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Digital Twin-Based Risk Monitoring for Construction

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Abstract. Due to the continuous changes in the construction site, construction equipment and working environment, the traditional manual and periodic site inspections have difficulty controlling the risk in time. Therefore, it is necessary to adopt a more continuous monitoring approach. This article adopts the method of literature synthesis and analysis of representative studies, organizes the data and supporting technology of the digital twin for construction safety management and analyzes related studies in three aspects, namely personnel safety and dangerous area monitoring, equipment and construction environment risk monitoring, fire risk monitoring and emergency response. Existing research shows that the digital twin can associate information such as Building Information Modeling (BIM), personnel positioning, wearable devices, equipment operation and environmental monitoring with digital models, and provide more continuous on-site information for dangerous area identification, lifting equipment risk analysis and fire condition monitoring. However, its actual effect is still affected by factors such as data accuracy, model update speed, sensor stability, system integration and field conditions. At this stage, the digital twin is more suitable as an auxiliary tool for construction safety management, and related systems still need to be continuously verified in more real projects.

Keywords: Digital twin, construction safety management, risk monitoring, building information model, Internet of Things

1. Introduction

The construction site has frequent personnel flow, many types of mechanical equipment, and frequent cross-operations between different types of work. The site status will change continuously with the construction stage. Problems such as personnel mistakenly entering dangerous areas, abnormal operation of mechanical equipment, changes in environmental conditions, and fires may increase construction safety risks. Traditional safety management mainly relies on manual inspections, regular inspections and on-site records, which can find some potential safety hazards. However, for the continuous changes of personnel location, equipment status and environmental parameters, information acquisition often lags. The digital twin can associate the Building Information Modeling (BIM) model with on-site data such as personnel positioning, equipment operation, and environmental monitoring, so that the safety status of the construction site can be continuously updated in the digital environment, providing new technical means for risk monitoring and on-site management [1, 2].

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Existing research has explored the use of digital twins and related digital technologies in construction safety management from multiple aspects. In terms of personnel safety, BIM, positioning equipment, wearable sensors and computer vision are used for personnel location monitoring, hazardous area identification and personal protective equipment testing [3-7]. In terms of equipment and construction environment, sensors and Internet of Things (IoT) data can reflect the operating status, operating range and environmental conditions of lifting equipment, and combine with digital models to carry out safety analysis [8, 9]. In fire and emergency management research, BIM, the IoT, artificial intelligence, and 3D digital models have also been used for fire condition monitoring, situational awareness, and evacuation support [10-12]. However, the data types, monitoring objects and technical schemes used in the existing research are quite different, and many studies still focus on a single person, equipment or specific risk scenarios. What a multi-source safety information is continuously fed into the digital model, as well as the stability and applicability of related systems in the real construction environment, still needs further discussion.

This paper adopts the methods of literature synthesis and analysis of representative studies. Firstly, it sorts out the data types and main supporting technologies required for the construction safety digital twin. On this basis, relevant research is analyzed from three aspects: personnel safety and dangerous area monitoring, equipment and construction environment risk monitoring, fire risk monitoring and emergency response, and the role and practical limitations of digital twins in different safety management tasks are discussed in combination with representative cases. Finally, the problems of current methods in data quality, model updating, system integration and field application are discussed, and the future research directions are summarized.

2. Data and technical basis of the digital twin for construction safety management

2.1. Construction safety related data

Construction personnel are important monitoring objects in construction safety management. Personnel positioning data, wearable device information, access control records and on-site video can be used to obtain personnel location, operating status and wearing of protective equipment [4, 6, 7]. After associating the personnel position with the construction area and the location of the hazard source, it can be judged whether the personnel enter the restricted area or whether they are spatially close to the operation range of the mobile machinery. Such monitoring requires high data accuracy and transmission timeliness. If the positioning deviation is large or the data update is not timely, it may cause false positives, omissions or early warning delays.

Mechanical equipment and working environment are other important data sources. Equipment such as tower cranes, cranes, and transport vehicles can obtain status information such as position, load, speed, and acceleration through sensors and operating recording devices. Environmental sensors can collect parameters such as wind speed, temperature, smoke, dust, and harmful gases [3, 8, 9]. After continuous transmission to the digital platform, these data can be used to update the equipment and environmental status, and provide the basis for hoisting stability analysis, construction environment anomaly identification and risk judgment. The data format and update frequency of different devices are not the same, so the data access method will directly affect the synchronization effect of the digital twin.

