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PROACTIVE SAFETY MANAGEMENT IN EARTHWORK OPERATIONS USING IOT-DRIVEN REAL-TIME RISK ANALYSIS

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Abstract

Earthwork operations are among the most hazardous construction activities due to frequent interactions between heavy machinery and workers in dynamic, constrained environments. Traditional safety practices remain largely reactive and insufficient for real-time accident prevention. This paper presents an IoT-driven real-time risk analysis framework for proactive safety management in earthwork operations. The system integrates machine-mounted telematics, spatial analytics, and dynamic heat-map visualization to assess collision risks at machine and zone levels. A three-week deployment on a construction site identified spatiotemporal risk hotspots and recurring near-miss patterns using meter-level positioning accuracy, demonstrating a shift from reactive control to proactive, data-driven safety management.

Introduction

In European construction, particularly in Denmark, earthwork operations pose a significant hazard due to frequent collisions involving heavy machinery. Confined workspaces amplify these inherent risks, leading to a high rate of severe accidents. Poor on-site conditions and human factors can lead to equipment-worker collisions, jeopardizing safety and operational efficiency (Son and Kim, 2021; Talmaki and Kamat, 2022). Machinery collisions are a significant concern on all construction sites. The close-quarters operation of heavy equipment, combined with poor visibility and miscommunication among operators, frequently leads to serious accidents. The shared workspace between workers and machinery increases the risk of injuries, making it essential to thoroughly investigate mitigation strategies (Kim et al., 2023). Existing methods, which rely on manual supervision and post-incident analysis, are reactive and insufficient for preventing collisions. These approaches often cause costly delays and make safety hazards worse (Soltanmohammadlou et al., 2019; Zhang et al., 2017) Therefore, the motivation to drive this research is to make a transition from reactive to proactive safety management systems that can effectively predict and prevent incidents on construction sites through innovative technology.

Despite advancements, construction safety still relies heavily on manual oversight and post-incident reviews. The use of flagmen and basic rear cameras exemplifies a reactive safety approach, underscoring the need for a shift toward real-time, technology-driven risk management. . There is a notable gap in using real-time data to prevent equipment collisions during rapidly changing earthwork operations (Waqar et al., 2023). Incorporating technologies such as the Internet of Things (IoT), Geographic Information Systems (GIS), and machine learning is crucial for advancing construction safety beyond traditional methods. However, current practices often fail to fully utilize these tools to build a cohesive, real-time monitoring system that adapts to the dynamic nature of construction sites. Existing literature lacks studies that show how to effectively integrate technology into safety systems that both identify risks and provide real-time insights to stakeholders (Talmaki and Kamat, 2022). The absence of real-time, tech-enabled risk assessment frameworks remains a significant barrier to safer construction sites (Häikiö et al., 2020). Dynamic risk assessments that combine real-time data with visualization tools, such as heat maps, enable swift hazard identification, supporting quick, informed decisions (Talmaki and Kamat, 2022). This research presents a novel, integrated IoT framework for construction safety that explicitly addresses the current gap by linking machine telematics, spatial analytics, and dynamic heat-mapping visualization to enable proactive safety management during earthwork operations. This research emphasizes equipment-based risk monitoring and does not address interactions between workers and equipment, which continue to be a major cause of fatal accidents. As a result, the proposed framework should be viewed as a partial safety measure rather than a complete safety system. The proposed system provides continuous, real-time spatial risk awareness, enabling immediate on-site decision-making, unlike traditional post hoc or isolated sensing approaches.

