Blockchain on Storing Satellite Updates

v. Smart Contract Implementation

Smart contracts automate telemetry data management by logging satellite parameters such as battery level, signal strength, and temperature. It ensures that only authorized users or system processes can update telemetry data.

- The chain code checks telemetry parameters against predefined thresholds.
- If no anomaly is detected, the telemetry data is stored normally in the blockchain.
- If an anomaly is detected, SetEvent is triggered.

vi. Triggering SetEvent() API in Hyperledger

The SetEvent API in Hyperledger Fabric is responsible for triggering real-time alerts when anomalies are detected in satellite telemetry data and considering the issues as an event. This ensures that operators are notified immediately while maintaining an immutable record of the event in the blockchain. Figure 3 depicts the workflow of SetEvent API.

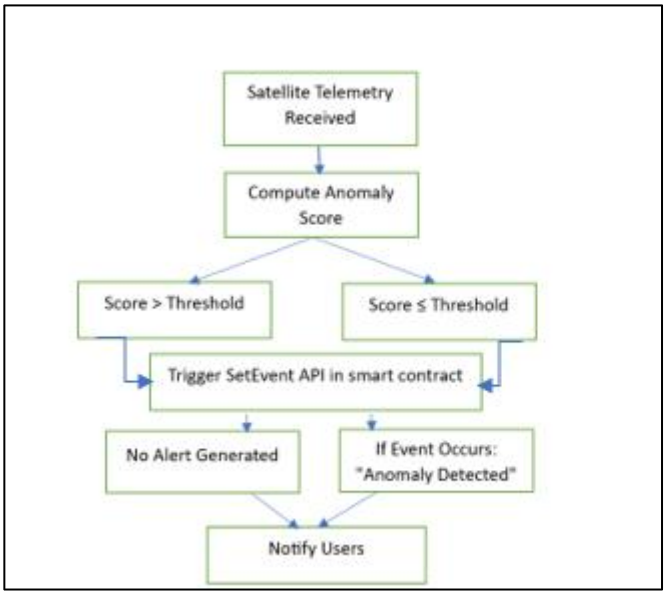

Figure 3. SetEvent API Workflow

vii. Docker and Docker Compose

Docker and Docker Compose are used to containerize and efficiently deploy the satellite monitoring system. Docker creates isolated containers for different components, such as Hyperledger Fabric, the Flask web application, and the data processing module. Docker Compose manages multiple containers by defining services in a docker-compose.yml file, ensuring seamless interaction between blockchain nodes, smart contracts, and the web dashboard. This setup allows for easy deployment and system portability, ensuring that the predictive monitoring tool runs consistently across different environments.

viii. Purpose and Scope

The integration of Hyperledger Fabric ensures that any attempt to modify satellite data will be immediately detected, preserving the integrity of the system. By securely logging all satellite status checks and predictions on an immutable blockchain ledger, this study provides a trustworthy framework for satellite telemetry management. It enhances data security ensuring that all recorded telemetry and anomaly detections remain protected from unauthorized modifications.

3.2.3 User Interface

This system is designed to operate efficiently using minimal hardware requirements. It uses a Python-based web application built with Flask to handle user input and output, and Pandas and NumPy for data processing and analysis. The web interface allows users to input a satellite ID and retrieve the satellite's status.

i. Libraries used:

- **Flask:** Manages the web server and handles requests for satellite telemetry data. It facilitates communication between the user interface and the backend, allowing operators to retrieve satellite status and alerts.

- **Pandas:** Handles reading, processing, and manipulating telemetry datasets, including battery level, signal strength, and temperature data. It enables efficient data structuring and analysis for anomaly detection.

- **NumPy:** Performs numerical computations to analyze telemetry data, helping to identify deviations from normal satellite performance. It is used for efficient array handling and mathematical operations in processing satellite parameters.

