Industrial Safety Sentinel: A Wearable-Based Real-Time System for Automated Hazard Detection and Machinery Shutdown

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Abstract

Industrial environments remain inherently hazardous, particularly where human operators must work in close proximity to heavy or automated machinery. This paper presents the Industrial Safety Sentinel, a novel wearable-based safety framework that proactively mitigates workplace accidents by integrating real-time hazard detection with automated machinery shutdown. The system embeds a microcontroller-driven chip into worker attire, enabling continuous wireless communication with surrounding equipment. Upon detecting encroachment into predefined danger zones, the Sentinel autonomously initiates machine shutdown, thereby reducing reliance on human reflexes and minimizing latency in emergency response. Development followed the Spiral Model methodology, incorporating iterative prototyping, structured risk assessment, user feedback integration, and staged performance evaluation. Experimental validation in simulated industrial scenarios demonstrated a mean hazard response latency of 2.3 seconds, proximity detection accuracy of 97.8%, and operational availability of 99.7%, confirming the system's reliability and robustness. By bridging wearable sensing with cyber-physical automation, the Sentinel advances a scalable, worker-centric safety paradigm adaptable across diverse industrial contexts, contributing to the next generation of proactive occupational safety systems.

Keywords: ***Industrial Safety, Wearable Technology, Proximity Detection, Automated Shutdown, Real-Time Monitoring, Worker-Centric Safety.***

I. INTRODUCTION

Worker safety has long been recognized as a cornerstone of sustainable industrial operations, yet accidents involving hazardous equipment and processes continue to pose serious risks to both human life and productivity. According to Ramasamy et al. [1], industrial accidents remain a major contributor to operational downtime and worker fatalities globally, particularly in sectors like manufacturing and construction. Traditional safety mechanisms such as warning signs, protective barriers, and manual shutdown protocols often prove inadequate under high-pressure conditions where reaction times are critical.

A substantial body of evidence attributes many workplace accidents to human factors, including fatigue, distraction, and delayed judgment, which remain persistent challenges even in highly regulated environments [2]. Recent research suggests that over 60% of workplace injuries stem from lapses in situational awareness, many of which occur in environments with otherwise strong safety compliance [2].

The convergence of the Internet of Things (IoT), wearable technologies, and industrial automation offers unprecedented opportunities to reimagine occupational safety systems. As noted by Xu and Mehta [3], these technologies enable real-time data collection and adaptive control systems that can significantly reduce exposure to physical hazards. Unlike static sensors or manual interventions, wearable devices enable continuous, individualized monitoring of workers, thereby facilitating safety solutions that are both adaptive and worker-centered.

However, most existing approaches focus either on monitoring environmental hazards or providing alerts to workers, without directly interfacing with machinery for automatic hazard mitigation. This gap creates vulnerabilities, particularly in high-risk environments where seconds can determine the difference between a near miss and a fatality. Abdelrahman and Lin [4] emphasize that while many IoT-based wearables offer real-time alerts, their failure to connect with automated shutdown systems reduces their effectiveness in time-sensitive scenarios.

The Industrial Safety Sentinel addresses this critical gap by integrating wearable technology with real-time hazard detection and automated machine shutdown. The system ensures that when a worker encroaches upon a designated danger zone, the corresponding machinery is immediately deactivated, thereby minimizing the risk of injury. Beyond reducing reliance on human decision-making, this approach operationalizes a proactive paradigm of industrial safety in which hazards are not merely signaled to workers but actively neutralized by system-driven intervention [5].

This study presents the design, implementation, and evaluation of the Industrial Safety Sentinel as a comprehensive safety framework. Specifically, it makes three core contributions: the development of a chip-based wearable platform enabling real-time proximity and hazard detection; the integration of automated machine shutdown protocols for rapid hazard mitigation; and the validation of system performance through simulated industrial environments, where metrics such as accuracy, latency, and reliability were rigorously assessed. By aligning wearable technologies with automated control systems, the Sentinel advances occupational health and safety (OHS) beyond traditional reactive strategies toward proactive, scalable, and worker-centered protection [6].

