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Original Article

Sensor-Based Systems for Harness Clamping Detection

Chethan. V[1,2], Nanjundaswamy P[3]

[1]*Department of Civil Engineering, JSS Science and Technology University, Karnataka, India.*
[2]*Department of Civil Engineering, Nitte Meenakshi Institute of Technology, Nitte (Deemed to be University), Karnataka, India.*
[3]*Department of Civil Engineering, JSS Science and Technology University, Karnataka, India.*

[1]*Corresponding Author : 27cnvn@gmail.com*

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Abstract *- Falls from heights are a common cause that contributes to construction fatalities, usually occurring due to poor enforcement of safety regulations. Absence of real-time monitoring mechanisms for ensuring proper PPE use poses major safety challenges in construction. Conventional safety monitoring and incident reporting systems are usually manual-based and are prone to errors. Advancements in existing technologies, such as Inertial Measurement Units (IMUs), Radio-Frequency Identification (RFID), and vision-based systems, are being adopted to ensure a safe working environment; however, they often face issues, including false alarms and high implementation costs. This leads to a major gap in safety monitoring, and there is a need for a low-cost and scalable IoT-based system capable of real-time compliance monitoring with alert generation. The present study introduces two novel harness clamping detection systems: Scaffold-Based and Advanced D-Ring Modification, which integrate low-voltage sensor networks with ZigBee-enabled wireless communication systems. Each system provides real-time monitoring, alert generation, and cloud-based data storage for further analysis. Experimental trials assessed detection accuracy, response time, and reliability, yielding accuracies of 95.33% for the Scaffold-Based System and 99.33% for the Advanced D-Ring Modification System, with an average response time of less than 1.5 seconds. The Advanced D-Ring Modification system achieved superior performance with minimal false positives, supporting an IoT-enabled framework that improves PPE compliance and reduces fall-related risks in construction.*

Keywords *- Construction safety, Harness monitoring, IoT, Real-time safety compliance, Wireless Sensor Networks.*

1. Introduction

The construction industry is often plagued by high fatality rates. The fatalities account for nearly one-fifth of workplace deaths worldwide [1, 2]. Many safety frameworks across the world mandate that workers on platforms beyond 1.8 m in height must use full-body harnesses that are securely fastened to a permanent support, preventing falls 3]. But compliance confirmation in real-time remains a challenge due to various factors. Manual monitoring methods are error-prone, defective, and labour-intensive, and often difficult to enforce compliance to their fullest [4]. Previous research on the technological intervention for real-time monitoring involving sensors, video cameras, and so on has focused on measuring a single parameter. For example, Inertia Measuring Unit-based systems [5] track the movements of workers but often generate false results due to unrelated worker movements, which may not be related to body harness clamping [6].

RFID [7] and UV band technology are effective for tracking worker movement but require appropriate infrastructure requirements and often face issues with signal interference [8]. Vision-based methods, on the other hand, are effective but require cameras to be placed at regular intervals and require vision-based deep learning methods [9] to track movements [10]. The main drawback of this technology is that it suffers from blind spots, line-of-sight issues, and is sensitive to lighting [11]. Though these systems are effective, scalability issues and high costs limit small and medium-sized companies from adopting them [12].

IoT-enabled hook monitoring systems that integrate sensors with communication networks have emerged as a positive solution that helps in real-time data acquisition and monitoring [13]. However, signal interferences, limited battery life, and high costs often limit the applications of existing systems. Conventional audio-visual systems, such as LED indicators and vibration alerts, are effective for immediate notifications but face scalability issues in construction sites [14]. Other monitoring systems also face high false alarms, reduced operational capacity [15, 16].

Also, existing systems operate as a standalone mechanism that lacks integration into the safety framework. The dynamic nature of the construction works further expedites these challenges, as frequent changes in layout, positions, and environmental conditions disrupt performance [15].

