Integrating Edge Computing and Cloud BIM for Enhanced Real-Time Safety Monitoring in Construction Sites: Reducing Time-Latency and Improving Data Accessibility

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Purpose

This study aims to reduce time latency and improve data integration in Proximity Warning Systems (PWS) used for construction safety monitoring. Traditional systems often suffer from delays that compromise worker safety, highlighted the need for a more responsive and integrated approach.

Methodology

This research proposes a hybrid PWS architecture that integrates edge computing with Industry Foundation Classes (IFC) to enhance real-time performance and data accessibility. The system was implemented and tested in a controlled laboratory setting, where its performance was compared to both local and centralized processing systems. Key performance metrics, such as latency and reliability, were measured over multiple iterations.

Findings

The hybrid system demonstrated latency comparable to local processing but significantly lower than centralized systems. It also maintained reliable performance with minimal variability and remained resilient to network disconnections. These characteristics make the proposed hybrid system highly effective for real-time monitoring in dynamic construction environments.

Originality

This study presents a novel hybrid architecture that uniquely combines the strengths of both local and centralized PWS, offering an optimal balance between real-time responsiveness and robust data integration. The integration of edge computing with combination with IFC for construction safety monitoring is an innovative approach that has not been previously studied.

Research limitations

Further research is required to validate the system in real-world construction sites and to address potential time delays in cross-system data access.

Keywords: Edge Computing, Building Information Modeling (BIM), Construction Safety, Ultra-Wide Band (UWB) tracking, Safety Monitoring

1 Introduction

The construction industry remains one of the most hazardous sectors worldwide, presenting significant safety risks to workers which ultimately affect project performance [1]. In 2022, for instance, the Canadian construction industry reported the highest number of fatalities across all sectors [2]. Studies shown that a significant portion of accidents in construction sites occur when workers are in close proximity to operating construction equipment [3-5], with falls from heights representing a leading risk [6], often due to poor situational awareness.

To mitigate these risks, the implementation of advanced safety technologies has shown promise in reducing the number of accidents on construction sites [7]. Real-time monitoring systems, in particular, have demonstrated potential in enhancing workers' situational awareness [5, 6, 8]. Among these systems, Proximity Warning Systems (PWS) have garnered significant attention, utilizing Real-time Location Systems (RTLS) to warn workers when they are in the proximity of hazardous areas to prevent collisions [3].

Various RTLS technologies have been utilized in the development of PWS, including GPS, RFID, Ultra-Wideband (UWB), Bluetooth Low Energy (BLE), and Vision Based systems. Previous studies have indicated that UWB RTLS offer higher accuracy compared to other alternatives, making them particularly suitable for construction sites [8-13]. However, a persistent challenge for proximity warning-based safety monitoring systems, is time latency in data communication, which creates a delay between the moment workers should receive a warning and the actual time they receive it. Time latency, though measured in milliseconds, can have significant consequences in safety-critical environments. In applications such as tracking workers to prevent entry into hazardous areas, even split-second delays can result in dangerous situations.

PWSs developed for construction site safety monitoring mainly follow two approaches: local processing systems and centralized processing systems. Local processing systems, designed for specific tasks and operating independently, provide fast responses with minimal time delay, making them suitable for immediate safety interventions. These systems are primarily used for prototype development or proof-of-concept in literature. However, their independent operation leads to a lack of data integration and accessibility, which is crucial for efficient and effective safety monitoring [14-16]. Without data integration and accessibility, different systems on construction sites cannot communicate or share data with other systems, meaning they are unable to reflect real-time changes in construction sites within their operations.

On the other hand, centralized processing systems utilize a central processing server communicating over a network to address the lack of data integration. While they leverage the advantages of integrated data, they rely on network connectivity, introducing network latency that can cause system delays in safety monitoring systems [17, 18].

This study aims to address the challenge of minimizing time latency while providing data accessibility in PWS. The objective is to develop a PWS using RTLS that integrates data while minimizing time latency. To achieve this, the study integrates Industry Foundation Classes (IFC) for data integration with the concept of edge computing. This integration enables processing at the network's edge, providing instant warnings to workers and operators. Additionally, using IFC ensures standardized communication across different systems.

2 Literature Review

2.1 Proximity Warning Systems in Construction Sites

Real-time safety monitoring systems have emerged as a promising tool in enhancing accident prevention and intervention capabilities in the construction industry [19]. These systems leverage continuous data collection and analysis from the dynamic construction site environment, offering comprehensive coverage and advanced analytical capabilities.

PWS are designed to enhance worker safety by providing real-time alerts when individuals approach hazardous areas. The literature predominantly focuses on two primary applications of PWS: alerting workers when entering fall-risk areas [20-23] and warning of potential collisions with construction equipment and machinery [4, 24-27].

