

Smart Safety Monitoring for Construction Sites

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ABSTRACT

On-site construction safety management continues to face significant challenges due to reliance on manual inspections, paper-based documentation, and reactive safety practices. The absence of automated and data-driven monitoring mechanisms limits timely risk identification and informed decision-making. This paper addresses this gap by proposing a conceptual design of a Smart Safety Monitoring and Decision Support System (DSS) that integrates Internet of Things (IoT) sensors and computer vision technologies. The proposed system is designed to capture real-time environmental data from IoT sensors, detect unsafe behaviours and conditions using computer vision techniques, and consolidate all information in a centralized monitoring dashboard. By enabling continuous data acquisition and real-time analysis, the system aims to support proactive safety management and improve the accuracy of on-site risk identification and safety-related decision-making. Although the study is limited to a conceptual design and does not include empirical implementation or validation, it demonstrates the potential of data-driven technologies to transform construction safety management from a reactive to a proactive approach. The paper contributes to the existing literature by providing a structured conceptual framework for smart, technology-enabled safety monitoring systems in construction environments.

Keywords: Smart Safety Monitoring, IoT Sensors, Real-Time Monitoring, Construction Digital, Built Environment

INTRODUCTION

Safety monitoring decision support systems are also an essential part of construction management because of the multitude of risks that are inherent in such environments. Construction sites entail constant interactions between construction personnel, heavy equipment, and variable environmental factors. This obviously increases the risk of construction site accidents if not handled carefully. In ensuring that construction sites are safe and comply with construction regulations, major stakeholders, such as Site Safety Officers, Project Managers, and construction personnel, consistently monitor construction site safety conditions. Safety officers use construction site safety inspection cards as part of their day-to-day operations in ensuring construction site safety.

Although safety management on construction sites remains very rigid and important, there are instances where sites have been observed manually collecting safety data. The current method includes paper documentation, logbooks, and message exchanges via WhatsApp or the phone (Knack Marketing, 2025). Messages from the workforce regarding dangers or incidents are normally relayed to superiors, whereas information about the construction site inspection is recorded manually in the logbooks.

Dependence on these manual processes places significant constraints that directly impact safety performance. Manual data-gathering processes are always prone to unstructured, incomplete, and inconsistent information, thereby increasing the likelihood of human error. More importantly, incident reports are not provided in real time, leading to delayed reporting and ineffective corrective actions. Safety data scattered across files and messaging platforms is not analytically sound, which creates difficulties in managing trends, spotting danger spots, and supporting well-informed decision-making (Knack Marketing, 2025). As a result, danger spots are

identified only during routine safety inspections rather than being tracked continuously, thereby reducing the effectiveness of proactive safety measures/strategies (Wong et al., 2025).

Despite the latest innovations in information technology, including the Internet of Things, cloud computing, and data analytics, their potential has proven quite effective in improving construction safety. The use of these innovations in construction safety monitoring, however, has not received much emphasis. Many construction companies lack the integrated systems needed to automate data generation for construction site safety. There exists a research gap in the development of smart construction safety monitoring systems. Accordingly, the goal of this research is to design and develop a smart safety monitoring and decision-support system for construction sites using the Internet of Things and data analytics. This research specifically aims to provide a solution to the problem of manual safety monitoring by enabling real-time hazard detection and demonstrating the effectiveness of a safety-related decision support system using technology to improve the accuracy and effectiveness of construction project decisions.

Problems Statement

In fact, even in the context of occupational health and safety in construction, it has been found that construction site-based monitoring procedures remain predominantly rudimentary. Occupational health and safety information is typically collected and shared in construction projects through paper-based inspection forms, word of mouth, messaging programs, and document spreadsheets. Even though this seems fairly straightforward to execute, it poses several difficulties regarding information sharing and occupational health and safety data.

Delayed reporting is one of the most important safety concerns when manually-based systems are involved. Information regarding potential hazards and incidents sometimes takes various unofficial routes before the concerned authorities are informed. This causes the involved company to fail to take timely corrective actions before the potential dangers develop. Manual reporting of incidents has been identified as particularly associated with underreporting of data on near misses and low-severity hazards. Delayed documentation of such data reveals the lack of early warnings of any major accident that could occur on the construction site (Zaira & Hadikusumo, 2019).

