ICCEPM 2024 https://dx.doi.org/10.6106/ICCEPM.2024.0431
The 10th International Conference on Construction Engineering and Project Management
Jul. 29-Aug.1, 2024, Sapporo

Technical Requirements for Applying Digital Technologies in Monitoring Unsafe Activities during the Construction Phase

Phuong-Linh LE[1]* and Jacob J. LIN[2]

[1] *Department of Civil Engineering, Construction Engineering and Management Division, National Taiwan of Civil Engineering, Taiwan*, E-mail address: *d12521021@ntu.edu.tw*
[2] *Department of Civil Engineering, Construction Engineering and Management Division, National Taiwan of Civil Engineering, Taiwan, E-mail address: jacoblin@ntu.edu.tw*

Abstract: Monitoring unsafe activities on construction sites is challenging due to a variety of factors including the diversity of tasks and workers involved, the potential of human error and lack of real-time hazard detection. With technological advancements, several digital technologies have been proposed and applied to improve the monitoring process. Despite the potential of these technological advancements to reduce manual effort in traditional monitoring, the challenge lies in selecting and implementing the technology that best meets the specific needs of contractors. This paper aims to streamline the research of digital technologies in the construction domain by achieving three key objectives: (1) classify the types of unsafe activities that can be monitored automatically, (2) determine the specific data required for effective monitoring processes, and (3) identify the technologies that can facilitate such data collection process. We conduct a systematic literature review on cutting-edge technological studies to achieve the research aims. The findings of this research serve as a valuable resource for construction practitioners, offering insights into both the benefits and limitations of digital technologies in enhancing the monitoring process. Moreover, the study recommends preparatory elements that practitioners should undertake to integrate these technologies effectively into their monitoring frameworks. The study empowers practitioners by providing a deep understanding, enabling them to create a comprehensive safety management program aligned with the digital transformation process.

Keywords: safety monitoring, requirements, digital technologies

1. INTRODUCTION

Safety management is an essential aspect of construction project management, comprising three main categories: training, monitoring, and planning [1]. Safety training is a crucial process that aims to equip individuals with the necessary knowledge and skills to maintain a safe working environment. In conjunction with safety training, safety planning is a thoughtful procedure involving anticipating potential risks and the development of strategies to navigate potentially hazardous situations [2]. Despite the positive impact of safety training and planning in making workers aware of unsafe conditions and minimizing potential hazards during planning, the construction industry continues to experience significant injuries and fatal incidents. This high rate can be attributed to human errors, time-consuming monitoring, and a lack of adaptability to urgent situations.

Consequently, safety risks demand careful monitoring during the execution phase. Traditional practices involve site engineers completing safety audits before executing construction activities to ensure a safe working environment [2]. Safety monitoring comprises general safety monitoring, equipment monitoring, and job-process monitoring. General safety monitoring evaluates proper signage, emergency exits, hazard absence, and cleanliness. Equipment monitoring ensures that machinery is in good working condition, properly maintained, and safe to use. Additionally, inspectors assess safety measures related to the job function before executing specific tasks, especially when handling hazardous working positions. Throughout these processes, safety engineers actively observe workers performing particular tasks or visually inspect dangerous areas and equipment using a detailed checklist to identify and mitigate potential causes of accidents [2]. Unfortunately, these processes require substantial human effort and time to ensure construction compliance with regulations [3].