A variety of technologies have been employed for worker localization in these systems, including Ultra-Wideband (UWB), ZigBee, Radio-Frequency Identification (RFID), Ultrasound, Light Detection and Ranging (LiDAR), Inertial Measurement Units (IMU), and Bluetooth Low Energy (BLE) [20, 28-31]. Among these, UWB tracking has gained prominence in the literature due to its superior positioning accuracy in construction environments, lower power consumption, and higher signal penetration compared to other methods. Despite a limited range of approximately 100 meters, UWB sensors demonstrate enhanced performance in indoor environments, making them particularly suitable for construction site applications [32-34].

Despite the development of these systems, one issue that has received relatively little attention is the challenge of time latency. Time latency in PWS refers to the delay between the moment workers enter a hazard zone and the time they receive the necessary warning. This delay is unavoidable due to the sequence of processes required to issue an alert, including sensor processing, data transmission, data analysis, and the final transmission of the alert to the worker [35]. Therefore, before claiming real-time functionality, it is crucial to assess and quantify the system's latency.

To the best of our knowledge, one of the few studies that directly addressed this issue is the work by Talmaki et al. [36], which evaluated internal system delays. However, the study identified that latency caused by data transmission between servers and sensors remains a significant challenge. To achieve true real-time performance in PWS systems, it is essential to analyze both internal and external processes comprehensively, and to develop targeted solutions to minimize these latency sources.

2.2 Proximity Warning System Architectures

Previous studies on Proximity Warning Systems (PWS) have employed two different architectural approaches, each with its own advantages and limitations. One such approach is the use of local processing, where sensor data is processed locally, and warnings are provided to workers and operators in near-real-time. This architecture is well-suited for safety-critical applications due to its minimal latency [22, 25, 37, 38].

However, the lack of interaction between these locally processed PWS and other construction site systems presents a challenge. The dynamic nature of construction sites, characterized by continuous and diverse activities, requires efficient monitoring and the ability to update information from various sources [39, 40]. For instance, changes in hazardous areas cannot be easily updated in PWS systems based on this static, locally processed architecture.

This local processing approach can be considered a traditional method of construction site safety monitoring, as it is generally designed based on static information, with limited capabilities for manual or automated data updates [41, 42]. Meanwhile, access to data from different sources is crucial for the development of effective safety monitoring systems [43]. The lack of integration and accessibility is a key challenge for PWS development following this architecture.

In contrast, the centralized processing architecture utilizes a central server, either local or cloud-based, to integrate and process data collected from various sources, including spatial data. This approach enables data integration and accessibility, allowing for more comprehensive safety monitoring [20, 43, 44]. However, the reliance on network connectivity to exchange information can introduce system latency, exacerbating another challenge in PWS development: time delays [17, 18].

The trade-off between real-time performance and data integration/accessibility represents a significant challenge in the development of effective Proximity Warning Systems. Addressing this challenge requires innovative approaches that can leverage the advantages of both local and centralized processing while mitigating their respective limitations.

2.3 Research Gap

Despite advancements in Proximity Warning Systems for construction safety, gaps remain. Local processing systems offer real-time response but lack integration with other site systems, limiting adaptability to dynamic environments. Conversely, centralized systems improve data integration but introduce latency due to network dependence, which is problematic in safety-critical situations. The literature lacks exploration of hybrid solutions that combine the strengths of both approaches. This study addresses these gaps by developing a hybrid PWS architecture that balances real-time performance with data integration, using edge computing and IFC for standardized communication.

3 Methodology

To achieve the objective of this research, developing a proximity warning system that provides real-time alerts with minimal latency while enabling data exchange with other construction management systems, this study follows a structured approach. Initially, the scope of the research will be clearly defined and then the expected functionality of the proximity warning system will be explained. Then three phases of developing and validating the system will be covered. In the first phase, a hybrid system architecture is proposed which combines edge computing concept with IFC to address the research objective. This phase is described in this section. Then based on proposed, local processing, and centralized processing architectures, three systems will be developed and implemented. This phase will be covered in the implementation section. The final phase, elaborated in the Validation section, evaluates the performance of these systems through comparative analysis, assessing the effectiveness and potential advantages of the proposed system in enhancing construction site safety and data integration.

3.1 Research Scope

As outlined in the literature review, PWSs are designed to enhance worker safety by providing real-time alerts when individuals approach hazardous areas. In this study, hazardous areas are defined as regions within a construction site that pose significant risks to worker safety, such as open floor openings, edges of floors, or areas containing hazardous materials. A safety margin is established around these hazardous zones, creating a buffer. When a worker enters this safety margin, an alert is triggered.