The present real-time monitoring systems that are applied to detect the clamping or secure attachment of full-body harnesses to permanent supports often integrate IoT sensors, RFID modules, and telemetry analytics [17]. A sensor-based system developed by [18]verifies the clamping of the d-ring by triggering audio-visual alerts while transmitting the data in real-time. Similarly, [19] developed a tag and RFID-based system to continuously monitor anchoring of the D-ring while sending data to the cloud for further analysis. A fall protection mechanism developed by [6, 18] detects the connection and logs unsafe conditions for further review. However, these technologies help in reducing human error but are often costly to implement on-site. It is observed that the above technologies focus on a single parameter (hook clamping only), and there is limited literature available on these kinds of applications [20].

With these limitations, the present research is focused on developing novel harness clamping detection systems that are capable of achieving real-time safety. The primary objective is to integrate multiple monitoring sensors into a verification mechanism that is Zigbee-enabled and has low latency to minimise false alarms and improve response accuracy. The relative assessment of the technologies determines the detection accuracy and integrity under site conditions, validating a scalable framework that can be applied to various site conditions.

The novelty of this research lies in its methodical integration of various sensor-based monitoring frameworks into a single safety framework that monitors multiple parameters in real-time. The proposed scaffold-based system and a modified D-ring system design, which has the ability to confirm the clamping status of the full body harness in real time, along with the location and altitude of the worker, generating alerts in real time. The present work tries to plug the gap in issues with real-time monitoring to ensure safety compliance. The objective of the present study lies in developing harness clamping systems that are suitable for scaffold environments.

2. Methodology

OSHA mandates that workers working on scaffold platforms or on elevated places are required to wear a full-body safety harness that must be securely attached to a permanent support. Though manual monitoring plays an important role in assuring the use of the full-body harness, it remains a major challenge to confirm whether the harness hook is securely clamped when the worker is on an elevated platform. To address these monitoring challenges, the present study introduces two novel real-time monitoring systems, namely i) a scaffold-based system that embeds copper wiring to ensure fault detection with dual-colour LED feedback and ii) an advanced D-ring system that involves covering a serrated copper contact on the D-ring to enhance precision, minimising interference from environmental factors.

2.1. System Design

When workers ascend on the scaffold, the system automatically initiates and monitors the input pin. The input pin is connected to the sensor through a microcontroller. The alert mechanism involves configuring the input pin to “active-low input” with a pull-up resistor to ensure the defined logic when the hook is connected. If there are no contact detections (unclamped status), the input pin will remain in a low condition. A 120-second delay is inserted in the design to accommodate the average time for the worker to climb on the platform and make necessary adjustments. Even after 120 seconds, if the hook is unclamped, the microcontroller triggers the RED LED to turn on, indicating non-compliance. Alternatively, if the hook is clamped, then the GREEN LED is activated. The system runs in this loop for every 100 milliseconds, ensuring real-time monitoring. The collected data is wirelessly sent to a central monitoring unit through a Zigbee trans-receiver, which documents the clamping status in the cloud. Figure 1 shows a graphical representation of the methodology adopted.

