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DIGITAL TECHNOLOGIES FOR ENHANCING CRANE SAFETY IN CONSTRUCTION: A COMBINED QUANTITATIVE AND QUALITATIVE ANALYSIS

Yunhan ZHANG, Ke CHEN*

National Center of Technology Innovation for Digital Construction,
Huazhong University of Science and Technology, Wuhan, China
School of Civil and Hydraulic Engineering,
Huazhong University of Science and Technology, Wuhan, China

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Abstract. A digital-enabled safety management approach is increasingly crucial for crane operations, which are common yet highly hazardous activities sensitive to environmental dynamics on construction sites. However, there exists a knowledge gap regarding the current status and developmental trajectory of this approach. Therefore, this paper aims to provide a comprehensive overview of digital technologies for enhancing crane safety, drawing insights from articles published between 2008 and 2021. Special emphasis is placed on the sensing devices currently in use for gathering "man-machine-environment" data, as well as the communication networks, data processing algorithms, and intuitive visualization platforms employed. Through qualitative and quantitative analysis of the literature, it is evident that while notable advancements have been made in digital-enabled crane safety management, these achievements remain largely confined to the experimentation stage. Consequently, a framework is proposed in this study to facilitate the practical implementation of digital-enabled crane safety management. Furthermore, recommendations for future research directions are presented. This comprehensive review offers valuable guidance for ensuring safe crane operations in the construction industry.

Keywords: crane operation, digital technology, safety management, literature review.

Introduction

In modern construction, cranes play a critical role in the transportation of large and heavy materials, making them one of the most important features of construction operations. However, the rapid industrialization of construction processes has resulted in an increasing number of cranes on construction sites, which has contributed to a significant number of accidents. According to public reports and statistics, cranes are responsible for a large portion of accidents in the construction industry. For example, in Australia, there are approximately 240 serious injury claims arising from crane accidents each year (Lingard et al., 2019), while in mainland China, more than 100 tower crane accidents occurred between 2015 and 2019 (Jiang et al., 2021a). As such, decreasing the likelihood of crane accidents has become a major issue in construction safety management.

The safety management of crane operations is a complex process involving various factors, such as organizational, managerial, legislative, social, environmental, and personnel factors (Zhou et al., 2018; Zhang et al., 2020). To prevent deaths and severe injuries, enforcement activities are performed from different perspectives. For instance, a large body of literature has endeavored to enhance crane safety through risk evaluation before actual lifting (Shapira et al., 2012). Nevertheless, lifting, handling, loading, and unloading activities are dynamic and can be affected by the changing site situations. Therefore, a parallel stream of literature concentrated on the real-time safety management of crane operations. This type of literature benefits from the rapid development of digital technologies such as sensors, BIM, VR, among others (Lee et al., 2006; Niu et al., 2019). The increasing number of studies in this field reflects the great potential of digital technology to address crane safety issues.

A retrospective investigation of existing literature can help to summarize current research achievements and

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*Corresponding author. E-mail: *chenkecm@hust.edu.cn* highlight possible directions for future study. Neitzel et al. (2001) reviewed available information on crane-related injuries, safety devices, and commonly adopted safety practices. Zhang and Pan (2020) reviewed 108 studies on lift planning and optimization in construction, and most of the literature treated safety assurance as one of the major issues. Sadeghi et al. (2021) reviewed 74 publications and contrasted the risk factors that have predominantly been investigated against those that received less attention. Hussein and Zayed (2021) reviewed crane operations and planning research in the specific context of prefabricated construction. However, to the best of our knowledge, no review study has focused on the role of digital technologies in improving crane safety. Therefore, this study attempts to uncover the recent research achievements and fulfill three specific objectives:

(1) To revisit the research trend of digital technologies in the crane safety setting;
(2) To synthesize the functions and performance of digital technologies in crane safety;
(3) To propose a comprehensive framework that guides crane safety practices and highlights future research directions.

The following section briefly describes the general crane operations in construction and the necessity of crane safety management. Then, Section 2 elaborates on the overall literature review process and strategy. Sections 3 and 4 present the quantitative and qualitative analysis of the existing literature, respectively. Section 5 proposes a comprehensive framework of digital technology-enabled crane safety. Section 6 discusses the research deficiencies and suggests possible research directions. Conclusions are drawn in the last section.

1. Crane operation and safety management

Two main categories of cranes are commonly used in the construction industry, namely, static cranes and mobile cranes. Static cranes are fixed to the ground or building structure, while mobile cranes are mounted on treads or wheels that can move within a construction site or between sites.

The tower crane is a typical static crane with an inverted L-shaped structure. In the vertical direction, the base of the tower crane supports the entire structure, and the mast provides the tower crane with its working height. In the horizontal direction, the jib extends perpendicular to the mast and supports the trolley and hook for load lifting. The mobile crane is generally comprised of a truss or telescopic boom mounted on a truck or mobile platform. The boom can rotate up to 360 degrees and extend to varying lengths depending on the crane's type and size.

Regardless of their categories, cranes are potentially dangerous equipment in construction. Many scholars, such as Tam and Fung (2011) and Raviv et al. (2017), have identified crane overturning and people being struck by moving payloads as the primary reasons for crane accidents. Other dangerous situations include hook overheight and unbalanced hoisting, particularly when lifting heavy loads. To ensure safe crane operations, built-in safety devices are recommended. For instance, the hook height limit will force the hoist drum to stop whenever the hook reaches a predetermined maximum height, and the overload limit switch will cause the hoist drum to stop when the load being hoisted exceeds the predetermined maximum load or the overturning moment exceeds the maximum load moment. Likewise, a trolley travel limit switch will stop the trolley motion when the trolley reaches the maximum out or maximum in position.

The above-mentioned safety devices help to reduce overturning possibilities in normal crane operations. However, external disturbances such as wind or uncertainties can also interrupt crane safety (Ramli et al., 2017). When loads are lifted off the ground, crane operators must be aware of different types of disturbances before determining whether they should slow down or pause operations. This might generate a heavy mental workload on the operators if they need to visually check each piece of disturbance (Li et al., 2013b). Thanks to advanced digital technologies, data about crane operations and the surrounding machinery, buildings, or workers at heights can be captured and analyzed promptly to facilitate safe crane operations.

The literature focusing on the safety management of crane operations adopted different technologies and generated various solutions. Depending on the particular safety issues, research achievements vary regarding the type of data (e.g., image, text, number) being captured and the way the captured data being processed. Additionally, integrated information platforms such as Building Information Modeling (BIM) provide a powerful tool to digitize and simulate the construction process. Enriched by the near real-time data, the model can be continuously updated to reflect ongoing crane operations and interact with crane operators through virtual reality (VR) and augmented reality (AR) tools. Such a connection loop between the physical crane operations and the mirrored digital model has been widely reported to outperform conventional manual monitoring (Liu et al., 2018). In this study, we will systematically analyze these research achievements and identify research gaps for future investigations.