Additionally, manual submission of safety data results in inconsistent, unstructured information. Since safety information is scattered across papers, messages, and sheets, it is neither integrated nor standardized. This scattered information makes it impossible to perform trend analysis or monitor performance. As a result, an organization cannot make judgments about potential risk areas or long-term safety performance. Thus, decisions on matters of safety remain uninformed or judgmental rather than data-driven (Mohammadi, Tavakolan, & Khosravi, 2018).

Another important drawback of existing safety monitoring methods is their lack of real-time monitoring capabilities. Construction sites are highly dynamic due to worker activities and other factors, such as rapidly changing environmental conditions. Conventional inspection and observation methods cannot keep a check on these factors or monitor them continuously as they change. Research studies have clearly shown that real-time analysis of construction sites for worker safety using technological methods of observation and analysis is highly efficient compared to conventional observation methods (Ganah & John, 2011). In summary, the inherent problem is that traditional manual safety monitoring methods cannot provide timely reporting, data management, or real-time monitoring of construction hazards. This can negatively impact construction organizations by preventing them from adopting proactive, data-driven strategies to manage construction site safety. Furthermore, it can increase risks for construction site workers, as they may face preventable hazards. Therefore, to overcome these problems, an efficient smart construction site safety monitoring decision-support system should be designed.

Review Of The Current Approach

In current construction practice, safety monitoring remains largely dependent on manual inspection procedures. Safety officers typically conduct physical walkthroughs using checklist-based inspection cards, while incidents and hazards are reported verbally or through messaging applications. Documentation is often recorded in logbooks or spreadsheet files, resulting in fragmented, decentralized safety records. Although such methods are

widely adopted due to their simplicity and low cost, they still rely heavily on human observation and judgement (Tripathi & Mittal, 2024; Ramos-Hurtado et al., 2022). Studies indicate that manual documentation processes can lead to inconsistencies, missing records and delays in reporting, which can negatively affect safety monitoring analysis (Ghosh & Kamakar, 2025).

A significant limitation of traditional safety monitoring systems is their reactive nature. Inspections are typically conducted at scheduled intervals, meaning that hazard that arise between inspections can remain undetected for some period. Winge et al. (2019) emphasize that inspection-based safety management often addresses risks only after incidents occur rather than preventing them. Furthermore, decentralized data storage limits project managers' ability to analyze trends, identify risk patterns, and generate predictive insights. Consequently, decisions are made based on experience rather than structured data analysis.

Due to the problem, past researchers have explored integrating digital technologies into construction safety management. For example, Internet of Things (IoT) sensors are introduced to enable real-time monitoring. This includes temperature, gas concentration, and equipment proximity detection (Teizer et al., 2010; Khan et al., 2024). Wearable sensing technologies have also been applied to monitor worker physiological conditions, movement patterns, and fall detection, thereby enhancing individual-level safety monitoring (Hasan et al., 2020). In addition, computer vision and machine learning techniques have been used to detect unsafe behaviours and violations of personal protective equipment (PPE) through automated image analysis (Zhou et al., 2019).

While these technological approaches demonstrate significant improvements in hazard detection accuracy and real-time monitoring capabilities, their implementation is often limited to isolated applications. Many studies focus on single-technology solutions, such as proximity alert systems or wearable monitoring devices, without integrating multiple data sources into a unified safety management framework (Okpala et al., 2020). As a result, although individual systems may enhance detection performance, the absence of a centralized, structured decision-support architecture limits their ability to support coordinated managerial decision-making.

Moreover, existing digital safety systems frequently emphasize detection efficiency rather than integration into comprehensive analytical dashboards that facilitate trend analysis and predictive safety intelligence (Daniel et al., 2025; Han et al., 2025). Without structured integration across environmental sensing, computer vision analysis, and managerial visualization layers, construction safety management remains partially reactive despite the presence of advanced technologies. As said before, several studies have explored construction safety monitoring using individual technologies however, limited research has conceptualized a unified multi-layer architecture that integrates these technologies into a comprehensive Decision Support System for a proactive smart safety monitoring system. Addressing this gap, it is essential to transition construction safety management from inspection-based practices toward proactive, data-driven safety intelligence.

Technological Solution And Available Tools

Construction sites have begun using wearable technology, the Internet of Things, data analytics, and cloud computing to overcome the limitations of traditional safety management methods (Hinze et al.). Traditional safety methods involve a reporting system, whether visual or paper-based. This may lead to poor, delayed, or biased reporting.