- **Scikit-learn**: Predict satellite anomalies and failure time using Linear Regression algorithm (supervised learning) based on historical telemetry data. The model learns patterns from past satellite logs to provide accurate predictions, ensuring early fault detection.Figure ,4 illustrates the parameter fluctuations across different satellites. The algorithm 1 depicts the work flow of hyperledger fabric for anomaly detection.

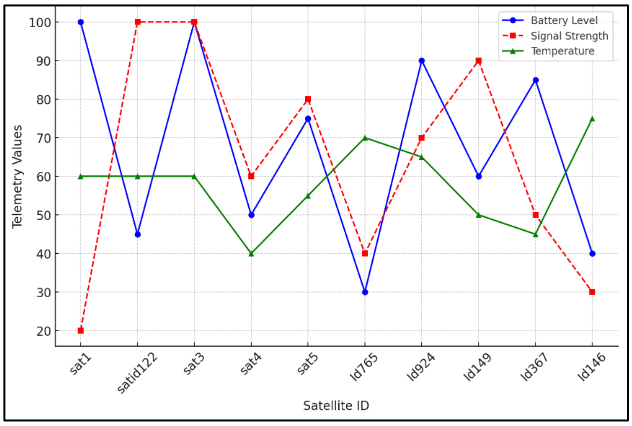

Figure 4. Parameters Fluctuations Across Different Satellites

Algorithm 1 : Hyperledger fabric for Anomaly Detection

1. BEGIN
2. INITIALIZE system
3. WHILE True:

    telemetry_data = GET_SATELLITE_DATA()

    formatted_data = FORMAT_DATA(telemetry_data)

    anomaly_score = DETECT_ANOMALY(formatted_data)

    hashed_data = HASH_DATA(formatted_data)

    STORE_IN_BLOCKCHAIN(hashed_data)

    status = FETCH_STATUS_FROM_BLOCKCHAIN()

    DISPLAY_STATUS_WEB(status)

4. IF anomaly_score > threshold:

    ALERT_OPERATORS()

    UPDATE_BLOCKCHAIN_LEDGER()

5. TERMINATE system
6. END

3.3 Flowchart:

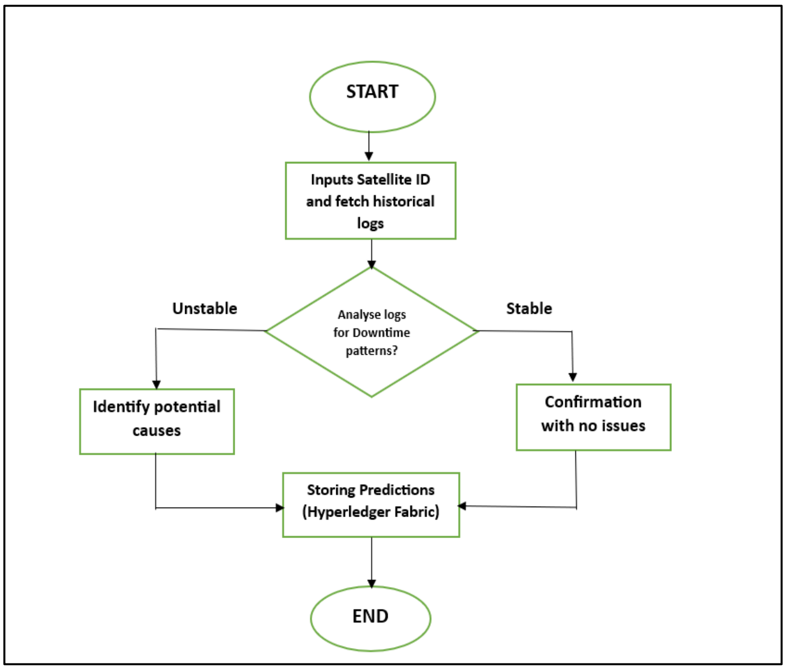

Figure 5. Working Methodology for Analysing Satellite Performance

This flowchart in Figure 5 illustrates the satellite monitoring process. It begins by fetching historical logs using the satellite ID. Logs are analyzed for downtime patterns, leading to either identifying potential causes for instability or confirming stability. Predictions are then stored in Hyperledger Fabric.