2. Research methods

To fulfill the research objectives, a mixed-methods approach was employed, combining a quantitative review and a qualitative analysis (as illustrated in Figure 1). The Web of Science (WoS) and Scopus databases were selected for the literature search, as they provide comprehensive coverage of academic literature in the fields of construction and civil engineering (Minhas & Potdar, 2020). The search was conducted using a set of keywords, including terms such as "Crane" AND "safety" AND "digital technolog*" OR "sensor" OR "sensing device" OR "camera" OR "RFID" OR "UWB" OR "laser scan*" OR "GPS" OR

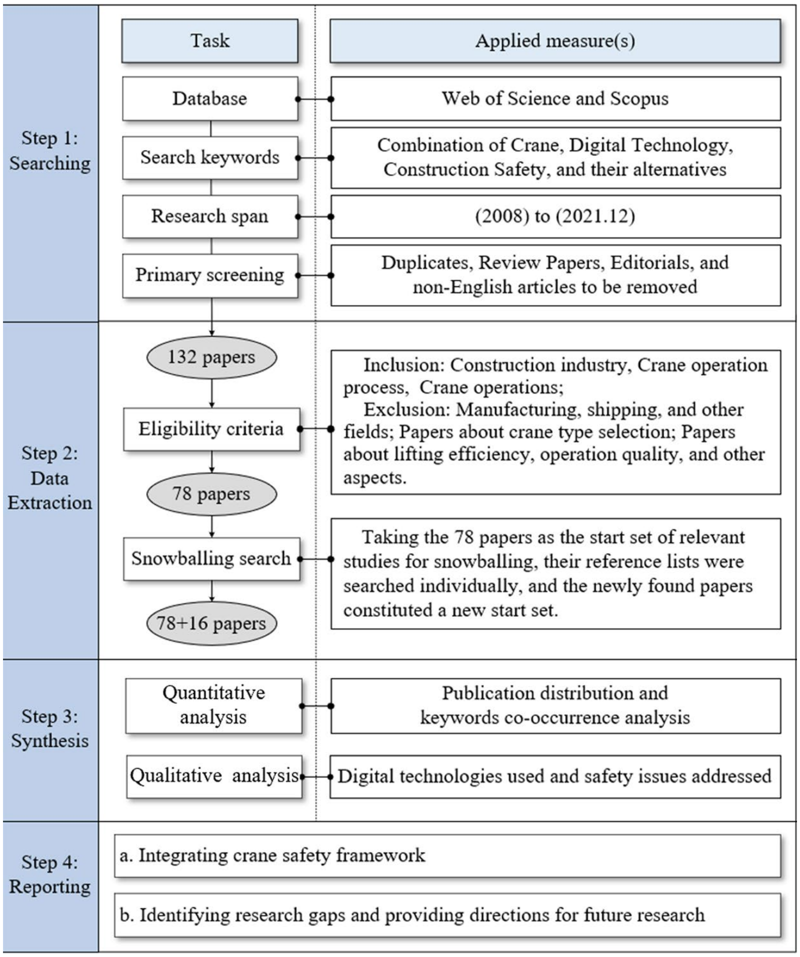

Figure 1. Flowchart of the literature review

“UAV” OR “IOT” OR “robot*” OR “artificial intelligence” OR “machine learning” OR “deep learning” OR “computer vision” OR “virtual” OR “video” OR “image” OR “BIM” OR “building information model*” OR “VR” OR “AR”. Only papers published in peer-review journals are considered since they are generally more rigorous than other types of literature, and the language of the paper is limited to English. The initial search identified that the first relevant article was published in 2008, and therefore, papers published between 2008 and December 2021 were included in this review.

The exhaustive literature search was conducted between 2 and 16 June 2022, and yielded a total of 132 papers. However, the screening of the title and abstract of these papers identified many irrelevant items. Therefore, three criteria were used to filter the literature further: 1) the use of cranes must be limited to the construction industry, not manufacturing, shipping, and other fields; 2) the research should focus on crane operation, and papers about crane type selection were not included; 3) the research target should be safety issues of crane operations, and papers about lifting efficiency, operation quality, and other irrelevant aspects were excluded. The filtering process obtained 78 papers, and then the backward snowballing search strategy was employed to identify studies missed from the keyword search (Wohlin, 2014). Taking the 78 papers as the initial set of relevant studies for backward snowballing, their reference lists were searched individually, and the newly found papers constituted a new start set. This cyclic process was iterated until no new papers were found. Thanks to this search strategy, 16 new papers were found, and the total number of eligible papers became 94.

For the quantitative analysis, a literature analysis tool named VOSviewer was used to analyze the distribution of publications and map the co-occurrence of keywords, providing an overview of the research progress. For the qualitative analysis, particular attention was given to how digital technologies have been used to enhance crane safety. The coded data were double-checked by another author to reduce potential bias.

3. Findings of quantitative analysis

3.1. Publication distribution by year

According to Figure 2, the distribution of published papers fluctuates from 2008 to 2021. Notably, the year 2021 saw the highest number of relevant papers published, with a total of 19 papers. The average number of publications across the time span is 6.71. This finding echoes Sadeghi

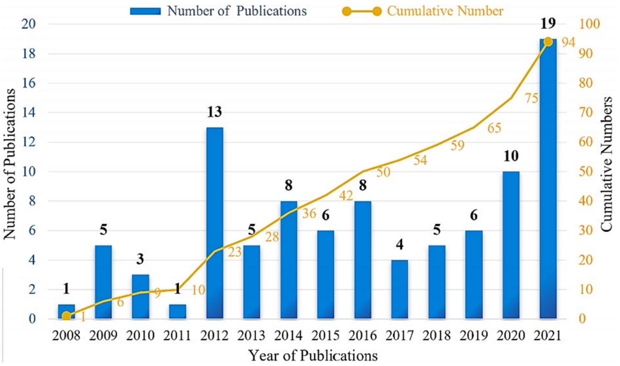

Figure 2. Publication distribution by year

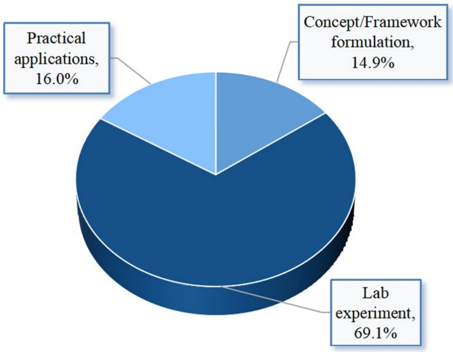

Figure 3. Publication distribution by solution readiness

et al. (2021) that crane safety in construction has received increasing attention from researchers. This also supports the idea that digital technologies have great potential in improving safety management in construction. Therefore, investigating different digital technologies to address crane safety issues is still an important topic for future research.

