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Integrated Technology and System for Risk and Safety Management in Smart Construction

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Abstract. With the advancement of the "dual carbon" strategy and the acceleration of digital transformation in the construction industry, smart construction sites have become a key path to enhancing construction safety and efficiency. This article systematically reviews the application of Internet of Things (IoT) technology in the integrated management of risks and safety in intelligent construction, covering the system architecture, key technologies, typical application scenarios, and future development trends. It analyzes the four-layer IoT architecture (perception, network, platform, and application) and explores the synergistic role of key technologies, including BIM, digital twins, AI video analytics, and electronic geofencing. Case studies demonstrate that this IoT-driven approach to IRSM can significantly reduce injury rates, shorten project durations, and improve overall operational efficiency. Finally, the study identifies persistent challenges—including technical integration complexities, data security concerns, and cost-benefit standardization—and proposes future research directions towards the integration of 5G, AI, edge computing, and green construction principles.

Keywords: Smart Construction Site; Internet of Things (IoT); Integrated Risk and Safety Management (IRSM); Digital Twin; Construction 4.0.

1. Introduction

The construction industry has traditionally been regarded as a high-energy-consumption, high-risk, and low-efficiency sector. Accidents, pollution, and delays often accompany construction sites with numerous tower cranes and flying sparks. With the implementation of the "carbon neutrality" strategy, the country has proposed to promote industry transformation and upgrading through digital and intelligent means. At the same time, the aging of the workforce and the skill gap have made extensive management unsustainable, and the contradiction between safety and efficiency has become increasingly acute. Against this backdrop, the smart construction site, as a key scenario of intelligent construction, has emerged. Its core goal is to fully map the five elements of personnel, machinery, materials, processes, and environment into the digital space, achieving real-time perception, precise control, and closed-loop management. The Internet of Things, with its "connecting everything" technical characteristics, has become a bridge connecting the physical construction site and the digital twin: sensors, positioning tags, smart wearables, and mechanical black boxes constitute the peripheral nerves, while 5G, Wi-Fi 6, LoRa, and other multi-protocol networks undertake the information arteries. Cloud computing and edge computing work together to complete data aggregation, analysis, and decision-making, ultimately releasing value in dimensions such as safety management, progress control, quality traceability, and green construction.

Among these value dimensions, enhancing safety management through proactive risk mitigation represents the most critical and immediate imperative. Risk and safety integrated management refers to integrating risk management and safety management in the strategic planning, system construction, organizational mechanism, and technical means of the organizational management system based on systematic thinking and the concept of the entire process management, achieving the coordinated operation of risk prevention and safety guarantee, thereby comprehensively enhancing the essential safety level and operational resilience of the organization. This is precisely the primary demand of smart construction site construction - only by identifying potential hazards before an accident occurs and intervening immediately when the hazards are in the bud, can the "people-oriented" industry bottom line be truly fulfilled. This article focuses on how the Internet of Things technology can be embedded in the entire life cycle of construction, and conducts a systematic review of the system architecture, key technologies, typical cases, and evolution trends, aiming to provide replicable paths and a quantifiable basis for government supervision, enterprise practice, and scientific research.