3.4 Block Diagram:

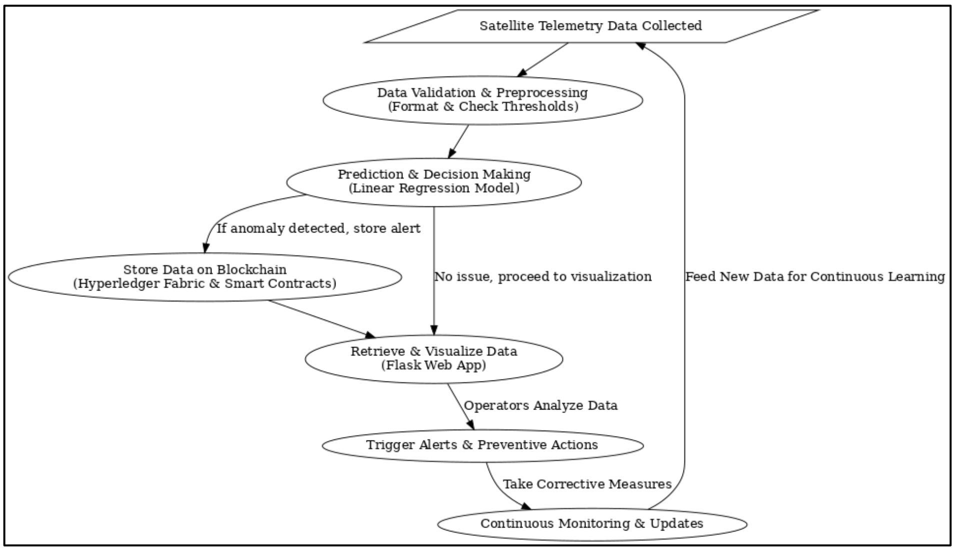

Figure 6. Satellite Data Processing Workflow

Figure 6 depicts a comprehensive satellite telemetry data processing pipeline. Raw telemetry data undergoes validation and preprocessing, including format checks and threshold assessments. A linear regression model predicts potential anomalies, triggering alerts and blockchain storage through Hyperledger Fabric and smart contracts. Non-anomalous data is visualized using a Flask web application for operator analysis. Based on the analysis, operators initiate alerts and preventive actions, leading to corrective measures and continuous monitoring. The system incorporates continuous learning by feeding new data back into the process, ensuring adaptive and efficient satellite management.