Literature review

State of practice in safety management for earthwork operations

Across the EU, 20% of accidents and deaths occur on construction sites (Hong and Teizer, 2024). Construction remains one of the most hazardous industries in the UK, accounting for 27% of workplace deaths in 2020/21, with 18% caused by moving vehicles (Walker et al., 2021). Earthwork operations, involving heavy machinery like excavators and bulldozers, pose significant safety risks, particularly collisions, which research shows are a leading cause of injuries (Shen et al., 2016; Teizer, 2015). Sites with multiple heavy equipment units operating simultaneously can create confusion regarding navigation and operational priorities. The presence of numerous personnel can further complicate coordination and increase the likelihood of accidental collisions (Kukoyi and Adebowale, 2021). Trenching and excavation activities are particularly hazardous due to the risk of collapse. OSHA reports that trenching cave-ins are among the top causes of construction-related fatalities, often resulting in severe injuries or deaths (Asadzadeh et al., 2020). The primary causal factors include inadequate protective systems and geological instabilities that are insufficiently assessed before excavation. Furthermore, Poor planning and unclear equipment paths often cause construction accidents. Research has linked inadequate design and maintenance negligence to collisions, highlighting the need for careful planning and regular inspections to ensure safe operation of machinery (Zhang et al., 2017).

Traditional safety management on construction sites during earthwork operations with heavy equipment has primarily relied on manual inspections, visual checks, and physical barriers to reduce the risk of collisions. For Instance, communication methods, such as walkie-talkies or visual signals, are not always effective in ensuring timely warnings, especially in sites with high noise levels or low visibility (Jo et al., 2019). Consequently, the risk of collisions among heavy equipment persists, resulting in serious accidents and injuries. Other methods, such as physical barriers and cones to delineate safe work zones, were prominent but not foolproof; they did not account for all variables that could lead to collisions between equipment and personnel (Kayhani et al., 2018).

Enhancements in communication, such as alarms and visual alerts, were limited and did not provide comprehensive real-time proximity awareness (Jo et al., 2019). Safety performance was largely reactive, focusing on accident responses rather than proactive hazard assessments and preventative measures (Leonardo et al., 2020).

Digital Technologies in Safety Management of Earthwork Operations

Innovative technologies like IoT are transforming construction safety through real-time data collection. Using wearable sensors and environmental monitoring, IoT enables continuous tracking of workers, machines, and site conditions. Similarly, Asadzadeh et al. (2020) discuss how sensor-based safety management integrated with IoT technologies improves responsiveness to dynamic working conditions (Asadzadeh et al., 2020). This shift towards automated, proactive monitoring systems has emerged as a necessity given the inadequacies of passive safety measures traditionally employed in construction settings (Häikiö et al., 2020; Kim et al., 2023). Another key innovation, heat maps, offers visual data representations that enhance decision-making for worker safety and operational efficiency.

Wearable sensors now play a vital role in construction safety by providing real-time monitoring to identify hazards before accidents happen (Zamani et al., 2020). Strategies for sensor placement, such as those by (Talmaki and Kamat, 2022), improve machinery safety. Positioning technologies like Global Positioning System (GPS), Radio Frequency Identification (RFID), Light Detection and Ranging (LiDAR), and computer vision enable real-time tracking of equipment and workflows(Kim and Xiong, 2025). GPS supports spatial awareness on large sites, reducing near-miss incidents (Cheng and Teizer, 2013), while LiDAR offers 3D mapping to identify high-risk zones (Rao et al., 2022). RFID enhances equipment tracking and accountability (Poudel and Assaad, 2025). Together, these technologies create integrated safety systems that improve visibility and hazard detection on construction sites. Golovina et al. developed heat maps that visually represent high-risk areas where worker-equipment interactions are most likely, supporting predictive safety planning (Golovina et al., 2016). These visuals help safety managers identify hazards and develop mitigation strategies by prioritizing areas needing immediate attention. Heat maps are also widely used outside construction, such as in traffic safety management, to analyze accident hotspots and implement preventive measures (Chung et al., 2023). They highlight high-traffic equipment zones, enabling proactive interventions before incidents occur. Managers can modify equipment routes or schedules based on this data to reduce interactions and risks.