Several key technological domains underpin the pursuit of integrated risk and safety management on smart construction sites. A review of recent literature reveals both progress and persistent challenges: Zhang, Hu & Lin systematically review the application of digital twin (DT) technology in smart construction site management. The main findings highlight DT's ability to enhance real-time monitoring, safety, resource optimization, and decision-making through the integration of BIM, IoT, AI, and data analytics. DT enables dynamic, bidirectional interaction between physical and digital environments, improving efficiency, quality, and cost control. However, challenges remain in data integration, model synchronization, system interoperability, and high implementation costs. The paper also identifies future research directions, including enhancing predictive capabilities, developing standardized frameworks, and conducting large-scale practical validations. Li, Chan & Skitmore reviewed the application of IoT in real-time monitoring at construction sites in their paper, identifying several key sensors and monitoring methods, such as location/positioning systems, environmental and safety sensors, and how the IoT platform collects, transmits, and analyzes these real-time data to support on-site decision-making. They found that IoT technology can significantly contribute to enhancing safety, improving worker behavior monitoring, warning of hazards/potential accidents, and improving resource scheduling efficiency. At the same time, it can also reduce the blind spots and delays of manual monitoring. However, the paper also pointed out several challenges, including data quality/reliability issues, communication/delay problems, insufficient system compatibility and standardization, as well as the impact of the complexity of the construction site environment (such as weather, obstruction, noise) on the performance of the IoT system. At the same time, it suggested that future research should place more emphasis on practical engineering case verification, end-to-end system integration, sensor fusion, and cost-benefit analysis. Zhou, Ding & Luo reviewed the application of artificial intelligence in construction safety early warning systems in their paper. They found that AI models (such as machine learning, deep learning, image recognition, etc.) can significantly enhance the ability to detect dangerous behaviors and environmental risks at construction sites at an early stage; the systems usually integrate multiple sources of data (visual, sensors, historical accident records, etc.) to achieve higher accuracy and real-time response; the warning system has shown good effects in improving safety management efficiency, reducing accident rates, and enhancing risk prediction accuracy. However, there are also challenges, such as high data quality and annotation costs, poor model transferability, the impact of on-site interference factors (lighting, occlusion, environmental complexity) on performance, and the difficulty in promoting the warning system from laboratory or case studies to large-scale real construction environments. Collectively, these studies underscore the transformative potential of DT, IoT, and AI in addressing construction site challenges. However, they also reveal a fragmented approach. Research often focuses on a single technology in isolation, leaving a gap in the understanding of how IoT—as the fundamental data acquisition layer—systematically enables and integrates with other technologies to achieve true risk and safety integration throughout the entire project lifecycle.

To address this gap, this article focuses specifically on the role of Internet of Things technology in enabling integrated risk and safety management. It conducts a systematic review from four perspectives: (1) system architecture, (2) key enabling technologies, (3) implementation challenges, and (4) future evolution trends, aiming to provide a replicable pathway and quantifiable basis for industry practitioners and policymakers.

2. System Architecture and Key Technological Components

2.1. The Four-Layer IoT Architecture

The system architecture of Internet of Things (IoT) technology in smart construction sites can be categorized into four layers: the perception layer, network layer, platform layer, and application layer [1]. The perception layer serves as the primary data source for IoT systems. It is composed of various sensors (such as stress, displacement, and inclination sensors), positioning tags (UWB, RFID), intelligent wearable devices (smart safety helmets, wristbands), and image acquisition devices (high-definition cameras, drones), and is widely deployed in key areas of construction sites. This layer is mainly responsible for real-time collection of personnel location information, the operating status of mechanical equipment (such as load, speed, oil pressure), environmental parameters (temperature, humidity, noise, dust, harmful gas concentration), and material status, forming high-precision, all-element on-site perception capabilities, and providing a solid and dynamic data foundation for building a digital twin that synchronously maps with the physical entities. The network layer is responsible for the reliable transmission and preliminary processing of sensed data. It adopts a hybrid networking mode that integrates multiple protocols (such as 5G with large bandwidth and low latency, Wi-Fi 6 with high concurrent access, and LoRa with long-distance and low power consumption) to meet the communication needs in complex environments of construction sites. By deploying edge computing gateways, it performs protocol conversion, filtering and cleaning, local storage, and real-time analysis on the collected data at the network edge. This not only reduces the transmission load on the cloud but also enables rapid response to scenarios with high real-time requirements (such as abnormal alarms and equipment linkage), effectively ensuring the real-time performance, reliability, and security of the data link. The platform layer is the information processing and value mining center of the system. It takes the high-precision three-dimensional spatial information provided by Building Information Modeling (BIM) and Geographic Information System (GIS) as the digital foundation, integrating a stream computing engine, a big data platform, and artificial intelligence algorithms. This layer cleans, fuses, integrates, and uniformly models the multi-source, heterogeneous, and massive spatio-temporal data from the perception layer, and ultimately builds a dynamic digital twin that integrates the five major elements of "personnel, machinery, materials, processes, and environment", providing unified data services, model services, and decision analysis support for upper-layer applications. The application layer directly focuses on safety management services, based on the modern risk management closed-loop concept of "preliminary intelligent prevention - real-time control during the process - post-event traceability and review". A series of functional systems has been developed. Specifically, these include: intelligent alarm for hazardous areas with electronic fences, real-name system and real-time trajectory tracking for personnel, collision prevention for large mechanical groups and towers, intelligent monitoring of temporary power usage safety, linkage control for environmental parameter over-limit (such as automatic sprinkler dust suppression), AI video violation identification and warning, as well as one-click emergency command dispatch. Through these applications, the final goal is to achieve visual presentation of safety risks at the construction site, hierarchical warning, intelligent intervention, and full-process closed-loop management, significantly enhancing the initiative and accuracy of management. The operation mechanisms at four levels can be illustrated in Figure 1.