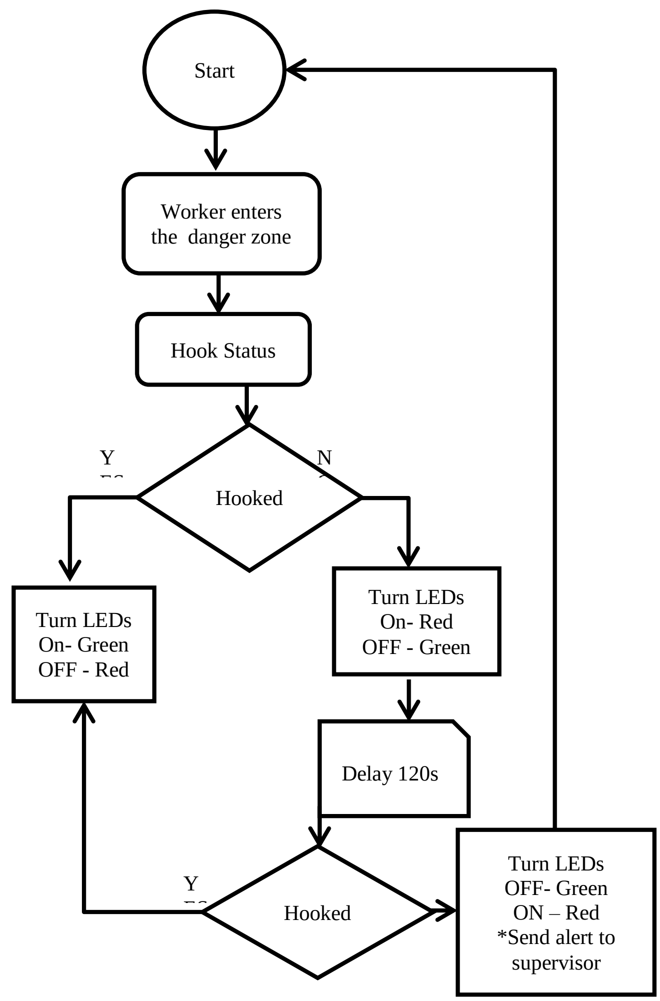

Fig. 1 Schematic representation of the methodology adopted for the detection system

The detection logic for identifying the clamping status through a microcontroller is based on real-time input from the attached sensors on the full-body harness hook. The input signal interpretation is described below

Status: Hook Securely Clamped:

- Sensor detects connection: Input Pin 4 = High.
- Output Pin 1 (Green LED) = High.
- Output Pin 2 (Red LED) and Output Pin 3 (Buzzer) are set to Low.
- Status: Hook Not Securely Clamped:
- No connection detected: Input Pin 4 = Low.

The logic diagram is depicted in Figure 2. The system is designed to operate with a loop monitoring the hook's status continuously.

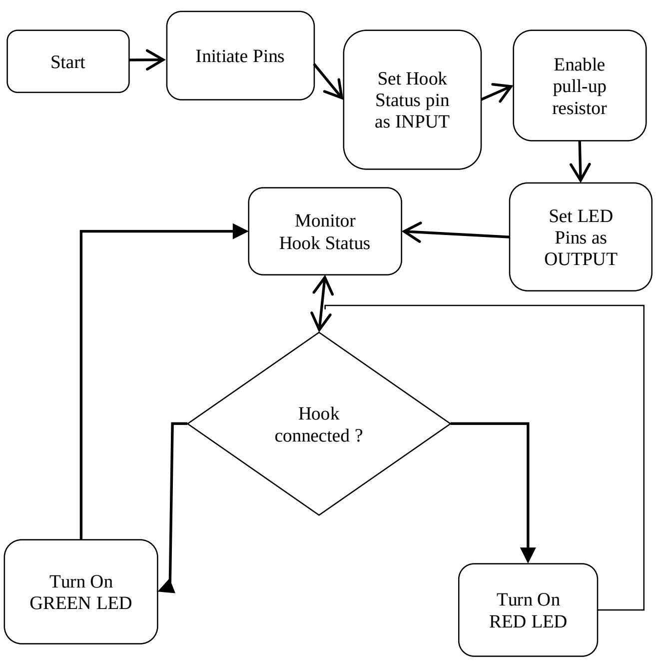

Fig. 2 Schematic representation of the process for monitoring the clamping status of a safety hook

The above-mentioned approach is indicated in Table 1 below.

Table 1. Logic table

Condition	Pin 1: GREEN	Pin 2:RED
Input Pin 4 = High (Connected)	High	Low
Input Pin 4 = Low (Disconnected)	Low	High
Condition	Pin 1 - (GREEN LED)	Pin 2 (RED LED)

The microcontroller regularly monitors the clamping status to ensure accurate detection. The data transmission generates and sends instant alerts to the worker and supervisor simultaneously, updating the cloud database.