In addition to real-time monitoring data, BIM model, construction plan, safety inspection records and historical risk information also constitute the data basis of the construction safety digital twin [1, 2]. The BIM model can provide information such as components, work areas, and spatial relationships. The construction plan can reflect the operation arrangements at different stages, and

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the safety inspection records retain the existing risks and processing conditions on the site. After associating this information with real-time data, the digital model can display current conditions and help users interpret changes in personnel, equipment, and the environment in the context of specific construction stages and locations.

2.2. Support technology of the construction safety digital twin

BIM is an important spatial basis for the construction safety digital twin. The model can record the building components, construction area and spatial relationship, and provide reference for personnel positioning, equipment monitoring and dangerous area division [1]. The digital twin does not simply mean adding a BIM model, but establishing a continuous data link between the digital model and the real construction site, so that the model can change with the site state [1, 2]. Therefore, BIM focuses more on engineering objects and their information expression, while the digital twin further emphasizes the access, update and feedback of field data.

The IoT, sensors and communication networks undertake the main tasks of field data acquisition and transmission. The personnel positioning equipment can record the position change of the construction personnel, the mechanical equipment sensor can obtain the operating parameters, and the environmental monitoring device is responsible for collecting information such as temperature, smoke, wind speed and harmful gas [1, 3]. In the study of tunnel construction safety, many types of field data are connected to the digital twin platform through the communication network for construction status update and safety warning [3]. Cranes and other lifting equipment can also combine encoders, operation recorders and other sensing devices to obtain data such as attitude, load and operating range to provide information for subsequent stability and risk analysis [8, 9].

Images obtained by cameras and drones on the construction site can also be used as data sources for digital twins. Computer vision can identify construction workers, personal protective equipment, mechanical equipment and some dangerous operation behaviors from images or videos [4-6]. Relevant research has associated computer vision results with BIM models for the expression of personnel location and on-site risk information [4]. When the positioning data, equipment sensors and image recognition results are connected to the digital model at the same time, the safety information scattered in different equipment and systems can be viewed in the same construction scene, but the effect still depends on the accuracy of data time synchronization and spatial matching [1, 2].

3. The main application of digital twin in construction safety management

3.1. Personnel safety and dangerous area monitoring

There are dangerous areas such as high working surface, hoisting area, edge hole and large mechanical operation range in the construction site. The digital twin can combine the spatial information in BIM with personnel positioning, wearable devices and on-site video to continuously record the personnel position in the digital model and determine whether they are close to or enter the restricted area [4, 7]. The role of different data in personnel safety monitoring is not the same. Positioning and wearable devices mainly reflect the spatial relationship between people and dangerous areas, and computer vision can supplement the identification information of personal protective equipment such as safety helmets and protective clothing [5, 6]. Chen and Demachi used deep learning and scene relationship analysis to identify the irregular use of personal protective equipment and achieved 94.47% accuracy and 83.20% recall in field data [6]. Such identification

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results can be used as input information for construction safety digital twins but cannot replace other field data such as personnel location and work area.

Saif et al. combined 4D BIM with wearable sensors and carried out on-site verification in the construction project of AstraZeneca Quality Assurance Building [7]. The study first identifies the dangerous areas corresponding to construction activities in 4D BIM and then uses on-site surveying and mapping to correct the regional location. The construction personnel wear sensors connected to the safety helmet, and associate the type of work, skills and regional access rights through the Radio Frequency Identification (RFID) card. In the field test, the steel structure installation area was finally selected for one-week monitoring, and the personnel position was updated every 30 s. When unauthorized personnel enter the dangerous area, the sensor will emit sound and vibration prompts, and the relevant entry time, personnel identity and stay information are recorded into the platform at the same time. When a person approaches a dangerous area at a speed of 4 mph, the system can identify cross-boundary behavior within a range of about 0.5 m, with an average response time of about 0.3 s [7]. Monitoring data can also be transmitted back to 4D BIM for reviewing personnel activities in hazardous areas and evaluating existing safety measures.

