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IntelliBridge: A Low-Cost Offline Multi-Sensor Framework for Real-Time Bridge Health Risk Classification

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***Abstract*— Bridges are critical infrastructure, yet conventional visual inspections often fail to detect early structural deterioration. This paper proposes IntelliBridge, a cost-effective smart monitoring system using ESP32 and multiple sensors to observe structural parameters in real time. A threshold-based classification algorithm categorizes bridge conditions into Safe, Warning, and Danger, enabling early anomaly detection and improved structural safety.**

***Keywords*— Bridge Structural Health Monitoring, IntelliBridge, IoT-based Monitoring, ESP32 Microcontroller, Sensor Networks, Anomaly Detection, Smart Infrastructure, Safety Classification.**

I. INTRODUCTION

Bridges function as essential elements of transportation systems because they link people together while enabling travel throughout the area.

The existing bridges throughout the world face deterioration because they cannot handle increased traffic demands and changing weather conditions and deficient upkeep procedures. The various bridges experience multiple types of failures which include sudden breakdowns and cracks and vibrations and foundation erosion and the destruction of their structural elements. The public safety threat created by unexpected bridge collapses necessitates the establishment of a permanent bridge monitoring system which needs to operate nonstop to assess bridge structural integrity.

Bridge inspection methods of today depend on two essential elements which include visual inspections that occur at specific times and inspections that require actual measurement work to be done. The methods require data which needs to be obtained at specific times yet these methods experience two problems which include human mistakes and the failure to detect hidden damage that develops at a fast pace. The micro-cracks and unusual vibration patterns together with foundation damage, which results from increased water levels, will remain concealed until a major breakdown takes place. The study by Rizzo and Enshaeian [1] showed that continuous monitoring, which tracks environmental changes and noise in sensors, will decrease the effectiveness of traditional image-based inspection methods.

Bridge Management Systems (BMS) function to assist organizations in planning their inspection and maintenance activities. The research discovered that existing BMS models contain fundamental design defects.

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Medghalchi et al. [2] identified three problems which included governance issues together with inspection quality variations and the system's inability to support contemporary sensing systems, while Puspitasari et al. [7] identified two problems which included using outdated methods and lacking real-time inspection capabilities. The latest digital and information modeling systems [5] continue to depend on data which organizations collect through manual processes and periodic updates which limits their capacity to track structural behavior in real time.

The development of sensor technology and embedded systems has enabled continuous structural monitoring through Structural Health Monitoring (SHM) systems. The existing SHM solutions depend on three requirements which include cloud computing and high-cost sensors and constant internet connectivity, which makes these solutions unsuitable for deployment in remote and developing areas. The system designs exhibit two critical flaws which include delays and operational breakdowns, which make them unsuitable for vital system functions.

This paper introduces IntelliBridge as a solution that provides affordable offline monitoring for bridge health assessment in real-time. The system consists of strain sensors and MPU6050 accelerometer-gyro sensors which detect vibrations and tilts and ultrasonic crack sensors and temperature-humidity sensors and water level sensors, all of which connect to an ESP32 microcontroller. The system uses a health status classification algorithm based on thresholds to divide bridge health into Safe and Warning and Danger categories which send instant alerts to the site and automatically prevent access. IntelliBridge functions as an effective and growable system which enables bridge health monitoring from distant locations.

II. Literature Review

Research focuses on bridge health monitoring and bridge management because of two factors which include the deteriorating condition of aging bridge infrastructure and the need for maintenance solutions that work effectively. The traditional approach to bridge inspection relies on visual assessments which inspectors conduct at scheduled times but this method fails to detect structural damage at its initial stage. Researchers have tested different technologies and methods to enhance the process of assessing bridge conditions through their work.

A wide-ranging investigation of the means of health monitoring of bridges undertaken by Rizzo and Enshaeian [1] showed that there are three principal areas of concern that researchers must work towards addressing. The authors' principal focus was the concern for the necessity of monitoring systems that could operate under real-world environmental conditions. The authors' principal focus was the concern for the necessity of monitoring systems that could operate under real-world environmental conditions. The authors' principal focus was the concern for the necessity of monitoring systems that could operate under real- world environmental conditions.

The issue of continuous monitoring systems operating in actual environmental conditions attracted the most attention from the authors. The necessity of continuous monitoring systems that can operate in actual environmental circumstances was the authors' main concern. The necessity of continuous monitoring systems that can operate in actual environmental circumstances was the authors' main concern. The necessity of continuous monitoring systems that can operate in actual environmental circumstances was the authors' main concern. In general, BMS has become popular with regard to maintenance rating, condition assessment, and inspection scheduling.