3.2. Publication distribution by journal

The searched papers come from 27 journals, and Table 1 shows the top five journals in terms of the number of publications. These journals published a total of 68 papers, accounting for 72% of the searched literature. Among them, *Automation in Construction* contributed to over one-third of the searched literature. The following positions are taken by *Journal of Computing in Civil Engineering* (15 papers) and *Journal of Construction Engineering and Management* (8 papers). The remaining journals contain relatively fewer publications, with each publishing only 1–3 relevant papers.

Table 1. Publication distribution by journal

Journal	Number of papers	Percentage
Automation in Construction	34	36%
Journal of Computing in Civil Engineering	15	16%
Journal of Construction Engineering and Management	8	9%
Advanced Engineering Informatics	7	7%
Sensors	4	4%

3.3. Publication distribution by solution readiness

The reviewed studies propose various solutions to crane safety, ranging from concept/framework formulation to real-world demonstration. As shown in Figure 3, 14.9% of the papers focused on concept or framework formulation, while only 16.0% of the studies validated their proposed prototypes through in-situ testing in actual projects. These findings suggest that the overall solution readiness is not yet mature for practical applications.

3.4. Keywords co-occurrence analysis

Keyword co-occurrence analysis can help to build up the knowledge domain of a particular research field by mapping the keywords occurrence patterns and interrelations (Eck & Waltman, 2014). Before analysis, keywords carrying the same connotation were merged (e.g., crane and cranes). Then, the keyword co-occurrence map was constructed in VOSViewer, where the minimum number of occurrences was set to 3 to generate a clearer presentation. As shown in Figure 4, one node represents a keyword, and its size denotes the occurrence frequency of that keyword appearing in all publications. The arcs illustrate the co-occurrence relationship between the keywords, and the line thickness denotes the strength of each relationship. The analysis of the keywords co-occurrence map can lead to the following findings.

First, the general term "crane" appears more frequently than specific types of cranes such as tower cranes and mobile cranes, indicating that most of the existing literature aims to develop general solutions to enable safe crane operations regardless of the crane type. However, given that different types of cranes have unique structures, operation mechanisms, and working environments that can lead to diverse safety risks, some studies have developed tailored solutions to meet the safety requirements of different types of cranes.

Second, Table 2 shows the most frequently co-occurring technology keywords with "crane", "mobile crane", and "tower crane", respectively. "Simulation" has a strong correlation with all types of cranes, and "Sensor", "BIM", and "3D modeling/visualization" also widely appear in crane safety research. In addition, the closer the color of the node to yellow, the later the year in which the keyword appears. Such a presentation in Figure 4 indicates that crane safety research in recent years is increasingly combined with more advanced technologies and methods such as "AI", "digital twin", "deep learning", "CNN", "computer vision", and "Cyber-physical System (CPS)".

Finally, Table 3 shows the most frequently co-occurring safety management keywords with "crane", "tower crane", and "mobile crane", respectively. "Path planning" (19 occurrences), "Collision-free" (10 occurrences), and

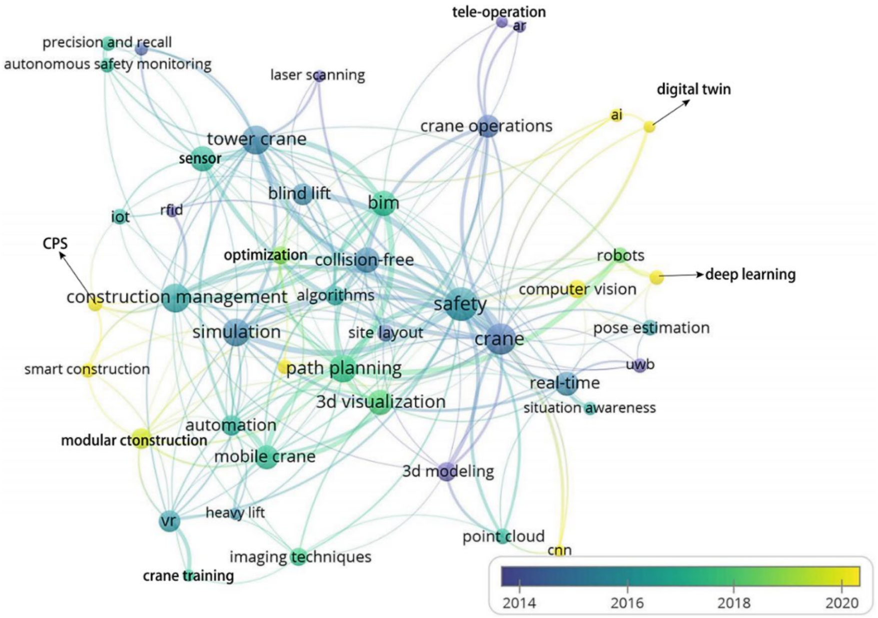

Figure 4. Keywords co-occurrence map

Table 2. Top five technology keywords

Item1	Item2	Link strength	Item1	Item2	Link strength	Item1	Item2	Link strength
Crane	Simulation	1.67	Tower crane	Sensor	1.75	Mobile crane	Automation	1.70
	Sensor	1.53		BIM	1.67		3D visualization	1.58
	Point cloud	1.08		Simulation	1.27		Simulation	0.45
	3D modeling	0.92		Automation	1.00		VR	0.25
	Imaging techniques	0.58		Algorithms	0.83		BIM	0.20

Table 3. Top three safety management keywords

Item1	Item2	Link strength	Item1	Item2	Link strength	Item1	Item2	Link strength
Crane	Path planning	1.20	Tower crane	Collision-free	1.00	Mobile crane	Path planning	1.78
	Blind lift	0.70		Path planning	0.33		Heavy lift	1.00
	Collision-free	0.33		Blind lift	0.33		Collision-free	0.67

“Blind lift” (8 occurrences) were the main issues repeated in the related research. Moreover, the “Heavy lift” of mobile cranes is also an important safety issue that receives research attention.

4. Findings of qualitative analysis

In addition to the quantitative analysis, the systematic review of selected papers attempts to provide an in-depth insight into the digital technologies used for crane safety management.

4.1. Data acquisition

Effective data acquisition is crucial for ensuring crane safety. This helps both the safety manager and crane operator to be aware of the real-time status of the crane structure, lifting operations, nearby workers, and environment. Different data acquisition technologies are adopted in the reviewed studies, depending on the type of data to be captured. These technologies help to automatically capture the required data throughout the crane operations, providing the basis for sequential safety monitoring and control (see Table 4).