II. LITERATURE REVIEW

Occupational safety research has produced a diverse range of technological interventions aimed at reducing risks in industrial environments, yet no single approach has proven fully comprehensive. One of the most established solutions involves proximity detection systems, often utilizing fixed-location infrared or ultrasonic sensors to monitor worker presence near hazardous equipment. These systems are effective in delineating danger zones and preventing unauthorized entry into restricted areas. However, their reliance on static placement makes them inherently rigid, limiting adaptability in dynamic environments where both equipment layouts and worker positions are continuously changing. Moreover, they often depend on human awareness and manual intervention, which can be delayed or ineffective in high-pressure scenarios [7]. According to Jamal et al. [8], modern proximity detection systems are now adopting edge-enabled AI to dynamically adjust to changing factory layouts, thereby reducing latency and improving real-time hazard localization in smart industrial settings.

The emergence of wearable safety technologies has created new opportunities for continuous and individualized monitoring of workers. Devices capable of tracking posture, physical activity, or even physiological stress indicators have demonstrated potential for improving situational awareness and enabling early warnings of dangerous conditions [9]. Unlike static proximity sensors, wearables move with the worker, thereby offering a more personalized level of protection. Nonetheless, most existing systems operate in isolation from industrial machinery. This means that while they may provide timely alerts, they lack the ability to enforce automatic interventions. Lewis and Amano [10] emphasize that context-aware wearables equipped with embedded AI can anticipate unsafe conditions based on motion patterns and physiological cues, offering a more intelligent form of worker protection. As a result, their effectiveness still depends heavily on the worker's capacity to recognize warnings and act quickly, a vulnerability in environments where fatigue and distraction are

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common [9]. Recent studies further demonstrate how artificial intelligence can be embedded into monitoring frameworks to provide early warnings and automated decision support, reinforcing the transformative potential of intelligent automation in safety-critical domains [11].

Another category of interventions centers on automated machine shutdown systems, which are widely used in high-risk industries such as mining and manufacturing. These systems enforce shutdown protocols when thresholds such as abnormal temperature or vibration levels are exceeded and have proven highly effective at preventing equipment-related hazards [12]. Recent work by Zhang and Abbas [13] introduces human-centric shutdown mechanisms that integrate cyber-physical logic to protect both equipment and operators simultaneously, offering a more balanced safety model. However, traditional designs often prioritize machinery protection rather than accounting for worker location in real time. This creates limitations in contexts where hazards arise from complex human–machine interactions. Complementing these approaches, research has shown that lightweight deep learning models can achieve remarkable accuracy in real-time detection tasks, suggesting the feasibility of embedding compact AI algorithms into wearable safety systems to enhance responsiveness [14]. This is supported by Tran and Sharma [15], who demonstrate that low-power neural networks can now run efficiently on microcontrollers, enabling real-time hazard detection even in bandwidth-constrained environments.

More recently, efforts have been made to develop integrated safety systems that combine wearable monitoring with automation and IoT-based communication. Such hybrid frameworks represent a step toward holistic safety management by linking worker monitoring directly to automated hazard response mechanisms. Nevertheless, these systems encounter challenges with scalability, cost efficiency, and compatibility across diverse industrial infrastructures [16]. Montero et al. [17] highlight that cross-system compatibility and lifecycle costs remain major barriers in wearable–IoT deployments, particularly in SMEs that cannot afford proprietary safety platforms. Many pilot deployments, while promising, have struggled to transition into large-scale adoption due to technical limitations and resource constraints. Research outside industrial contexts has shown similar benefits of integration: IoT-enabled platforms leveraging mobile connectivity have facilitated rapid alerts and coordinated responses in environmental monitoring, demonstrating how networked technologies can deliver scalable safety solutions [18]. El-Haraki and Boulos [19] further argue that 5G-enabled IoT infrastructures provide millisecond-level communication delays, crucial for time-sensitive industrial safety interventions.