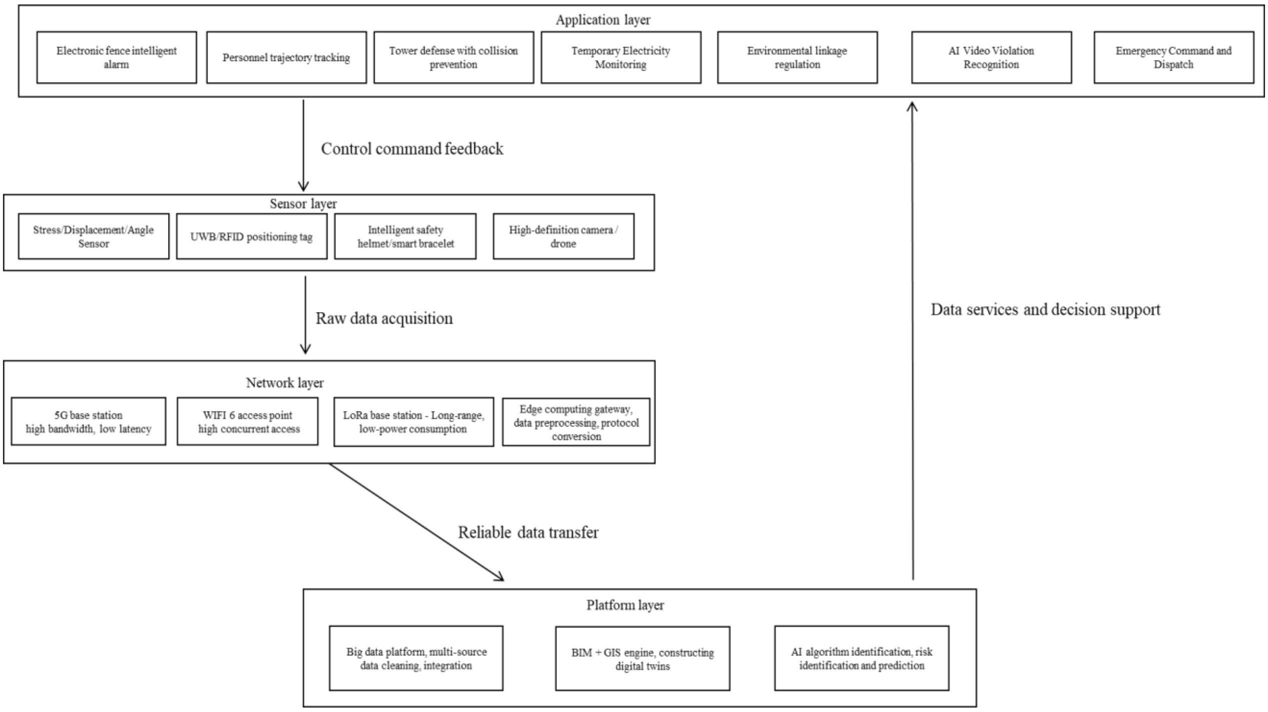

Fig 1. The operation mechanisms at four levels (Photo credit: Origin)

This four-layer architecture provides the infrastructural backbone for smart construction sites. At the heart of this system, particularly within the platform layer, lies the Digital Twin (DT) technology, which serves as the core for data integration and visualization, enabling advanced applications.