Numerous approaches have been suggested to enhance safety monitoring within construction sites. Over the past two decades, there has been a noticeable surge in the use of technology for safety monitoring, aiming to boost safety performance by improving emergency response accuracy and minimizing human effort [4]. In the construction phase, the Building Information Modeling (BIM) model, developed during the design stage, is frequently employed to reference and inspect potentially hazardous areas [5, 6]. An innovative method involves registering both the BIM and reality models to identify and differentiate dangerous zones within construction sites precisely. Additionally, integrating computer vision and sensors has proven valuable in identifying unsafe behaviors [5]. Camera systems are installed for security and to monitor worker behaviors [7]. Computer vision techniques are employed to analyze the images from camera systems to automatically assess safety levels, including recognizing the correct usage of personal protective equipment and identifying improper working postures [8, 9]. Wearable devices, such as those measuring heart rates and providing location tracking, have gained popularity as sensors ensuring the well-being of workers [8, 9]]. Other sensors focus on environmental conditions, monitoring factors like temperature, humidity, and air quality to maintain a safe working environment [10]. Various endeavors have been undertaken to introduce and embrace digital technologies within safety monitoring, showcasing the effort to digitalize and automate safety practices in the construction industry.

Despite the numerous methods and procedures proposed to enhance safety across various categories in safety monitoring, practitioners still struggle with understanding the advantages of technologies and the prerequisites for their practical application in specific contexts [4]. This study offers a comprehensive document systematically outlining the benefits of digital technologies, addressing critical research questions to guide construction professionals. The key questions are: (1) Which unsafe activities can be monitored automatically? (2) What data is required for the safety monitoring process? (3) What digital technologies can facilitate such data collection process? The outcomes of this study aim to serve as a practical guide for construction practitioners, enabling them to strategically identify and implement digital technologies tailored to their specific needs. By addressing these research questions, this study contributes valuable insights for developing an effective construction safety monitoring process, aligning with the evolving digital transformation landscape in the construction industry.

2. DIGITAL TRANSFORMATION IN CONSTRUCTION SAFETY

The Occupational Safety and Health Administration (OSHA) has issued laws and regulations that standardize and categorize unsafe conditions and activities on construction sites [2]. Monitoring tasks in the construction phase typically fall into three main categories: general safety monitoring, including working environment and personal protective equipment; equipment monitoring; and job-process monitoring [11]. Therefore, carefully monitoring unsafe conditions and activities alongside these monitoring tasks is crucial. However, most literature reviews have primarily focused on categorizing high-level safety management tasks, including safety planning, monitoring, and education. For instance, safety planning often utilizes BIM models for risk simulation, enabling the identification and effective mitigation of safety hazards at construction sites [12]. BIM models extend beyond the design phase, pivotal in transferring information from design to construction and defining hazardous areas. Hence, integrating BIM with other technologies is essential to create a digital twin, enabling automated monitoring for safety compliance [13, 14]. Moreover, visualization-based technologies demonstrate promising capabilities in training workers on construction safety. Simulated situations presented and integrated into VR glasses can enhance awareness of potential dangers on construction sites. Regarding safety monitoring on-site, various research reviews have delved deeply into specific hazards such as falls from heights, struck-by incidents, and near-miss detection.

Existing literature highlights a diverse range of studies investigating and analyzing the utilization of advanced technologies, including Building Information Modeling (BIM) [6, 15], sensing and wireless technologies [4, 8], and Artificial Intelligence (AI) [16-19]. A plethora of advanced technologies have been extensively employed within the construction safety domain to mitigate the risk of workers' injuries and fatalities. These studies primarily summarize and analyze the trend of digital technology studies, pointing out the practical issues of adopting these advanced technologies for different safety problems during the construction lifecycle. However, accidents mostly happen in the construction stage, so it is essential to have thorough and systematic examinations, along with clear categorizations, of existing and emerging safety technologies within the construction phase. These efforts are necessary to fully harness the capabilities and suitability of these technologies in enhancing construction safety audit practices.

To fill in these gaps, the main objective of this study is to broaden the existing literature on construction safety monitoring by presenting a thorough categorization of technology applications utilized in monitoring unsafe conditions and activities. Furthermore, the paper identifies the technical requirements for selecting and implementing appropriate technologies to enhance safety performance during construction.