With this background, the following sections detail the detection systems that are developed to detect clamping status. Each system emphasises real-time monitoring, continuous data collection, and rapid alert mechanisms to mitigate risks effectively.

2.2. Scaffold-Based Clamping Detection System

This system is designed to monitor altitude, location, and the status of clamping of the full body harness in real-time. The system configuration involves the use of sensors that are capable of detecting the clamping status. The data collected is processed by microcontrollers and transmitted to cloud-based data storage via Zigbee technology.

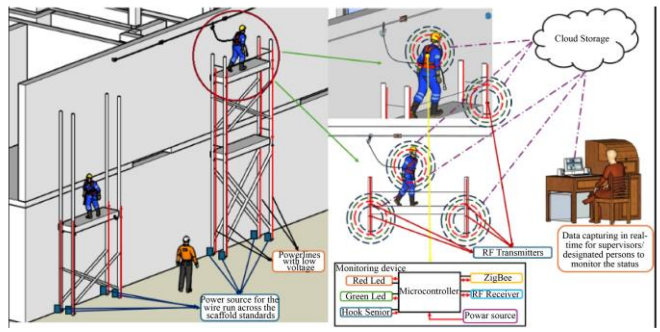

Fig. 3 Graphical representation of the proposed Scaffold-based Harness Clamping detection system

Figure 3 shows the graphical representation of the proposed scaffold-based system. The operational principle of the system is simple and revolves around an electrical circuit. The scaffold standards are lined with a low-voltage, surface-mounted wiring network that forms the base of the detection circuit. Whenever the worker ascends on the scaffold and the height from ground level exceeds 1.8m, the harness must be clamped as per OSHA. To accommodate the time required for the worker to stand on the platform, adjust posture, and retrieve tools, a cushion of 120-second delay is merged into the system before it gets activated.

The circuit remains in a closed condition before clamping, and the RED LED on the body harness of the scaffold worker is lit up to indicate an unsecured condition. Once the harness is clamped, the circuit is broken, and the indicator turns GREEN (safe condition). This mechanism is continuously monitored by a microcontroller in real-time. The processed data is transmitted wirelessly via Zigbee protocols to a centralised receiver, which has its interface shared with a cloud monitoring system. This method ensures adaptability in actual site conditions as it is easily scalable because of its low-voltage operability and real-time monitoring capabilities as per OSHA requirements. As it addressed an important challenge, the system can be looked upon as a scalable option for dynamic construction sites.

2.3 The Advanced D-Ring Modification System

The system, which follows a novel approach, modifies the D-ring of the full body harness with appropriate sensor use to ensure safety, particularly in high-risk construction activities, such as work at heights.

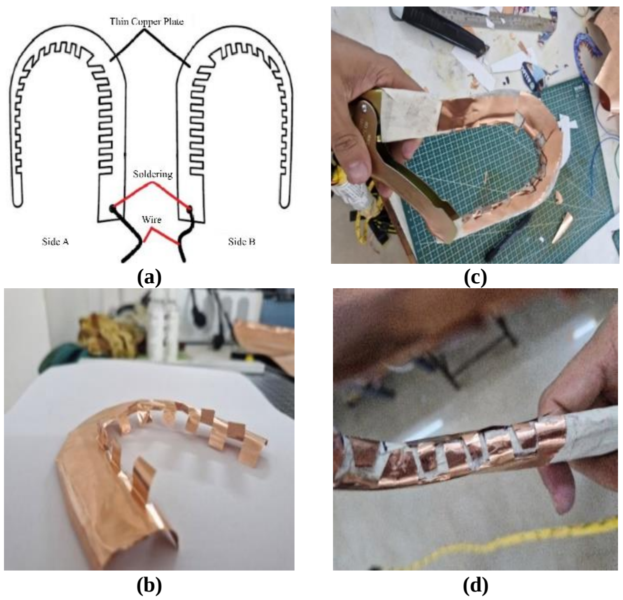

Fig. 4 Typical representation of the modified D-ring of a full-body harness with Serrated Contacts (a) Serrated contacts with connections, (b) Thin copper plate with serrations, (c) Modifications of the D-ring, and (d) Serrations on top of insulation on D-ring.

