Hybrid Sensor System Using a Profile-Based Reference Sensor

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1. Introduction

With the growing use of sensor data, data analysis services are being implemented, resulting in a more analysis-friendly environment." In a Nuclear Power Plant (NPP), the stability of sensor systems is crucial. ASTM standards are selected for their ability to provide reliable operation and critical integrity monitoring in harsh environments [1,2].

To ensure the stability of sensor systems, multiple sensors and reference sensors are used [3]. The concept of mathematical replication in a sensor context can be used for modeling complex systems. In this work, this concept may be applied to the idea of redundancy and increased reliability.

In this paper, we propose a hybrid sensor system to ensure the reliable operation of a sensor using a reference sensor. Integrating multiple sensors provides a hybrid system for more comprehensive and accurate data. This results in a more robust and reliable sensing solution.

2. Methods and Results

2.1 Problem Statement

Reliability issues in sensor systems can arise from problems inherent in the sensors themselves, such as sensor defects, sensor aging in a harsh environment. If a sensor system generates unreliable and anomalous data, it can lead to incorrect decision-making or malfunctions. When sensor does not operate normally due to internal or external factors, the measured value of the sensor becomes invalid.

Data detected by a single sensor deployed in harsh environments is insufficient and unreliable for decision-making. To tackle the problem, multiple sensors are considered, but their implementation is costly. Instead, a software-defined reference sensor is used to minimize the inherent uncertainty of the acquired sensor data.

We assume that ultrasonic sensor data from pipes in the NPP can use Singular Value Decomposition(SVD) to create a software sensor that predicts the normal behavior of the sensors. Deviations from this predicted behavior might indicate a leak or other anomaly.

2.2 SVD based Sensor Profile

SVD is a matrix factorization technique that enables the decomposition of data into fundamental components, facilitating pattern identification, noise filtering, and dimensionality reduction. It decomposes a matrix A into three other matrices: U, Σ, and V^T as defined in Equation (1).

(1) $A = U \Sigma V^T$

where,

U : A left singular matrix.

Σ : A diagonal matrix containing singular values.

V^T : The transpose of the right singular matrix.

Meaningful features can be extracted from data through the application of SVD. The Σ matrix, which holds the singular values, is the key here, while the U and V matrices contain the singular vectors. A sensor profile may be defined as the set of singular values, derived from the sensor data.

2.3 Acoustic sensor profile

In the secondary system of NPP, acoustic sensors play a role in maintaining the safety and efficiency. Ultrasonic signals perceived from these sensors are weaken rapidly over distance. They can be mounted externally, avoiding the need to penetrate pipes or equipment. Their ability to detect early signs of potential problems makes them indispensable for preventing accidents and ensuring reliable operation.

To configure sensor profiles, frequency domain sensor values are used. These values are calculated by performing a one-dimensional Discrete Fourier Transform (DFT) on sensor data from acoustic signal acquisition. The DFT provides a robust method for decomposing a signal into its constituent frequencies. 320 average spectrum values are used, obtained through Fourier transform, within the 20 kHz - 100 kHz frequency band at 0.25 kHz intervals.

For the input for matrix decomposition using SVD, normal data with dimensions (9100, 320) and (11532, 320) are combined, and then matrix decomposition is performed. Figure 1 shows the data distribution of sensor data collected in an edge device.

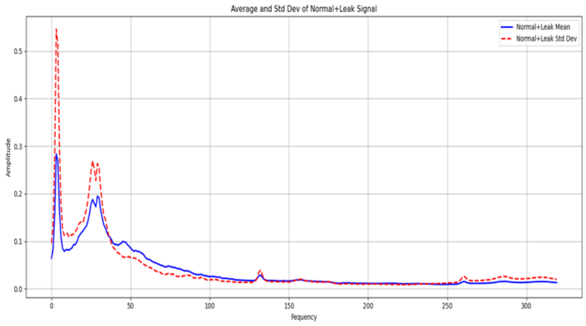

Fig. 1. Output of Frequency-wise Normal and Abnormal Sensor Data Distribution.

2.4 Evaluation of Sensor Stability

We select the most significant singular values. To reduce the dimensionality of the feature space, the top k singular values from the Σ matrix are chosen, where k is less than the original dimensionality of the feature vectors obtained from the sensor data. The reliability of sensor is evaluated by comparing it with the SVD constructed as a reference.

Figure 2 shows the importance features constructed singular values Σ from SVD. Figure 2 demonstrates that the data distribution in Figure 1 is comparable to the Σ matrix of the SVD. Changes in the main feature vectors indicate significant changes in the sensor or its environment. Virtual sensors, without requiring additional physical hardware, detect shifts in sensor data distribution, facilitating the identification of decreasing sensor accuracy and the need for calibration. Furthermore, we can confirm that recalibration is needed for decision-making based on sensor data.

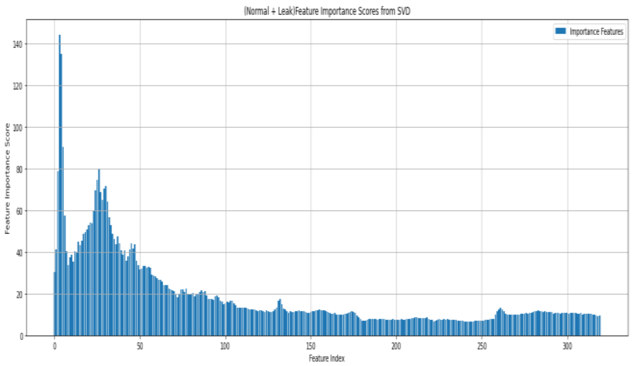

Fig. 2. Output of importance feature Σ outputted of SVD based on normal and leak sensor data.

3. Conclusions

In the secondary system of NPP, the role of the sensor system is crucial. The malfunction of the sensor system determines the overall NPP functionality. To ensure the stability of the sensor system, a proposed reference sensor can be improved the safety of NPP. By implementing this SVD-based software sensor, NPPs can enhance their leak detection capabilities and improve overall safety and reliability. To evaluate the stability of a sensor, by comparing a similarity between singular values constructed from the sensor data, and other one, the profile of the reference sensor, is compared.

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