3. SYSTEMATIC REVIEW

A systematic review was implemented to introduce and investigate unsafe activity categories and the technologies of construction safety monitoring. The review process conducted in this study includes five distinct steps. Figure 1 presents the research process, including (1) formulating research questions, (2) identifying keywords, databases, and criteria, (3) collecting relevant data, (4) data analysis, and (5) result presentation. First, the research questions were stated in the introduction part. Subsequently, the Web of Science Core Collection was utilized to search for and identify useful publications using keywords associated with the research questions. WoS provides authoritative content, supports bibliometric analysis, and remains a premier source for researchers worldwide. Boolean operators AND and OR were used to formalize keyword searches. The search strings used were (construction OR construction site) AND (safety monitoring OR safety management OR safety monitoring OR safety audit*) AND (technolog* OR digital technolog* OR digital* OR innovation OR automat*). The search explored the title, abstract, and keywords sufficient to identify and extract the relevant articles. The filtering process was employed by evaluating the search results against three selection criteria: (1) Non-English papers and papers without full text are excluded. (2) Article types include journal articles, peer-reviewed articles, book chapters, dissertations, and conference papers (3) The paper should entirely focus on digital technologies in safety monitoring during the construction stage. A total of 108 documents were extracted as a result of this exercise.

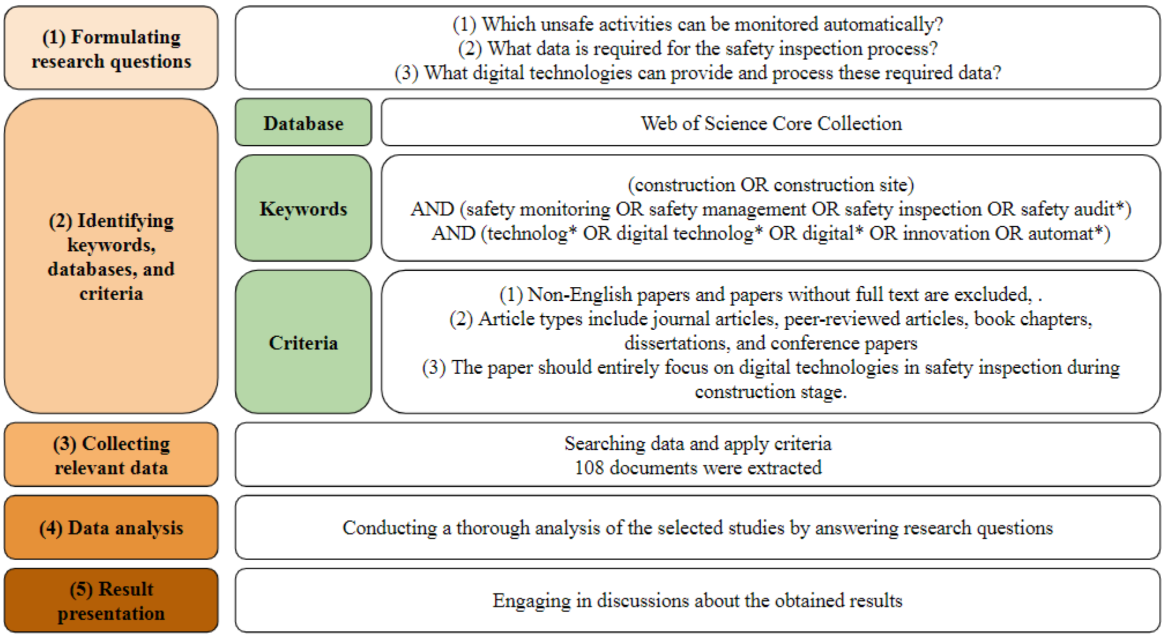

Figure 1. Research Process

Figure 2 denotes the distribution of selected publications by year, and Figure 3 illustrates the number of publications distributed by sources.

