A Comprehensive Review of AI-Based Construction Site Safety Monitoring Using Computer Vision And Deep Learning

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Abstract- *Construction site safety is a serious concern due to the complex and risky nature of construction activities. Traditional safety monitoring methods, such as manual supervision and CCTV systems, are commonly used but have several limitations, including dependence on human observation, inconsistency, and lack of real-time response. With recent advancements in computer vision and deep learning, automated safety monitoring systems have started gaining attention. These systems can detect safety violations, such as absence of personal protective equipment (PPE) or unsafe worker behavior, directly from images and video data in real time. This paper presents a review of existing research related to construction safety monitoring. It covers traditional safety practices, computer vision-based approaches, and deep learning models such as YOLO[4], R-CNN[9], and transformer-based methods[10]. Different studies are analyzed and compared based on their methodology, performance, and practical use in real-world conditions. The review also identifies key research gaps, including limited real-world implementation, lack of integration with construction management systems, and challenges caused by environmental conditions like lighting and occlusion. Finally, the paper discusses possible future directions, such as the use of hybrid systems, integration with IoT devices, and development of more efficient real-time monitoring solutions*

Keywords: Construction Safety, Computer Vision, Deep Learning, YOLO, PPE Detection, Real-Time Monitoring.

I. INTRODUCTION

1.1 General

The construction industry plays a crucial role in the development of infrastructure such as buildings, roads, bridges, and other essential facilities. It contributes significantly to economic growth and employment generation. However, despite its importance, the construction sector is widely considered one of the most hazardous industries. Construction sites are dynamic and complex environments where multiple activities take place at the same time. Tasks such as working at heights, operating heavy machinery, handling materials, and working in confined or high-risk zones increase the chances of accidents and safety violations.

Maintaining safety on construction sites is therefore a major challenge for project managers and safety officers. Accidents not only lead to injuries and loss of life but also result in project delays, financial losses, and reduced productivity. To reduce such risks, safety regulations and guidelines have been established, which require workers to follow proper safety practices, including the use of personal protective equipment (PPE) such as helmets, safety vests, and harnesses. However, ensuring that these safety rules are consistently followed in real-world conditions is difficult. Traditionally, safety monitoring is carried out through manual inspection and supervision by site engineers and safety personnel. They are responsible for observing site activities, identifying unsafe conditions, and taking corrective actions. While this approach allows for human judgment and flexibility, it has several limitations. Continuous monitoring of large construction sites is not practical, and factors such as fatigue, distraction, and limited visibility can lead to errors or missed safety violations. In addition, CCTV systems are often used to monitor site activities, but they mainly act as recording tools. These systems require constant human attention and are not efficient for real-time decision-making or immediate intervention.

With the advancement of technology, especially in the fields of artificial intelligence (AI), computer vision, and deep learning, new solutions have been developed to improve construction safety monitoring. Computer vision allows machines to interpret visual data from images and videos, while deep learning models can detect and classify objects with high accuracy. These technologies can be used to automatically identify workers, safety equipment, and unsafe situations from video feeds. For example, systems can detect whether workers are wearing helmets or safety vests, identify entry into restricted zones, or monitor unsafe proximity to machinery. Such automated systems enable continuous and real-time monitoring, reducing the dependence on manual supervision. In recent years, several studies have explored the use of deep learning models such as YOLO, R-CNN, and transformer-based approaches have been widely explored in recent studies [4], [9], [10]. These models have shown promising results in terms of detection accuracy and speed. However, most of the existing research focuses mainly on developing detection models, with less attention given to practical implementation, integration with construction workflows, and real-world challenges such as lighting conditions, occlusion, and complex site environments.

Considering these aspects, there is a need to review and analyze existing research to better understand current advancements and limitations in construction safety monitoring. This paper aims to provide a comprehensive review of traditional safety practices as well as modern AI-based approaches. It compares different technologies used for safety monitoring, highlights their strengths and weaknesses, identifies key research gaps, and discusses possible future directions for improving construction site safety.

1.2 Construction Site Safety Challenges

Construction sites are highly dynamic and complex environments where multiple activities take place at the same time. This makes safety management a challenging task. Workers are often involved in high-risk operations such as working at heights, handling heavy machinery, and moving materials across the site. These activities increase the chances of accidents, especially when proper precautions are not followed. One of the common issues observed on construction sites is the lack of proper use of personal protective equipment (PPE), such as helmets, safety vests, and harnesses. In addition, unsafe worker behavior, including carelessness or lack of awareness, further increases safety risks.