The advantage of this method is that the dangerous area division, personnel access and real-time location monitoring are placed in the same spatial model, so that safety managers can timely view the relationship between personnel and hazard sources and retain traceable monitoring records. However, building components and large machinery on the construction site may affect the positioning signal, and video recognition will also be affected by changes in illumination, occlusion, and shooting angle [4, 7]. The boundary of the dangerous area in the digital model also needs to be consistent with the actual isolation range on site, otherwise it may cause error warning. Data access and privacy issues are also involved in the continuous collection of personnel positions by wearable devices, so the system deployment needs to clarify the scope of data use and access rights [7].

3.2. Equipment and construction environment risk monitoring

The construction site uses many types of mechanical equipment such as tower cranes, cranes and transport vehicles. The operation status of the equipment and the environmental conditions such as wind speed and temperature will affect the safety of the operation. The digital twin can associate equipment sensors and environmental monitoring data with on-site digital models, so that equipment posture, load and external environmental changes can be continuously recorded. Jiang et al. constructed the digital twin of tower crane hoisting based on the physical scale model and analyzed the stability changes caused by different unsafe hoisting behaviors [8]. It is found that the influence of cable-stayed hoisting on the stability of tower crane is obvious, and the tower crane foundation and tower body are also the key parts susceptible to dynamic load [8]. This study shows that the digital twin can not only display the state of the equipment but also be used to analyze the relationship between the operation behavior and the stability of the equipment.

Liu et al. further applied a digital twin to the coupling analysis of safety risk of prefabricated building hoisting [9]. This study uses smart cameras, environmental sensors, tower crane data recorders, and RFID tags to obtain information on people, environments, equipment, and components, and associates these data with BIM models. The hoisting risk index system including personnel operation, mechanical state, component quality, management conditions and wind speed is established. The Apriori algorithm is used to identify the association rules between risk factors, and the key risk factors are analyzed by complex network [9]. Compared with only focusing on a single equipment parameter, this method can put equipment operation, environmental conditions and on-site management information in the same risk analysis framework and display the analysis results in

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the BIM model. The case of a large-scale prefabricated building project shows that the framework can be used for multi-source information fusion and hoisting risk visualization, but the indicators and rules used in the study are still related to specific engineering conditions [9].

Equipment and environmental risk monitoring require high data continuity. Sensor failure, communication delay or insufficient data update frequency may make the equipment state in the digital model deviate from the actual situation on site. There are many types of equipment in the construction site, and the interfaces and data formats of different equipment are not completely consistent. Multi-source data access will increase the difficulty of system integration. At the same time, there are still differences between the stability test in the scale model and the real construction site, and the risk coupling model also needs to be further verified under different engineering and equipment conditions [8, 9]. Therefore, the role of the digital twin in equipment safety management is more suitable for positioning as condition monitoring and risk analysis support, rather than an independent safety determination method.

3.3. Fire risk monitoring and emergency response

In the construction stage, there is temporary electricity consumption, welding fire, flammable material stacking and temporary facilities concentration, etc., and the fire risk needs continuous attention. Traditional fire management mainly relies on fire facilities, manual inspection and on-site alarms. Digital twins can correlate monitoring data such as temperature and smoke with spatial models to display abnormal locations and surrounding people and evacuation channels in a digital environment. Chen et al. used BIM, IoT, Augmented Reality and Virtual Reality in building fire safety and training research, indicating that sensor data, building spatial information and immersive display can jointly improve fire situational awareness [10]. Although this kind of research is not specifically for the construction stage, its data connection and spatial expression have reference value for fire monitoring at the construction site.

Zhang et al. constructed a digital twin system based on the Artificial Intelligence of Things (AIoT) for tunnel fires and verified it through numerical simulation and full-scale experiments [11]. Based on the experimental environment of a 140 m long full-scale railway tunnel, the Transformer model was trained using fire simulation data. The fire location and heat release rate were predicted according to the top temperature sequence. The R^2 of the training and validation data reached 96.5% [11]. The prediction model is then connected to the Unity 3D digital twin platform to reconstruct the flame and smoke development process, and the performance of the system in real-time fire identification is verified by full-scale fire test. The case study shows that the sensor data, prediction model and 3D scene can form a continuous information chain, which provides more intuitive information for fire state judgment and emergency response. It should be noted that this study is oriented to tunnel fire safety and is not a direct application of general construction sites.