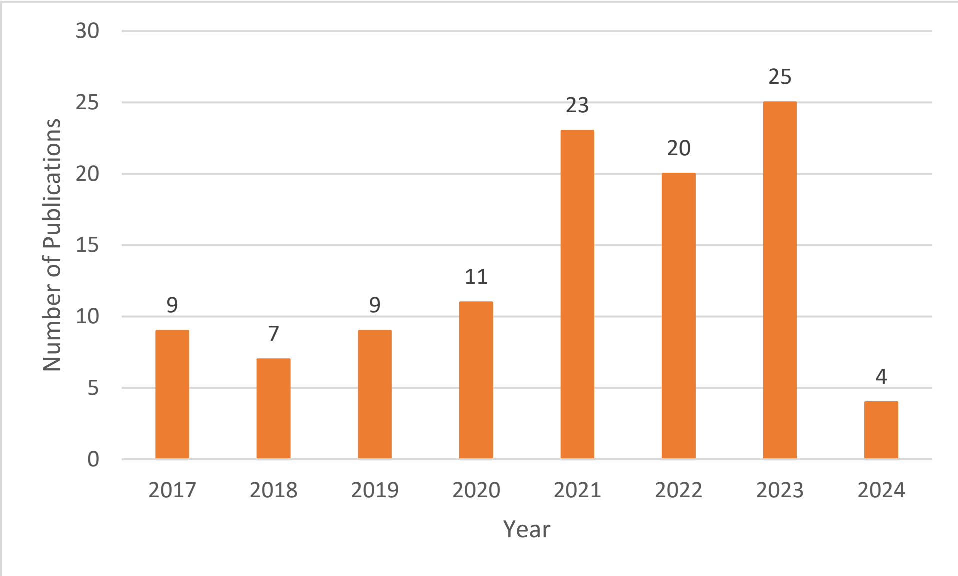

Figure 2. Publication distribution by years

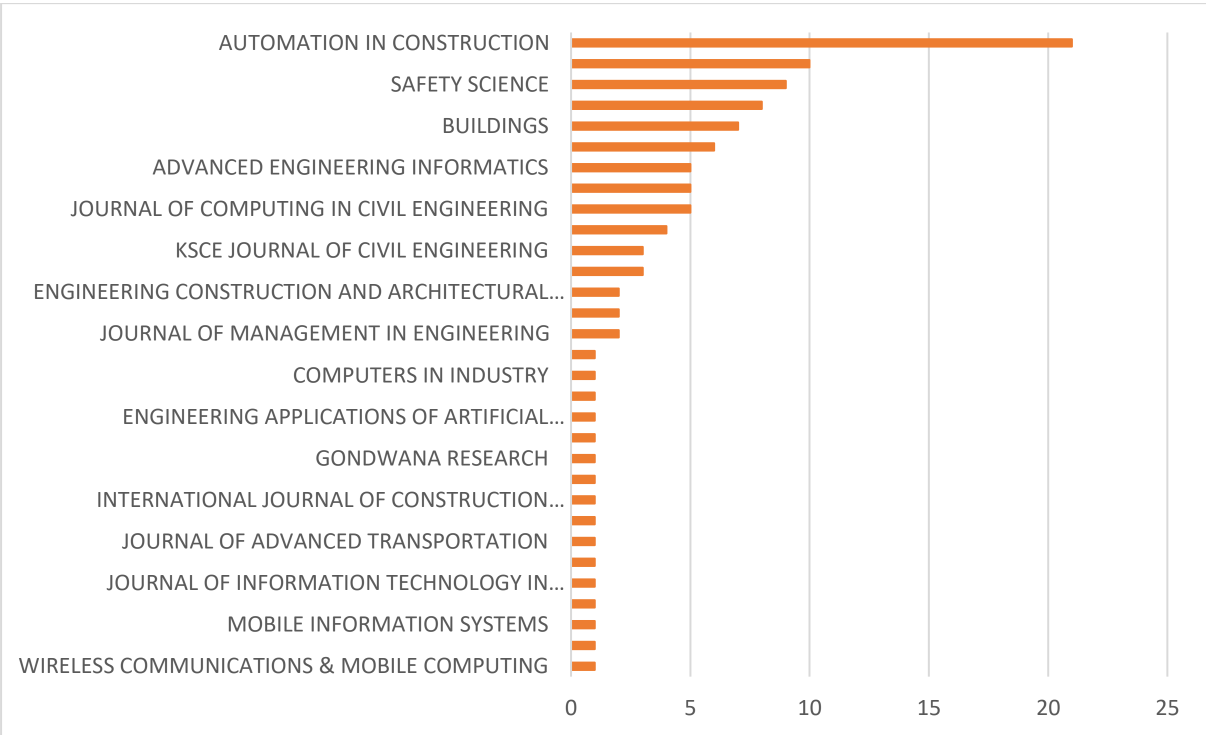

Figure 3. Publication distribution by sources

4. RESULTS AND DISCUSSION

Table 1 presents a comprehensive overview of the technology requirements for safety monitoring within construction sites. Safety monitoring has been methodically categorized into three primary types: General safety monitoring, Equipment monitoring, and Job-process monitoring. The detailed description of conditions to be inspected is provided in the second column of the table, while the subsequent columns (third to sixth) define the technical prerequisites necessary for automating the monitoring of each category. These technical requirements, involving data requirements, digital technologies, devices, and techniques, have been obtained from an analysis of the gathered literature.

Table 1. Technology requirements for safety monitoring categories

Safety monitoring category	Description	Data requirement	Digital technology	Device	Technique
General safety monitoring					
Personal protective equipment	Verify that workers wear the appropriate personal protective equipment, such as helmets, gloves, boots, etc.	Visual data	Visual sensors, deep learning	Camera	Object detection, pose detection, rule-based reasoning
Hazardous area identification	Identifying and marking any areas that pose a potential risk to workers	Visual data	Visual sensors, image processing	Camera, UAV	Object detection and distance calculation