The process from when a worker enters the safety margin to when the system issues a warning involves a sequence of events, each contributing to a short delay. These delays, referred to in this study as time latencies, can impact the system's efficiency, which relies on real-time operation. Although some latencies cannot be entirely eliminated, they can be minimized.

This research focuses on mitigating specific latencies, identified as D2, D3, and D4 in Figure 1. Latencies caused by sensors and those resulting from worker feedback fall outside the scope of this study. The proposed system aims to reduce the targeted latencies by addressing delays related to network data exchange. Additionally, by leveraging IFC files as a central data server, the system enhances data interchange between various systems.

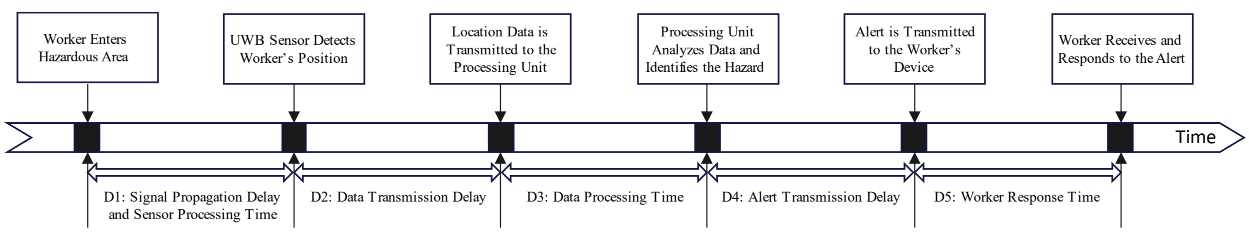


Figure 1. Overview of Latencies in Proximity Warning Systems

3.2 Proposed System Architecture

The proposed hybrid architecture is designed to combine the strengths of both local and central processing architectures while addressing their respective limitations. As illustrated schematically in Figure 2, this architecture utilizes edge computing to minimize response time and employs Industry Foundation Classes IFC as a central data repository. By integrating edge computing, the system effectively eliminates the network latency associated with central processing architectures, enabling faster warnings to workers. Additionally, the use of IFC as a central data server ensures data access across various systems within construction sites. The following subsections will explain in detail how IFC and edge computing enable the architecture to achieve these objectives, providing both the low-latency response of local processing systems and the data integration capabilities of centralized systems.

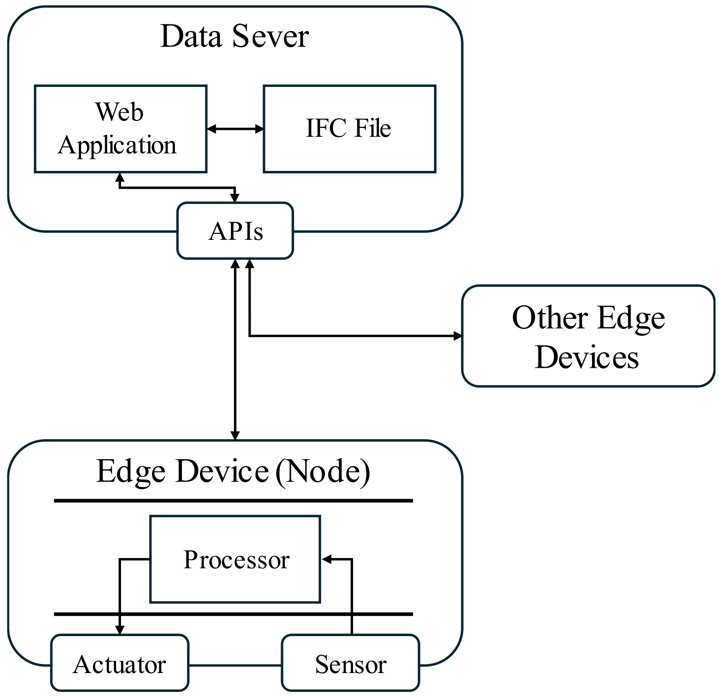


Figure 2. Proposed System Architecture

3.2.1 Leveraging Edge Computing to Minimize Latency

The emergence of edge computing (EC), a paradigm characterized by distributed computing, storage, and control at the network edge, has presented a promising approach to mitigate latency and enhance system resilience in safety applications [45]. The use of EC, as opposed to centralized or cloud-based processing, offers several advantages. One key benefit is improved privacy and data security. Data leakage often occurs during the transfer of data to centralized servers. By storing and processing data on edge devices, EC can protect against such data breaches [46]. Additionally, EC can help manage energy consumption more effectively, as it reduces network bandwidth constraints and mitigates the high energy demands inherent in cloud computing [47].