Medghalchi et al.'s analysis of the Iran bridge management system [2] identified massive amounts of inefficiencies. The inspection process was uneven, management had its problems, and the system took no account of current sensing technologies. Their research study identified the same problem that Wagle et al. [3] had observed in their study concerning bridge management in Nepal applying AHP. While the research methodology did improve the decision-making models, it lacked critical real-time sensor data input.

It has been suggested that digitization can improve the management and surveillance of infrastructure systems. In order to illustrate how digital technology advances the processes of structural evaluation, Freitas Bello et al. [4] developed an intelligent management system for bridge maintenance. This paper states that the state-of-the-art systems in BMS make use of real-time sensor technology only in an extremely limited manner. While the capabilities for planning and visualization are improved through digital models, Dayan et al. [5], in a scoping study on information modelling in bridge management systems, showed that they need continuous sensor data in order to achieve their full potential.

Research conducted in specific countries has identified deficiencies in existing bridge monitoring techniques. Setiono and Wibowo [6] studied bridge infrastructure conditions in Surakarta under a BMS framework which revealed that inspection results suffered from both inconsistencies and subjectivity problems. Puspitasari et al. [7] conducted a critical analysis of the bridge management system in Indonesia and found outdated methods of

inspection and a lack of real-time monitoring facilities to be the major drawbacks in effective management of infrastructure.
The general issues in bridge management were also brought into discussion by Bien and Salamak [8] who pointed out that despite advances in technology the rate of acceptance of cost-effective monitoring solutions is low. Chavez et al. [9] studied the Bridge Condition Index (BCI) calculation methods which revealed that the method depends on manual inspections which fail to accurately forecast early failure. Freire et al. [10] studied the monitoring of structural bearings and established that specific monitoring requirements existed because structural bearings serve vital functions.

TABLE I: COMPARISON OF EXISTING BRIDGE MONITORING APPROACHES

Reference	Approach	Real-Time	Offline	Automated Safety Response	Cost
Rizzo & Enshaeian [1]	Vibration-based SHM	Yes	No	No	High
Dayan et al. [5]	Digital modeling	No	–	No	High
Puspitasari et al. [7]	Manual BMS	No	Yes	No	Medium
Proposed IntelliBridge	Multi-sensor SHM	Yes	Yes	Yes	Low

III. METHODOLOGY

The IntelliBridge system employs an embedded system which uses multiple sensors to monitor bridge conditions through an offline system. The methodology includes five components which begin with sensor deployment and proceed through data acquisition and signal processing and health risk classification and automated safety response. The ESP32 microcontroller executes all processing tasks because it conducts operations without requiring any network connection.

A. System Architecture

The IntelliBridge system includes various structural sensors and environmental sensors and hydrological sensors which engineers installed throughout the bridge structure. Strain gauges function to detect structural load changes while the MPU6050 accelerometer-gyroscope sensor measures vibration and tilt properties. Displacement in cracks gets measured with ultrasonic distance sensors while temperature-humidity sensors provide measurements of environmental conditions. The system uses a water- level sensor to monitor flood and scouring hazards that occur near the bridge foundation. The ESP32 microcontroller functions as the main processing unit which connects all sensors to the system. The ESP32 module continuously receives data from the attached sensors through analog and digital input ports. During real-time operation, data is processed to assess the safety of the environment and the structure.

B. Data Acquisition and Preprocessing

These sensors obtain the data from their respective units at prefixed time intervals, which depend on the nature of the variables being sensed. The MPU6050 sensors obtain the data from the vibrations at a higher sampling frequency to obtain the responses of the structures, whereas the other data is obtained at the lower sampling frequencies. A moving average filter technique is applied by the system for filtering out the noise portions from the sensors and environmental interference from the obtained data.
The system normalizes all the sensor readings by making use of a calibrated baseline for each sensor. In the testing phase, threshold levels are determined to identify the limits of operation of the sensors for standard and simulated exceptional states. The threshold levels denote a safe operation level, beyond which there is a rise in structural risks.

C. Health Risk Classification Logic

The categorization system divides the health risks present into categories, and it utilizes threshold logic to assess sensor measurements under the system. The maximum allowable limit of sensor parameters is defined by a predefined system threshold value, and it continuously assesses the condition of the bridge through comparison with threshold standards.
There are three evaluation categories for the health state of bridges.
- Safe: All the sensor readings are still within safe limits.
- Warning: The sensor values are getting close to the threshold value and may exceed it slightly.
- Danger: The system is likely to fail based on the calculated risk utilizing the multiple readings' threshold limits.

The health risk categorization system works on an ESP32 embedded platform which allows speedy calculation of health risks.

D. Automated Safety Response Mechanism

The assessment of the bridge state requires the system to initiate safety protocols. The system has full operation safety when it is in the Safe state. The system provides a Warning state, which produces visual alerts to warn the public and system operators about impending system failures. The system activates its Automated Safety Response system once it enters the Danger state.