Emergency Preparedness	Ensuring the site has adequate fire extinguishers, first aid kits, evacuation plans, etc.	BIM model, OSHA Safety Rules	BIM, Optical Character Recognition, Blockchain	Mobile device	A visual language algorithm blockchain-based android application
Equipment monitoring					
Machinery and tool condition assessment	Checking the machines, such as cranes, excavators, bulldozers, etc., are in good working order and have the necessary safety features	Geo-positioning data, 3D model, safety regulations, project schedule, construction method	Location sensor	Light Detection and Ranging (LiDAR)	Multi-Agent System (MAS) architecture
		Visual data	Visual sensor, computer vision-based (CVB) technology	Monocular far-field cameras	Camera autocalibration, equipment segmentation, reconstruction, 3D localization estimation
Job-process monitoring					
Unsafe behaviors identification	Recognizing and reporting incidents that could have resulted in injury or damage	Worker location, Hazardous location, visual data	Visual sensor, location sensor, IoT, Computer vision-based technology	BLE, IMU sensors, personal mobile device,	Worker tracking, distance calculation, pose detection, action recognition
Extraction of relevant safety requirements	Checking the task execution procedure following safety regulatory guidelines	Safety regulations, visual data	Computer vision-based technology, knowledge graph	Camera, C-BERT network	Object detection, scene analysis, Natural Language Processing