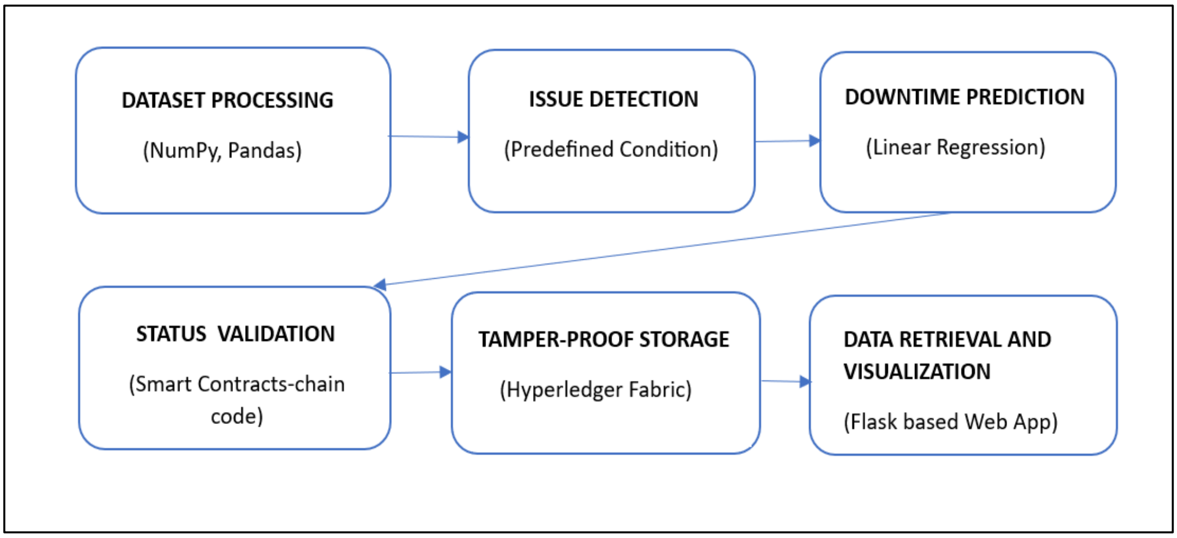

Figure 7. Workflow of the Proposed System

Figure 7. illustrates the workflow of the complete system and its steps are as follows.

Step 1: Initialize the process.

Step 2: Process the dataset using NumPy and Pandas library used in ML-python.

Step 3: Retrieve real-time satellite data (Battery Level, Signal Strength, Temperature)

Step 4: Format the collected data and apply predefined conditions(e.g.,<30% in battery level) to analyse telemetry data and detect anomalies.

Step 5: Applying Linear Regression algorithm under supervised learning ML model to predict potential downtimes.

Step 6: Using smart contracts validate the status, if no issues detected, results are stored in ledger otherwise notify the user through the web app.

Step 6: Hash the telemetry data and store it in hyperledger fabric to ensure tamper-proof logging.

Step 6: Fetch the satellite status from the blockchain and display them through a Flask-based web Application.

Step 8: The system continuously processes new telemetry data, updating the blockchain ledger and refining predictions.

Step 9: Terminate the process.

4. Results and Discussion

4.1 Workflow

Input: The input comprises historical logs collected from satellites. These metrics include important parameters. The user provides a specific satellite ID, which serves as the identifier for the system to retrieve and analyse the corresponding satellite's operational data.

Output: The output presents the current operational status of the identified satellite. It indicates whether the satellite is online or offline using the predefined conditions. If the satellite is experiencing issues, the output details the specific problems. Based on the analysed parameter level consists of the satellite's operational status and predicted results as illustrated in Figure 8 to 11.

