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Ultrasonic Guided Waves-Based Structural Health Monitoring System for Pipeline Integrity Assessment

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Abstract—

The integrity and safety of large-scale infrastructure are vital to prevent catastrophic failures. Traditional pipeline inspection techniques are often manual, time-consuming, and susceptible to human error. To overcome these limitations, this study proposes a resilient structural health monitoring (SHM) framework utilizing ultrasonic guided waves (UGW) combined with machine learning algorithms. The system employs Isolation Forest for primary anomaly detection, Autoencoders for threshold refinement, and LSTM networks for predictive forecasting. Experimental results on a dataset of 591,652 pipeline measurements demonstrate the system's effectiveness in detecting anomalies with high precision (10% detection rate), classifying severity levels, and predicting remaining useful life (RUL). The multi-model approach achieves superior performance compared to traditional statistical methods, enabling proactive maintenance and reducing operational risks in smart city infrastructure.

Index Terms—Structural Health Monitoring, Ultrasonic Guided Waves, Anomaly Detection, Machine Learning, Pipeline Integrity, LSTM, Isolation Forest, Smart Infrastructure

I. INTRODUCTION

Civil infrastructure, including pipelines, bridges, and buildings, is vulnerable to deterioration over time due to natural wear, environmental factors, and mechanical loads [1]. Pipeline failures can result in catastrophic consequences, including inspections or basic sensor systems, which often fail to detect damage at early stages and require significant labor and operational downtime.

Wireless Sensor Networks (WSNs) combined with advanced data analytics offer a compelling solution for continuous structural health monitoring (SHM). Ultrasonic Guided Waves (UGW) provide an effective means of inspecting pipelines over long distances, as these waves propagate through the structure and interact with defects or material changes [2]. However, environmental variations—such as temperature fluctuations—can influence signal characteristics without indicating actual structural damage, creating challenges in distinguishing true anomalies from environmental noise.

Recent advancements in machine learning (ML) have enabled more sophisticated anomaly detection capabilities. Deep learning models, including Autoencoders and Long Short-Term Memory (LSTM) networks, can learn complex patterns in sensor data and adapt to changing operational conditions [3]. This study addresses the research gap by integrating multiple ML algorithms into a unified framework that combines real-time anomaly detection, severity classification, and predictive maintenance capabilities.

A. Research Objectives

The primary objectives of this research are:

1. Develop a multi-model anomaly detection system combining Isolation Forest, Autoencoders, and LSTM networks

2. Classify detected anomalies into severity categories (Major, Minor, Micro, Normal)

3. Predict pipeline remaining useful life (RUL) using survival analysis techniques

4. Validate the system using real-world pipeline monitoring data

5. Provide comprehensive visualizations for decision support

B. Contributions

This work makes the following key contributions:

* A novel integration of Isolation Forest, Autoencoders, and LSTM for robust pipeline anomaly detection

* Multi-level anomaly severity classification enabling prioritized maintenance

* Kaplan-Meier and Cox Proportional Hazards (CoxPH) analysis for RUL prediction

* Comprehensive experimental validation on large-scale real-world dataset (591,652 samples)

* Open-source implementation facilitating reproducibility and deployment

II. RELATED WORK

A. Structural Health Monitoring Systems

Lynch and Loh [4] pioneered the application of wireless sensor networks for cost-effective real-time monitoring of civil infrastructure. Their work demonstrated that WSNs could provide comparable accuracy to traditional wired systems while reducing installation and maintenance costs. However, challenges remain in ensuring reliable communication and data accuracy in harsh environmental conditions.

B. Ultrasonic Guided Wave Techniques

Lowe et al. [5] investigated the use of the first longitudinal guided wave mode for pipeline inspection, demonstrating effective defect detection over distances exceeding 100 meters. Yang et al. [6] proposed feature extraction methods using group sparse wavelet transform with tunable Q-factor, improving signal-to-noise ratios in ultrasonic guided wave detection. These studies established UGW as a viable technology for long-range pipeline monitoring but did not address automated anomaly classification.

C. Machine Learning for Anomaly Detection

Recent research has explored various ML approaches for SHM. Support Vector Machines (SVM) and decision trees have been applied to classify structural damage based on sensor data [7]. Deep learning methods, particularly Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), have shown promise in identifying complex patterns indicative of structural degradation [8]. However, most studies focus on individual algorithms rather than integrated multi-model approaches.

D. Research Gap

Existing research typically treats SHM system components—sensor hardware, communication protocols, and data analysis algorithms—in isolation. Few studies attempt to merge these elements into a unified, scalable framework capable of operating under real-world conditions. Additionally, most work focuses on detection rather than comprehensive assessment including severity classification and RUL prediction. This study addresses these gaps through an integrated approach combining multiple complementary ML techniques.

III. METHODOLOGY

A. System Architecture

The proposed SHM system comprises four main components: Data Acquisition Layer for collecting ultrasonic guided wave measurements, Preprocessing Module for normalizing data and extracting features, Multi-Model Detection Engine applying Isolation Forest, Autoencoders, and LSTM sequentially, and Classification & Prediction Module for categorizing anomalies and estimating RUL.

B. Data Collection and Preprocessing

1) Dataset Characteristics

The study utilizes a publicly available dataset from Kaggle [9] containing real-time measurements from pipeline infrastructure. The dataset comprises 591,652 data points with features including Torsional voltage, Flexural voltage, Distance (meters), and Timestamps collected over a multi-month period.

2) Preprocessing Steps

Data preprocessing involved missing value handling, feature scaling, Z-score normalization, and sequence generation for

LSTM training. Standard scaling was applied to normalize feature ranges, ensuring all features contribute equally to model training.

C. Anomaly Detection Models

1) Isolation Forest

Isolation Forest is an unsupervised learning algorithm that isolates anomalies by randomly selecting features and split values [10]. Algorithm parameters include contamination rate of 0.10 (10% expected anomalies), 200 estimators, and random state of 42 for reproducibility.

2) Autoencoder for Threshold Refinement

An Autoencoder neural network learns to reconstruct normal patterns in the data. The architecture consists of an encoder (128 → 64 → 32 units) and decoder (32 → 64 → 128 units) with dropout regularization of 0.2. Mean Squared Error (MSE) serves as the loss function, with the threshold set at the 95th percentile of reconstruction errors.

3) LSTM for Predictive Forecasting

Long Short-Term Memory networks capture temporal dependencies in sensor
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