2.2. The Core of the Platform: Digital Twin and BIM

A digital twin is an information construct that enables people to simultaneously understand various aspects of a physical asset through the fully visualized replica of its virtual counterpart. This allows for the visualization, analysis, and most importantly, the application of meaningful and practical information about the physical asset for decision-making [2].

2.3. Integrated Applications and Case Evidence

BIM and digital twin technologies, through 4D, 5D, and 6D extensions, can simulate scenarios such as structural force, fire evacuation, and group tower operations. After being applied in a certain super high-rise project, 27 cases of group tower interference were detected in advance, saving 9 million yuan in rework costs. This case demonstrates the DT’s capability to preempt costly safety incidents and optimize construction planning.

This proves that digital twins can significantly improve the accuracy of safety pre-control. Video intelligent analysis is based on deep learning algorithms to complete target detection and behavior recognition at the edge. Electronic fences and hazardous area management set up multi-level fences through UWB positioning, achieving sound and light alarms, smart bracelet vibration, and mechanical power cut-off. Temporary power supply and mechanical equipment monitoring collect electrical and mechanical parameters through smart electrical boxes and black boxes, and combine AI algorithms to identify overloading, oblique lifting, and group tower interference. Currently, these technologies have been applied in the field of intelligent construction, such as using BIM and digital twin “digital embryos” to build accurate models before physical construction. This allows 3D simulations for plant layout and logistics, reducing design errors and costs. It provides real-time monitoring of equipment, production, and logistics via sensors and data feedback [3]. Also, AR/VR integration can be used for collaborative operations and training workers; it combines humans, machines, sensors, and AI for decision-making and execution in complex manufacturing [3]. For the case study in the hydraulic cylinder factory, the technology was applied to plant reconstruction, production optimization, and supply chain tracking. As a result, the delivery date improved by 13 days, work-in-progress inventory reduced by 37.3%, defective rate dropped by 3.2%, and capacity utilization increased by 5% [3]. This integrated application highlights how IoT-driven smart construction management can lead to significant improvements across multiple performance metrics.

3. Problem Analysis and Suggestion

3.1. Cultural Issues and Explainable AI

The construction industry remains one of the least digitized sectors, characterized by a slow adoption rate for new technologies [4,5]. This is probably because most construction processes involve risks and are costly, and even a minor mistake can lead to serious consequences. In the construction industry, people prefer traditional and known ways of working rather than new technologies that promise big returns but lack credibility. This indicates that the construction industry has been slow in adopting innovative technologies. Unlike other industries, such as manufacturing, construction workers often have their own unique skills and need to possess the ability to quickly learn and adapt to the constantly changing artificial intelligence environment. This means that the artificial intelligence technologies applied in the construction industry must be verified in various construction projects or sites, and undergo comprehensive testing, so as to provide a basis for construction contractors and enterprises to use these technologies. This may include leveraging other digital technologies like blockchain to enhance trust and integrity.

Furthermore, most machine learning systems operate in a "black box" mode, which means they cannot explain the reasons behind their conclusions. To build trust in such systems, practitioners must understand how these systems make decisions. Therefore, there is a need to use explainable artificial intelligence (XAI) to build interpretable models that enable humans to understand, trust, and manage these systems. Some popular XAIs include Local Interpretable Model Association Explanations (LIME) and Layer-wise Relevance Propagation (LRP) [6,7]. The adoption of such XAI methods is a critical step in overcoming the industry's inherent cultural resistance by fostering transparency and trust in AI-driven decisions.

3.2. Data Security and Privacy Protection

Although artificial intelligence can enhance security and detect intrusion activities, it is also a major target for hackers, cybercrime, and privacy infringement [8]. This is a crucial issue with significant economic and environmental impacts. Minor errors during the construction process often lead to huge quality, cost, and time-related effects, and trigger a chain reaction throughout the project plan (time, cost, supply chain and logistics, procurement, etc.) [9]. Most importantly, the safety of construction workers may be compromised, leading to potentially fatal accidents or even casualties. To mitigate these severe risks, proactive defense mechanisms against such adversarial attacks are essential.