General safety monitoring consists of auditing construction safety working conditions as workers commence their tasks. This critical aspect involves thoroughly assessing various factors, including the availability and proper usage of Personal Protective Equipment (PPE), identifying and mitigating hazardous working areas, and ensuring emergency readiness. PPE such as helmets, gloves, and boots are detected by applying deep learning algorithms on visual data acquired by camera systems. Chen and Demachi [20] proposed a framework utilizing YOLOv3 to detect PPEs, OpenPose to extract worker key points, and regulatory rules to identify improper usage. Other research has explored different algorithms to establish the relationship between workers and PPEs, enabling the identification of potential hazards. Identification and control of hazardous areas are essential components of safety monitoring. Visual data aids in identifying such unsafe conditions. Hou, Li and Fang [21] introduced a computer vision-based method to determine the distance between workers and hazardous sources. Emergency preparedness involves ensuring the presence of adequate first aid equipment and evacuation kits on site. Khan, Lee, Baek and Park [22] leveraged visual data to implement fire safety PPE installation inspection. This process uses the BIM model and safety regulations as prerequisite inputs. After using optical character recognition to translate digital image data into text and documents, they employed a multi-agent simulation to assess the installation procedure virtually.

Equipment monitoring entails systematically examining machinery utilized within construction sites, such as cranes, excavators, and bulldozers. The primary objective of this monitoring is to ensure that all machinery is in optimal working condition, equipped with necessary safety features, and poses no potential hazards to workers or the surrounding environment. Vahdatikhaki, Langari, Taher, El Ammari and Hammad [23] introduced a Multi-Agent System (MAS) that leverages machine-level information, including states and poses, to coordinate the operations of individual equipment. This method integrates geo-positioning data collected by surveyors via location sensors with information from the design stage and project monitoring documents. The proposed MAS effectively manages the safety of earthwork operations by utilizing a spectrum of information to detect underground utilities and identify damaged equipment. Additionally, Wang, Zhang, Yang and Zhang [24] proposed a computer vision-based method to determine the position of tower cranes, facilitating operational monitoring and identifying potential collisions to ensure safety during the operation process.

Lastly, job-process monitoring focuses on overseeing the execution of construction tasks by workers. This comprehensive monitoring encompasses several aspects, including identifying unsafe behaviors during task execution, such as falls from heights or dangerous psychological states. In addition, it ensures that execution procedures adhere to safety regulatory guidelines, ensuring compliance and minimizing associated risks. Hou, Li and Fang [21], Li, Lin and Jin [25] introduced methods to identify whether workers are entering hazardous areas, utilizing visual and location sensors combined with deep learning techniques to track worker positions and calculate distances from dangerous areas. The overlapping of a worker's position with these zones activates automatic alerts. Furthermore, significant attention has been devoted to preventing falls from heights during task execution [26-30]. Khan, Khalid, Anjum, Khan, Cho and Park [27] proposed a comprehensive system integrating vision-based detection, IoT sensors, a web-based management platform, and a backend cloud server to monitor multiple workers' safety in real-time, particularly in complex construction sites where hazardous activities at height pose fatality risks. The combination of wearable technology for physical data collection and PANAS questionnaires for psychological data collection can be utilized to evaluate the psychological status of workers [31]. Besides, it is essential to guarantee adherence to safety regulations throughout the execution process. Technologies that generalize and incorporate safety regulations into a database have been developed, making extracting task procedures and verifying safety compliance more manageable. [32-35]. These systems automatically store, validate, and query task procedures by integrating with BIM models and building ontologies using natural language processing techniques.

5. CONCLUSION

This study aims to identify technical requirements supporting the implementation of digital technologies for safety monitoring during the construction phase. Various safety technologies are necessary to identify potential risks at construction sites. In this research, we categorized unsafe conditions and activities, conducting a systematic literature review to identify suitable technologies for automated monitoring. The review aimed to gather and analyze scholarly articles addressing digital technologies in safety monitoring. The study results include categorizing safety monitoring tasks, unsafe conditions, data requirements, and the hardware and software for the initial setup.

However, this study faces several limitations that require further investigation. Firstly, although our systematic literature review identified technical requirements, it does not account for currently employed technologies within organizations. Consequently, the study findings may not universally apply to practical resources. Future research should incorporate expert opinions to assess the technical prerequisites before implementing digital technologies. Secondly, this research exclusively focuses on technical aspects, overlooking social factors such as worker intention, privacy, security, and legal considerations. An alternative research direction could explore the motivations behind adopting digital technologies in safety monitoring. Nonetheless, this study offers valuable insights for construction practitioners planning to use digital technologies for safety monitoring during the construction process.