Figure 8. User Input for Specific Satellite ID’s

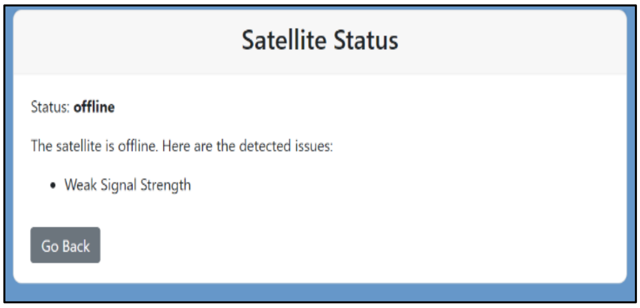

Figure 9. Status of the Satellite with Predicted Issues

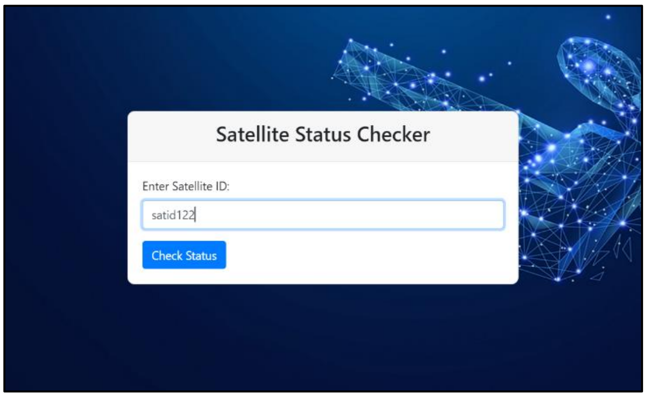

Figure 10. User Input for Specific Satellite ID's

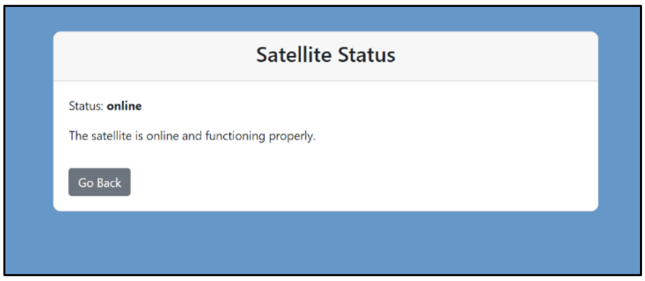

Figure 11. Stable Status with No Possible Issues

4.2 Performance Metrics:

The system's evaluation time, encompassing both status determination and blockchain logging, averaged 3.5 seconds per satellite. This duration was observed to directly correlate with the size of the satellite data being processed, indicating a linear increase in processing time as data volume grows.

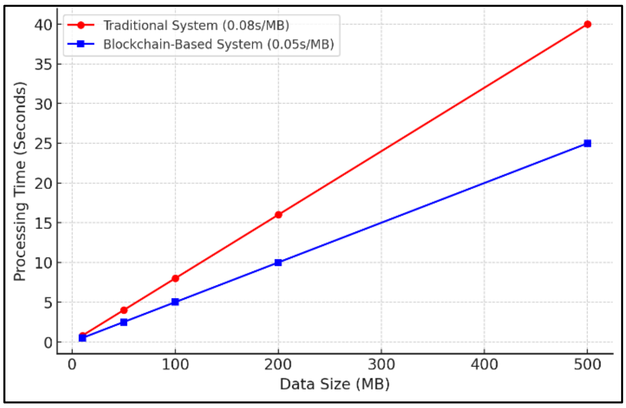

Figure 12. Processing Time vs. Data Size

The graph in Figure 12 illustrates the relationship between data size and processing time for both the traditional system and the proposed blockchain-based system. The traditional system exhibits a higher processing time leading to delays as data volume increases. In contrast, the blockchain-based system processes data more efficiently, ensuring faster evaluations and real-time updates

5. Future Enhancements

The system is so far designed to efficiently collect, process, and analyse operational parameters and provide users with insights into satellite performance. The Flask-based web interface allows operators to access telemetry data based on predefined conditions. While the core functionalities of data collection, processing, and anomaly detection have been successfully implemented as shown in the results, the integration of blockchain technology is still in progress. The goal is to incorporate Hyperledger Fabric to enhance data security and immutability, ensuring that telemetry records remain tamper-proof. The technological stack used in the system has been briefly explained above, outlining the tools and frameworks that support its development and future enhancements. As development continues, efforts are being made to establish a seamless connection between the existing system and blockchain infrastructure, enabling a decentralized and verifiable approach to satellite data management. Additionaly, the system aims to improve integration with advanced technologies. The implementation of AI-driven predictive analytics can enhance anomaly detection by learning from historical telemetry data. These improvements will ensure long-term reliability, efficiency, and adaptability in satellite monitoring and management.

6. Conclusion

The Satellite Downtime Prediction Tool ensures secure and accurate satellite monitoring by integrating predictive analytics with blockchain technology. It analyses satellite operational parameters to forecast potential failures, enabling proactive maintenance and reducing unexpected downtimes. Hyperledger Fabric creates an immutable ledger, ensuring tamper-proof storage and preventing unauthorized modifications. Each status check generates a new blockchain block, securely logging operational data with timestamps for future verification. The decentralized system enhances data integrity, transparency, and accountability in satellite management. By providing traceability and security, the tool is ideal for aerospace, government, and telecommunications sectors. This approach ensures long-term reliability, making it a robust solution for critical satellite operation.

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