4.1.1. Sensor

One of the most flexible data acquisition technologies is sensors. Sensors can be divided into different types based on their sensing principles, such as angle, vibration, and temperature. Nearly 20% of the reviewed studies used sensors for data collection. For instance, Zhong et al. (2014) used a group of sensors to obtain real-time status information of individual tower cranes, including the horizontal and vertical displacement sensors for the trolley, the angle sensor for the crane arm, and the load and tilt sensors. Fang et al. (2018) adopted wired rotary encoder sensors and wireless inertial measurement units (IMUs)

Table 4. Data acquisition techniques for crane safety

Technologies	Applications	Examples
Sensor	Acquire mechanical attitude and component status data	Lai et al. (2021), Wang et al. (2021), Fang et al. (2018)
	Acquire environment information (e.g., wind speed, noise, humidity, temperature)	Liu et al. (2021), Niu et al. (2019), Zhong et al. (2014)
	Acquire locations of workers	Jiang et al. (2021a, 2021b), Luo et al. (2015)
Camera	Monitor hoisting behaviors	Zhou et al. (2019), Chen and Luo (2019), Chen et al. (2017)
	Monitor dynamic resources around the crane on the ground level	Yang et al. (2019), Ray and Teizer (2012), Shapira et al. (2008)
	Acquire locations of workers	Price et al. (2021), Yang et al. (2019)
	Acquire mechanical attitude and component status data	Yang et al. (2014)
AutoID	Acquire locations of workers and cranes	Kim and Kim (2012), Chae and Yoshida (2010), Cho et al. (2010)
	Monitor hoisted objects (prefabricated building component)	Liu et al. (2021)
UWB	Acquire locations of worker, crane and other equipment	Hwang (2012)
	Acquire mechanical attitude and component status data	Zhang et al. (2012), Zhang and Hammad (2012b)
Laser scanning	Monitor dynamic resources around the crane on the ground level	Jeong et al. (2019), Zhou et al. (2019), Wang and Cho (2015)
	Monitor hoisted objects (cutting wheel)	Zhou et al. (2019)
	Measure construction site conditions and geometry	Cheng and Teizer (2014)
GPS	Acquire locations of worker, crane and other equipment	Zhou et al. (2019), Chen and Luo (2019), Wu et al. (2017)
UAV	Monitor the geological environment of construction site	Tian et al. (2021)
	Monitor hoisting behaviors	Gheisari and Esmaeili (2019)
Ultrasonic positioning	Monitor hoisted objects	Zhou et al. (2019)

to measure the critical motion of the crane module (e.g., boom lifting angle, boom extension length, boom turning angle, and load swing). Additionally, Luo et al. (2015) used location-aware sensors to collect the dynamic positions of workers, which improved the situational awareness of crane operators. Considering that crane operations could also be affected by the changing environment, Niu et al. (2019) and Liu et al. (2021) utilized environmental sensors, such as wind speed, temperature, and humidity sensors, to capture conditions of the site environment. Real-time data on site elements acquired by sensors is a prerequisite for implementing proactive safety management, helping staff to be aware of the edge of danger in time.

4.1.2. Camera

Camera is also widely used for acquiring spatiotemporal data of the surrounding environment. Its advantages are cost effectiveness and high-resolution data (Price et al., 2021). During crane operations, cameras can help gather images about the state of lifting object (Chen & Luo, 2019), workers (Yang et al., 2019), and environment (Ray & Teizer, 2012), allowing site managers and crane operators to directly see the lifting process. Chen et al. (2017) mounted an overhead wide-angle camera on a crane boom and used kernel-based visual tracking on lifting objects. Their approach can continuously monitor the location and clearance between objects to automatically warn the operator when a potential conflict is detected. The retrieved information, together with the site plans, help to identify the activity state of the crane without frequent manual review, especially with the current rapid development of computer vision algorithms (Yang et al., 2014). However, finding the ideal place to put the camera remains a challenging task because flat panels, built-in walls, and other objects can obscure the camera's vision, making it difficult to continuously watch the target.

4.1.3. AutoID

AutoID, a technique for automatic detection and identification, is also adopted for data acquisition. Among all the AutoID devices, RFID has emerged as the most promising one, providing a convenient and efficient way to identify, record, and track objects on construction sites. In the reviewed studies, RFID is adopted to trace the locations of workers, equipment, and materials. For instance, Chae and Yoshida (2010) attached the RFID tag to the worker and mobile crane that should report their working areas. The tag periodically emitted an identification signal, which if captured by the readers would indicate unauthorized access to high-risk areas. Once attached to the worker's safety helmet, the RFID tag made the helmet identifiable and could be monitored by readers installed on the crane.

The distances between tags and readers were estimated using the signal strength (Kim & Kim, 2012). In this way, problems that construction workers and equipment are in too close proximity can be prevented. However, this method requires a new piece of hardware to be installed for each desired tracking point, and the signal is susceptible to electromagnetic interference, fading, and scattering, which is exacerbated by metallic materials commonly found in construction environments (Cho et al., 2010).

4.1.4. UWB

UWB, a technique for transmitting data over a large bandwidth, has been used in tracking and locationing. Although only four reviewed studies used UWB in crane safety, this technique showed notable benefits in collision prevention. For example, Hwang's (2012) study showed that the incorporated UWB technology was effectively implemented to accurately track the positions of cranes over time and to assess potential collisions in real-time. In the study by Zhang et al. (2012), the agent can reprogramme the crane's path to avoid collisions by using information on crane attitude collected in nearly real-time using ultra-wideband technology. Furthermore, the UWB can also help different teams working together on site to make more reliable decisions. In the study of Zhang and Hammad (2012b), the UWB was used to collect the location and pose of moving equipment and sent such information to crane riggers, based on which, real-time collision avoidance can be achieved by providing awareness of the site situation through communication between multiple riggers. While there is a technical similarity between UWB and RFID, UWB has unique features that are superior to those of RFID: it can transmit more data with less interference than RFID; it has a wider range of coverage and higher response rate; it can provide a more accurate position measurement in metallic and densely packed environments.

4.1.5. Laser scanning

Laser scanning techniques were used in three reviewed studies to capture precise data on the real-world scene. The techniques rely on the laser ranging principles that send a number of laser beams to the object to be measured, receive the reflected signal, and calculate the 3D coordinates of the point on the surface of the target object. The crane operator's poor visibility is one of the biggest hazards when using a crane. In order to aid crane operators in understanding the actual environment of a dynamic building site, Cheng and Teizer (2014) employed a laser scanner to acquire a point cloud of the site and transform the point cloud into a 3D model. Field tests revealed that tower operators might greatly improve present dangerous operations by employing the established approach to better understand the whereabouts and timing of occluded spaces and ground operations. Apart from the overall site conditions, the laser scanner showed great potential in measuring crane movements. Zhou et al. (2019) designed a laser-ranging device to measure the distance between the bottom of the hoisted object and the ground in real-time, thus assisting the operation of the tower crane during the blind lift. Laser scanning provides high dense point cloud data that can benefit rapid and large-scale topographic mapping, especially for large construction sites. However, the filtering and segmenting laser-scanned data is currently a complex and time-consuming task, which has to some extent hindered its large-scale usages in construction.