However, with IoT technology, site condition monitoring is now conducted continuously, with real-time data collection for automatic danger detection. This means that safety issues can now be detected and resolved before they become a concern. The use of data analytics has led to many solutions emerging in construction management. These solutions are based on data, cloud, and sensor technology applied to construction sites to enhance situational awareness. (Aziz et al., 2019).

Technology Used

The selection of the technology tools for this study relied on the relevance and ability to facilitate real-time, integrated, and data-driven safety observation during the construction process. The application of IoT sensors and wearable technology was relevant for continuously monitoring environmental and worker safety data. Additionally, the use of a cloud-based database platform such as Firebase or similar systems was relevant for

facilitating data storage and accessibility. Also, data interpretation and decision-making processes required the use of analytical platforms, such as Power BI, to present safety data in charts, trends, and risk assessments. The choice of technology tools was based on relevance, scalability, and the ability to support the effectiveness of proactive safety management during the construction process.

IoT Sensors and Environmental Monitoring Devices

Here, where work happens, the weather changes quickly from cold to hot, dust builds up, the ground shakes, and sometimes the air smells bad. People checking things by hand can miss what's hidden behind smoke or tiny particles, like toxic gases that have seeped in (Chi et al., 2009). Sensors that never stop watching allow systems to detect hazards before anyone gets hurt.

Sensors such as temperature, humidity, gas or particulate matter detectors are often connected to microcontrollers. The data travels via lightweight, sometimes cable-free communication methods. Wireless links make this possible. A 2010 study by Teizer and his team showed that these setups respond more quickly when hazards appear near or around people. This is because responses come faster than old-fashioned visual inspections would allow. Take Khan and colleagues from 2024: their work shows that IoT devices help ensure safer operations and sharper awareness on the jobsite.

However, although IoT devices improve detection accuracy and reduce checking intervals, stable internet access is essential, along with frequent tuning, to ensure stable performance (Sadeghi et al., 2015).

Wearable Safety Devices

Fatigue, overheating, and missteps on the job often tie back to how workers feel day to day. Instead of just watching for signs of trouble, using devices that track body signals can give a clearer picture. This kind of feedback happens as situations unfold, not after something goes wrong.

Wearable tech tracks body signals, showing when actions go off track - Hasan and team noticed this during 2020 studies. Movement flaws or signs of tiredness appear clearer through such tools, making it easier to catch issues before they worsen. Without constant human oversight, systems like these help shift attention toward automation. In 2014, Li's group pointed out something extra: these gadgets do more than monitor; they spark healthier habits on job sites where work wears people down. Even with perks, gadgets worn by people raise issues such as trust, safety, and control over information. According to Sadeghi and team (2015), robust protection methods are essential when using such tools appropriately.

Cloud Databases and Platforms

A major problem with old safety tracking methods is the scattered data between handwritten logs and standalone electronic records (Ghosh & Karmakar, 2025). Because these pieces do not connect well, tracking changes over time becomes difficult if not impossible. Data syncs across systems in real time through tools like Firebase or comparable databases, storing information centrally (Aziz et al., 2019). Digital connections enhance how openly and easily safety data is shared within construction projects, say Daniel and team (2025). One way cloud tools help is by letting multiple users share information easily. However, when teams rely too much on online systems, risks pop up - like data threats - that slow things down (Sadeghi et al., 2015).

Analytical Dashboards and Visualization Tools

Just gathering data will not automatically boost safety results. What matters is turning that information into something usable - seeing patterns through clear visuals helps leaders act wisely. Instead of piles of numbers, analytical tools shape them into clean visuals, such as charts, heat maps, or indicators of noncompliance. Looking at Hinze and team from 2013, key safety metrics matter most when outcomes are closely monitored. Tools like Power BI let those in charge of safety spot patterns, identify danger areas, and check whether rules are being followed in real time. From Zhou's group: Visual insights added to safety tools help managers react faster while strengthening risk-handling (2019). So dashboards do more than show data - they help people make choices in real time.

Machine Learning and Rule-Based Hazard Detection Systems

Traditional rule-based monitoring systems rely on predefined safety thresholds and may fail to recognize complex behavioural patterns. Machine learning approaches provide a more adaptive solution by analyzing historical and real-time datasets to detect anomalies.