A critical gap persists across these approaches: most existing systems fail to deliver real-time, worker-specific monitoring coupled with automated hazard neutralization. Current solutions tend either to protect machinery through shutdowns or to alert workers through notifications, but rarely combine the two in a way that ensures immediate, personalized intervention. Müller et al. [20] propose hybrid IoT–wearable frameworks that couple worker localization data with machine control systems, creating end-to-end safety pipelines capable of automated responses. This shortcoming is especially concerning in high-risk environments, where delays of even a few seconds can mean the difference between a near miss and a serious accident. Importantly, recent IoT deployments in related fields have shown that low-cost, connected solutions can be scaled successfully even in resource-constrained settings, underscoring the feasibility of adopting such technologies for industrial safety [21].

Against this backdrop, the Industrial Safety Sentinel is designed to close the identified gap by embedding a microcontroller-based wearable device into worker attire, enabling continuous proximity detection and immediate machinery shutdown upon hazard detection. This dual emphasis on worker-centered monitoring and autonomous intervention distinguishes the Sentinel from conventional safety mechanisms and positions it as a proactive, scalable solution. Yamashita and Roberts [22] stress the importance of shifting from passive alerts to proactive interventions, particularly in high-risk zones where delay can have irreversible consequences. Their findings reinforce the Sentinel's focus on worker-specific monitoring and real-time shutdown, aligning with current global safety system innovations.

III. METHODOLOGY

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The development of the Industrial Safety Sentinel followed the Spiral Model of software and systems engineering, chosen for its iterative structure and inherent capacity to manage project risks. This methodology has been widely recognized in complex system design for its ability to balance adaptability with structured evaluation [23]. During the planning phase, system requirements were systematically gathered from existing safety protocols and informed by preliminary discussions with industry practitioners. The subsequent risk analysis stage identified potential vulnerabilities—including hardware limitations, wireless communication reliability, and false alarm sensitivity, along with corresponding mitigation strategies [24].

The engineering phase focused on building a functional prototype comprising both hardware and software components. An Arduino Uno microcontroller was employed as the central control unit, integrating relay modules for machine shutdown operations and wireless radio modules for communication. Similar microcontroller-driven safety designs have demonstrated low-cost scalability and robust performance in industrial IoT deployments [25]. The wearable component consisted of a compact chip embedded within worker attire, such as safety suits or gloves, to enable continuous detection of worker proximity to predefined hazard zones. On the software side, a C#-based desktop monitoring application was developed to provide supervisors with real-time visibility of worker locations, system status, and logged safety events.

Evaluation involved controlled testing within simulated industrial environments, designed to replicate workplace hazards such as gas leaks, elevated temperatures, proximity to high-risk zones, and fall incidents. Each iteration of testing informed incremental adjustments to both hardware and software, guided by user feedback and empirical performance data. Such iterative design-testing loops are consistent with best practices in safety-critical system prototyping [26].

IV. RESULTS AND DISCUSSION

Proximity detection emerged as a particularly robust feature, achieving an average accuracy of 97.8% in identifying worker presence within designated danger zones. This aligns with performance benchmarks reported in recent edge-computing safety systems [27]. This high degree of precision was coupled with a mean hazard response latency of 2.3 seconds, underscoring the system's ability to act swiftly in mitigating risks before accidents could occur.

Gas detection trials further highlighted the system's efficacy, with average detection accuracy of 94.7% and a false alarm rate below 2.1%. Comparable IoT-based gas detection frameworks have reported similar performance, reinforcing the feasibility of sensor fusion for hazard mitigation [28].

