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Recurrent normalizing flow-based monitoring framework for cutter seal temperature sensors in earth pressure balance shield tunneling: A sensor validation approach

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ABSTRACT

Reliable monitoring of cutter seal temperature is essential for the safe and efficient operation of earth pressure balance (EPB) machines. Faulty temperature sensors can mislead operators, potentially leading to seal degradation, slurry or water ingress, and costly downtime. This study introduces a data-driven monitoring framework that automatically detects and reconstructs faulty temperature sensor readings to ensure robust information during tunneling. The proposed method combines a long short-term memory-based autoencoder with a recurrent autoregressive flow, namely RAF-LSTM, to learn normal temperature patterns over time and model the probability of those patterns to distinguish normal from abnormal behavior. The proposed method was assessed using operational data from an EPB project, where synthetic faults representing realistic sensor failures have been introduced. Results show a fault detection accuracy of 96 % with 100 % recall and reconstruction errors below 0.6 °C. These outcomes demonstrate that the proposed framework can reliably identify and correct faulty sensor signals, reducing false alarms and supporting proactive maintenance strategies for EPB machine operations.

1. Introduction

Tunnel-boring machines (TBMs) and shield excavation with Earth Pressure Balance (EPB) machines have recently emerged as preferred tunnel engineering methods for urban environments due to their efficiency, cost-effectiveness, safety, and minimal disturbance (Yin et al., 2024). However, the operational performance of TBMs depends heavily on continuous monitoring of both machine components and ground responses, affecting the excavation efficiency, budget, and duration of a tunneling project (Pan et al., 2022; Wang et al., 2018). Faulty or unreliable sensor measurements can mislead operators, potentially causing undetected failures, unexpected downtime, or costly repairs. As tunneling projects become increasingly data-rich, there is a growing interest in adopting advanced monitoring methods to ensure robust decision-making (Akhlaghi et al., 2025).

With the emergence of Industry 4.0 and Construction 4.0, various artificial intelligence (AI) methods, IoT-enabled sensing, and digital twin technologies into construction and tunneling (Gomaa et al., 2023; Tariq et al., 2024). These advances created opportunities for predictive maintenance, automated quality control, and process optimization in underground works. Recent studies have demonstrated the value of smart monitoring across a broad range of tunneling applications. For instance, disc cutter wear and lifetime have been predicted using neural approaches (Elbaz et al., 2021), while gripper cylinder faults have been identified through vibration analysis and signal processing methods (Li et al., 2017). On the other hand, when monitoring ground responses, machine learning (ML) approaches have been widely applied to predict surface settlement and detect sinkhole formations (Liu et al., 2024; Loy-Benitez et al., 2024). These investigations illustrate the potential of data-driven methods to support machine reliability and ground safety. Sensors are a valuable tool for monitoring abnormal events during the operation of TBMs and ensuring the integrity of the constituent elements by sounding an alarm when maintenance or replacement is necessary (Wang et al., 2019). However, during excavation, strong and continuous vibrations and the harsh tunneling conditions (e.g., wet and highly pressurized) can damage these sensors, leading to biased information or sensor drift. To address this issue, it is useful to integrate sensor information with emerging data-driven techniques to identify faulty sensors

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Highlights

- Data-driven sensor validation promotes EPB safety by detecting faulty temperature sensors.
- Hybrid LSTM-AE and RAF model captures temporal patterns of EPB operational data.
- This method achieved a 100% fault detection rate and 96% overall accuracy.
- This method achieved low errors in reconstruction, RMSE: 0.35–0.45°C, MAPE: 0.81–1.13%.
- This method enables proactive and accurate maintenance through accurate sensor correction.

Abstract

Reliable monitoring of cutter seal temperature is essential for the safe and efficient operation of earth pressure balance (EPB) machines. Faulty temperature sensors can mislead operators, potentially leading to seal degradation, slurry or water ingress, and

Outline