4.1.6. Other techniques

Since one single type of data can be captured by different techniques, other data acquisition techniques have also been utilized in the reviewed studies. For instance, Wu et al. (2017) used GPS to address deficiencies of closed-circuit television system (CCTV)-based crane monitoring approaches, including the confined vision field and short detection distance. Their proposed method integrated GPS data and an artificial immune algorithm to optimize the transit route for collision prevention. Zhou et al. (2019) adopted an ultrasonic positioning device to improve the detection accuracy and positioning efficiency of moving hoisted objects, especially with varying distances between the moving objects and existing structures. However, the use of GPS or ultrasonic devices alone cannot inspect the changes to guide the crane operations. Therefore, Tian et al. (2021) took advantages of UAVs to collect visual data for a large-scale construction site and inform crane operations about potential collisions. Acknowledging more advanced data acquisition techniques can help to obtain more accurate data regarding the entire crane operations and the associated objects, the selection of appropriate techniques should consider factors such as cost, speed, and ease of use.

4.2. Communication networks

Communication networks provide channels for three main purposes: (1) the passage of data captured on-site, (2) the feedback of control instructions, and (3) the communication among different actors (e.g., crane operator, signaler, rigger, and manager). Both wired and wireless networks were adopted by the reviewed studies. Wired networking is generally cheaper and more secure than wireless networking but faces difficulties in cable installation and maintenance. In contrast, wireless networks mediate problems with distance and other physical limitations. On the basis of uniformly defined data interface protocols and middleware technologies, portable and fast channels can be formed to support timely information sharing.

Out of the 94 reviewed papers, eleven mentioned the specific networks used, and ad hoc wireless networking was the most used. They comprise numerous wireless sensors and communication systems, such as Wi-Fi, ZigBee, and Bluetooth (ElNimr et al., 2016; Gheisari & Esmaeili, 2019). The sensor node transmits the collected data to the sink node (the destination of all data in the network) through the self-organizing network between nodes (Liu et al., 2021). In the tower crane safety management system proposed by Zhong et al. (2014), the Tower Crane Safety Terminal Equipment (TC-STE) installed in the operator cab can communicate with the local monitoring terminal (LMT) at the ground worksite through the ZigBee wireless network. However, ZigBee has a short range and low network stability. Therefore, Jiang et al. (2021b) used Bluetooth and WiFi to transmit the real-time position of workers and cranes to the back-end system for data processing to control safety risks in time. However, the information received from the camera in wireless communication of tower crane is limited due to the low bandwidth. Therefore, Li and Liu (2012) designed a data transmission system based on intelligent controller local area network (CAN) bus conforming to IEEE 1451.2 standard, which effectively improves the flexibility and quantity of information acquisition. Similar to the data acquisition techniques, the selection of transmission and communication networks should consider the network performance, and in the meantime, the cost and easy-to-use factors.

4.3. Data analysis

The analysis of data involves using various algorithms to transform it into useful information, which facilitates precise decisions made by crane operators and safety managers. Table 5 presents the detailed applications supported by various data analysis technologies.

4.3.1. Crane layout and path planning

Conventionally, crane layout and lift planning are based on practical experience and expertise. However, such an approach may lead to low efficiency and a high accident rate due to the complex site situations. Hence, researchers have developed crane layout and path planning approaches to guide on-site operations. Field data collected by sensing devices and manually input variables, such as the weight of the lifting load and the loading capacity of the crane, are primarily used to identify the optimal plan through mathematical models and simulation methods. The Rapidly-exploring Random Tree algorithm is a popular path planning technique that uses sampled field data

Table 5. Data analysis techniques for crane safety

Analytical applications	Technical details	Examples
Crane layout and path planning	Use rapidly exploring Random Trees (RRTs) algorithm to ensure safety during the execution stage by lift path planning	Hu et al. (2021), Zhou et al. (2021b), Lin et al. (2016), Huang et al. (2021), Zhang and Hammad (2012a)
	Use simulation models to reduce collisions in crane operations	Khodabandelu et al. (2020), Younes and Marzouk (2018), Al Hattab et al. (2017)
	Use optimization algorithms to automatically generate the layout plan	Ji and Leite (2018), Wang et al. (2015), Marzouk and Hisham (2013)
Crane motion and load analysis	Use specific algorithms to process field perception data and monitor the real-time crane motions	Jeong et al. (2019), Ren and Wu (2015), Yang et al. (2014)
	Visualization of crane movements through parametric simulation in a virtual environment to identify and assess operational risks	Lin et al. (2012)
	Calculate load balance using field data to reduce crane oscillation vibration	Gutierrez et al. (2021), Smoczek (2014)
	Development of an automated system to calculate support reaction forces in real time	Hasan et al. (2010)
	Automatically estimate crane poses and hoisting motions from field images using computer vision techniques	Li et al. (2020), Luo et al. (2020)
	Use 3D visualization and algorithms to analyze crane motions to prevent collisions	Han et al. (2015, 2016)
	Develop a robotic tower crane system using laser devices, encoders and accelerometers	Lee et al. (2009)
Object recognition and proximity evaluation	Automatic monitoring of construction site personnel or objects by using computer vision/machine learning techniques	Zhou et al. (2021a), Xu and Wang (2020)
	Process images to obtain pixel coordinates of workers and hazardous areas and measure their distances	Yang et al. (2019)
Scene reconstruction	Transform point cloud data into 3D models to visualize the site environment	Chen et al. (2017), Fang et al. (2016), Wang and Cho (2015)
	Segment point cloud data of crane and environmental background to avoid collisions	Jeong et al. (2019)
	Locate and quantify the blind spots/areas based on 3D range data	Cheng and Teizer (2014)

to find a collision-free path from the starting state to the target state (Zhang & Hammad, 2012a; Lin et al., 2016; Hu et al., 2021; Zhou et al., 2021b). Huang et al. (2021) employed the Mixed Integer Linear Programming model to further provide an optimal solution to the scheduling problem of multiple cranes. The test results show that the method effectively avoids collisions caused by concurrent crane operations by optimizing the position and movement of the crane in the overlapping area. Younes and Marzouk (2018) used an agent-based simulation method to simulate tower crane operations and interactions between different agents. This method was able to compare between several combinations of tower crane layouts to achieve the optimum solution that fulfills the time and cost requirements. The integration of simulation with optimization algorithms can effectively achieve the automatic generation of the optimal crane layout scheme (Marzouk & Hisham, 2013; Wang et al., 2015; Ji & Leite, 2018).

4.3.2. Crane motion and load analysis

Crane motion and load analysis play a critical role in recognizing potential risks associated with crane operations. Han et al. (2015) built a 3D visualization for the crane motions, which can help to maintain sufficient clearance between existing obstacles and the crane body configuration to prevent potential collisions. Apart from the collision, the sway of crane loads also requires attention since they could cause payload damage or crane overturning. Smoczek (2014) presented a fuzzy logic-based robust feedback anti-sway control system. The results of experiments proved that the fuzzy logic-based approach can ensure robustness of closed-loop system performances within the expected range of parameter variations.