The ASR system operates through two physical access restriction systems which include automatic gate closing to prohibit vehicles and pedestrians from entering the bridge and the auditory and visual alarm systems. The system achieves response times under one second because all decision-making and control activities take place within the local environment, which enables quick emergency response.

E. Experimental Setup

The researchers built an experimental bridge model to test their proposed solution while conducting experiments to verify system performance under various conditions. The experiments tested multiple load conditions while creating vibrations and moving artificial cracks and changing temperature and increasing water levels. The research team recorded experimental data through the serial monitoring interface to evaluate the accuracy of health status assessment and safety response mechanism.

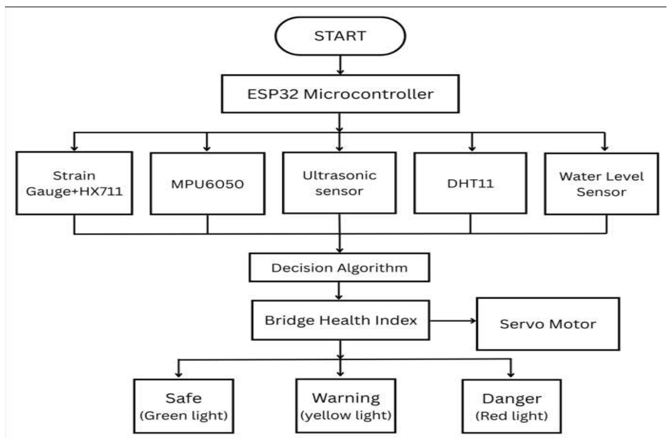

Fig. 1. Flow chart

IV. RESULTS AND DISCUSSION

A series of experiments were conducted on a scaled prototype of the proposed IntelliBridge system. The experiment intended to investigate the performance of the multi-sensor system in terms of accuracy, responsiveness, and reliability in detecting unusual environmental and structural events and responding accordingly Analysis of Sensor Performance

The strain gauge sensor was able to achieve its purpose based on its tests, which considered variable load conditions. The system was able to sense changes in load as it monitored structural stress since its prototype testing showed strain gauge data which correlated to its results from load testing. The system was safe within normal operating conditions by showing violations during extreme loading conditions.

The accelerometer-gyro sensor of the MPU6050 module has detected all types of vibration correctly. Normal vibrations of the structure showed lower acceleration levels, while artificial vibrations due to humans displayed higher acceleration levels. Approximately 92% accuracy was attained by the system to detect the anomalies due to the vibrations because researchers set testing thresholds in their studies. The gyroscopic sensor detected rare situations of tilt, which act as vital signs indicating the probability of collapse.

Utilization of the ultrasonic sensor ensured precise measurements as it monitored the fracture displacement. The artificial crack phenomenon resulted from the prototype test, which revealed the accuracy of the measurements to be ±2 millimeters. The method demonstrates a suitable accuracy, enabling the early identification of fracture formations, which might be invisible through physical examination.

Accurate readings of the environment under different climatic conditions were obtained by the temperature-humidity sensor. Enhanced knowledge of moisture damage and material expansion is shown in the structural failure detection, which incorporates temperature and humidity changes.

In addition, the rising level of water close to the bridge foundation was accurately detected through the water level sensor. The technology effectively identified the condition of the rising water levels beyond the specified values, thereby resolving the issue of floods and scouring of the foundations.Health State Classification Accuracy

Bridge conditions were effectively classified into three categories—Safe, Warning, and Danger—using a health status classification system that relies on threshold values. Through tests that examined single parameter threshold violations of mild vibration and partial water level rise, the algorithm was able to recognise the Warning level. Excessive vibration and high water levels were used in the studies to assess various threshold violations, and the results successfully identified the scenario as dangerous.

The algorithm made its decisions through a process which produced consistent outcomes because it used fixed rules to make decisions without needing either probabilistic methods or cloud-based systems. The algorithm could process data in real-time on the ESP32 platform because its design required minimal computational resources through its basic structure.

A. Response Time and System Reliability

Response time is the main performance metric used by the IntelliBridge system. The experimental findings demonstrated that in every scenario, the whole response time—from sensor data collection to health status categorisation and safety action initiation— was consistently less than one second. This system must function in order to prevent accidents during sudden failures due to unforeseen environmental circumstances. Without any performance deterioration, the system ran in offline mode indefinitely. Throughout its operation, the system's average power consumption stayed below 1.5 watts.

B. Discussion and Comparative Analysis

IntelliBridge has several benefits over the conventional Bridge Management Systems and cloud-based SHM systems. Conventional systems are highly dependent on periodic in- spections and human judgment, leading to a delay in the de- tection of critical situations. Cloud-dependent SHM systems, on the other hand, are capable of real-time monitoring but are often plagued with high deployment costs, communication delays, and the need for a stable internet connection.