Zhou et al. (2019) demonstrated that AI-based safety systems can identify unsafe conditions more efficiently than manual monitoring methods. Chong et al. (2025) further emphasized that integrating AI into construction safety frameworks represents a transition towards intelligent safety management systems.

Machine learning-based hazard detection enhances predictive capability, enabling early identification of risk patterns before accidents occur. Nevertheless, implementation requires high-quality datasets and computational infrastructure, which may increase initial investment costs (Okpala et al., 2020).

Comparative Analysis

Table 1 presents a comparison of several digital safety monitoring systems based on their actual performance on a construction site. Internet of Things-based environmental sensors are particularly well-suited to construction sites because they can detect hazards invisible to the human eye, such as vibrations and gas leaks. In addition, they require internet access and routine maintenance to function properly (Chi et al., 2017).

Table 1: Comparative Analysis of Common Digital Safety Monitoring Tools

| Tool Type | Strengths | Weaknesses |
|----------------------------------|--|---|
| IoT Environmental Sensors | Real-time data, continuous monitoring, detects invisible hazards | Requires stable internet sensor maintenance needed |
| Wearable IoT Devices | Monitors worker condition - high accuracy for fall/fatigue detection | Privacy concerns may cause discomfort |
| Cloud Databases (e.g., Firebase) | Fast sync, low setup cost, scalable storage | Data security concerns internet dependency |
| Analytics Dashboards (Power BI) | Easy visualisation, integrates multiple data sources | Requires data-cleaning skills znot real time unless properly configured |
| Mobile Inspection Apps | Reduces paperwork improves documentation consistency | Still relies partly on human input |
| AI/ML Hazard Detection | Predictive insights, automated alerts | Requires high-quality dataset cost of implementation |

Wearable IoT devices are highly effective for monitoring employees' physical condition and detecting fatigue and fall incidents. Wearable devices are more appropriate in high-risk activities and hot work environments. Nevertheless, to facilitate employee acceptance of these technologies, issues related to employee comfort and privacy must be effectively addressed (Hasan et al., 2020).

Although they promote data sharing and record management, cloud databases such as Firebase are well-suited for large-scale operations, such as construction projects with multiple supervisors. Nevertheless, reliance on the internet and data insecurity remain major drawbacks (Sadeghi et al., 2015).

Table 2: Strengths and Weaknesses of IoT-Based Safety Monitoring Systems

| Strengths | Weakness |
|---|--------------------------------|
| Real-time data improves proactive safety management | High initial installation cost |

| | |
|--|---|
| Automated alerts reduce reliance on human judgment | Requires continuous calibration |
| Enhances transparency & traceability | Needs robust data protection |
| Integrates multiple data sources | Potential resistance from workforce |
| Improves accuracy compared to manual methods | Battery life & hardware durability concerns |

The advantages and disadvantages of IoT-based safety monitoring are listed in Table 2 below. Compared with traditional methods, the use of automated systems greatly improves safety management, enhances the accuracy of results, and boosts transparency. The introduction of the system requires a considerable initial financial outlay. Ongoing maintenance costs are also higher than for a manual system. Furthermore, staff members may be opposed to using the new system if they are unfamiliar with computers. (Aziz et al., 2019; Zhou et al., 2019).

Process of Safety Monitoring

Right off, live information flows from smart sensors and personal wearables scattered throughout the building. Wirelessly, updates on the surroundings and the site crew are recorded in a web-hosted logbook without cables. After that, come software analysis patterns detected and risks flagged when something seems off track. When something dangerous shows up, an automatic signal goes out, appearing on screens that watchdogs can see right away. Because everything ties together now, people react faster than if they had to check things one by one (Teizer et al., 2010).

One key benefit is that the system brings together sensing, computing, memory, and display tasks into a single structure. Instead of just reacting after problems arise, it enables early action guided by insights from large datasets (Zhou et al., 2019; Chong et al., 2025).