For instance, a visual computer system capable of identifying automated construction equipment might be misled, thereby mistakenly classifying a construction worker working at heights as an equipment operator. Utilizing artificial intelligence to comprehensively control certain life processes or enhance the working capabilities of construction workers requires minimizing or eliminating safety risks to the greatest extent possible. This requires mitigation strategies such as adversarial machine learning. Adversarial machine learning (ML) is the study of effective machine learning techniques that are designed to counter adversaries [10]. The application of adversarial machine learning is from the perspective of security defense, and it is also used to design algorithms that can resist advanced attacks. Furthermore, further research is needed in this area, especially for emerging architectural research techniques such as computer vision and robotics.

3.3. High Initial Cost

The advantages of AI-driven solutions in the construction industry are undeniable. However, the final cost required for investing in such AI solutions (such as robotic technology) is often very high. Moreover, the cost of maintaining such solutions also needs to be considered. This may be unaffordable for most subcontractors and small businesses that form the backbone of the construction industry [6, 7]. Therefore, enterprises must calculate the cost savings and return on investment of such technologies in order to make the investment. Additionally, as the acceptance and popularity of these technologies in the construction industry continue to increase, their prices are expected to decrease, making them more affordable for smaller enterprises. Therefore, demonstrating clear and short-term return on investment (ROI) remains paramount for wider adoption across the industry, especially among SMEs.

4. Systemic Integration Barriers and Mitigation Strategies

These obstacles include difficulties in system integration; lack of trust in data security; diversity and interoperability issues of source systems; scalability problems; fragmentation of data management; difficulties in software selection; absence of standard tools and methods; quality and uncertainty of data; problems in data storage, processing and analysis; the need for continuous network connection; limited support technologies; and sudden and unexpected system failures [11-14]. As earlier studies [15,16] have shown, the construction industry faces a crisis in technology adoption. These challenges hinder the smooth implementation of digital twin technology within the industry. A key challenge in adopting technologies like digital twins in CI is the difficulty of system integration. This involves migrating legacy systems, equipment, and technologies to new, advanced technologies, such as BIM (Building Information Modeling) and digital twins. This challenge also includes integrating disparate technologies.

In response to these obstacles, the following comprehensive improvement measures are proposed:
System Integration & Interoperability: Adopt phased migration strategies and middleware technologies to bridge legacy and new systems. Promote open standards (e.g., Industry Foundation Classes - IFC) and unified data interfaces to enhance interoperability between disparate software and technologies.

Data Management: Establish a centralized data platform with a robust governance framework to eliminate fragmentation, ensure data consistency, and address quality issues through validation rules.
Scalability & Reliability: Implement a hybrid computing architecture that combines cloud and edge computing. This enhances system performance for real-time processing, reduces reliance on continuous high-bandwidth connectivity, and improves overall reliability.

Security & Trust: Enhance data security and transparency by adopting blockchain for immutable audit trails or implementing a zero-trust security architecture that verifies every access request.

Standardization & Support: Develop industry-wide software evaluation guidelines and standardize tools and methods to reduce selection complexity. Concurrently, promote the development and integration of supporting technologies (e.g., IoT, 5G, low-cost sensors).

Resilience: Establish redundant systems and comprehensive disaster recovery mechanisms to ensure business continuity and enable rapid system restoration in the event of unexpected failures.

5. Conclusion

In conclusion, the application of IoT-enabled smart construction sites and digital twins holds significant potential for transforming the construction industry. However, multiple obstacles persist in cultural cognition, data security, cost investment, and technical integration.

To promote their effective implementation, the industry needs to, on one hand, enhance transparency and trust through interpretable artificial intelligence, and strengthen security through adversarial machine learning; on the other hand, it should gradually lower the investment threshold for intelligent solutions and improve the implementation effect of technology through phased system integration, unified standards, improved data governance, cloud-edge collaboration, and blockchain security mechanisms, thereby providing solid support for the digital transformation and high-quality development of the construction industry. Through a systematic review, this article has demonstrated how the IoT architecture facilitates significant advantages across the entire data pipeline—from perception and transmission to processing and application—thereby providing a solid foundation for the industry's digital transformation and high-quality development.

