An Edge-AI Framework for Real Time PPE Compliance Monitoring at Construction Sites Using IOT Device

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Abstract: Construction industry is one of the fastest-growing sectors in India and a major contributor to employment and infrastructure development. The design focuses on three operational states for each PPE item: Wearing, Partially Wearing, and Not Wearing. This distinction is important because a simple binary detector can fail to capture unsafe conditions such as an incorrectly positioned helmet or incomplete use of protective equipment. However, it is also one of the most hazardous industries due to the involvement of heavy machinery, work at height, electrical operations, and manual handling of materials. High occupational injury and fatality rate in the construction industry is a serious global concern. Construction accidents lead to loss of life, injuries, project delays, and financial losses. Research has shown that deep-learning based vision systems can automatically assess hard-hat and safety-vest compliance from images and video, while dedicated PPE detectors have demonstrated the feasibility of detecting multiple PPE categories in construction environments. This research proposes the development and validation of an Edge-AI framework for real-time PPE compliance monitoring at construction sites using IoT device (Raspberry Pi). The proposed system uses a camera to continuously capture images/video of workers and applies a lightweight deep-learning object detection model to identify PPE such as safety helmets, reflective safety vests, safety shoes, gloves and safety goggles. The trained model is optimized for edge deployment using techniques such as model compression and conversion into an appropriate lightweight inference format.

Keywords: *Accidents on Construction Site, Safety Management System, Raspberry Pi, PPE Kit.*

INTRODUCTION

Constructional sites are exposed to numerous safety hazards, and inadequate use of Personal Protective Equipment (PPE) remains one of the important contributors to construction accidents. PPE provides the final level of protection when engineering and administrative controls cannot eliminate a hazard. Conventional PPE monitoring primarily depends on safety officers, supervisors, safety audits, CCTV & Cloud-based-AI monitoring and periodic inspections, which may be affected by limited manpower, human error, site size, and the inability to continuously monitor workers. In other words, conventional PPE monitoring approaches have limitations. Therefore, there is a need for an automated, real-time and cost-effective PPE compliance monitoring system. Research proposes the development and validation of an Edge-AI framework for real-time PPE compliance monitoring at construction sites using IoT devices. The proposed system uses a camera to continuously capture images/video of workers and applies a lightweight deep-learning object detection model to identify PPE such as safety helmets, reflective safety vests, safety shoes, gloves and safety goggles. The device performs local image processing and PPE compliance assessment at the construction site, thereby reducing dependence on cloud computing and improving response time and data privacy. The design focuses on three operational states for each PPE item: Wearing, Partially Wearing and Not Wearing. This distinction is important because a simple binary detector can fail to capture unsafe conditions such as an incorrectly positioned helmet or incomplete use of protective equipment. When a violation is detected, the system generates an immediate warning and records the event for subsequent safety analysis.

Problem Statement: Despite mandatory safety procedures and PPE requirements, construction workers may fail to consistently use required PPE due to negligence, discomfort, lack of supervision, work pressure or inadequate safety culture. Manual PPE inspection cannot continuously monitor large and dynamic construction sites.

Aim: To develop and validate an Edge-AI framework for real-time PPE compliance monitoring based on object detection and classification on construction sites using IoT device.

Objectives:

- To identify the critical PPE requirements applicable to selected construction activities and establish PPE

compliance criteria.

- To develop a Camera to Single Board Computer edge vision pipeline for monitoring compliant and non-compliant PPE conditions at a construction site.
- To train a lightweight deep-learning object detection model for the selected PPE categories to determine PPE status as Wearing, Partially Wearing, or Not Wearing thus developing a PPE compliance decision and alert mechanism.
- To optimize and deploy the trained model on Raspberry Pi for real-time edge inference.

