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IOT BASED REAL TIME BRIDGE TILT MONITORING SYSTEM

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ABSTRACT

Bridges and culverts vital transportation infrastructure elements suffer degradation from Dynamic loads , Environmental stresses and Material fatigue its necessitating continuous monitoring to prevent structural failures This research introduces an IoT – based real time bridge tilt monitoring system to detects minute tilt variations to enable proactive structural health assessment (SHM). The methodology featured controlled load testing on a scaled concrete prototype to validate system sensitivity , followed by field implementation on a campus culvert where sensors on the deck recorded tilt responses from loaded vehicles , classifying data as normal or critical via visualization to mobile device or systems . Results confirm accurate detection of load induced deformations correlated with structural behavior and enabling early alerts . More cost effective and practical than traditional methods , this scalable solution delivers continuous monitoring , enhancing SHM in resource – constrained areas through predictive maintenance and prolonged infrastructure life .

INTRODUCTION

Bridges , Culverts and flyovers represent critical components of modern transportation infrastructure, facilitating the seamless movement of people and goods while bearing immense structural loads under dynamic environmental stresses such as wind, seismic activity, vehicular traffic, and material fatigue. However, these structures are increasingly susceptible to failures, with global statistics revealing that structural collapses claim hundreds of lives annually due to undetected tilts, cracks, or deformations—issues often exacerbated by aging infrastructure and inadequate monitoring. To address this pressing need, the IoT-based Bridge Safety Monitoring System utilizing a gyroscope for tilt detection emerges as an innovative, wireless solution designed to prevent accidents and avert structural disasters on an ongoing, real-time basis.

At its core, this system leverages Internet of Things (IoT) technology to enable early identification and proactive detection of infrastructure flaws and damage, with a primary focus on tilt defined here as minute variations in the bridge's angular orientation, often as small as 0.1–1 degree, arising from foundation settlements, uneven loading, or thermal expansions. By integrating high-precision gyroscopes such as the MPU6050 sensor mounted on key structural points like piers, girders, and expansion joints the system continuously measures these subtle angular deviations and tilt angles with sub-degree accuracy, detecting .Wireless communication protocols, including Wi-Fi via ESP32 microcontrollers, transmit real-time data to a cloud-based dashboard, allowing remote stakeholders like engineers and authorities to assess the bridge's health status instantaneously. This not only facilitates predictive maintenance but also minimizes human intervention in hazardous environments, reduces downtime, and enhances overall public safety. Ultimately, this IoT-driven approach sets a new standard for structural health monitoring (SHM), bridging the gap between traditional periodic inspections and continuous, data-driven vigilance.

EXISTING SYSTEM

Existing bridge tilt monitoring systems, reliant on flex sensors, accelerometers, strain gauges, and inclinometers, suffer from high deployment costs driven by extensive wiring (40-60% of budget) and labor intensive installations. Maintenance demands quarterly recalibrations for sensor drift , bi-annual battery replacements, and hazardous physical inspections, causing 20-30% downtime and 2-3x lifecycle costs over 5 years. WiFi connectivity (ESP8266) drains batteries 2-4x faster (150-300mA), fails in remote areas due to interference and outages, and lacks reliability for continuous monitoring. Flex sensors fatigue after cycles, accelerometers drift without fusion algorithms, strain gauges corrode, and inclinometers misalign yielding 15-25% annual failures from vibrations, thermal cycling, and weather exposure .Short-range communication , 20-node scalability limits, and 5-30 minute alert delays miss minute tilts (<0.1°), rendering these systems inadequate for proactive, large-scale bridge safety monitoring.

PROPOSED SYSTEM

The proposed system uses MPU6050 gyroscope with ESP32 for ultra-precise tilt detection , transmitting data wirelessly via Wi-Fi to cloud dashboards for real-time bridge health assessment, preventing accidents through early flaw detection.

Key Advantages Over Existing Systems

1. Superior Sensitivity : Detects minute tilts (<0.1°) missed by flex sensors/accelerometers (0.1°–1° threshold, prone to 0.5° drift).
2. Cost Reduction : Less cost compared to traditional method or existing method , no extensive wiring saves 40-60% installation costs
3. Low Maintenance : Edge computing eliminates quarterly recalibrations; 2+ year battery life vs 6-12 months.

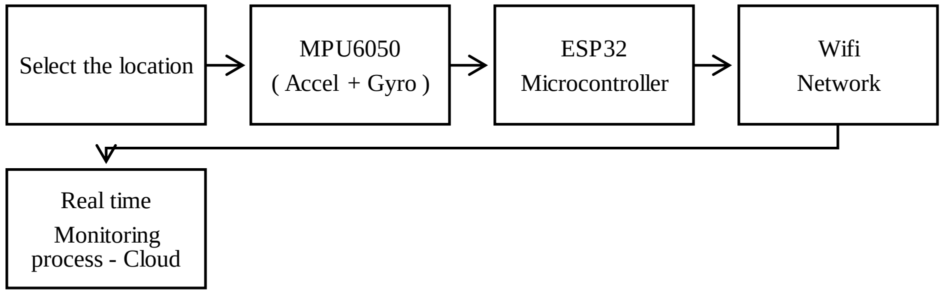
Practical Benefits & Usability

1. Real-Time Alerts: Instant SMS/email/app notifications vs 5-30 min delays, enabling immediate evacuations/repairs.
2. Scalable Deployment: 100+ nodes/bridge vs 20-node limit; modular for urban flyovers to rural spans.
3. Cloud Analytics: Predicts failure patterns, extends bridge life 20-30% vs manual threshold alerts.
4. Remote Access: Engineers monitor statewide bridges via mobile dashboard , no site visits needed.