The modification of the D-ring of the full-body harness is made using copper plates with serrations as indicated in Figure 4. Before the attachment of this modification, an insulating material is wound around the ring to prevent short circuits and ensure safe operation under various environments.

The serrations are fixed onto the D-ring and powered with a low-voltage wiring, which is supported by a rechargeable battery, completing the detection mechanism circuit.

The detection principle is based on circuit continuity; whenever the current flows through the modified D-ring, an unclamped condition maintains the circuit integrity, indicating the unsecured state. Whenever the hook is securely clamped, the circuit is disrupted, indicating the safe condition. This mechanism is supported by RED and GREEN LED, respectively, indicating unclamped and clamped conditions.

An Arduino microcontroller embedded in the full-body harness assembly is responsible for monitoring the circuit changes and interacting with a ZigBee module for wireless data transmission. The processed clamping data is transmitted to a centralised cloud platform via the ZigBee communication protocol in real-time. The integration of modifications to the d-ring, ensuring low-voltage circuitry and data transfer in real-time, completes the regulatory requirements as prescribed by OSHA.

2.4. Testing of the Proposed System

The proposed system will be tested under the following scenarios and test conditions for its performance evaluation. Scenarios considered:

- Scenario 1: The worker is below 6ft from ground level
- Scenario 2: The worker is above 6 feet, with the harness clamped.
- Scenario 3: The worker is above 6 feet, with the harness clamped.
- Scenario 4: The worker is over 6ft tall, and the harness is not properly clamped.
- Scenario 5: The worker is above 6ft, and the harness is not clamped.

Conditions Considered:

- Condition 1: Whether the height (altitude-wise) exceeded by the worker
- Condition 2: Time Elapsed.
- Condition 3: Clamping Status
- Condition 4: Circuit Status
- Condition 5: LED Indicator
- Condition 6: Data transmitted to the cloud

The systems will be tested under multiple scenarios as stated above, and also by varying height, clamping status, and time duration. The individual system was tested across 150 repetitions to ensure reproducibility. The repeated trials also enhanced the accuracy of the system under controlled conditions, which reflected actual construction scenarios. The performance parameters like accuracy in detection to identify between clamped and non-clamped status of the harness, response time, and communication integrity are prioritised during the testing stage itself, which satisfies the objective of this study. On the other hand, the response time accuracy reflects the capacity of the proposed system to generate and send real-time alerts and communications, ensuring no data loss.

3. Results and Discussions

The developed system was subjected to performance evaluation as per the earlier defined scenarios and conditions. The test cases were designed to reflect real site conditions, which included worker movement across scaffolding zones above the defined height of 1.8m as per OSHA and failure to clamp the harness within the 120-second window. Tables 2 and 3, mentioned below, reflect the scenario-based performance of scaffold-based harness clamping detection.

The reproducibility of the systems was tested under conditions that represented on-site conditions. The field tests were conducted using a standard scaffold framework with altered worker heights (elevation) to assess clamping detection above the OSHA threshold of 1.8 m. Five predefined scenarios were created based on the worker's height of work, the full body harness clamping status, and the time spent by the worker in the critical zone. These scenarios were repeated across 150 repetitions, both systems, for consistency and reliability. A 120-second delay was included in the design to reflect the average time required for a construction worker to climb and clamp the harness after reaching threshold height-zigBee modules transmitted monitoring data in real-time.