Regarding the limitations of this article, no extensive data experiments or field investigations were conducted. Instead, it merely summarized previous research papers. It is hoped that these limitations can be addressed through future experiments and data-based explanations.

In the future, with the further integration of technologies such as 5G, AI, and digital twins, smart construction sites will gradually achieve a higher degree of automation, intelligence, and greenness, providing solid support for the sustainable development of the construction industry.

References

[1] Arun Kumar, Sharad Sharma, Nitin Goyal, Aman Singh, Xiaochun Cheng, Parminder Singh. Secure and energy-efficient smart building architecture with emerging technology IoT. Computer Communications, 2021, 176, 207-217.

[2] Rolando Chacon, Hector Posada, Carlos Ramonell, Manuel Jungmann, Timo Hartmann, Rehan Khan, Rahul Tomar. Digital twinning of building construction processes. Case study: A reinforced concrete cast-in structure. Journal of Building Engineering, 2024, 84, 108522.

[3] Xia Luyao, Lu Jianfeng, Zhang Hao, Xu Mengying, Li Zhaojia. Construction and application of a smart factory digital twin system based on DTME. The international journal of Advanced Manufacturing Technology, 2022, 120(5), 4159-4178.

[4] Sofiat O. Abioye, Lukumon O. Oyedele, Lukman Akanbi, Anuoluwapo Ajayi, Juan Manuel Davila Delgado, Muhammad Bilal, Olugbenga O. Akinade, Ashraf Ahmed. Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. Journal of Building Engineering, 2021, 44, 103299.

[5] Chui Michael, and S. Francisco. Artificial intelligence the next digital frontier. McKinsey and Company Global Institute, 2017, 47(3): 6-8.

[6] Ribeiro, Marco Tulio, Sameer Singh, and Carlos Guestrin. Why Should I Trust You?: Explaining the Predictions of Any Classifier, California, San Francisco, 2016, 1135-1144. ACM.

[7] Binder, Alexander, et al. Layer-wise Relevance Propagation for Neural Networks with Local Renormalization layers, Springer, Barcelona, 2016, 63-71.

[8] Frank, Jeremy. Artificial Intelligence and intrusion detection: current and future directions. S.l, in: Proceedings of the 17th National Computer Security Conference, 1994, 1-12.

[9] Oyedele, Lukumon O., et al. Critical factors affecting construction quality in Nigeria: evidence from industry professionals. International Journal of Sustainable Building Technology and Urban Development, 2015, 6(2): 103-113.

[10] Huang Ling et al. Adversarial machine learning. Proceedings of the 4th ACM workshop on Security and artificial intelligence, 2011, 43-58.

[11] De-Graft Joe Opoku, Srinath Perera, Robert Osei-Kyei, Maria Rashidi, Keivan Bamdad, and Tosin Famakinwa. Barriers to the Adoption of Digital Twin in the Construction Industry: A Literature Review. MDPI, 2023, 10 (1): 14.

[12] Qi, Qinglin, and Fei Tao. Digital twin and big data towards smart manufacturing and industry 4.0: 360 degree comparison. Ieee Access, 2018, 6: 3585-3593.

[13] Ayoub, Mohammed. A review on machine learning algorithms to predict daylighting inside buildings. Solar energy, 2020, 202: 249-275.

[14] Botín-Sanabria, Diego M., et al. Digital twin technology challenges and applications: A comprehensive review. Remote Sensing, 2022, 14(6): 1335.

[15] Liu Zhen, et al. Immersive technologies-driven building information modeling (BIM) in the context of metaverse. Buildings, 2023, 13(6): 1559.

[16] Latif, Kamran, Abubakar Sharafat, and Jongwon Seo. Digital twin-driven framework for TBM performance prediction, visualization, and monitoring through machine learning. Applied Sciences, 2023, 13(20): 11435.