Perhaps the most critical advantage of EC in construction safety monitoring is the ability to provide real-time responses. The proximity of data processing to the data source significantly reduces service response time, enabling near-instantaneous performance - a capability that centralized processing systems often struggle to achieve [47, 48]. This near-real-time responsiveness is particularly crucial in safety-critical applications, such as PWS, where even minimal delays can have serious consequences. The integration of EC into PWS can effectively address the challenge of latency. By processing data at the edge, PWS can minimize the time delays that can occur in centralized systems reliant on network connectivity. This approach enhances the effectiveness of safety monitoring and intervention, ultimately leading to improved worker safety on construction sites.

While implementing edge computing for this application, it's essential to maintain a mechanism for updating edge nodes with relevant information from a central server. In this research, Industry Foundation Classes are employed for both data definition and exchange. The proposed system, based on this architecture, involves two concurrent processes at each edge node: monitoring worker entry into safety margins based on their coordinates, and continuously updating safety margins using a central data server that stores information in an IFC format. This dual-process approach ensures both real-time safety monitoring and adaptability to dynamic changes in the environment.

3.2.2 Industry Foundation Classes for Data Exchange

Building Information Modeling (BIM) offers a solution to the need for data integration and accessibility in construction site safety monitoring systems. However, the primary applications of BIM in construction safety have largely been confined to identifying high-risk areas [48, 49] and visualization [50, 51]. BIM's potential as a platform for data integration and accessibility remains largely untapped, particularly through the use of Industry Foundation Classes.

IFC is an open, standardized data model designed to facilitate interoperability between BIM software applications in the Architecture, Engineering, Construction, and Facilities Management (AEC/FM) industry [52]. It provides a common schematic for data storage and retrieval, enabling seamless integration with diverse systems. The flexibility of IFC in accommodating a wide range of building-related information makes it a versatile foundation for developing various applications.

The adoption of IFC-based files as an alternative to traditional databases allows for the creation of a unified data structure [50]. This approach facilitates the development of generic Application Programming Interfaces (APIs) for data retrieval and storage without necessitating modifications to the server infrastructure. Consequently, IFC promotes data integration and enhances interoperability among systems.

This research leverages Industry Foundation Classes for the seamless exchange of essential data between network nodes and the central data server, enabling the implementation of edge computing. By adopting IFC, the proposed system facilitates the integration of information from various systems and enables the automatic identification and extraction of safety margins based on IFC objects retrieved from the server. This capability presents a significant advantage over local processing architectures, which lack the ability to integrate information from disparate sources.

4 Implementation

While the proposed system architecture theoretically meets the research objectives, its performance must be evaluated against other system architectures to confirm its feasibility. To assess the effectiveness of the proposed hybrid architecture, the PWSs was implemented using three distinct processing architectures: Local Processing, Centralized Processing, and the proposed Hybrid architecture. This comparative analysis allows for a thorough evaluation of the strengths and weaknesses of each approach. To ensure that performance differences are attributable solely to the system architecture, the physical components and system objectives for all three implementations were kept consistent. The following sections provide detailed descriptions of each architecture’s implementation, with particular emphasis on their distinguishing characteristics.

4.1 Systems Hardware Configuration

As previously mentioned, the main components of all three systems were kept consistent to ensure that performance differences would be attributable solely to the system architecture. Ultra-Wideband (UWB) Real-Time Location Systems (RTLS) were selected for worker localization due to their suitability for precise indoor positioning, offering sub-decimeter accuracy. These systems operate within the 6 GHz to 8.5 GHz frequency band with a bandwidth exceeding 500 MHz. For this research, DWM1001C 6.5 GHz transceiver modules were employed for tracking workers and objects. These modules were configured into groups of five for experimentation, with four modules serving as reference points (anchors) and one as a tag for localization.

To generate warnings in each system, a buzzer was used to emit an audible alert when a worker entered a safety margin. Although an audible warning was chosen for this study, it is recognized that this may not be the most effective form of alert in hazardous situations. This decision was made solely to demonstrate the concept, and further research is necessary to determine the most appropriate form of warning for workers, which is beyond the scope of this study.

For local processing in each system architecture, a Raspberry Pi Zero 2 W was employed. In the proposed hybrid architecture, it functions as a network edge node; in the local processing architecture, it serves as the local processor; and in the centralized processing architecture, it acts as a client to the central server.

4.2 System Implementations

The first implementation follows the local processing architecture. The data flow and components of the PWS, as designed and implemented based on this architecture, are illustrated in Figure 3. In this system, spatial information and safety margins extracted from a BIM model were preloaded onto the local processor. The system continuously receives worker coordinates from UWB sensors and triggers an alarm when a worker enters a safety margin. Any changes to the safety margins must be manually updated in the system. While this architecture is simple and lacks communication with other systems, it offers near-instantaneous performance.