The constant load analysis provides essential support to automate several crane operations. Lee et al. (2009) demonstrated the feasibility of a laser-based lifting-path tracking system for a robotic tower-crane system under various outdoor conditions. Hasan et al. (2010) created an automatic crane lift analysis system that displayed the support force of each outrigger at different horizontal swing angles and vertical boom angles. Additionally, Li et al. (2020) developed an intelligent hoisting system involving the application of robotic cars and vision-based recognition. In their designed system, electric hooks were maneuvered by a robotic car, and a visual recognition system was used to guide the robotic motion. More than 30 trials proved that the system had a success rate of approximately 92.5% for hook grappling hoist points.

4.3.3. Object recognition and proximity evaluation

Conventional manual evaluation is commonly used to recognize objects on site, which requires the crane operator or signaler to observe the surroundings with the naked eye and is therefore accused of being time-consuming and error-prone (Everett & Slocum, 1993). Computer vision techniques offer new solutions to this problem by acquiring a high level of understanding from digital images or videos. For example, Zhou et al. (2021a) developed an image-based real-time recognition approach for lifting objects, and their approach consisted of Faster R-CNN-based object detection, Canny, Hough transformation, Endpoint Clustering Analysis, and Vertex-based Determining Model. Experimental results show that the lifting component can be efficiently detected with a bounding box from the complicated background on the 2D image, achieving an accuracy of 99.2%. Apart from object recognition, measuring the distance between workers and dangerous objects or areas for safety warning is necessary. Yang et al. (2019) used RGB color extraction to obtain the pixel coordinates of workers and danger zones in the image and compared their distance with a predefined safe value. The entire process from image recognition to distance conversion can be completed in less than 2 s. The developed system enabled automatic collection, analysis and safety early-warning without affecting the normal behavior of workers. It is worth noting that these studies typically used self-created datasets rather than well-established public datasets for model training to accurately identify specific objects involved in the crane operation scenarios.

4.3.4. Scene reconstruction

The efficiency of crane lifting and maneuverability depends on the geometric constraints in the surrounding environment. However, traditional lift planning approaches have a major limitation due to the lack of information that can inform the current site condition. The reviewed studies showed advances in rapid data acquisition and real-time spatial feedback with less manual effort (Price et al., 2021). The point cloud is a popular type of data collection that provides a set of points containing coordinate data (XYZ) and color data (RGB) of objects in the captured scene. In Wang and Cho (2015), the target's point cloud data were converted into a 3D surface model in less than 0.5 s using the concave hull surface modeling algorithm after data filtering and downsizing, and the generated digital model helped the crane operator to rapidly perceive the jobsite environment. Similarly, Cheng and Teizer (2014) presented an algorithm to identify blind spots from point cloud data and integrated the tracking data of construction resources into a blind-spot map to avoid struck-by-object accidents. Moreover, Fang et al. (2016) converted site point cloud data into bounding box objects to represent site obstructions that can be visualized with the adjustment of surface transparency level. Test results indicate that the prototype system was able to reconstruct crane motions with an average error of 0.43 m for load positioning in X-Y plane. These recognized obstructions represent possible collisions that can be addressed using real-time proactive warning and alert algorithms (Lai & Kang, 2009; Teizer et al., 2010; Wang et al., 2021).

4.4. Visualization and reaction

Once the captured data is converted into valuable information, visualization provides crane operators and safety managers with intuitive information to support their reactions. Early research efforts used vision systems to present information directly to crane operators or safety managers. With the development of digital modeling, Building Information Modeling (BIM) dominated the information visualization strategy, and other vision-aid techniques, such as Virtual Reality (VR) and Augmented Reality (AR), were also used to enhance the operator's spatial perception of the workspace (Wang & Cho, 2015). Table 6 shows a summary of these technologies with detailed applications and typical references.

4.4.1. Vision system

Crane operators usually have a limited visual field when sitting in the operator cab, which can result in accidents caused by poor visibility. To address this issue, Shapira et al. (2008) installed a live video system on top of the crane to provide crane operators with a bird's eye view of the surrounding environment during lifting operations. Furthermore, Fang and Cho (2016) developed a user interface (UI) that can enhance the operation and decision-making processes involved in crane activities. The UI includes three main views of the virtually reconstructed lift scene, which enable the operator to understand the elevation and position of lifting objects with fewer occlusions. A voice control panel was also integrated into the UI to minimize operator distraction during lifting tasks.

4.4.2. BIM

Building information modeling (BIM) is a digital representation of the physical and functional characteristics of a project, providing a reliable basis for decision-making (Chen et al., 2015). BIM can integrate specific information related to the construction site (e.g., site boundaries, site location, environment, and sizes of temporary facilities), crane information (e.g., the number of cranes, types of cranes, configurations of cranes, crane movements), and task information (e.g., weight, dimensions, pick position), which facilitates efficient coordination of construction operations and accommodation of temporary facilities.

In the reviewed studies, BIM has been adopted to carry out spatiotemporal analyses of the construction site, including the occupied spaces and interaction between temporary resources. Marzouk and Abubakr (2016) developed a BIM-based simulation model that applied several clash detection scenarios (e.g., collisions between the crane jibs, between the tower crane and the building structure, and between different cranes during lifting operations) to assure safe operations of multiple tower cranes. Dutta et al. (2020) developed an animation system that illustrated various motions of cranes with different types, which can streamline path planning through visual demonstration. Tak et al. (2021) also developed an integrated 4D crane simulation and operation management framework that provides functions of BIM-based multi-crane lift animation, clash detection, spatiotemporal analyses, and real-time visual assistance. Moreover, BIM can integrate various information sources and applications, such as safety monitoring and code validation, in a single environment. In Li and Liu's (2012) study, rich kinematic information was embodied into a 3D model of the crane built with CATIA and 3DMAX, which can precisely express the alarming of activities.

4.4.3. VR

Virtual reality (VR) is a computer-simulated environment that enables users to have a realistic experience by interacting with a realistically portrayed computer-simulated world (Zheng et al., 1998). To acquire the skill set required to operate cranes, hands-on operations and coaching have long been emphasized, but real-world practices can

Table 6. Visualization and reaction techniques for crane safety

Technologies	Applications	Examples
Vision system	Increase the operators' visibility of the load during loading and unloading	Shapira et al. (2008)
BIM	Develop collision simulation model to enhance safety awareness	Shahnavaz et al. (2020), Lee et al. (2012), Marzouk and Abubakr (2016)
	Assist crane layout and motion planning by model-based animation	Han et al. (2021), Tian et al. (2021), Dutta et al. (2020)
	Integrate multi-source information to achieve multiple functions such as crane lift animation, collision detection, spatio-temporal analysis, etc.	Liu et al. (2021), Tak et al. (2021), Li and Liu (2012)
VR	Develop VR training system that allows workers to learn crane installation, lifting, and dismantling processes in a virtual environment	Song et al. (2021), Li et al. (2013a), Rezazadeh et al. (2011)
	Allow realistic simulation of operation features in order to understand hazard issues	Juang et al. (2013)
	Provide evaluations of operation safety and practicability to workers	Pooladvand et al. (2021)
AR	Align digital information with real-world surroundings to support the teleoperation of cranes	Chen et al. (2016), Chi et al. (2012)

be expensive and hazardous. In contrast, VR can act as a promising substitute for hands-on practice, as it presents a realistic experience of crane operations while reducing possible costs and hazards.