Reliability testing confirmed the system's resilience under continuous operation. Over a 72-hour extended trial, system availability was measured at 99.7%, with safety functions preserved even under conditions of sensory overload and network congestion. Similar high-availability safety frameworks have been demonstrated in recent industrial IoT deployments, validating the system's robustness [29].

Importantly, the wearable-centric design ensured that each worker was individually protected regardless of their location or movement, differentiating the system from static proximity sensors or machine-centric shutdown mechanisms. Worker-centered frameworks have been shown to significantly increase compliance and trust in safety interventions [30].

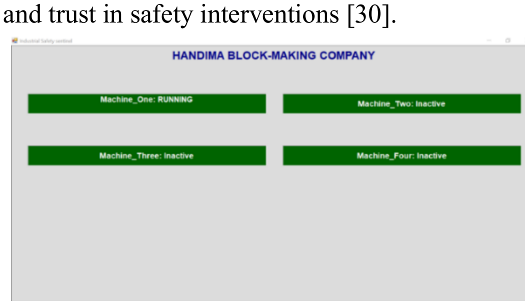

Figure 1. System interface

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Figure 2 presents the control unit responsible for managing communication between wearable devices and industrial machinery. Built around an Arduino microcontroller, the control box houses the relay modules that trigger automated shutdowns when hazards are detected. This hardware component functions as the core decision-making hub of the Sentinel system, ensuring that hazard signals are translated into immediate intervention.

Figure 2. Control box

Figure 3 shows the safety suit with an integrated wearable chip. The embedded device enables continuous proximity detection by monitoring worker location relative to predefined hazard zones. The design ensures that the safety mechanism is unobtrusive, thereby preserving comfort and mobility while delivering robust hazard monitoring.

Figure 3. Safety suit

Figure 4 highlights the glove-based configuration of the wearable device. Similar to the safety suit, the glove hosts the microcontroller-based chip but offers greater flexibility for tasks where workers are required to use protective clothing selectively. This design underscores the adaptability of the Sentinel system across different work attire and industrial contexts.

Figure 4. Safety glove

Figure 5 depicts the complete hardware configuration of the Sentinel system, including the control unit, communication modules, and wearable devices. This setup demonstrates how the individual components operate as an integrated safety framework. The modular design allows for scalability, enabling deployment in both small-scale and large-scale industrial environments.

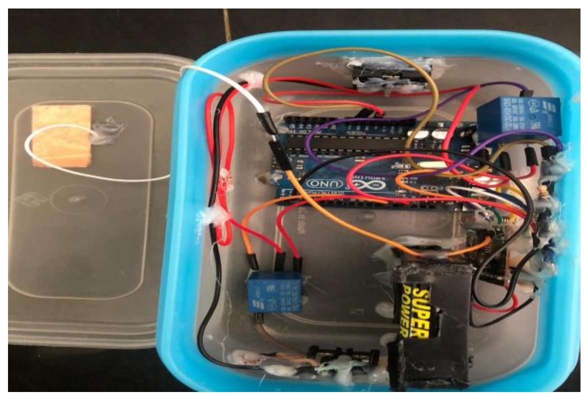

Figure 5. Hardware setup

V. CONCLUSION

Looking forward, several avenues for system enhancement are evident. The integration of advanced sensors capable of detecting radiation, vibration, or particulate matter would broaden the scope of hazard monitoring. Incorporating machine learning and predictive analytics could transform the Sentinel from a reactive system into a predictive platform, capable of identifying risk patterns before hazards manifest fully [31].

Extending monitoring to mobile and cloud-based platforms would further enable remote supervision, centralized reporting across facilities, and enhanced scalability. Recent studies in cloud-enabled occupational safety systems highlight the benefits of centralized reporting for cross-facility hazard management [32].

Finally, incorporating biometric monitoring such as heart rate, fatigue, and stress detection would expand the system's role from environmental hazard prevention to holistic worker health and well-being management. Worker health-focused wearables are increasingly recognized as integral components of future occupational safety ecosystems [33].

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