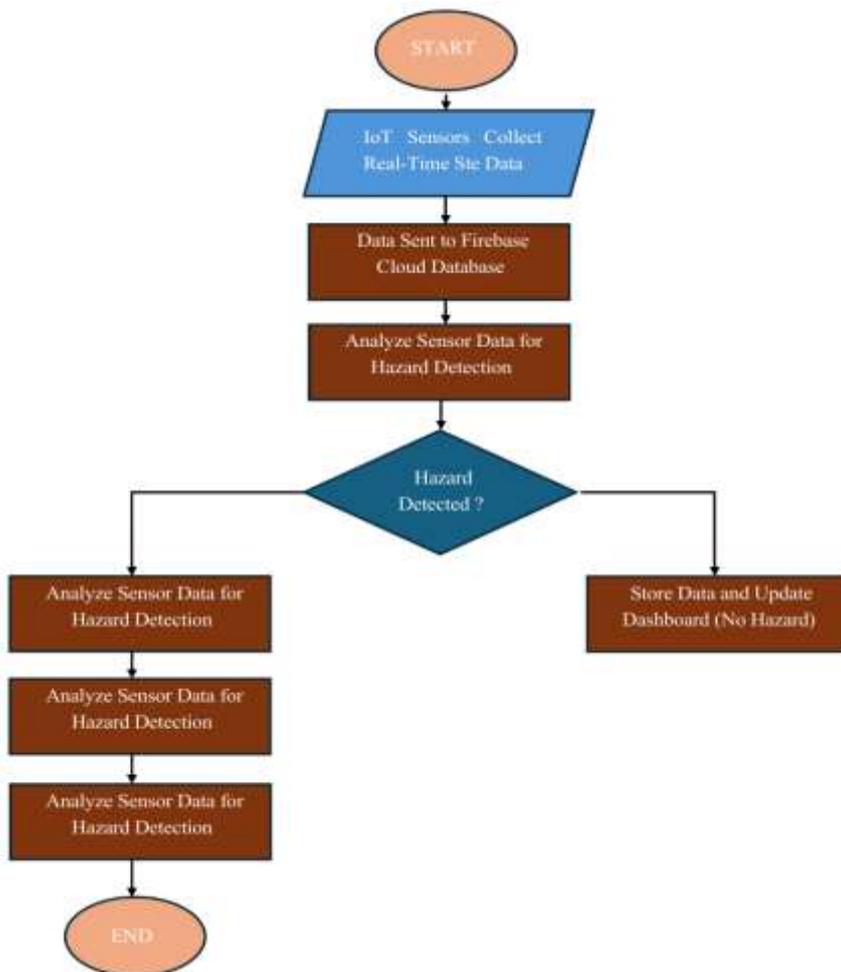


Figure 2: Process of Safety Monitoring Integrated With Technologies

Proposed System Development

The proposed Smart Safety Monitoring and Decision Support System (DSS) is designed using an integrated architecture that combines Internet of Things (IoT) sensing, computer vision processing, cloud data management, and real-time visualization. The system aims to overcome the limitations of conventional manual safety monitoring by enabling continuous hazard detection, automated analysis, and real-time decision support. The system architecture is based on a three-tier model consisting of the sensing layer, processing layer, and application layer.