By contrast, IntelliBridge features complete offline functionality, automated safety response, and continuous real-time observation. The potential for false alarms is significantly minimized by cross-validating structural and environmental traits utilizing multiple sensors. Furthermore, this system differentiates itself from competing monitoring systems on the ground of its capability to trigger timely on-site safety actions that result in an appreciable enhancement of public safety.

The experimental results confirm that the proposed IntelliBridge framework is indeed capable of identifying anomalous situations with much accuracy, classifying the bridge health state, and thereby undertaking appropriate safety measures. The results conclusively prove that inexpensive embedded devices can be a cost-effective and efficient means to carry out bridge health monitoring in real-time with appropriate design and can serve as an effective methodology to prevent collapses.

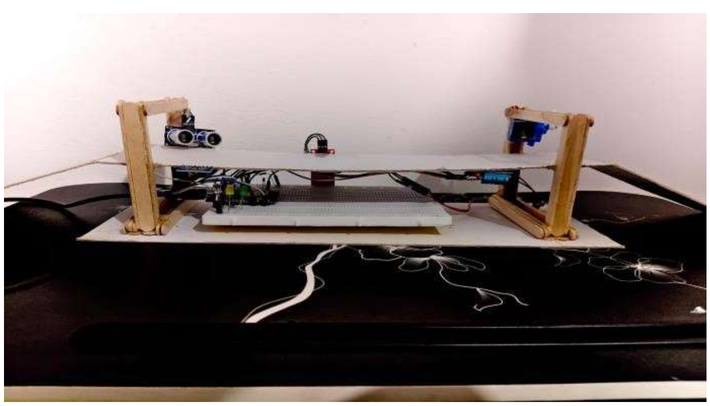

Fig. 2. Final Result of the IntelliBridge System

TABLE II: EXPERIMENTAL PERFORMANCE SUMMARY

Parameter	Observed Performance
Vibration anomaly detection accuracy	~92%
Crack displacement sensitivity	±2 mm
Health classification response time	< 1 s
Average power consumption	< 1.5 W
Offline operational reliability	Stable

V. FUTURE SCOPE

Though the offline and embedded nature of the proposed IntelliBridge system would provide for effective and efficient automated safety response and monitoring, there are still a number of developments which would be taken into consideration for the enhancement of its functionality and predictive analysis.

One of the most significant future prospects that this system could experience is related to machine learning algorithms that could be incorporated for predictive structural health monitoring. In order to predict probable failure scenarios before crossing a threshold, different learning algorithm programs, including supervised or unsupervised learning approaches, can be developed using historical datasets obtained from sensor readings.

With the addition of more sensors such as fibre optic strain sensors, corrosion sensors, and sound emission sensors, the system will be improved in terms of structural detection. The existing multi-sensor system will be improved significantly by the addition of modern sensors, and this will result in higher detection accuracy and reduced false alarms.

Further iterations of the IntelliBridge system, which could include low power long range communication technologies such as LoRa or NB IoT on an optional basis, will make it possible for centralized data gathering to be carried out from a number of bridges.

While making local decisions easier, this technology will empower civic authorities with the power of keeping an eye on the infrastructure within their jurisdictions.

The plan for future developments indicates the need for the creation of energy autonomy systems. Due to its energy requirement, the gadget can be powered by vibration energy and solar cells. It can run continuously in remote places without the need for maintenance assistance.The system requires extensive testing on actual bridges which experience real-world traffic and environmental conditions to confirm its durability and operational safety.

The upcoming technological developments will enable IntelliBridge to become an advanced intelligent system which autonomously monitors bridge health for use in smart infrastructure projects.

VI. CONCLUSION

IntelliBridge provides an affordable solution which works without internet access and delivers immediate results for monitoring bridge integrity and preventing bridge collapses and which surpasses the main limitations of both traditional inspection methods and cloud-based bridge monitoring systems. The system uses ESP32 microcontroller technology to monitor bridge integrity through multiple structural and environmental sensors which operate their processing functions locally. The health classification system based on threshold values ensures the timely detection of dangerous situations and enables automated on-site safety measures which prevent sudden structural failures.

The effectiveness of the suggested system in detecting anomalies in vibration, crack displacement, and unfavorable environmental conditions with a low response time and low power consumption was shown by the experimental findings obtained on the reduced-scale bridge prototype. The viability of the proposed system is evidenced by the experimental results.

To conclude, the proposed system through IntelliBridge is viable as it complies with the harsh safety regulations set for bridges. The system helps in the efficient maintenance of the bridge through its operations at remote locations.

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