

Fault Detection Algorithm Implementation for Distributed Sensor Networks

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1 Abstract

This work presents the development of a data-driven digital twin at sensor level for structural health monitoring of a metallic suspension bridge in Portugal, with a focus on local validation of strain sensors using long-term monitoring data acquired between 2014 and 2017. The central challenge lies in the automated distinction between normal environmental variations and the onset of critical sensor faults. Using the Prophet library, the proposed model effectively captured the dominant 12-hour and 24-hour cycles governing bridge behavior. The results demonstrate that integrating external temperature and solar position as predictive variables results in a substantial improvement compared to models based solely on solar radiation, reducing the Mean Absolute Percentage Error to 2.5%. The anomaly detection system, based on a Binomial Hypothesis Test, exhibited high sensitivity, successfully identifying debonding faults as small as 5%. It is concluded that the reliability of the digital twin depends on empirically calibrated control limits, as the theoretical uncertainty intervals provided by the software proved unreliable for this application. Overall, this work establishes a robust methodology for long-term sensor self-validation in critical infrastructure.

Keywords: Sensor Network, Local Fault Detection, Digital Twin, Strain Sensors.

2 Introduction

The structural integrity of critical civil infrastructures, such as metallic suspension bridges, is an absolute priority. Ensuring the safety and long-term durability of these structures relies on Structural Health Monitoring (SHM) systems, which are based on sensor networks providing continuous and reliable data on structural response. A central challenge in such systems lies in the automated analysis of large volumes of data, particularly in accurately distinguishing between normal operational variability and the emergence of potentially critical faults within the sensor network [2]. This work addresses this challenge through the development of a digital twin at sensor level: a data-driven model designed to replicate the normal behavior of strain sensors installed on metallic suspension bridges.

3 Methods

The analysis relied on a curated subset of sensor data from 2014 to 2017 to ensure statistical control and reliable modeling of normal structural behavior. Hourly strain and temperature data were preprocessed to address missing values, and Welch's spectral method identified dominant 24-hour and 12-hour cycles. Solar position features were engineered using pvlib, and forecasting was performed with the Prophet library. Two models were evaluated: one using only solar position and another including both solar

position and temperature, with performance assessed via Mean Absolute Percentage Error (MAPE). A statistical control framework based on a Binomial Hypothesis Test (BHT) was applied to detect anomalies, and its sensitivity was evaluated through simulated debonding faults derived from Reis et al. [2].

4 Results

For the 2014 dataset, solar position features (azimuth and altitude) were computed using the bridge's geographical coordinates. The data was split into training and testing subsets. Model A, a Prophet-based forecast using only solar position as external regressors with a 99.73% prediction interval, achieved a MAPE of ~5% in cross-validation and showed strong agreement with the test set, with only one statistically insignificant anomaly detected via the BHT. Model B incorporated temperature as an additional regressor, following the same procedure, and achieved a lower MAPE of ~2.5%, maintaining statistical control. Model B consistently outperformed Model A, demonstrating that temperature is essential for complex and long-term forecasting, as reflected in results for 2015–2017. A debonding fault simulation based on Reis et al. [2] confirmed the system's high sensitivity, detecting statistically significant anomalies with only 5% simulated debonding, showing clear deviations from model predictions.

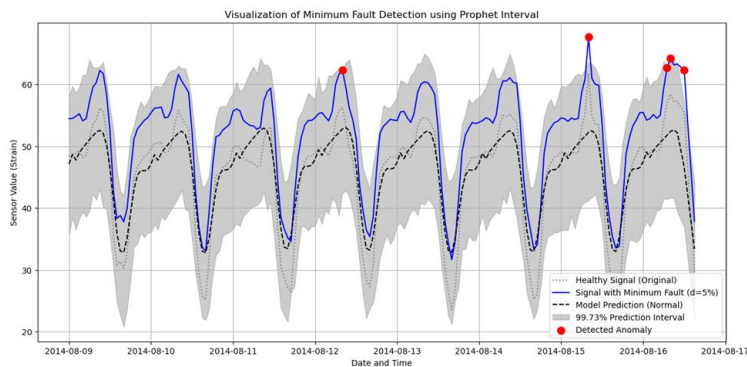


Fig. 1. Anomaly detection model of a debonding fault simulation assuming a 5% debonding level.

5 Conclusions

This project developed and validated a data-driven local sensor validation method for metallic suspension bridges, designed for integration within a digital twin framework, demonstrating that the Prophet model, enhanced with solar position and temperature regressors, can effectively capture complex strain sensor behavior. Future work will extend the validation to 2015–2020 data and further refine the statistical control strategy.

References

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