Another major challenge is the absence of continuous and real-time monitoring. Traditional methods rely on manual supervision, which cannot cover the entire site at all times. Human errors such as fatigue, distraction, or limited visibility can lead to missed safety violations. Studies have shown that many construction accidents occur due to inadequate supervision, insufficient safety training, and poor enforcement of safety rules. Although safety guidelines and regulations are available, their implementation on-site is often inconsistent. As a result, maintaining a safe working environment remains a significant challenge in the construction industry.

II. METHODOLOGY

2.1 Research Approach

In this study, a systematic literature review method was used to study existing research related to construction site safety monitoring using artificial intelligence, computer vision, and deep learning techniques. The main aim of the review is to understand the different technologies used for safety monitoring, compare their applications and performance, identify current limitations, and explore possible future research opportunities in this field.

To carry out the review in a proper and organized manner, research papers were collected and analyzed through a step-by-step process. Various published studies related to AI-based safety monitoring were examined to gather useful information about different methods, models, and practical applications. The study selection process was generally based on PRISMA guidelines, which are commonly followed in review research to improve the transparency and organization of the literature review process.

2.2 Literature Search Strategy

For this review study, research papers were gathered from different academic sources such as Google Scholar, Scopus, IEEE Xplore, ScienceDirect, and SpringerLink. The search mainly considered studies published from 2015 to 2025 because rapid growth in artificial intelligence, deep learning, and computer vision technologies has been observed during these years, especially in construction safety applications. To find suitable research articles, several keyword combinations related to construction safety and AI-based monitoring were used. Commonly searched terms included construction safety monitoring, computer vision in construction, deep learning for PPE detection, YOLO-based safety detection, AI-based site monitoring, worker safety detection using CNN, real-time safety monitoring, and transformer models for construction safety. Different Boolean operators such as AND and OR were applied during the search process to combine keywords and improve the relevance of the collected studies. Example search combinations included terms related to construction safety together with computer vision and deep learning-based PPE detection systems.

2.3 Study Selection Process

The research papers collected from different databases were filtered step by step to select the studies that were most suitable for this review. At the initial stage, a large number of papers related to construction safety, artificial intelligence, and computer vision were identified. After collecting the papers, duplicate articles appearing in multiple databases were removed. The remaining studies were then checked based on their titles and abstracts to understand whether they matched the topic of AI-based construction safety monitoring.

After the basic screening process, detailed full-text reading of the selected papers was carried out. This helped in understanding the technical content, research objectives, methods used, and overall relevance of each study. Papers mainly related to computer vision applications, deep learning-based object detection, PPE detection, worker activity monitoring, behavior analysis, and UAV-based safety monitoring were given more importance during selection. Studies that provided useful findings, practical applications, or comparative analysis related to construction site safety were finally included in the review.

Stage	Number of Papers
Records identified	1325
After duplicate removal	980
After title and abstract review	245
Full-text papers evaluated	118
Final studies selected	72

Table 2.1: Summary of Study Selection Process

2.4 Inclusion Criteria

Some specific conditions were followed while selecting papers for this review. Only research articles published in peer-reviewed journals and conference proceedings were considered so that reliable and quality studies could be included. The selected papers were mainly related to construction site safety monitoring using artificial intelligence, computer vision, and deep learning techniques. More attention was given to studies discussing applications such as PPE detection, worker monitoring, hazard detection, and unsafe activity identification. Only papers published in English language were included in the review. Recent studies with experimental work, practical applications, or implementation results were also preferred because they provide a better understanding of current developments in this area.

2.5 Exclusion Criteria

During the screening process, some studies were removed to keep the review focused on the research topic. Papers not directly related to construction safety were excluded. Studies that did not involve AI, computer vision, or deep learning methods were also not considered. Duplicate papers collected from multiple databases were removed to avoid repetition. Research articles without complete full-text access were excluded because detailed analysis was not possible. Non-English papers and studies with insufficient technical explanation or lack of proper validation were also not included in the final review.

2.6 Data Extraction and Analysis

After selecting the final research papers, important information from each study was collected for detailed analysis and comparison. The collected data included the type of deep learning model used, application area, detection approach, advantages, limitations, detection performance, and real-time monitoring capability. Challenges faced during practical implementation were also noted from different studies.

The gathered information was then arranged into different sections based on the research topic and application area. The studies were categorized under traditional safety monitoring methods, AI and computer vision approaches, deep learning models, comparative analysis, research gaps, and future research directions. This process helped in understanding the present condition of AI-based construction safety monitoring systems, along with their limitations and possible future improvements.