A recent perspective by Bęś et al. (2025) highlights the integration of IoT sensors with digital twins, GIS/BIM, and real-time visualization for construction safety. It emphasizes sensor networks, RTLS, and connected systems for dynamic site monitoring, enabling data-driven dashboards and risk visualization (Bęś et al., 2025). Modern safety management combines automation, real-time visualization, and dynamic risk assessment, but fully integrated solutions remain limited. Advances in IoT, digital twins, and AI now allow automated systems to track hazards, assess risks, and support decisions through live dashboards and heatmap-style risk views. An ideal system would unify hazard detection, risk prioritization, and KPI monitoring into a single, scalable platform for real-time safety management (Khajavi et al., 2023)

Research gaps & objectives

The integration of IoT-based monitoring systems with heat map generation holds significant promise for improving safety in earthwork operations, yet several gaps limit its effectiveness. One identified gap is that current systems lack real-time data analytics capable of processing high-volume sensor data quickly enough to provide immediate hazard detection and dynamic heat map updates (Liu et al., 2021; Niu et al., 2019). Moreover, most tools rely on historical data rather than proactive hazard prediction models, thereby limiting their ability to anticipate collision risks. Machine learning approaches are needed to analyze equipment movement and generate predictive, forward-looking heat maps (Moe et al., 2023). Real-time integration of IoT-based construction safety systems remains constrained by data heterogeneity, latency, and weak governance, which limit the seamless integration of sensor streams (e.g., wearables, RTLS, environmental data) with dynamic heatmap or risk visualization outputs. Even where real-time dashboards exist, they often rely on static thresholds or simplified models, reducing the accuracy and responsiveness of risk prioritization in fast-changing site conditions. Additionally, many solutions lack robust governance frameworks that link sensor data to safety actions, decision logs, and audit trails across the project lifecycle, raising concerns about data reliability and regulatory compliance. While digital twin approaches offer promise for auditable and traceable safety management, their large-scale deployment e,g. With consistent rule versioning and intervention tracking, it remains underdeveloped. Furthermore, existing studies are often limited to specific use cases, with insufficient evidence on how these integrated systems perform across design, procurement, and on-site execution, hindering broader industry adoption (Arya et al., 2025; Catalán et al., 2025). Addressing these gaps calls for research that advances real-time analytics, develops predictive modeling capabilities, and incorporates user-centered design principles to enable practical adoption and enhance the effectiveness of digital safety management in construction. This study contributes by delivering a practical, real-time IoT-integrated safety framework that unifies data, visualization, and actionable risk monitoring, bridging the gap between fragmented tools and scalable, proactive construction safety management

Methodology

This section outlines the core theme of developing a real-time risk management system, including the design framework, data collection methods, and technology integration strategy used to enable proactive safety monitoring in earthwork operations. This study will follow a Design Science Research (DSR) methodology structured into four sequential steps:

1. *Identification of research gaps and system requirements* through a systematic literature review and expert consultation.
2. *Evaluation Metrics for Safety Performance* to evaluate system performance, a set of safety KPIs, including proximity violations, duration of unsafe interactions, near-miss detection, and severity classification based on a risk matrix, was defined.
3. *System design and technical development* of IoT-based heat map solutions integrating real-time analytics and predictive modeling.

Step #1: system requirements:

This stage ensured technical robustness and practical relevance by grounding the system design in two approaches: (1) a systematic literature review (on IoT safety, positioning, and heat maps), and (2) semi-structured interviews with three experienced safety managers to translate theoretical advances into operational needs.

The project requirements spanned three areas: Functional (system capabilities, including continuous tracking and heat map generation), Technical (performance, with a focus on low-latency, real-time processing of diverse data streams), and User-Oriented (practicality for safety managers, requiring an intuitive interface and clear, actionable visuals).