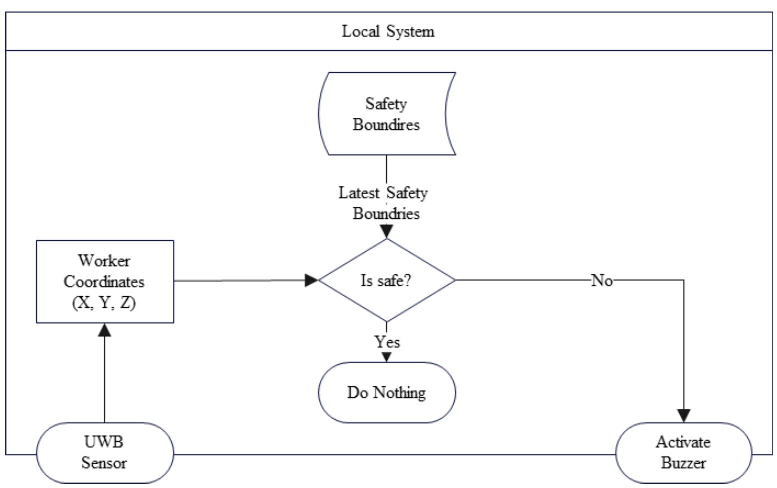


Figure 3. Data Flow and Components of the PWS in the Local Processing Architecture

The second implementation follows the centralized processing architecture. In this architecture, sensor data representing worker locations is transmitted to a central server for processing. When a worker enters a predefined safety margin, an alert is triggered by the server. The centralized architecture allows for real-time system updates and the integration of data from various sources. However, network latency introduced by data transmission can delay the delivery of alerts. The PWS based on this architecture is depicted in Figure 4. In this system, spatial information and safety margins are stored on a central server and are automatically updated based on changes in the building's BIM model. Sensor data is transmitted to the server, which activates an alarm when a worker enters a safety margin. The system was implemented using the Django web framework and REST APIs for the server side, with the server running on a computer over a local network.

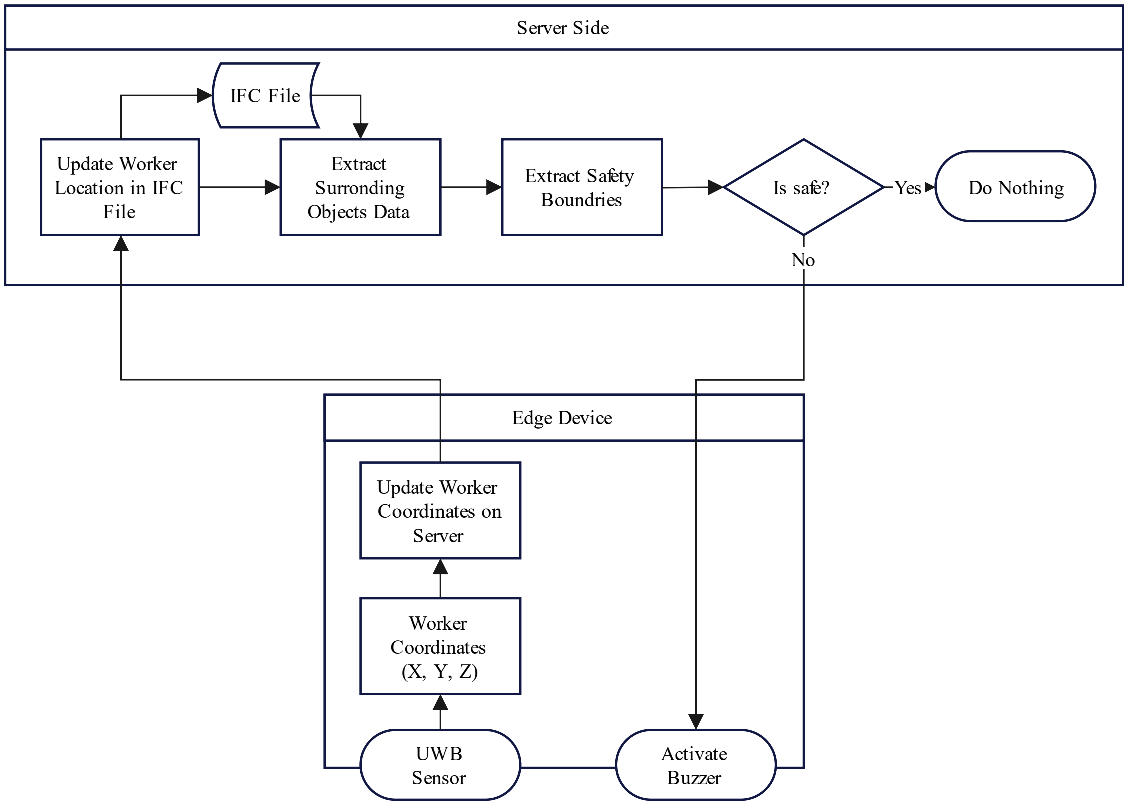


Figure 4. Data Flow and Components of the PWS in the Centralized Processing Architecture

The third implementation is based on the proposed hybrid system architecture. The data flow and components of the developed PWS, based on this architecture, are shown in Figure 5. This system implements the proposed logic, which involves processing data at the edge while simultaneously updating data with the central server. Similar to the centralized system, the Django web framework and REST APIs were used for the server implementation. Additionally, the IfcOpenShell library was employed to perform create, read, update, and delete operations on the IFC file on the server.