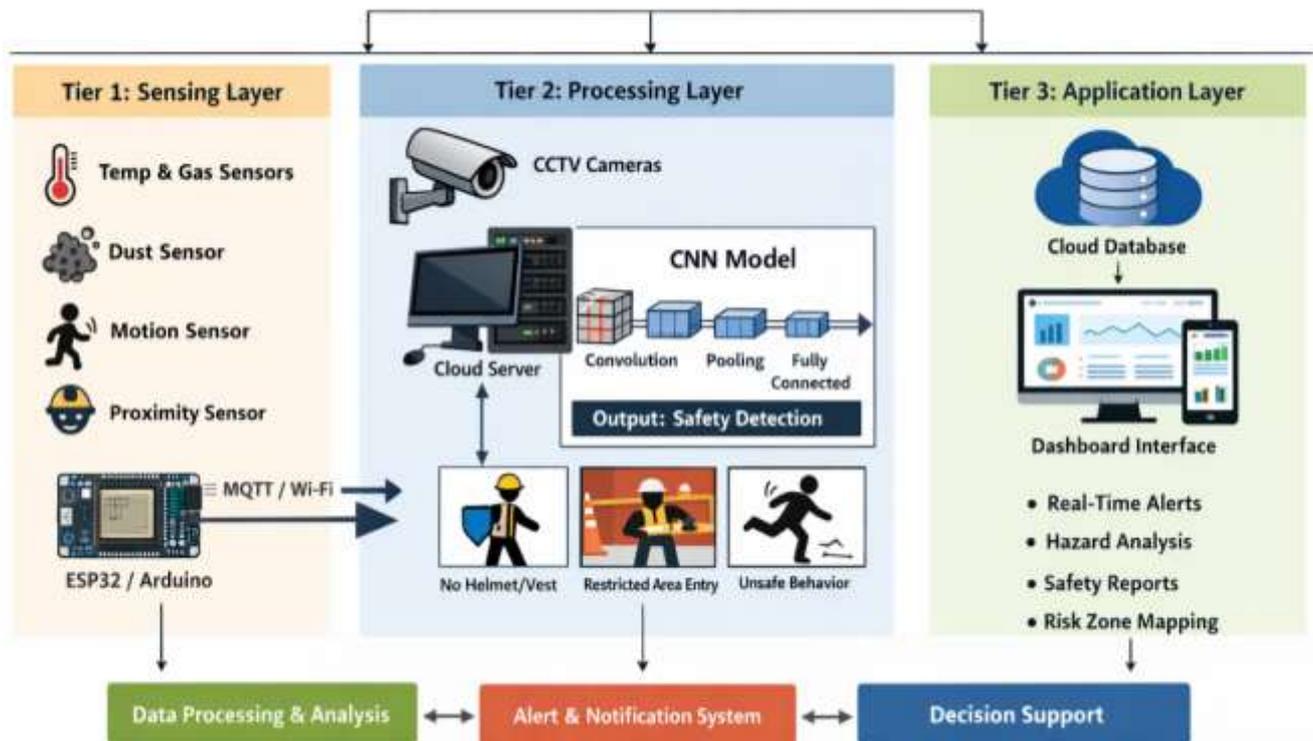


Figure 5.0: Proposed Development System

System Architecture Overview

The proposed system adopts a three-tier architecture to ensure efficient data acquisition, processing, and decision support. This layered architecture separates sensing, data processing, and user interface functions, thereby improving system scalability, reliability, and maintainability. It also enables real-time data transmission and parallel processing, ensuring that hazard detection, analysis, and alert generation can be performed with minimal delay and high operational efficiency.

Tier 1: Sensing Layer (IoT Data Acquisition Layer)

The sensing layer collects real-time environmental and safety-related data from the construction site. IoT sensors are deployed at critical locations to monitor site conditions continuously. The sensors include:

- Temperature and humidity sensors for monitoring heat stress conditions
- Gas sensors for detecting hazardous gases
- Dust sensors for monitoring air quality
- Proximity sensors (ultrasonic sensors) for detecting unsafe distances between workers and equipment
- Motion sensors for detecting worker presence in restricted zones

These sensors are connected to microcontroller units such as ESP32 or Arduino, which transmit the collected data wirelessly via protocols such as MQTT or HTTP. This enables continuous environmental monitoring and eliminates reliance on periodic manual inspection.

Tier 2: Computer Vision Processing Layer (CCTV and CNN-Based Hazard Detection)

The second tier consists of CCTV cameras integrated with computer vision algorithms to monitor worker behaviour and safety compliance. Video data captured by CCTV cameras is processed using Convolutional Neural Network (CNN) models for automated hazard detection. CNN was selected over rule-based detection methods because rule-based systems rely on predefined logical conditions and cannot reliably interpret complex visual patterns. In contrast, CNN models automatically extract spatial features from images and achieve significantly higher detection accuracy in object recognition tasks.

The CNN model performs the following functions:

- Detection of missing personal protective equipment (helmet, vest)
- Identification of unsafe worker positions
- Detection of entry into restricted zones
- Recognition of unsafe behaviour patterns

The CNN processing architecture consists of:

| | |
|------------------------------|--|
| Input layer | CCTV image frames (resolution 640 × 480 pixels) |
| Convolution layers | extract visual features such as shape and edges |
| Pooling layers | reduce dimensionality and improve efficiency |
| Fully connected layer | Classify detected objects |
| Output layer | safety violation classification and confidence score |

The use of CNN enables automated visual safety monitoring without human intervention.

Tier 3: Cloud Processing and Application Layer (Decision Support Dashboard)

The application layer serves as the central decision-support interface for supervisors and safety officers. All sensor data and computer vision results are transmitted to a centralized cloud database such as Firebase, AWS, or MySQL.