Step #2: evaluation metrics for safety performance

To strengthen the evaluation of the proposed system, a set of quantitative safety performance indicators (KPIs) was defined based on proximity analysis, temporal patterns, and risk severity classification. These indicators provide a structured framework to assess unsafe interactions and interpret safety conditions beyond simple tracking performance. The primary KPIs include: (1) proximity violations per operational hour, representing the frequency of safety threshold breaches between machines or between machines and static hazards; (2) duration of unsafe interactions, capturing the exposure time during which equipment operates within unsafe proximity ranges; and (3) severity classification of safety violations, derived from a dynamic 5 × 5 risk assessment matrix combining likelihood and consequence levels. In this study, near-miss events are defined as interactions occurring within critical distance thresholds (e.g., <5 m), thereby enabling the identification of high-risk situations before actual incidents occur.

Table 1: Assessment of metrics

KPI	Description	Unit
Proximity violations per hour	Number of safety threshold breaches between entities	events/hour
Duration of unsafe interactions	Time spent within unsafe proximity ranges	Seconds
Severity classification	Risk level based on likelihood × consequence matrix	Categorical (1-5)
Near-miss events	Interactions below the critical distance threshold (<5 m)	events

Step #3: system design and implementation:

Employing a Design Science Research (DSR) methodology, this study developed a real-time safety monitoring framework. The system uses IoT sensors on heavy machinery to collect positional and operational data. This data is managed, stored, processed, and analyzed efficiently by a hybrid InfluxDB (time-series database)–AWS architecture, which facilitates dynamic heat map and risk matrix visualization. The system comprises three layers: sensor, database, and visualization (Figure 1).

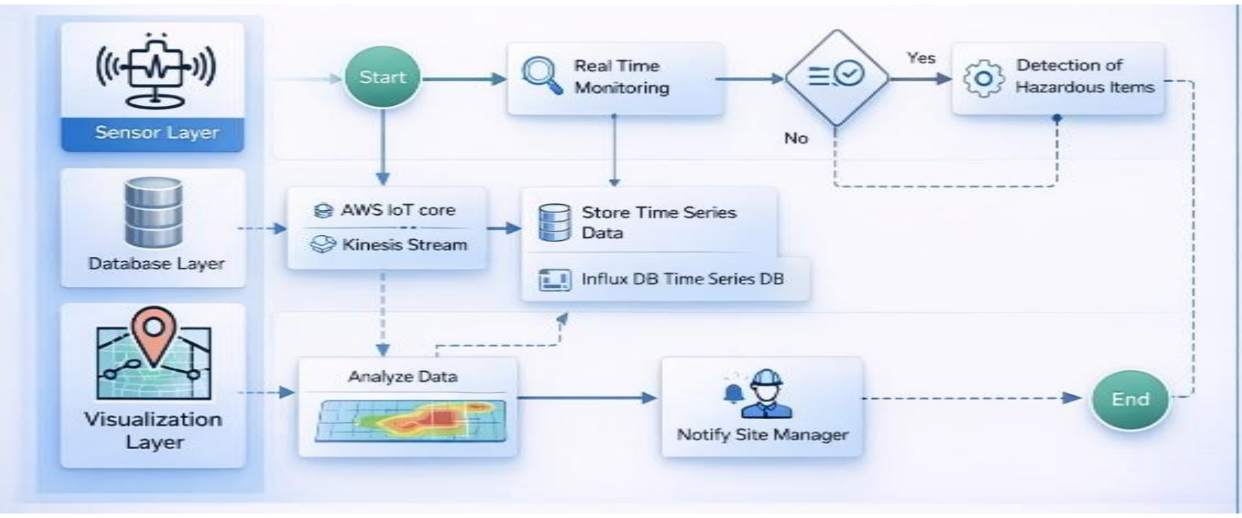

Figure 1:System overview

Sensor layer: IoT devices with GNSS-enabled telematics continuously stream high-frequency positional and kinematic data (location, movement) from heavy machinery. This data enables precise, real-time mapping of equipment trajectories, providing the technical foundation for dynamic heat maps and proactive hazard assessments. These sensors provide latitude–longitude coordinates at approximately 1 Hz, with a typical horizontal accuracy of 0.5-1.5 m under open-sky conditions. Such accuracy is consistent with prior construction safety studies that employ GNSS-based equipment tracking and is sufficient to detect spatial overlaps and proximity risks during earthwork operations.