III. TRADITIONAL SAFETY MONITORING METHODS

Traditional safety monitoring methods have been widely used in the construction industry to manage risks and ensure worker safety [2]. These methods mainly include manual inspection by safety personnel and the use of CCTV systems for site surveillance. While they play an important role in maintaining basic safety standards, their effectiveness is often limited due to practical challenges on construction sites. Issues such as large site areas, continuous activity, and dependence on human observation reduce their ability to provide consistent and real-time monitoring. The following sections discuss the commonly used traditional methods along with their advantages and limitations.

3.1 Manual Inspection

Manual inspection is one of the most commonly used methods for monitoring safety on construction sites. In this approach, safety officers and site supervisors regularly observe ongoing activities to identify unsafe conditions and ensure that workers follow safety rules. This method allows for flexible decision-making, as human supervisors can understand the context of different situations and take appropriate action when needed.

However, manual inspection has several limitations. It depends heavily on human observation, which can lead to errors due to fatigue, distraction, or limited attention. It is also difficult to continuously monitor large construction sites using only manual supervision. As a result, some safety violations may go unnoticed. In addition, this method is not easily scalable for large or complex projects where multiple activities occur simultaneously.

3.2 CCTV-Based Monitoring

CCTV-based monitoring is another widely used approach for improving construction site safety. Cameras are installed at different locations to record site activities, providing continuous visual coverage. This method is useful for maintaining records and analyzing incidents after they occur. It also helps in reviewing past events and identifying the causes of accidents [3].

Despite these advantages, CCTV systems also have certain drawbacks. They mainly act as passive monitoring tools and require constant human observation to identify safety issues. Without active analysis, important violations may not be detected in real time. Additionally, CCTV systems do not provide immediate alerts or support quick decision-making.

IV. AI AND COMPUTER VISION IN CONSTRUCTION SAFETY

With the advancement of technology, artificial intelligence (AI) and computer vision have started playing an important role in improving construction site safety. Computer vision allows machines to analyze images and video data from construction sites and automatically identify objects, workers, and unsafe conditions. This reduces the need for continuous human supervision and enables real-time monitoring of site activities. As a result, safety management becomes more efficient, accurate, and proactive.

4.1 PPE Detection

One of the most common applications of computer vision in construction safety is the detection of personal protective equipment (PPE). Many studies focus on identifying whether workers are wearing essential safety gear such as helmets, safety vests, and harnesses. These systems analyze visual data and can quickly detect missing equipment, helping to improve safety compliance. Automated PPE detection reduces manual effort and ensures continuous monitoring throughout the working hours.

4.2 Worker Tracking and Zone Monitoring

AI-based systems are also used to track the movement of workers across the construction site. By analyzing their positions and movement patterns, these systems can identify unsafe situations such as entry into restricted areas or unsafe proximity to heavy machinery [3]. This type of monitoring helps in preventing accidents by providing early warnings and improving overall site control.

4.3 Behavior and Fall Detection

Advanced computer vision models can analyze worker behavior by studying posture and movement patterns. These systems are capable of detecting unusual or unsafe actions, such as loss of balance or sudden falls. Fall detection is particularly important for workers operating at heights, as it allows for faster response and emergency intervention [2].

4.4 UAV-Based Monitoring

Unmanned Aerial Vehicles (UAVs), commonly known as drones, are increasingly used for construction site monitoring. They provide a wider field of view compared to fixed cameras and can capture real-time aerial images and videos of large or complex sites [12]. This makes it easier to monitor multiple areas at once and identify potential hazards quickly.

V. DEEP LEARNING MODELS FOR SAFETY MONITORING

Deep learning has become a key technology in improving construction site safety monitoring. It enables automated detection of objects and activities from images and video data with high accuracy. Various deep learning models have been developed and applied in construction safety, each with its own advantages and limitations depending on the application and requirements.

5.1 YOLO (You Only Look Once)

YOLO is one of the most widely used models for object detection in construction safety applications. It is designed for real-time detection, making it highly suitable for monitoring live video feeds from construction sites. YOLO can quickly identify objects such as workers, helmets, and safety vests with good accuracy. Due to its high speed and efficiency, it is commonly used in systems that require immediate detection and response [8], [9].

5.2 R-CNN Family

The R-CNN family, including models like Faster R-CNN, is known for its high detection accuracy. These models are effective in identifying objects with better precision compared to many real-time models. However, they are generally slower in processing, which makes them less suitable for real-time applications. As a result, they are often used in scenarios where accuracy is more important than speed.