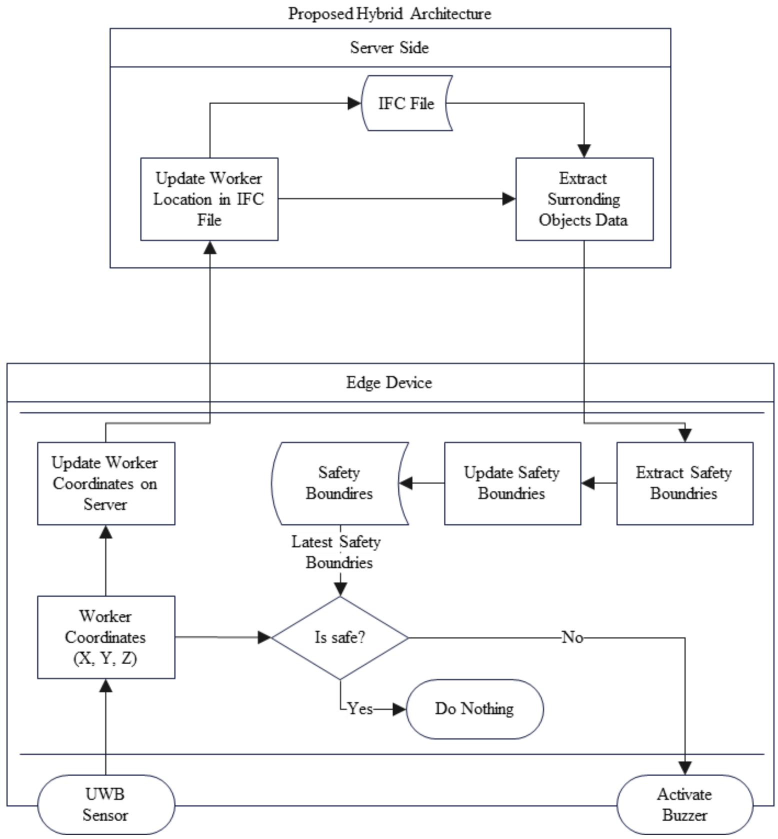


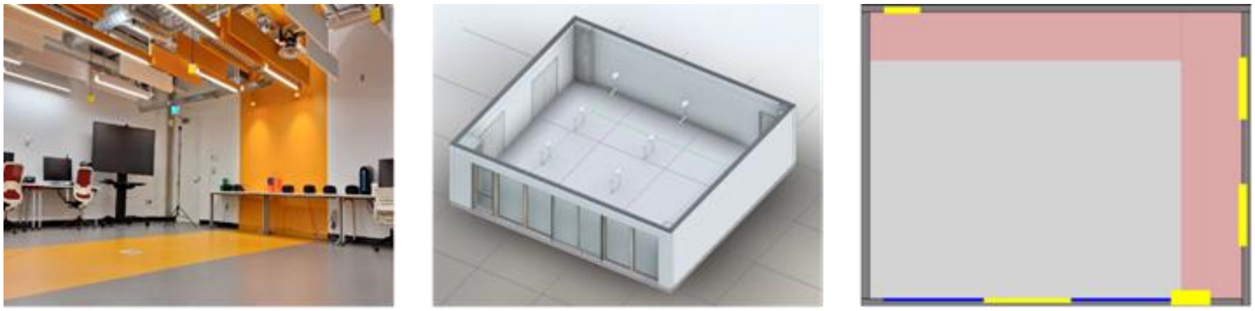
Figure 5. Data Flow and Components of the PWS in the Proposed Hybrid Architecture

5 Validation

To validate the functionality and performance of the proposed hybrid system, an experiment focusing on site safety monitoring was conducted. This experiment simulated a site safety monitoring scenario designed to track workers and issue warnings. The primary objective, as defined within the scope of this research, was to measure the time taken from the moment sensors generate data to when a warning is issued to the worker in each PWS system architecture, thereby calculating the time latency between these two events. This comparison of time latencies across the systems will help determine whether the proposed hybrid system achieves a latency comparable to that of the local processing system and a lower latency than the centralized processing system.