In the reviewed studies, VR simulations have been implemented for safety training in crane operations. For example, Rezazadeh et al. (2011) developed a virtual crane training system to simulate the lifting of goods at a construction site. The concept of affective computing was also incorporated into the training platform, allowing the training interface to adapt to the user's affective state during performance in real time to improve training effectiveness. Juang et al. (2013) developed a crane simulator and integrated kinesthetic and stereoscopic visions into the simulator to enable realistic simulation for depth perception. Later, Song et al. (2021) invented a head-mounted VR display to make the simulation more applicable to reality, which can save training costs and enhance training outcomes. Pooladvand et al. (2021) presented an interactive system developed in VR, which can timely evaluate the lift operation quantitatively in terms of safety and practicability.

4.4.4. AR

AR is a technology that offers a cyber-physical interactive experience by superimposing digital objects into the real-world scene (Azuma, 1997). Unlike VR which only shows digital information, AR aligns digital information with real-world surroundings to enhance people's perception of information. Although only two of the reviewed studies attempted to use AR to improve crane safety, they have shown obvious benefits in supporting the teleoperation of cranes to keep the operators away from hazardous operational environments. AR can be used to attach virtual information, mainly in the form of computer-generated graphics, to real scenes such that the remote operator's visual sense can be augmented by the additional information. As a result, Chi et al. (2012) and Chen et al. (2016) focused on the UI design of an AR-enabled teleoperated crane, and their experiment results indicate that AR can assist the operators in remote crane control in a more efficient way with much less mental load.

5. An integrated crane safety framework

Through the review of 94 relevant papers, we found that significant achievements have been made in digital technology-enabled crane safety in construction. The research efforts were gradually transferred from being in a piecemeal fashion to developing an integrated solution. Fang et al. (2018) developed a comprehensive framework for real-time proactive safety assistance. Jiang et al. (2021b) further proposed a system based on the concept of cyber-physical system, which enabled effective crane safety management through data acquisition, processing, and visualization. However, considering the dynamically changing environment and the complex interactions among different objects throughout crane operations, multiple technologies should be fused into a hybrid system to comprehensively address crane safety issues. Therefore, this study proposes a framework for comprehensive crane safety management (see Figure 5).

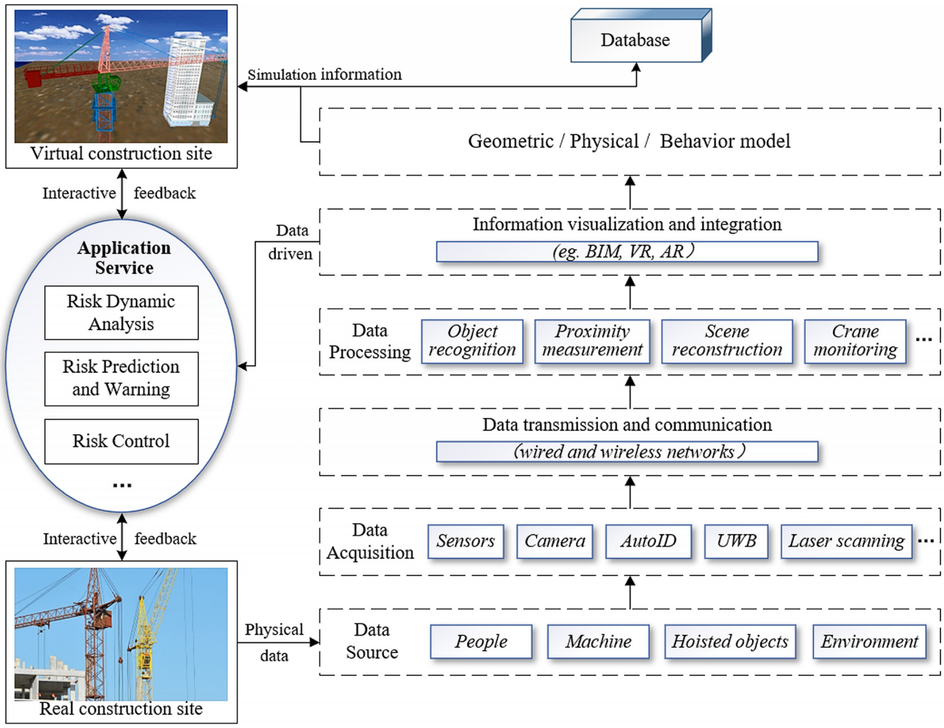

Figure 5. Framework for comprehensive crane safety management

5.1. Overall framework

The framework presented in this study aims to establish a seamless connection between the physical construction site and the virtual model through data acquisition, communication networks, data processing, visualization, and reaction modules. The closed-loop flow of data, which includes people, machinery, hoisted objects, and the environment, is utilized to activate safe crane operation and management decisions. The data acquisition layer is composed of objects involved in crane operations, and their behaviors and conditions, whether immobile or mobile, can significantly affect crane safety. Therefore, various data acquisition technologies should be used together to capture the required information in real-time. A two-way data synchronous transmission channel between the physical space and the virtual space should be established based on high-speed and low-delay data transmission protocols. The processed data is then transmitted to the backend system, and BIM is utilized to integrate multi-source heterogeneous information and enable real-time information interactions. In the virtual environment, dynamic modeling and simulation of safety risks are performed, followed by the development of safety analysis and warning applications. Control mechanisms are also designed to ensure automatic braking in case of emergency.

5.2. Illustrative scenario

To further illustrate how the framework works, a prefabricated component hoisting scenario is presented. The hoisting process is prone to several safety accidents, such as crane collapse, mechanical collision, or falling objects. Therefore, the crane operation and environmental changes are monitored through three collection terminals, including (1) sensors for recording the mechanical status of the crane and site environmental information (including wind speed, etc.); (2) smart camera for tracking the locations and behaviors of workers; and (3) AutoID tags for grasping the status of the prefabricated components. A self-organizing Wi-Fi network is used to transmit the data to the processing layer in real-time, enabling crane motion and load monitoring, object identification, proximity measurement, and site reconstruction. The information obtained is fused and visualized using BIM to build a virtual construction site model that enables real-time sensing and virtual-real interaction of multi-source information during the lifting process. The safety analysis and early warning applications developed based on the BIM platform effectively improve the crane safety management process. The real-time dynamic visualization of the crane workspace helps identify potential collision hazards, provides real-time visual aids and feedback for operators, and helps them operate the equipment safely. Mechanical analysis and calculations identify any potential structural failure, load or lifting risks, and an early warning message is generated and sent to the crane operator and safety manager. The continuous monitoring of site conditions supports the automated operation of the crane, and automatic braking can be achieved through the control mechanism. Such an operation process will effectively reduce safety incidents caused by human error.