The cloud system performs the following functions:

- Data storage and management
- Real-time hazard detection analysis
- Risk assessment and hazard classification
- Alert generation and notification management

A web-based dashboard displays safety information using visual indicators such as:

- Hazard alerts
- Environmental condition charts
- Safety compliance status
- Risk zone identification

Supervisors can access the dashboard remotely using computers or mobile devices. The alert response time target is less than 3 seconds after hazard detection.

System Data Flow and Operational Process

The system operates through a continuous automated data processing cycle consisting of the following steps:

| | |
|---------------|--|
| Step 1 | IoT sensors collect environmental data from the construction site. |
| Step 2 | CCTV cameras capture real-time video frames |
| Step 3 | Sensor data is transmitted to the cloud server via wireless communication. |
| Step 4 | Video frames are processed using CNN algorithms. |
| Step 5 | The hazard detection algorithm evaluates sensor thresholds and CNN classification results. |
| Step 6 | Hazard events are recorded in the centralized database. |
| Step 7 | Dashboard displays real-time safety status. |
| Step 8 | Alert notifications are automatically triggered if hazard conditions are detected. |

This process ensures continuous monitoring and immediate hazard detection.

Hazard Detection Logic and Threshold Parameters

Hazard detection is based on predefined threshold values and machine learning classification confidence scores. Examples include:

| | |
|---|--|
| Temperature hazard threshold | greater than 40°C |
| Gas hazard threshold | exceeds safe ppm limit |
| Dust hazard threshold | exceeds safe PM2.5 concentration level |
| CNN detection confidence threshold | greater than 85% |

When these thresholds are exceeded, the system automatically generates alerts. This automated logic ensures consistent hazard detection without human subjectivity.

Technical Specifications of the Proposed System

The conceptual system is designed using commonly available hardware and software technologies. Hardware components include:



| | |
|------------------------------|---------------------------------|
| IoT microcontroller | ESP32 or Arduino |
| Environmental sensors | DHT22, MQ-135, PM2.5 sensor |
| CCTV camera | standard IP surveillance camera |
| Server infrastructure | cloud-based hosting platform |

Software components include:

| | |
|----------------------------------|-----------------------------------|
| Programming language | Python |
| Computer vision framework | TensorFlow or OpenCV |
| Database platform | Firebase or MySQL |
| Dashboard platform | Power BI or a web-based interface |

These technologies are selected due to their scalability, reliability, and compatibility with real-time monitoring applications.

System Performance Metrics and Expected Performance

Although the system is currently conceptual, its expected performance can be evaluated using standard system performance indicators.

Target performance metrics include:

| | |
|---------------------------------------|---------------------|
| Hazard detection accuracy | greater than 90% |
| System response time | less than 3 seconds |
| Data transmission success rate | greater than 95% |
| False alarm rate | less than 10% |
| System uptime availability | greater than 99% |

These performance targets are based on benchmarks from existing IoT and computer vision safety monitoring systems.

Conceptual Validation and Feasibility

Although full deployment has not yet been conducted, the feasibility of the proposed system is supported by existing research demonstrating the effectiveness of IoT sensors and CNN-based hazard detection in construction safety monitoring.

Conceptual validation is based on:

- Proven accuracy of CNN models in object detection tasks
- Reliable performance of IoT sensors in environmental monitoring
- Established the effectiveness of cloud-based real-time monitoring systems

Simulated testing using sample video and sensor datasets can be used in future work to evaluate system accuracy and response time. This conceptual validation confirms that the proposed system is technically feasible and capable of improving performance in construction safety monitoring.

CONCLUSION

In conclusion, the relevance of this study lies in its highlighting the importance of integrating IoT and data analysis within a comprehensive system for construction site safety monitoring. Based on the research findings, data acquisition for safety information notifications can yield a significant increase in accuracy compared to conventional techniques used for construction site safety information. This research also highlights a new idea regarding construction site safety. The research's relevance lies in providing a platform for centralising safety data. It demonstrates the relevance of a system functionality required to move forward, recognising that real-time monitoring can promote safety performance in a building environment. It also shows the relevance of research in advancing understanding that real-time monitoring can promote safety performance in a building environment.

Notwithstanding these contributions, this research endeavour has been acknowledged as having certain limitations in the implementation of the system and in sensor calibration. Future research could include pilots or studies on system dynamics, as well as sensor calibration optimisation, to improve relevance to construction through smart safety systems.

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