To achieve this goal, as described in the implementation section, three PWS implementations were developed based on the three architectures. A laboratory environment was then modeled using Revit software to create a detailed BIM model for simulation purposes. Within this virtual lab model, specific zones were designated as safety margins, as depicted in Figure 6b, to mimic potential danger zones typically found on real construction sites.

To minimize the impact of external factors on system performance, a four-wheel remote-controlled robot was used in place of a human for the experiment. This approach eliminates variables associated with human behavior, such as movement pace, perception reaction time, and potential signal interference caused by the human body. Additionally, the UWB modules in this experiment were configured to operate at a frequency of 5 Hz. The experiment was conducted over 100 iterations for each system to ensure reliable and consistent results. The performance of the hybrid system was then compared with that of the other two systems, and the results of this experiment are presented in the following section.



(a) (b) (c)

Figure 6. (a) Real Laboratory Environment, (b) BIM Model Created Using Revit Software, (c) Safety Boundaries Defined in the Virtual Model

6 Results

After conducting the validation experiment, timestamps associated with key events in each system were carefully recorded using checkpoints embedded in each system's code. The total latency for each system was then calculated. To ensure a comprehensive evaluation of system reliability, none of the calculated latencies were excluded from the final results. Statistics and results regarding the calculated latencies are presented in Table 1.

System	Mean (ms)	Median (ms)	Min (ms)	Max (ms)	Std. Dev. (ms)
Centralized Processing	754.2	707.7	519.4	1444.2	138.3
Local Processing	50.5	51.4	28.9	98.5	6.9
Proposed Hybrid	52.2	51.7	30.1	102.6	9.1

Additionally, a violin plot illustrating the distribution of latency times for each system architecture is shown in Figure 7. As the results indicate, the centralized system exhibited the highest latency and the greatest variability, reflecting the delays inherent in server processing and potential network congestion. In contrast, both the local processing and the proposed hybrid systems demonstrated significantly lower latency and minimal variability. While the local processing system performed slightly better than the proposed hybrid system, the difference is negligible, allowing us to conclude that their performance is effectively similar.