6. Deficiencies in existing studies and research directions

To apply the proposed crane safety framework in actual practice, deficiencies drawing from existing research should be addressed.

6.1. Expanding data collection

The review presented in this paper discusses various data collection techniques adopted to collect data related to mechanical attitude and component state, worker location, and environment during crane operations. However, this review highlights two main deficiencies that need attention.

Firstly, the accuracy and speed of data collection need improvement, particularly on dynamic construction sites with moving objects (Luo et al., 2015). To address this issue, the deployment of sensors needs enhancement, and better-performing sensors such as multi-view stereo or dynamic laser scanning should be explored. Tailored filtering algorithms can also be developed to reduce noise in the raw data. These approaches can enhance load tracking and collision avoidance while monitoring the moving objects that enter the crane workspace.

Secondly, the types of data collected need to be expanded to enable a comprehensive assessment of risk factors that affect crane safety. While current research has focused on identifying spatial conflicts and blind spots to support managers and crane operators, the physiological state of crane operators should also be considered. This is because fatigue and distraction can negatively impact the identification of hazardous situations. Therefore, wearable sensors and real-time monitoring technologies should be deployed to monitor the physiological state of crane operators (Soltanmohammadlou et al., 2019). The physical and mental health data collected can then be inputted into the crane safety management system to reduce human failures and prevent accidents. Additionally, VR/AR technology can be used to verify the skill level and risk response capabilities of crane operators, authorizing only qualified personnel to operate the crane.

In this direction, it is important to address the following questions:

(1) How can the most suitable sensor (or the combination of different sensors) be selected and deployed to improve data accuracy while reducing deployment costs?

(2) How can digital technologies be effectively used to collect and benchmark the physiological state, skill level, and risk response capabilities of crane operators?

6.2. Improving data processing and information integration

The collected data require different levels of processing before it can be transformed into decision support information. Prior research has emphasized the need to improve data processing approaches. Inefficient data processing and visualization will result in unsatisfactory 3D reconstructions of construction sites from point cloud data and hinder real-time updating of the site model. Furthermore, extracting 2D poses or estimating 3D poses of different machineries by synchronizing the time and coordinate systems of multiple cameras and real-time location systems is time-consuming (Yang et al., 2019). Therefore, the proposed solutions should be further developed to improve their efficiency, for example, by combining them with the stereovision method to reconstruct 3D objects through stereo matching (Juang et al., 2013). Additionally, to measure inter-object distances, computer vision algorithms for 3D ranging need to be developed as translating pixel values taken from 2D images into ground distances is not accurate. However, existing studies have primarily used live images and self-annotation to extract datasets for model training, limiting the dataset size and constraining the model's performance. This issue could be addressed by augmenting standardized open-source datasets.

Previous research has focused on specific crane safety problems that could be resolved by the availability of one or a few types of information. However, for more complex safety issues during dynamic crane operations, integrating information is crucial to generate appropriate safety decisions (Shahnavaz et al., 2020). While BIM-based activity simulation and monitoring have been well-established in the literature, a dynamic crane behavior model must be established by integrating multiple sources of heterogeneous information to create a more accurate safety management system.

In this direction, the following questions need to be addressed:

1. How can the processing efficiency of massive image and point cloud data be improved in crane safety management?
2. How can an effective information integration mechanism be established to achieve a more comprehensive understanding of the lifting process?

6.3. Enhancing safety decision and control

Safety decisions in crane operations are often based on predefined thresholds, such as minimum distances between workers and danger zones. However, these thresholds may not be sufficient to ensure safe operations. Digital twin (DT) technology can be employed to enhance safety decisions by integrating information from both real and virtual spaces. DT enables real-time tracking of crane activities and can predict potential hazards under various scenarios, which can assist in keeping the crane operating in the safest possible condition For instance, it is currently challenging to calculate the impact of combined loads on crane components due to the unpredictable environment (Moi et al., 2020), but DT can compute real-time loads in individual components (e.g., cables, hydraulic cylinders) and combine the mechanical nature of the material to estimate structural failures.

Once accurate state estimation becomes available, future research can explore incorporating autonomous crane control. One of the major hurdles is to transition from the current manual joystick control to digital signal control (Price et al., 2021). Robotic technologies may enable unmanned safety operation of cranes in construction, but a clear definition of safe crane operations is needed (Minay-Hashemi et al., 2020).

In this direction, questions to be addressed include:

1. How can trigger conditions be designed through DT applications to ensure accurate safety decisions?
2. How can robotic technologies be deployed to conduct safe crane operations automatically?

6.4. Strengthening in-situ testing

Insufficient application testing refers to a lack of construction site trials or insufficient testing samples. While the majority of solutions proposed by reviewed studies have passed laboratory experiments, in-situ testing requires more robust solutions that can handle dust, weather conditions, continuous vibration, and other unexpected factors on construction sites. This review identifies a significant gap between academic research and practical applications. Therefore, it is necessary to undertake more testing on actual construction sites to assess the functionalities and capabilities of proposed solutions in real crane operations (Zhang & Hammad, 2012b).

Although some existing studies have conducted in-situ testing, the sample size of operators participating in field tests may not be large enough to demonstrate the statistical significance of the system's performance. Specifically, the limited number of subjects and significant differences in experience and maneuver patterns among them can lead to large variances in measurements (Lee et al., 2012; Gheisari & Esmaeili, 2019). Hence, it is necessary to conduct more in-situ testing and collect larger sample sizes to comprehensively assess crane safety solutions.

Conclusions

The integration of digital technologies to support safe crane operations in construction has been a focus of research for many years. This review study analyzes the research achievements and developmental trajectory from multiple perspectives, including data acquisition, communication networks, data analysis, and visualization and reaction. The study makes significant theoretical contributions by highlighting the various types of sensors used to collect data related to crane components, lifting objects, workers, and other elements involved in crane operations. The study also emphasizes the importance of data processing methods and algorithms to convert raw data into useful information for informed safety management decisions.

Building on the review findings, this study proposes a framework for comprehensive crane safety management. The framework comprises several components, including a physical layer representing the crane operations and data collection techniques, a data transmission layer building a two-way communication channel between the physical space and the virtual space, a data analysis layer that uses various algorithms to process data, and an application layer that provides safety management and control functions.

To materialize this framework in actual practices, the study recommends several future investigations. These include expanding data collection to capture additional aspects of crane operations, improving data processing and information integration, enhancing safety decision and control functions, and strengthening in-situ testing to ensure the reliability of the proposed framework. These recommendations represent important practical contributions that can help advance crane safety management practices in construction. The proposed framework and recommendations can be used by practitioners to ensure safe crane operations, making construction sites safer and more efficient.

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Author contributions

YZ was responsible for Data curation, Visualization, Writing-Original draft preparation. KC was responsible for Conceptualization, Methodology, Writing-Reviewing and Editing, Supervision.

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