Personnel evacuation is also an important aspect of fire emergency management. Ding et al. constructed a digital twin system for building fire evacuation based on computer vision. They obtained the location of people through cameras, target detection and tracking algorithms, and reflected the evacuation process in the digital interface [12]. In the experiment, the success rate of personnel detection in multi-person scenario is about 90%, which can provide real-time information for evacuation process monitoring [12]. Like the tunnel fire research, the application scenario of this case is not the construction site, but the personnel identification, spatial mapping and dynamic visualization methods can provide technical reference for fire emergency monitoring in the construction stage. In the actual construction environment, temporary facilities and evacuation routes change rapidly, and the fire monitoring results are also affected by sensor layout, on-site

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occlusion and model update speed. Therefore, digital twins still need to be used together with fire protection facilities, on-site alarms and manual emergency response.

4. Limitations and development direction

When the digital twin is used for construction safety management, it is necessary to continuously access various data such as personnel location, equipment operation, environmental monitoring and on-site video. Different safety tasks have different requirements for data types and update frequency. Personnel safety monitoring relies more on positioning and video information. Equipment risk monitoring needs to obtain operating parameters and operating status. Fire monitoring requires data such as temperature, smoke and personnel distribution. Because these data come from different devices and systems, there are differences in format, acquisition frequency and transmission mode. Therefore, data synchronization is not easy [1, 2]. If the field data is not updated in time, or the digital model fails to reflect the construction status in time, it may affect the accuracy of risk judgment.

The on-site environment will also affect the monitoring results. Building components, mechanical equipment and temporary facilities may interfere with personnel positioning signals. On-site video is susceptible to changes in illumination, occlusion and shooting angles. The stability of sensors and equipment monitoring devices also affects data quality [4, 7-9]. At the same time, the deployment and maintenance of personnel positioning equipment, environmental sensors, video surveillance and digital platforms will increase project costs, and the software and management systems used by different participating units may also be different. For projects with short construction period or weak digital foundation, excessive configuration of equipment and functions may increase the implementation burden. The digital twin can provide more continuous risk information, but it still cannot replace the professional judgment of on-site inspection and safety management personnel at this stage.

Further research can pay more attention to the continuous operation of digital twins in the real construction environment. In addition to improving the accuracy of identification and prediction, it is also necessary to improve the connection between multi-source data and model updating methods, and to test the stability of the system under different construction stages and different project conditions. Technologies such as drones, wearables, computer vision, and artificial intelligence can be selected based on specific risk types and management needs, without having to be deployed simultaneously in all projects. For fire and emergency management, it is also necessary to increase the verification of real scenarios in the construction phase to avoid directly equating the results in the operating building or the experimental environment with the construction site effects [10-12]. Only by maintaining a good match between data collection, model update and on-site management requirements can the digital twin be used more stably for construction safety risk monitoring.

5. Conclusion

This paper summarizes and analyzes the relevant research on the data and technical basis of construction safety digital twin, as well as personnel safety and dangerous area monitoring, equipment and construction environment risk monitoring, fire risk monitoring and emergency response. Existing research shows that the digital twin can connect information such as BIM, personnel positioning, wearable devices, equipment operation and environmental monitoring to a unified digital model, so that the personnel, equipment and environmental status of the construction site can be recorded more continuously. In personnel safety management, such methods can be used

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for dangerous area entry monitoring and personal protective equipment identification. In equipment safety management, stability and multi-factor risk analysis can be carried out in combination with equipment operating parameters and environmental information. In fire and emergency scenarios, the combination of sensing data, prediction models and three-dimensional spatial information also provides a new technical path for condition monitoring and evacuation support. The actual effect of the digital twin still depends on field data quality, sensor stability, model update speed and system integration level. The construction environment, equipment conditions and management requirements of different projects are different, and the technical schemes in the existing cases cannot be directly applied to all construction sites. Therefore, the digital twin is more suitable as an auxiliary tool for construction safety management at this stage. Subsequent research needs to strengthen continuous verification in real projects, and further improve multi-source data access, model synchronization and cross-scenario adaptability, so that digital twins can serve construction site risk monitoring more stably.

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