LITERATURE REVIEW

- One of the important developments in this area has been the application of computer vision and deep learning for automated safety monitoring. Nath, Behzadan and Paal (2020) investigated deep-learning-based detection of PPE in construction environments and demonstrated the potential of object-detection algorithms for automatically identifying safety equipment from site images. They reported that their best model could process more than 10 images per second in uncontrolled job environments. Their work established that deep learning could reduce dependence on manual inspection and enable continuous monitoring of PPE compliance. However, the computational requirements of deep learning models present challenges when the system is intended to operate on low-cost edge devices.
- Ferdous and Ahsan developed a YOLO-based PPE detector for construction sites and introduced a dataset containing multiple hard-hat, vest, and safety-glass categories.
- A 2024 study evaluated a real-time YOLOv5 PPE-compliance system and reported strong prototype-level results, while also noting the need to expand PPE categories and training data.
- More recent research has addressed temporal consistency. Zhang et al. combined YOLOv9, pose estimation, and StrongSORT to associate helmets with workers and track helmet-wearing states over time, reporting 98.89% accuracy on their self-built dataset.
- An IEEE conference study in 2025 combined YOLOv8 and human pose estimation for construction-site safety monitoring and explicitly identified IoT-based warning mechanisms as a future direction.
- Fang et al. (2018) investigated computer-vision applications for construction safety management and highlighted the increasing use of image-based techniques for identifying unsafe conditions. The research analyzed various visual conditions of the construction sites and classified images according to their visual condition. Their work demonstrated that computer vision can assist safety professionals in monitoring workers, equipment and hazardous conditions. Nevertheless, variations in site conditions, worker movement, illumination, occlusion and camera positioning remain important challenges for reliable automated detection.
- Research on YOLO-based object detection has further improved the feasibility of Realtime PPE monitoring. Lightweight YOLO models can simultaneously detect multiple objects and provide bounding boxes and confidence scores at relatively high processing speeds. Several international studies have subsequently investigated automatic detection of safety helmets, reflective vests and other PPE using YOLO and related convolutional neural-network architectures. These studies generally report good detection performance under controlled conditions; however, detection accuracy tends to decrease when workers are partially occluded, located far from the camera, or exposed to poor lighting and complex construction backgrounds.

RESEARCH METHODOLOGY

Review national and international research on construction safety, PPE compliance, computer vision, deep learning, Edge-AI and Raspberry Pi. Identify PPE requirements applicable to selected construction activities and establish the research gap.

Data Collection and Dataset Development: Collect construction-site images/videos showing workers with compliant and noncompliant PPE. Develop a dataset focusing initially on safety helmets and reflective safety vests, considering different lighting conditions, camera distances, worker positions and levels of occlusion.

Image Annotation and YOLO26n Model Development: Annotate the collected images using suitable annotation software and classify PPE objects. Train a lightweight YOLO26n deep learning model using training and validation datasets to detect workers and selected PPE items.

Model Testing, Validation and Optimization: Evaluate the trained model using pixel/classification level matrix and matrix based visual summaries. Optimize the model for edge deployment by reducing computational requirements while maintaining acceptable detection performance.

Raspberry Pi-Based Edge-AI Implementation: Integrate the optimized AI model with Raspberry Pi and a camera. Develop a realtime processing system in which video frames are captured, processed locally and analyzed for PPE compliance without

continuous dependence on cloud computing.

Real-Time Construction-Site Validation and Performance Evaluation Test the system under actual or simulated construction-site conditions. Evaluate detection accuracy, latency, frame rate, and false-positive/false-negative rates.

Construction Safety Management and Comparative Analysis: Compare AI-based monitoring with conventional manual PPE inspection in terms of monitoring time, response time, documentation, manpower requirements and implementation cost. Analyze the results and develop recommendations for integrating Edge-AI into construction safety management.

Construction industry is synonymous with potential hazards. Injuries from falling objects, contact with heavy machinery, falling from heights, exposure to harmful materials, and many other risks can pose serious threats. Ensuring worker safety is not just a legal obligation but a moral one, demanding constant attention and regular improvements.

PPE is the frontline defense against work related hazards, preventing injuries and saving lives. An array of equipment, from helmets to gloves to protective clothing and sturdy boots, plays critical role in maintaining a safe working environment on construction sites.

Essential types of PPE for construction works:

•Head Protection: Hard hats, helmets, etc.

•Body Protection: Safety vests, coverall, etc.

•Eye and Face Protection: Safety goggles, face shields, etc

•Hand Protection: Gloves.

•Foot Protection: Safety shoes, boots, etc.

•Hearing Protection: Earplugs, earmuffs, etc.

PPE priority:

Sr.	PPE Equipment	AI Detection	Priority	Reason
1	Safety Helmet/Hard Hat	Yes	Very High	Highly visible and critical for head protection.
2	Reflective Safety Vest/Jacket	Yes	Very High	Large, visually distinctive and suitable for camera detection.
3	Safety Goggles	Yes	Medium	Important but small object and difficult at distance.
4	Safety Gloves	Yes	Medium	Useful but frequently occluded.
5	Safety Shoes/Boots	Yes	Low Medium	Important but difficult to detect from surveillance
6	Hearing Protection	Possible	Low	Difficult to identify reliably from normal CCTV.
7	Safety Harness	Possible	Medium	Important for work-at-height activities but require activity/context detection.
8	Face Mask/ Respirator	Yes	Medium	Detectable but applicability depends on activity.

Recommended scope. For the subject thesis, the scope of PPE detection is restricted to the undermentioned equipment:

- Safety Helmet
- Reflective Safety Vest

Why Safety Helmet and Vest are considered the subject of research study:

•Helmet detection is particularly suitable because it is normally located on the worker's head, it has a relatively distinctive shape, it occupies sufficient pixels in most surveillance images.

