Structural Health Monitoring: Damages Detection through a Machine Learning Approach

Liliana Cecere
DIIN
University of Salerno
Fisciano, Italy
lcecere@unisa.it

Francesco Colace
DIIN
University of Salerno
Fisciano, Italy
fcolace@unisa.it

Angelo Lorusso
DIIN
University of Salerno
Fisciano, Italy
alorusso@unisa.it

Domenico Santaniello
DISPAC
University of Salerno
Fisciano, Italy
dsantaniello@unisa.it

Alfredo Troiano
NetCom Group
Naples, Italy
a.troiano@netcomgroup.eu

Carmine Valentino
DIIN
University of Salerno
Fisciano, Italy
cvalentino@unisa.it

***Abstract*—In a time when the stability and security of infrastructure are of increasing concern, the application of machine learning to Structural Health Monitoring (SHM) is reshaping the way we approach maintenance and risk prevention. This research presents an advanced monitoring framework that leverages machine learning to enhance the speed and precision of damage identification and classification. The proposed solution is structured around a four-layer architecture that seamlessly combines intelligent algorithms, IoT-enabled sensor networks, and modern data processing tools. Specifically, the use of autoencoders for anomaly detection and the k-Nearest Neighbour (kNN) method for damage categorization enables a robust diagnostic process. The effectiveness of this system has been validated through testing on a custom-built prototype, demonstrating high accuracy in recognizing structural faults. This work offers a significant contribution to the field of civil and structural engineering by promoting smarter, more predictive maintenance strategies through the integration of artificial intelligence.**

***Index Terms*—Structural Health Monitoring, Machine Learning, Autoencoder, Nearest Neighbor**

I. Introduction

As infrastructure safety becomes an increasingly pressing concern, integrating machine learning into Structural Health Monitoring (SHM) offers a transformative approach to predictive maintenance and risk mitigation [1]. This study introduces a novel SHM framework that combines intelligent algorithms with sensor networks and IoT technologies to enhance the speed and precision of structural damage detection [2]. Leveraging the concept of Digital Twins, virtual models that mirror real-time structural conditions, the system provides accurate insights into the health status of built environments.

The proposed architecture follows a four-layer design: sensor data acquisition, intelligent processing, result evaluation, and decision-making support [3]. Core components include autoencoders for unsupervised anomaly detection and the k-Nearest Neighbour (kNN) algorithm for damage classification [4], [5]. This combination allows for early identification and categorization of structural faults, enabling timely interventions [6].

By merging advanced data analysis with real-time monitoring, this system improves infrastructure resilience, supports proactive maintenance strategies, and contributes to the development of safer, more responsive engineering solutions.

II. The Proposed Approach

This section outlines the proposed methodology for Structural Health Monitoring (SHM) in buildings, which is structured around a four-layer architecture designed to collect, manage, and process data for expert-level analysis. As illustrated in Figure 1, the architecture comprises the Sensor Layer, Knowledge Base Layer, Inference Engine Layer, and Application Layer.

The Sensor Layer includes IoT-enabled devices, specifically accelerometers, that capture structural vibrations. These devices transmit data to centralized units, which forward it to the Thingsboard platform that manages time-series data in JSON format for further analysis.

The Knowledge Base Layer serves as the data repository to handle semi-structured data. Before processing, a pre-elaboration step is applied to clean and normalize the data, ensuring consistency and quality through statistical filtering techniques.

At the heart of the system is the Inference Engine Layer, which performs damage detection and classification. It includes a Data Management Module, responsible for converting JSON data into structured formats and extracting relevant features, and a Damage Analysis Module composed of two components:

- The Damage Detector, powered by a trained AutoEncoder, identifies anomalies in the data [7];
- The Damage Classifier, which uses the k-Nearest Neighbour (kNN) algorithm to classify the type of damage based on labeled training data.

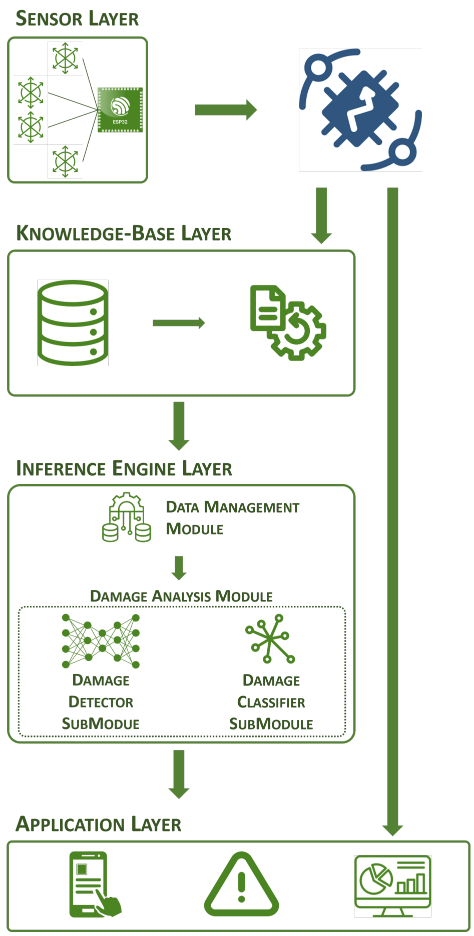

Fig. 1. The architecture related with the proposed approach.

When anomalies are detected, the classifier further analyzes the irregularities to determine the specific nature of the structural issue.

Finally, the Application Layer offers user-facing services. Experts can visualize structural data, receive real-time alerts, and access interactive dashboards via the Thingsboard platform. Additionally, a dedicated application enables users to interact with a digital twin of the monitored building, offering insights into current conditions and detected damage types.

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