By incorporating engine RPM and load, the system reliably classifies machine activity, as these variables strongly correlate with operational status (Talmaki & Kamat, 2022). The system distinguishes among idle, down, and active working time, enabling granular monitoring and a more realistic representation of operational risk, both of which are essential for safety management.

Database layer: The database layer uses a hybrid InfluxDB–AWS architecture for scalable, real-time safety. InfluxDB efficiently handles high-frequency data ingestion (via REST APIs) and time-based queries for hazard detection. AWS services (IoT Core, Kinesis, S3) ensure scalability, secure connection management, real-time ingestion, and long-term storage. This setup delivers reliable, low-latency insights crucial for proactive safety visualization management. Machine-installed telematics securely stream GNSS, motion, and engine data via APIs.

Visualization layer: The visualization layer delivers a dynamic spatial and temporal view of machine movements across a specific geofenced earthwork site. This area is defined by GNSS coordinates in the WGS84 reference frame: (55.719581, 9.128638) → (55.719998, 9.126529) → (55.722117, 9.127383) → (55.721882, 9.129044) → (55.722466, 9.129268) → (55.722419, 9.129801) → (55.719581, 9.128638), forming a closed polygon that marks the operational boundary of the jobsite. Machine telemetry is processed as continuous time-series data and refreshed at fixed intervals to maintain current situational awareness. Operational states are classified into time windows based on proximity events and hazard interactions, then mapped to a heatmap layer using color-coded risk indicators: blue (Idle), yellow (Down), and red (Working). Static hazard zones are defined through structured user input, with each hazard characterized by its spatial location, influence radius, and severity classification. These hazards are modeled as persistent spatial entities that serve as fixed reference points against which the movements of live machines are continuously evaluated for proximity violations.

Machine-level safety indicators are derived from live telemetry streams updated at a fixed refresh rate. For each machine, a continuous safety evaluation is performed, capturing the amount of unsafe work it performs at any given time. Unsafe work is identified when the real-time distance between machines, or between a machine and a static hazard zone, falls below predefined safety thresholds.

Zone Safety Status is derived by continuously evaluating unsafe activity within each spatial zone. For a given zone, safety status indicates the level of safety at any time, based on the machines operating within its boundaries and their ongoing proximity violations. A zone is considered increasingly unsafe when multiple machines, or the same machine repeatedly, perform unsafe work—defined by distance-based threshold violations with other machines or static hazard zones—while operating in that zone. The zone safety status is updated in real time and visualized as a zone-level indicator, enabling supervisors to rapidly identify areas where unsafe work is accumulating due to congestion, overlapping tasks, or hazardous spatial configurations. Both machine-level and zone-level safety states are translated into a standardized 5 × 5 risk assessment matrix to support consistent interpretation and prioritization of safety conditions. In this mapping, likelihood is derived from the extent and persistence of unsafe work, as reflected in the machine or Zone Safety