Table 2. Results of the scenario-based test of the scaffold-based harness clamping detection system

Test Scenarios	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6
Scenario 1	No	NA	NA	NA	NA	No
Scenario 2	Yes	<120 seconds	Clamped	Closed	Green	Yes
Scenario 3	Yes	>120 seconds	Clamped	Closed	Green	Yes
Scenario 4	Yes	<120 seconds	Not Clamped	Open	Red	Yes
Scenario 5	Yes	>120 seconds	Not Clamped	Open	Red	Yes

Table 3. Detection accuracy assessment of the scaffold-based harness clamping detection system

Performance Parameters								
Sl. No.	Number of Trials conducted	Number of Successful clamping detections	Number of unsuccessful clamping detections	Sensor detection accuracy	Average response time	Comm. integrity	Failures Due to Interference	Maintenance Frequency
1	150	143	07	95.33%	1.5 Seconds	97% (within 30-m range)	3%	5% of cases (due to wiring wear from scaffold operations)

Table 3 indicates the scaffold-based system's performance against the test conditions. 150 trials were conducted, and it was observed that a detection accuracy of 95.33% was achieved. A total of 143 detections were successful, and 7 unsuccessful detections were observed during the testing. The system recorded 1.5 seconds of average response time for the trials conducted with 97% communication integrity. 5% maintenance frequency was observed due to wear and tear of the wires during shifting operations (assembly and disassembly), while 3% failure was observed due to interference. The scaffold-based system was found to be effective, and it can be applied to stationary scaffold frameworks.

The modified D-Ring system was also tested under similar conditions. Visual indicators were adopted to communicate the status of clamping to the assigned. A RED LED indicator reflected unsafe conditions, while a GREEN LED meant compliance with safety standards. The system sent no alerts when the worker remained in the critical zone for less than 120 seconds, even when the harness was fully clamped and the GREEN LED was turned ON. But if the worker is stationed in the critical zone for more than 120 seconds, and the harness is unclamped, the RED LED turns on, and a safety alert is sent.

Table 4. Various test scenarios and cases to determine hook clamping status

Sl No	Scenario	Case	Workers' Zone	Hook Clamping Status
(1)	**(2)**	**(3)**	**(4)**	**(5)**
1	1	1	Workers not in the critical zone	Not hooked
2	1	2	Worker in the critical zone.	Not hooked
3	1	3	Worker in the critical zone for < 120 seconds	Not hooked
4	1	4	Worker in the critical zone for < 120 seconds	Hooked
5	2	1	Workers not in the critical zone	Not hooked
6	2	2	Worker in the critical zone.	Not hooked
7	2	3	Worker in the critical zone for < 120 seconds	Not hooked
8	2	4	Worker in the critical zone for > 120 seconds	Not hooked

The test results in Table 4 indicate that the system monitored the hook's clamping status in real-time and generated correct responses. Table 5 recaps the LED responses for the test scenarios, supporting that the system delivered accurate and timely feedback to enhance safety. The results validated the detection accuracy for worker movements and time thresholds, giving real-time feedback. The detection accuracy of 99.33% was achieved during testing. It is to be noted that only one missed detection was observed during testing, which was largely due to signal interference. The average response time was recorded to be less than 1 second, and the communication integrity was 99%. It was observed that there were very few false detections and limited instability of hook contact.

Comparative analysis of both the systems indicates that the detection accuracy of the scaffold-based system was 95.33% and the advanced-ring system showed an accuracy of 99.33% with less than one second response time for alerts. A two-proportion z-test confirmed that the difference in detection accuracy was statistically significant ($p<0.05$) and is indicated in Tables 6 and 7, respectively.