REFERENCES

[1] Park, C.-S., and Kim, H.-J., "A framework for construction safety management and visualization system", Automation in Construction, 33, pp. 95-103, 2013.

[2] Reese, C.D., and Eidson, J.V., "Handbook of OSHA construction safety and health", crc press, 2006.

[3] Stellman, J.M., "Encyclopaedia of occupational health and safety", International Labour Organization, 1998.

[4] Maali, O., Ko, C.-H., and Nguyen, P.H.D., "Applications of existing and emerging construction safety technologies", Automation in Construction, 158, pp. 105231, 2024.

[5] Li, X., Yang, D., Yuan, J., Donkers, A., and Liu, X., "BIM-enabled semantic web for automated safety checks in subway construction", Automation in Construction, 141, pp. 104454, 2022.

[6] Zhang, S., Teizer, J., Lee, J.-K., Eastman, C.M., and Venugopal, M., "Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules", Automation in construction, 29, pp. 183-195, 2013.

[7] Teizer, J., and Vela, P.A., "Personnel tracking on construction sites using video cameras", Advanced Engineering Informatics, 23, (4), pp. 452-462, 2009.

[8] Ahn, C.R., Lee, S., Sun, C., Jebelli, H., Yang, K., and Choi, B., "Wearable sensing technology applications in construction safety and health", Journal of Construction Engineering and Management, 145, (11), pp. 03119007, 2019.

[9] Hamshar, C., "FitLinxx Announces AmpStrip Wearable Heart & Activity Monitor", Wearable Tech World2014.

[10] Kiani, A., Salman, A., and Riaz, Z., "Real-time environmental monitoring, visualization, and notification system for construction H&S management", Journal of Information Technology in Construction, 19, pp. 72-91, 2014.

[11] Rey, R.O., de Melo, R.R.S., and Costa, D.B., "Design and implementation of a computerized safety monitoring system for construction sites using UAS and digital checklists–Smart Inspecs", Safety science, 143, pp. 105430, 2021.

[12] Wang, J., Zhang, X., Shou, W., Wang, X., Xu, B., Kim, M.J., and Wu, P., "A BIM-based approach for automated tower crane layout planning", Automation in Construction, 59, pp. 168-178, 2015.

[13] Wang, J., Zhang, S., and Teizer, J., "Geotechnical and safety protective equipment planning using range point cloud data and rule checking in building information modeling", Automation in Construction, 49, pp. 250-261, 2015.

[14] Park, J., Kim, K., and Cho, Y.K., "Framework of automated construction-safety monitoring using cloud-enabled BIM and BLE mobile tracking sensors", Journal of Construction Engineering and Management, 143, (2), pp. 05016019, 2017.

[15] Sidani, A., Martins, J.P., and Soeiro, A., "BIM Application for Construction Health and Safety: Summary for a Systematic Review", Occupational and Environmental Safety and Health IV, pp. 553-563, 2022.

[16] Hou, L., Chen, H., Zhang, G., and Wang, X., "Deep Learning-Based Applications for Safety Management in the AEC Industry: A Review", Applied Sciences, 11, (2)2021.

[17] Nath, N.D., Behzadan, A.H., and Paal, S.G., "Deep learning for site safety: Real-time detection of personal protective equipment", Automation in Construction, 112, pp. 103085, 2020.

[18] Fang, W., Love, P.E.D., Luo, H., and Ding, L., "Computer vision for behaviour-based safety in construction: A review and future directions", Advanced Engineering Informatics, 432020.

[19] Seo, J., Han, S., Lee, S., and Kim, H., "Computer vision techniques for construction safety and health monitoring", Advanced Engineering Informatics, 29, (2), pp. 239-251, 2015.