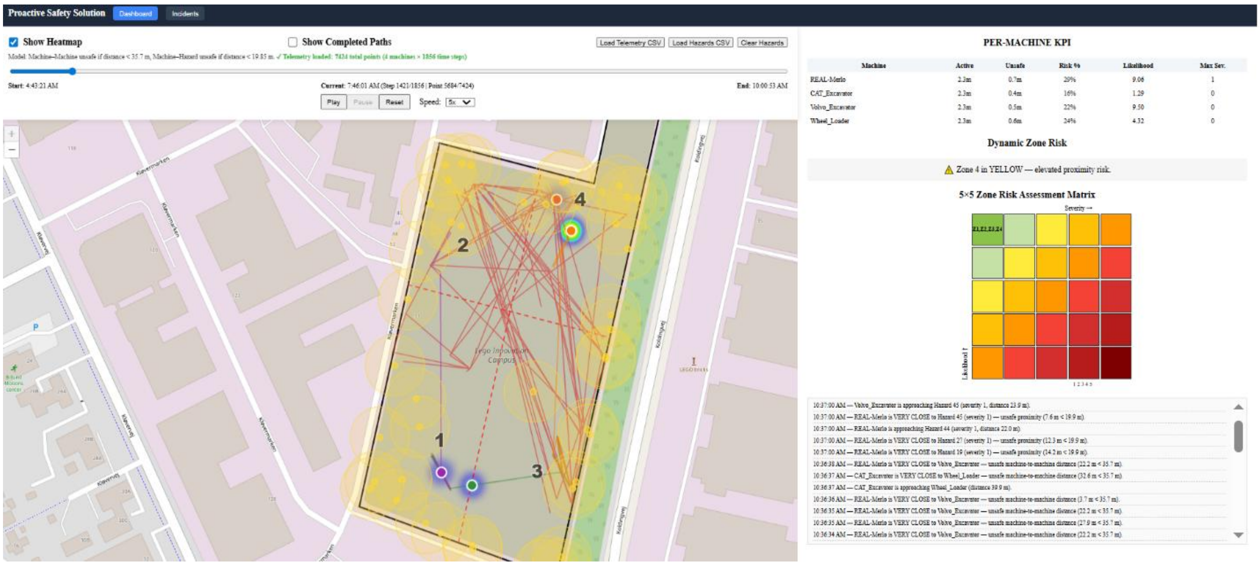

Figure 2: Visualization layer

KPI, capturing how frequently and for how long distance-based safety thresholds are violated. Severity is determined by the classification of the interacting hazards or machines involved in those violations, reflecting the potential consequences of the unsafe condition. By combining these two dimensions, each machine and zone is assigned to a corresponding risk cell that represents its current safety state. The matrix is continuously updated as KPIs evolve and rendered in the visualization interface to provide a clear, comparable view of escalating or diminishing risk across the site. Additionally, live commentary is provided to enhance the system's decision-making robustness.

The visualization layer is implemented as a fully client-side JavaScript dashboard using Vue 3 for reactive state management and Leaflet for heat plugin, for geospatial rendering. Vue components maintain live state for machine telemetry, static hazard definitions, safety KPIs, and risk states, while Leaflet renders the geofence polygon, 2 × 2 zone partitions, machine markers, trajectories, static hazard zones, and a continuously updated risk heat map. The heat map visualizes the spatial accumulation of unsafe activity by projecting machine- and zone-level safety KPIs onto the map surface, thereby highlighting areas of elevated risk. Telemetry and hazard data are ingested via browser-based CSV parsing and replayed at a fixed refresh rate using a JavaScript timing loop. Distance-based proximity evaluation and safety status updates are computed in JavaScript and propagated through Vue's reactivity system, triggering synchronized updates of the heat map, map layers, machine and zone KPIs, and the 5 × 5 risk assessment matrix. This fully browser-based architecture enables continuous, low-latency visualization of evolving safety conditions without server-side processing.

Step #3: System implementation:

The system was implemented and evaluated on a live construction site in Billund, Denmark, covering approximately 19,000 m² and involving intensive earthwork activities, including excavation, grading, and site preparation. For this pilot study, four machines were instrumented and monitored simultaneously: a telescopic handler (13013-MerloP40.17), two excavators (Volvo and CAT), and a wheel loader (Figure 2). These machines are the primary sources of dynamic interaction and collision risk on earthwork sites, owing to overlapping workspaces and frequent material-handling operations. The system was deployed over a three-week monitoring period, providing a realistic operational context for continuous telemetry acquisition and for evaluating real-time hazard detection, zone-level risk accumulation, and heat-map-based visualization within a space-constrained, dynamically evolving site. In addition to mobile equipment, predefined static hazardous items (Table 1) were incorporated prior to system execution and remained fixed throughout the monitoring period, serving as continuous reference points for distance-based safety evaluation.