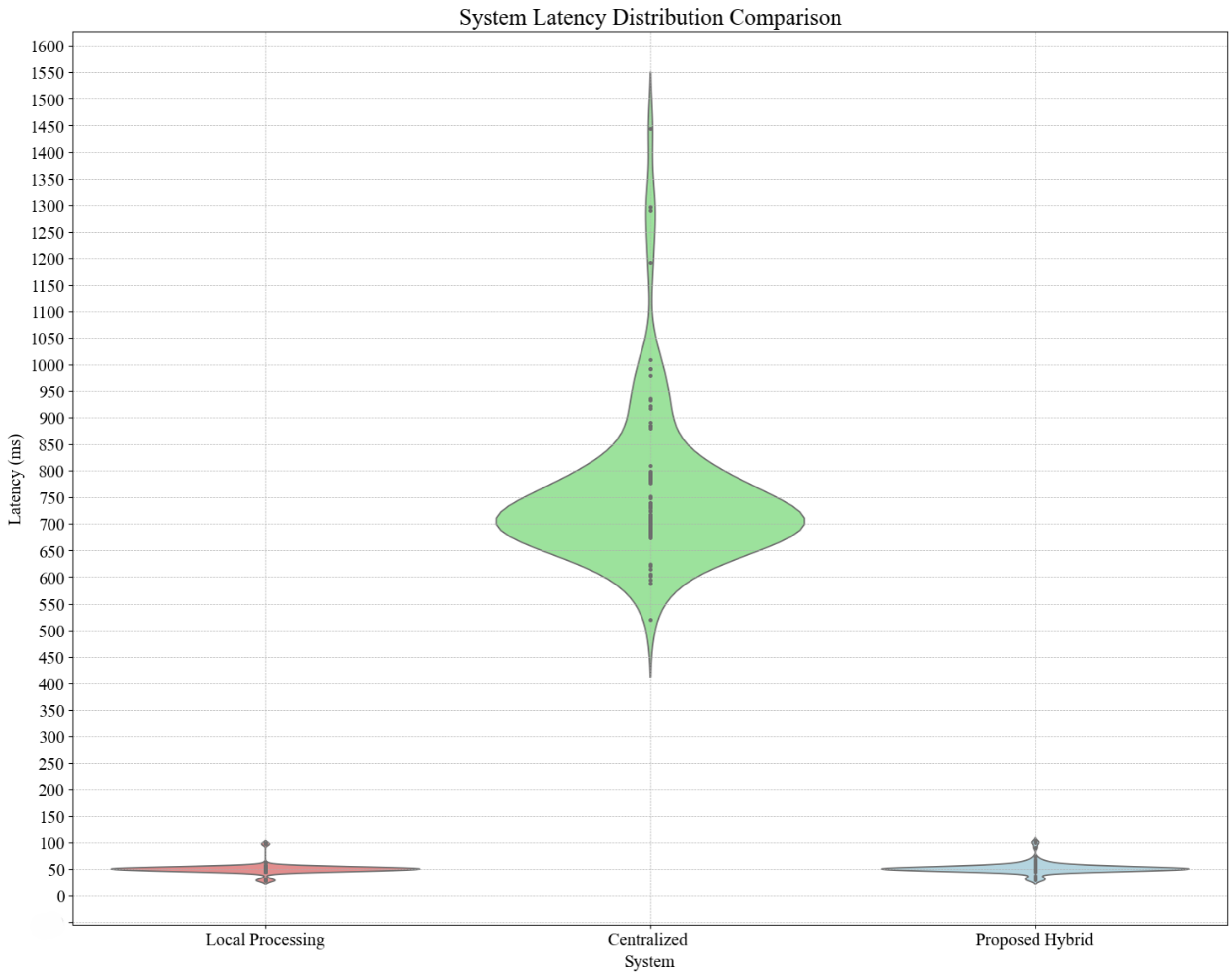


Figure 7. System Latency Distribution Comparison Across PWS Architectures

7 Discussion

The experimental results underscore the performance advantages of the proposed hybrid system over traditional centralized and local systems. By integrating edge computing with IFC, the hybrid system enables immediate data processing and rapid response to potential hazards, significantly enhancing safety monitoring on construction sites.

The proposed hybrid system demonstrated a mean latency of 52.2 milliseconds, which is comparable to the 50.5 milliseconds observed in the local processing system. Both systems significantly outperformed the centralized system, which exhibited a mean latency of 754.2 milliseconds. The reduced latency in the hybrid system highlights its ability to provide timely alerts, which is critical for preventing accidents and enhancing site safety.

The standard deviation in latency for the hybrid system (9.1 milliseconds) was slightly higher than that of the local processing system (6.9 milliseconds), but the difference is negligible. Importantly, the hybrid system's standard deviation was substantially lower than that of the centralized system (138.3 milliseconds), indicating that the hybrid system offers not only rapid response times but also consistent performance with minimal fluctuations, which is essential for maintaining reliable safety standards.

The hybrid system's capability to issue warnings within 52.2 milliseconds means that, at a walking speed of 5 km/h, a worker would move only 7.25 cm before receiving an alert, compared to 104.25 cm with the centralized system. This significant reduction in response distance can greatly mitigate the risk of accidents in dynamic and hazardous construction environments. While increasing the width of safety margins could be considered as a solution for the centralized system's higher latency, doing so would cover a large area of the construction site, challenging its practicality.

In addition to its comparable performance to local processing systems in terms of latency, the proposed hybrid system also offers data accessibility and integration across different systems and nodes on construction sites—features that local processing systems lack. During the validation experiment, data update latency was also measured, and while the centralized system outperformed the hybrid system in this regard, it is important to consider that the hybrid system is designed primarily to provide real-time warning capabilities while still enabling data accessibility and integration.

Another key advantage of the proposed hybrid system is its resilience to network disconnections. By leveraging edge computing, the system can continue processing data and issuing timely alerts, even if the connection to the central server is temporarily lost. This robustness ensures continuous safety monitoring, which is critical in the unpredictable and often harsh environments of construction sites, where network connectivity can be unstable or compromised.

The integration of IFC files within the hybrid system facilitates standardized data management and seamless incorporation of additional nodes, enhancing the system's scalability. This flexibility allows for the development of diverse applications without requiring major modifications to the system architecture, making the hybrid system adaptable to various construction site monitoring needs.

8 Conclusion

Construction sites are dynamic environments with inherent risks to workers, making continuous monitoring essential for ensuring safety. Proximity Warning Systems are a key component of safety monitoring; however, time delays in their operation can have serious consequences. This research aimed to address these challenges by proposing a hybrid architecture that combines edge computing with Industry Foundation Classes, thereby maintaining the strengths of previous systems while overcoming their limitations.

The results of the performance evaluation demonstrated that the system developed using the proposed hybrid architecture offers real-time performance, data accessibility, and data integration with other systems on construction sites. Moreover, the standard deviation of the delays showed that the proposed architecture delivers more reliable performance. Its resilience to unforeseen events, such as network outages, further underscores its suitability for construction site applications.

However, this research had some limitations. The system's performance was tested in a laboratory environment, and further studies are needed to evaluate its effectiveness in real-world construction site conditions. Additionally, future research could focus on addressing time latencies in data access between systems.

9 Acknowledgement

The authors gratefully acknowledge the financial support received from the Natural Sciences and Engineering Research Council of Canada (NSERC) and the New Frontiers in Research Fund (NFRF). This support was instrumental in facilitating this research.

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