Table 5. LED status indicators for the scenarios considered

Sl No	Scenario	Case	Hooked Status	Red LED	Green LED	Supervisor Monitor
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	1	1	Not hooked	OFF	OFF	No alert
2	1	2	Not hooked	ON	OFF	No alert
3	1	3	Not hooked	ON	OFF	No alert
4	1	4	Hooked	OFF	ON	No alert
5	2	1	Not hooked	OFF	OFF	No alert
6	2	2	Not hooked	ON	OFF	No alert
7	2	3	Not hooked	ON	OFF	No alert
8	2	4	Not hooked	ON	OFF	Alert

Table 6. Comparative analysis of test results

Sl no	Method	Results
1	Scaffold-Based System	95.33% accuracy, 1.5-second response.
2	Advanced D-Ring System	99.33% accuracy, <1 second response.

Table 7. Two-proportion Z-test results of the scaffold-based and advanced ring system

System	Total Trials	Successful Detections	Missed Detections	Detection Accuracy (%)	Z - statistic	p-value
Scaffold-based	150	143	7	95.33%		
Advanced D-ring	150	149	1	99.33%		
Z-test Results					**-3.04**	**0.0024**

3.1. Discussions

The developed clamping detection systems were found to be effective in enhancing real-time safety monitoring; however, some limitations were observed. The scaffold-based evaluation system, with the temporary nature of the framework, introduced maintenance challenges due to frequent wear and tear of the system's circuit. This resulted in signal loss, and frequent assembly and disassembly of the system resulted in durability issues, and the chances of system degradability increased over time. This required periodic inspections and application of human intervention for the same.

The need for a stable and continuous power supply was also a challenge, especially due to the temporary nature of the scaffold network. Prior IoT solutions [21] identified power continuity as a critical constraint [13, 15] in wearable and distributed sensing systems. Exposure to weather conditions could also hamper the working of the sensors and their data transmission quality, as observed by [22, 23]

The advanced d-ring modification system demonstrated significant resilience and stability. The integration of serrated copper contacts directly on the harness d-ring eliminated the dependence on the scaffold-mounted system, thereby overcoming the limitations of the previous system.

The system exhibited high detection accuracy of 99.33% and a response time of less than 1 second, which was supported by a communication integrity of 99%. These findings align with the contemporary findings in wearable safety IoT devices, which were coupled with hardware integration methods that improved signal reliability and reduced false alarms [16, 24].

The dual feedback mechanism (LED alerts with real-time data transfer) enhanced usability by supporting on-worker and remote monitoring. The comparative analysis in Table 6 indicated that the advanced d-ring system outperformed the scaffold-based system. Similarly, it was also validated with a two-proportion z-test ($Z = -3.04$, $p = 0.024$), exhibiting the distinction in detection accuracy to be statistically significant rather than standing alone. The assessment framework tested under OSHA compliance thresholds and a 120-second grace period indicated advancements over the previous systems, like vision-based monitoring approaches [9, 10] or RFID-based systems [25, 26] which need investments and precise measurements [19].

The developed system uses low-voltage, low-maintenance hardware that is integrated together to provide real-time detection and is aligned with OSHA fall protection requirements [3, 27]. The previous IoT-based fall protection systems offer monitoring solutions without a multi-level feedback mechanism in comparison to the present system, which demonstrates a closed-loop feedback mechanism and alert system. The obtained results indicated that the proposed advanced d-ring monitoring system is a scalable option, and future works should look into the durability aspects and the use of technologies like LoRa or BLE mesh [28] to improve accuracy.

4. Conclusion

The present research, which revolves around a novel harness clamping mechanism, addresses challenges of real-time safety monitoring in elevated work environments. Each system demonstrated significant potential in detecting clamping status and generating real-time alerts.

The advanced D-ring modification approach was found to be more accurate, 99.33% during testing, and the findings ensured that the integration of sensors with Zigbee-enabled communication is successful in improving monitoring reliability compared to conventional systems. The study also stressed the essential requirements for enhancements required to further strengthen the system, not limited to power management and network-related issues.

The outcomes support that IoT driver safety technologies, when appropriately integrated, can significantly change the approach to real-time monitoring of workers.

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