Table 2: Static hazardous items in jobsite with severity

Group Name	Total Items	Severity Level (Out of 5)
Access & Road	15	3
Perimeter & Boundary	11	2
Storage & Stockyard	9	4
Cranes, Panels & Heavy Machinery	8	5
Facilities	2	1

The system captured live location, movement, and engine performance data, enabling accurate machine tracking. This data was integrated with a digital jobsite map (including obstacles/boundaries) to create dynamic heat maps. These maps moved beyond simple movement tracking to identify actual collision risks, significantly enhancing safety awareness (see Figure 3, which highlights high-risk zones).

Results and discussion

During the three-week monitoring period, the machines continuously streamed high-frequency GNSS data (location, movement, status). This positioning information was integrated with the site's digital boundaries. The data's consistency with planned routes and physical constraints confirmed its reliability for proximity-based safety analysis, even without ultra-high precision. This study focuses on equipment-centric risk monitoring and does not capture worker–equipment interactions, which remain a primary source of fatal incidents; therefore, the proposed framework should be interpreted as a partial safety solution rather than a comprehensive systemThe system successfully tracked equipment movement patterns across 504 operational hours, generating comprehensive telemetry records that captured real-time positioning and operational status. Analysis of this data revealed distinct patterns of spatial clustering and temporal risk concentration. Machine activity was visible in the heatmap, including down periods (equipment powered off during breaks and end-of-shift), idle states (engine running but stationary during excavation or loading work), and active movement between work locations. This operational state classification, derived by combining GNSS positioning with RPM and load-sensor data, proved essential for accurate risk assessment.

Dynamic heatmaps clearly visualized equipment activity and identified spatiotemporal safety hotspots near excavation fronts, loading zones, access routes, heavy machinery areas, and excavation perimeters. These high intensity clusters showed elevated collision risk caused by dense machine movement and repeated machine to hazard proximity violations, with extreme cases recording minimum distances below 1 m. The analysis also revealed that risks increased during peak operational periods when multiple machines worked in confined spaces, allowing the framework to distinguish hazardous zones from safer staging areas and provide a live, transient safety assessment beyond static safety methods

Additionally, the dynamic heat map visualization provides situational awareness superior to fixed zones or manual checks. By continuously displaying shifting risk patterns and congestion clusters, it enables safety managers to visually identify emerging hazards and facilitate timely, targeted interventions (e.g., rerouting). This shifts safety management from post hoc analysis to real-time, proactive spatial intelligence. The system's capacity to update visualizations in near-real-time (refresh intervals under 30 seconds) allowed supervisors to observe evolving safety conditions and respond before critical thresholds were breached.

The proposed system is designed to support safety managers or designated personnel in monitoring and managing safety risks in earthwork operations in real time. When the dashboard detects unsafe proximity between machines or hazards, risks are immediately visualized through heat maps, KPI dashboards, risk matrices, and live commentary, enabling rapid identification and communication to operators and nearby workers via tools such as walkie-talkies, radios, or mobile devices, or through public announcement systems when necessary. If no corrective action is observed, the system supports escalation by continuously monitoring the condition, triggering repeated alerts, and enabling stronger interventions such as issuing urgent warnings, halting machinery, or clearing workers from risk zones. In critical situations involving high-severity hazards, operations may be paused entirely until safe conditions are restored. By combining real-time detection, communication, and escalation mechanisms, the system facilitates a structured response process that enhances situational awareness, supports timely intervention, and enables continuous improvement of safety practices through the analysis of recurring risk patterns

This study presents the methodology for an integrated IoT safety monitoring system based on commercial telematics and cloud infrastructure. Our findings indicate that meter-level positional consistency is adequate for proactive safety decision-making and identifying hazardous zones, effectively overcoming the limitation of lacking quantitative accuracy validation. The system's reliance on industry-standard GPS accuracy (typically 2–5-meter precision) proved sufficient for safety zone monitoring, confirming that sub-meter precision is not a prerequisite for effective proximity-based risk assessment in open earthwork environments. Future work is necessary to integrate predictive analytics and model complex multi-equipment interactions for broader applicability.