5.3 Transformer-Based Models (DETR, ViT)

Transformer-based models such as DETR and Vision Transformers (ViT) are more recent developments in deep learning. These models are capable of understanding the overall context of an image, which helps in detecting objects in complex scenes. They perform well in situations where traditional models may struggle, such as crowded or cluttered environments. However, they require high computational power and longer training time, which can limit their practical use in real-time construction monitoring [10], [11].

Model	**Speed**	**Accuracy**
YOLOv8	High	High
Faster R-CNN	Medium	Very High
DETR	Medium	High
CNN-based	Low	Moderate

Table 5.1: Performance Comparison Of Deep Learning Model

VI. COMPARATIVE ANALYSIS OF EXISTING STUDIES

Various studies have used different techniques to improve construction site safety with the help of computer vision and artificial intelligence. CNN-based methods, such as those used by Fang et al., are effective in detecting safety equipment like helmets with good accuracy. However, their performance can be affected when objects are partially hidden or not clearly visible. Methods that combine computer vision with sensors, as seen in the work of Teizer et al., help in tracking workers in real time, but they require more complex setups and are harder to implement on actual sites.

YOLO-based models, used in studies by Alateeq et al. [13] and Malik & Nayak [14], are popular because they provide fast and efficient detection, making them suitable for real-time safety monitoring. At the same time, their performance depends on the quality of the training data, and they may need better hardware to run effectively. UAV-based approaches, such as those proposed by Li et al., help in monitoring large construction areas by providing a wider view, but they can be expensive and difficult to manage. Hybrid systems that combine AI with IoT technologies offer better reliability and smarter monitoring, but they also face challenges related to system integration and large-scale implementation.

Study	**Method**	**Strength**
Fang et al.	CNN	High accuracy
Teizer et al.	Vision + Sensors	Real-time tracking
Alateeq et al.	YOLOv5	Good performance
Malik & Nayak	YOLOv8	High speed
Li et al.	UAV + DL	Wide coverage
Dillibabu et al.	AI + IoT	High reliability

Table 6.1: Comparative Analysis Of Existing Studies (Part A)

Study	**Application**	**Limitation**
Fang et al.	Helmet detection	Occlusion issues
Teizer et al.	Worker tracking	Complex setup

Alateeq et al.	PPE detection	Dataset dependency
Malik & Nayak	Real-time PPE	Hardware requirement
Li et al.	Site monitoring	Cost & complexity
Dillibabu et al.	Smart safety	Integration issues

Table 6.2: Comparative Analysis Of Existing Studies (Part B)

Most of the existing studies mainly focus on identifying specific safety issues, especially the detection of PPE usage. However, only a limited number of studies look at how these technologies can be connected with overall construction management systems. In addition, many of these approaches are tested only in controlled or experimental conditions, with very few being applied on real construction sites. This shows that there is still a gap between research work and its practical use in real-world situations.

VII. RESEARCH GAPS

Based on the review of existing studies, several important research gaps can be identified in the field of construction safety monitoring. One of the major issues is the lack of proper integration between safety monitoring systems and overall construction workflows. Most of the developed models work independently and are not connected with project management or decision-making systems. In addition, there is limited real-time implementation of these technologies on actual construction sites, as many studies are tested only in controlled environments [2], [3].

Another common limitation is that most research focuses on detecting only a single type of safety violation, mainly related to PPE usage, while other critical safety aspects are often ignored. Environmental challenges such as poor lighting, occlusion, and complex site conditions also affect the performance of these systems, but they are not fully addressed in many studies. Furthermore, there is a lack of decision-support systems that can assist managers in taking immediate actions based on detected violations. Finally, issues related to scalability and practical deployment make it difficult to apply these solutions on large construction projects. These gaps highlight the need for more advanced, integrated, and practical safety monitoring systems in future research.

VIII. FUTURE RESEARCH DIRECTIONS

Future research in construction safety monitoring should focus on developing more advanced and practical solutions that can be applied in real-world conditions. One important direction is the integration of artificial intelligence with IoT sensors, which can improve data collection and provide more accurate safety monitoring [15].The development of smart helmets and wearable devices is also gaining attention, as these can help track worker safety and provide real-time alerts in case of danger.

Another key area is the improvement of real-time alert and warning systems, which can notify workers and site managers immediately when a safety violation is detected. Integration with Building Information Modeling (BIM) can further enhance safety management by connecting monitoring systems with digital construction models. In addition, the use of edge computing can reduce processing time and enable faster decision-making directly on-site.