[20] Chen, S., and Demachi, K., “Towards on-site hazards identification of improper use of personal protective equipment using deep learning-based geometric relationships and hierarchical scene graph”, Automation in construction, 125, pp. 103619, 2021.
[21] Hou, X., Li, C., and Fang, Q., “Computer vision-based safety risk computing and visualization on construction sites”, Automation in Construction, 156, pp. 105129, 2023.
[22] Khan, N., Lee, D., Baek, C., and Park, C.-S., “Converging technologies for safety planning and monitoring information system of portable firefighting equipment”, IEEE Access, 8, pp. 211173-211188, 2020.
[23] Vahdatikhaki, F., Langari, S.M., Taher, A., El Ammari, K., and Hammad, A., “Enhancing coordination and safety of earthwork equipment operations using Multi-Agent System”, Automation in construction, 81, pp. 267-285, 2017.
[24] Wang, J., Zhang, Q., Yang, B., and Zhang, B., “Vision-Based Automated Recognition and 3D Localization Framework for Tower Cranes Using Far-Field Cameras”, Sensors, 23, (10), pp. 4851, 2023.
[25] Li, M., Lin, Q., and Jin, H., “Research on Near-Miss Incidents Monitoring and Early Warning System for Building Construction Sites Based on Blockchain Technology”, Journal of Construction Engineering and Management, 149, (12), pp. 04023124, 2023.
[26] Park, M., Bak, J., Kulinan, A.S., and Park, S., “Real-time monitoring unsafe behaviors of portable multi-position ladder worker using deep learning based on vision data”, Journal of safety research, 87, pp. 465-480, 2023.
[27] Khan, M., Khalid, R., Anjum, S., Khan, N., Cho, S., and Park, C., “Tag and IoT based safety hook monitoring for prevention of falls from height”, Automation in Construction, 136, pp. 104153, 2022.
[28] Hu, Q., Bai, Y., He, L., Huang, J., Wang, H., and Cheng, G., “Workers’ Unsafe Actions When Working at Heights: Detecting from Images”, Sustainability, 14, (10), pp. 6126, 2022.
[29] Guo, H., Zhang, Z., Yu, R., Sun, Y., and Li, H., “Action Recognition Based on 3D Skeleton and LSTM for the Monitoring of Construction Workers’ Safety Harness Usage”, Journal of Construction Engineering and Management, 149, (4), pp. 04023015, 2023.
[30] Anjum, S., Khan, N., Khalid, R., Khan, M., Lee, D., and Park, C., “Fall prevention from ladders utilizing a deep learning-based height assessment method”, IEEE Access, 10, pp. 36725-36742, 2022.
[31] Guo, H., Yu, Y., Xiang, T., Li, H., and Zhang, D., “The availability of wearable-device-based physical data for the measurement of construction workers' psychological status on site: From the perspective of safety management”, Automation in Construction, 82, pp. 207-217, 2017.
[32] Guo, H., Yu, Y., Ding, Q., and Skitmore, M., “Image-and-skeleton-based parameterized approach to real-time identification of construction workers’ unsafe behaviors”, Journal of Construction Engineering and Management, 144, (6), pp. 04018042, 2018.
[33] Zhang, L., Wang, J., Wang, Y., Sun, H., and Zhao, X., “Automatic construction site hazard identification integrating construction scene graphs with BERT based domain knowledge”, Automation in Construction, 142, pp. 104535, 2022.
[34] Hong, S., Yoon, J., Ham, Y., Lee, B., and Kim, H., “Monitoring safety behaviors of scaffolding workers using Gramian angular field convolution neural network based on IMU sensing data”, Automation in Construction, 148, pp. 104748, 2023.
[35] Shen, Q., Wu, S., Deng, Y., Deng, H., and Cheng, J.C., “BIM-Based Dynamic Construction Safety Rule Checking Using Ontology and Natural Language Processing”, Buildings, 12, (5), pp. 564, 2022.