The analysis revealed that unsafe interactions were not uniformly distributed but concentrated in specific spatial zones and time periods. Temporal risk analysis revealed high-risk operational periods, while spatial clustering identified recurring hotspots near excavation fronts and in high-traffic areas. Additionally, machine-specific risk profiles indicated that certain equipment types exhibited higher frequencies of proximity violations, highlighting opportunities for targeted safety interventions. While no historical baseline or incident logs were available for direct comparison, the system detected multiple proximity violations and near-miss patterns over 504 operational hours, demonstrating its ability to uncover latent safety risks that are typically not observable with traditional monitoring approaches. These results support the system's role in enabling proactive safety management by providing real-time, data-driven insights into hazardous interactions. Future work will focus on validating these indicators through longitudinal studies and integrating incident records and near-miss reporting systems to establish quantitative links between detected risk patterns and actual safety outcomes.

Limitations and conclusions

The proof-of-concept system was tested for only three weeks at a single site, limiting generalizability. Machine telematics lacked survey-based validation, so it supports relative risk identification rather than precise localization. GPS positioning also introduces accuracy uncertainty, especially near obstructions, though this was minimal at the study site. The absence of baseline safety records limits the ability to quantify absolute reductions in incidents, and future work will address this through before–and–after comparative analysis.

Finally, the study was limited to two machine types and omitted critical factors like worker-on-foot interaction, multi-machine dynamics, and environmental/behavioral context. The absence of worker tracking represents a significant limitation, as pedestrian-equipment interactions constitute a major source of construction site accidents. Additionally, the system did not account for visibility conditions, operator experience levels, or communication patterns among crews, all of which influence real-world safety outcomes.

Despite these constraints, the system demonstrates strong technical feasibility and practical value by integrating IoT telemetry with dynamic heat maps for proactive safety management. Continuous risk visualization reveals high-risk spatiotemporal patterns, providing actionable insights beyond traditional static plans. Its reliance on operational context confirms the effectiveness of real-time spatial analytics, while hazard detection and visual risk zones address key safety gaps.

From an implementation perspective, the system uses commercially available telematics and cloud infrastructure, making it accessible without major customization. Its compatibility with existing fleet systems, along with standard data formats and open-source tools, supports easy adoption, scalability, and site-specific customization

The research demonstrates that IoT-enabled proximity monitoring can transition construction safety from reactive incident response to predictive hazard prevention. By providing continuous spatial awareness and enabling early intervention before accidents occur, the system exemplifies how digital construction technologies can fundamentally enhance worker safety. The framework's capacity to identify recurring risk patterns also supports organizational learning, allowing firms to refine operational procedures and training programs based on empirical evidence of actual site behavior rather than theoretical hazard assessments.

To advance this work, future efforts must quantitatively validate positioning accuracy and assess system robustness across various sites. Research should incorporate new data sources, including worker tracking and multi-equipment modeling. Expanding the framework to include wearable sensors for workers on foot would enable comprehensive monitoring of all site personnel, thereby addressing the current limitation of equipment-only tracking. Integration of computer vision systems could complement GPS-based positioning, particularly in confined spaces or in areas with degraded GPS signal. Crucially, the integration of machine learning for predictive risk forecasting will be key to transitioning construction safety management from reactive to a predictive practice. Advanced analytics could leverage historical proximity patterns to forecast collision probabilities from current operational configurations, enabling preemptive interventions when risk thresholds are projected to be exceeded.

Long-term deployment across multiple sites can establish industry benchmarks and validate risk patterns. Integrating BIM and construction schedules can contextualize proximity data, enabling a scalable, data-driven approach to improving construction safety and preventing accidents.

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