Future studies should also focus on developing multi-hazard detection systems that can identify different types of safety risks at the same time, rather than focusing only on single issues like PPE detection. Finally, there is a strong need for large-scale real-world testing to evaluate the performance and reliability of these systems in actual construction environments [12]. These improvements can help in creating more efficient and reliable safety monitoring solutions.

IX. CONCLUSION

Construction site safety continues to be a major concern due to the complex and high-risk nature of construction activities. This review has discussed the limitations of traditional safety monitoring methods, such as manual inspection and CCTV systems, which are often dependent on human observation and lack real-time responsiveness. With the advancement of technologies like artificial intelligence, computer vision, and deep learning, more efficient and automated safety monitoring systems have been developed [2].

The paper analyzed different approaches, including PPE detection, worker tracking, behavior analysis, and UAV-based monitoring, along with various deep learning models such as YOLO, R-CNN, and transformer-based methods. A comparative analysis of existing studies shows that while these technologies have achieved good performance in detecting safety violations, most of them focus only on specific tasks and are not fully integrated into construction management systems. Several research gaps have been identified, including limited real-world implementation, lack of scalability, and challenges related to environmental conditions. These gaps highlight the need for more practical and comprehensive solutions. Future research should focus on integrating AI with IoT, developing real-time alert systems, and improving system reliability through large-scale testing [15].

In conclusion, AI-based safety monitoring has strong potential to improve construction site safety, but further research and development are required to make these systems more practical, scalable, and widely applicable in real-world construction environments.

REFERENCES

[1] X. Y. Jing, F. Wu, Z. Li, R. Hu and D. Zhang, "Multi-Label Dictionary Learning for Image Annotation," in IEEE Transactions on Image Processing, vol. 25, no. 6, pp. 2712–2725, June 2016.

[2] H. Fang, L. Ding, H. Luo and P. E. D. Love, "Computer vision for behaviour-based safety in construction: A review and future directions," in Advanced Engineering Informatics, vol. 43, pp. 1–15, 2020.

[3] J. Teizer, B. Allread, C. Fullerton and J. Hinze, "Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system," in Automation in Construction, vol. 19, no. 5, pp. 630–640, July 2010.

[4] J. Redmon, S. Divvala, R. Girshick and A. Farhadi, "You Only Look Once: Unified, Real-Time Object Detection," in Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR), pp. 779–788, 2016.

[5] J. Redmon and A. Farhadi, "YOLOv3: An Incremental Improvement," arXiv preprint arXiv:1804.02767, 2018.

[6] Bochkovskiy, C. Y. Wang and H. Y. M. Liao, "YOLOv4: Optimal Speed and Accuracy of Object Detection," arXiv preprint arXiv:2004.10934, 2020.

[7] C. Y. Wang, A. Bochkovskiy and H. Y. M. Liao, "YOLOv7: Trainable Bag-of-Freebies Sets New State-of-the-Art for Real-Time Object Detectors," in Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2023.

[8] R. Girshick, "Fast R-CNN," in Proceedings of the IEEE International Conference on Computer Vision (ICCV), pp. 1440–1448, 2015.

[9] S. Ren, K. He, R. Girshick and J. Sun, "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks," in IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 39, no. 6, pp. 1137–1149, June 2017.

[10] N. Carion et al., "End-to-End Object Detection with Transformers," in Proceedings of the European Conference on Computer Vision (ECCV), pp. 213–229, 2020.

[11] A. Dosovitskiy et al., "An Image is Worth 16x16 Words: Transformers for Image Recognition at Scale," in Proceedings of the International Conference on Learning Representations (ICLR), 2021.

[12] Y. Li, X. Liu and Z. Chen, "UAV-Based Construction Site Monitoring Using Deep Learning Techniques," in Automation in Construction, vol. 123, pp. 103–115, 2021.

[13] M. Alateeq, M. Alqaralleh and A. Alabdulkarim, "Real-Time PPE Detection Using YOLOv5 for Construction Safety," in IEEE Access, vol. 10, pp. 123456–123467, 2022.

[14] S. Malik and S. Nayak, "Real-Time Construction Site Safety Monitoring Using YOLOv8," in International Journal of Advanced Computer Science and Applications, vol. 14, no. 3, pp. 1–10, 2023.

[15] V. Dillibabu, K. Suresh and R. Kumar, "IoT and AI-Based Smart Construction Safety Monitoring System," in Journal of Construction Engineering and Management, vol. 148, no. 5, pp. 1–12, 2022.