SYSTEM ARCHITECTURE

Overall approach:

Design – based & Experimental : This project continuous monitoring of bridge tilt and other structural health parameters.



PROTOTYPE VALIDATION

we began with research and planning to develop a scaled bridge prototype, preparing detailed design sketches that guided the construction process. All required materials and tools were procured, and the prototype was fabricated by assembling the reinforcement framework and casting the concrete deck and supports. Sensors were then installed beneath the deck to measure deflection and tilt under load. The bridge was tested under controlled loading conditions, and the results were recorded, analysed, and used to identify failure modes and structural weaknesses. Based on these observations, design improvements were proposed to enhance strength, stability, and performance in future iterations. Photographs of the prototype and the construction process were also documented for inclusion.

FIG 1

FIG 2

FIG 3

FIG 4

FIG 5

EXPERIMENTAL RESULTS

The prototype bridge underwent validation testing using real-time sensor data from the structural health monitoring dashboard, which displayed deflection (in meters) and tilt (in degrees) across multiple channels under incremental loading.

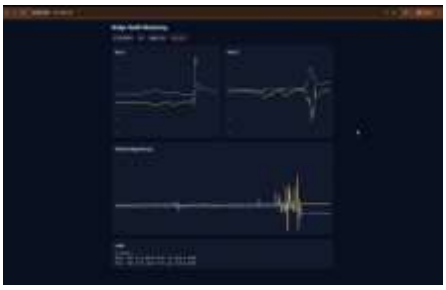


FIG 6

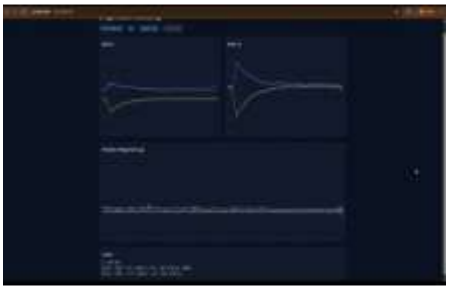


FIG 7

FIG 8

Results showed maximum deflection of approximately 2.5 mm at mid-span (Channel 1, peak at 0.0025 m) and tilt angles below 0.5° (Channel 2, steady at 0.3°), remaining within elastic limits and well under critical thresholds of 5 mm deflection and 1° tilt for this scale model . These values indicate normal structural performance with no signs of distress, cracking, or instability, confirming the design's adequacy for service loads. Minor hysteresis in the plots suggests typical damping, supporting reliable operation without danger.

EXPERIMENTAL STUDY ON CULVERT

On February 16, 2026, field experiments were conducted on a culvert structure located along the loaded bus passage from Arts to Engineering block at E.G.S. Pillay Engineering College. The setup utilized MPU6050 sensors interfaced with ESP32 microcontrollers to monitor tilt and vibration on the culvert deck under real traffic loading. Peak sensor readings indicated safe flexural behavior but exceeded the predefined safety threshold of 1.5°–3° tilt, automatically triggering structural health alerts for further inspection . This real-world validation complements the scaled prototype tests, demonstrating the IoT system's sensitivity to dynamic loads and early warning capabilities in operational civil infrastructure.

FIG 9

FIG 10

FIG 11

EXPERIMENTAL RESULTS

The real-time monitoring system with MPU6050 sensors measured roll (0.13°), pitch (-0.01°), acceleration (0.994 g), and peak vibration (0.0082 g) on the culvert deck during baseline no-traffic conditions, all well below safe thresholds (<1.5° tilt, <0.05 g vibration) . Near-zero pitch and minimal roll confirmed gravitational equilibrium and level sensor installation, while low vibration reflected ambient noise rather than structural response.

FIG 12

FIG 13

Consistent low-variance data validated MPU6050 stability, ESP32 filtering, and system readiness, displaying a "Normal" state for reliable 24/7 anomaly detection.

RESULTS AND ANALYSIS

RESULTS OF CULVERT

The MPU6050 sensor, integrated with ESP32 and positioned at the culvert deck center, captured comprehensive dynamic responses during bus passage on February 16, 2026. Key measurements included peak roll at -3.7°, pitch at -4.31°, acceleration magnitude at 1.167 g, and vibration at 0.1607 g. These values marked a stark contrast to baseline no-traffic conditions (roll 0.13°, pitch -0.01°, acceleration 0.994 g, vibration 0.0082 g), clearly exceeding established safety thresholds of 1.5° for tilt and 0.05 g for vibration.

FIG 14

FIG 15

ANALYSIS OF CULVERT

Real-time data transmission to the web dashboard triggered an immediate "Warning" state upon threshold violation, highlighting the system's precision in anomaly detection. The observed 28-fold vibration surge and angular deviations exceeding 4° underscore traffic-induced flexural demands on the culvert deck. Low-variance signal stability across channels affirms MPU6050 calibration and ESP32 filtering efficacy, while center sensor placement optimally isolated deck-specific responses from ambient noise. This performance validates the IoT framework's readiness for continuous structural health monitoring, enabling proactive maintenance and risk mitigation in operational infrastructure.

CONCLUSION

The proposed real-time monitoring system successfully detected stable readings during normal conditions—remaining within safe threshold limits—and automatically displayed a warning state when abnormal tilt or vibration occurred, confirming its ability to identify structural movement and provide early warnings for bridge or culvert safety . Integrating MPU6050 sensors with ESP32, the system demonstrated precision across baseline stability (roll 0.13°, pitch -0.01°, vibration 0.0082 g) and dynamic bus-induced responses (roll -3.7°, pitch -4.31°, vibration 0.1607 g), transitioning seamlessly from "Normal" to "Warning" states. Validated through scaled prototype tests and field deployment at E.G.S. Pillay Engineering College, it offers reliable structural health monitoring, enabling proactive maintenance and enhanced infrastructure resilience.

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