Thus, AI can classify:

Person + Helmet -------- Compliant

Person + No-helmet -------- Violation

•Reflective Safety Vest covers relatively large area of the worker's body, High visibility colors make it comparatively easier to detect and it can be detected together with the worker.

Thus, AI can classify:

Person + Vest -------- Compliant

Person + No-vest ------- Violation

METHODOLOGY

Image annotation and yolo26n model development: The development of an Artificial Intelligence (AI)-based Personal Protective Equipment (PPE) compliance monitoring system requires a properly prepared image dataset and a trained object detection model. The performance of the system depends on the quality, variety and accuracy of the images used for model training. Therefore, image annotation and model development are important stages in the proposed Edge-AI framework for realtime PPE compliance monitoring at construction sites. Since the collection of a large, properly labelled construction-site dataset may require considerable time and resources, the model

development process will be carried out in two major phases. The first phase will involve the development of a prototype model using suitable open-source datasets and pre-site images. The second phase will involve improving the prototype with additional verified images and testing it under realistic construction-site conditions.

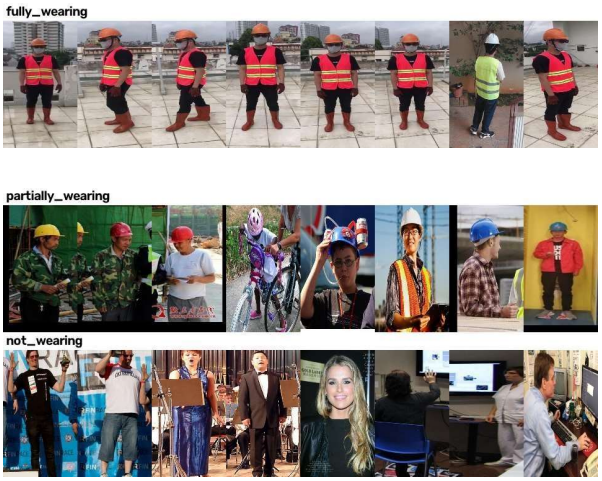
The image annotation and model development process will follow the sequence below.

Dataset identification → Image collection → Image cleaning → Image annotation → Annotation verification → Dataset splitting → YOLO26n prototype training → Performance evaluation → Model improvement → Edge deployment preparation → pre-site testing → Construction-site validation.

Dataset Splitting and Organization for Model Development:

Dataset group	Proposed percentage	Purpose
Training dataset	70%	Used to train the AI model
Validation dataset	20%	Used to assess training progress and adjust model settings
Testing dataset	10%	Used for final performance evaluation

The dataset is also checked to ensure that the Wearing, Partially Wearing and Not Wearing conditions are represented adequately. If one category has very few images, additional data collection may be required before training.



RECOMMENDATION

The work completed during the initial stages has established the research background, identified the research gap, defined the PPE requirements, and developed the methodology for data collection, dataset preparation, image annotation and YOLO26n model development. The initial prototype developed using publicly available Construction-PPE data has also provided useful insights into the model's performance and the limitations associated with the identification of partially worn PPE. The subsequent stages of the research will focus on improving the model using additional verified construction-site images, testing its performance, optimizing it for deployment on Raspberry Pi, and validating the complete system under actual or simulated construction site conditions. The emphasis will be on achieving an appropriate balance between detection accuracy, computational efficiency, response time and practical applicability.

REFERENCES

1. Nath, N. D., Behzadan, A. H., & Paal, S. G. (2020). "Deep learning for site safety: Real-time detection of personal protective equipment". Automation in Construction, 112, 103085.
2. M. Ferdous and S. M. M. Ahsan (2022), "PPE Detector: A YOLO-based architecture to detect personal protective equipment (PPE) for construction sites", PeerJ Computer Science, Vol 8, e999, 2022, DOI: 10.7717/peerj-cs.999.
3. Nur Amielia N. Mohamad Nazli, N. Sabri, R. Aminuddin, S. Ibrahim, S. Yusof, S. Diana N. Mohd Nasir (2024), "A real-time system for detecting personal protective equipment compliance using deep learning model YOLOv5," Procedia Computer Science, Vol. 245, pp. 647–656, 2024, doi: 10.1016/j.procs.2024.10.291.
4. Y. Zhang, S. Huang, J. Qin, X. Li, Z. Zhang, Q. Fan, and Q. Tan (2025), "Detection of helmet use among construction workers via helmet-head region matching and state tracking,"
5. Automation in Construction, Vol. 171, Art. no. 105987, 2025, doi: 10.1016/j.autcon.2025.105987.
6. Fang, Q., Li, H., Luo, X., Ding, L., Rose, T. M., An, W., & Yu, Y. (2018). A deep learning-based method for detecting non-hardhat-use by construction workers. Research in computer vision-based construction safety.
7. Redmon, J., Divvala, S., Girshick, R., & Farhadi, A. (2016). You Only Look Once: Unified, real-time object detection. Proceedings of the IEEE

Conference on Computer Vision and Pattern Recognition (CVPR), 779–788.

8. Bahar Zamani (2026). AI-Driven Safety Protocols Developments in Construction Management. International Journal of Industrial Engineering and Construction Management, Volume 1, No. 2, 2026.
9. Ali Sharifi (2026). AI-Driven Safety Protocols in Construction: Enhancing Interpretability and Risk Assessment. International Journal of Industrial Engineering and Construction Management, Volume 4, No. 3, 2026.
10. S. J. Badhan, R. Samsami (2025). Artificial Intelligence in Construction Safety: A Systematic Literature Review. Buildings 2025, 15, 4084. https://doi.org/10.3390/buildings15224084.
11. Ahmed Bin Kabir Rabbi, Idris Jeelani (Aug 2024). AI Integration in Construction Safety: Current State, Challenges, and Future Opportunities in Text, Vision, and Audio Based Applications; Automation in Construction.
12. Role of AI in Enhancing Safety Measures on Construction Sites; article by Navitech Group, an Abu Dhabi based firm, in Construction Technology on 07 April 2025.
13. Mohamad Iyad Al-Khiami, Mohamed M ElHadad (2024). Enhancing Construction Site Safety using AI: The Development of a Custom Yolov8 Model for PPE Compliance Detection. 2024 European Conference on Computing in Construction held in Chania, Crete, Greece, July 14-17, 2024.
14. Nguyen Quoc Khanh (2024). Computer Vision for Safety Management: A Case Study in the Construction Industry. orcid.org/0009-0007-4278-149X. 10.13140/RG.2.2.36654.93767.
15. A.B. Landage, A. Mane, S. Shirdhankar, A. Jadhav (2026). Computer Vision for Construction Site Safety and Progress. International Journal of Engineering Research & Technology (IJERT) ISSN: 2278-0181 Vol. 15 Issue 05, May - 2026.
16. Anjum, Kazi Nafisa & Luz, Ayuns. (2024). Investigating the Role of Internet of Things (IoT) Sensors in Enhancing Construction Site Safety and Efficiency. International Journal of Advances in Engineering and Management. 06. 463-470. 10.35629/5252-0612463470.
17. Bureau of Indian Standards, IS 2925:1984, Specification for Industrial Safety Helmets, BIS, New Delhi relevant to the PPE/helmet component of the research.
18. Mistry, Mr & Shah, Mr & Biswal, Ms. (2026). Artificial Intelligence in the Construction Industry in India: Opportunities, Challenges Future Prospects. International Journal of Latest Technology in Engineering Management & Applied Science. 589-593. 10.51583/IJLTEMAS.2026.150600046.
19. M. Patil, Dr M. P. Kadam (2021). Construction Site Safety using Internet of Things. International Journal of Innovative Research in Science, Engineering and Technology, https://doi.org/10.15680/IJIRSET.2021.1005106.
20. International Journal of Advanced Research in Science, Communication and Technology, ISSN: 2581-9429, Volume 5, Issue 3, November 2025.
21. Tanish Patel, Spandan Acharya, Ranjan Ray, Prof. Vibha Pandey (2026). Safe Sight: AI Based Construction Safety Monitoring. International Journal of Research Publication and Reviews ISSN 2582-7421, Vol (7), Issue (5), May (2026), Page – 3026-3028.
22. Chethan G R, T K Pradeep Kumar, Darshan M, Darshan D, Darshan R Naik (2025). Safe Sight: AI-Based Multi-Industry PPE Detection System Using YOLOv8. International Research Journal on Advanced Engineering and Management, e ISSN: 2584-2854, Volume 03 Issue 09 Sep 2025 Page No. 2906-2909.
23. Raspberry Pi Ltd., “AI Camera,” Raspberry Pi Documentation”, 2026. [Online]. Available: https://www.raspberrypi.com/documentation/accessories/ai-camera.html
24. Raspberry Pi Ltd., “AI HAT+,” Raspberry Pi Documentation”, 2026. [Online]. Available: https://www.raspberrypi.com/documentation/accessories/ai-hat-plus.html
25. Y. Zhang, P. Sun, Y. Jiang, D. Yu, F. Weng, Z. Yuan, P. Luo, W. Liu, and X. Wang, "ByteTrack: Multi-object tracking by associating every detection box," in Proc. European Conf. Computer Vision (ECCV), 2022.
26. Tencent, A high-performance neural network inference framework optimized for the mobile platform." [Online]. Available: https://github.com/Tencent/ncnn
27. Government of India, The Digital Personal Data Protection Act, 2023. New Delhi, India, 2023