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## Automated PPE Compliance Verification Using YOLOv11l Spatial Logic: Verifikasi Kepatuhan APD Otomatis Menggunakan YOLOv11l dan Logika Spasial

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### Abstract

**General Background:** Monitoring personal protective equipment (PPE) usage is a critical component of occupational health and safety (OHS) in construction, yet manual inspection remains inconsistent and prone to error. **Specific Background:** Recent advances in computer vision, particularly YOLO-based object detection, have improved PPE detection accuracy in complex environments. **Knowledge Gap:** However, existing approaches primarily detect PPE presence without verifying its correct usage or associating it with individual workers, leading to inaccurate compliance interpretation. **Aims:** This study develops an automated PPE compliance verification system using YOLOv11l combined with spatial association logic to assess PPE completeness and anatomical correctness at the individual worker level. **Results:** The system was trained on 2,788 construction images and achieved high performance with mAP@50 of 0.979, precision of 0.976, recall of 0.954, and peak F1-score of 0.97, while demonstrating accurate classification across PPE categories including helmets, vests, and shoes. **Novelty:** The integration of zone-based spatial verification enables validation of PPE placement within anatomically defined regions, addressing the limitation of detection-only systems. **Implications:** This approach supports objective, continuous, and reliable safety auditing in construction environments, offering a scalable alternative to manual OHS monitoring.

#### Highlights

- Multi-class detection identifies workers and safety equipment with high accuracy
- Region-based validation distinguishes proper gear usage from misplacement
- System classifies compliance status through structured decision logic

#### Keywords

Automated PPE Verification; Construction Safety; Deep Learning; Spatial Association Logic; YOLOv11l

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## INTRODUCTION

The construction industry remains one of the most hazardous sectors globally, with many accidents caused by unsafe worker behavior and complex site environments. According to the International Labour Organization, millions of occupational accidents occur annually, with a substantial portion attributed to the lack of proper safety measures. In Indonesia, the number of workplace accidents has shown a worrying upward trend, necessitating stricter enforcement of Occupational Health and Safety (OHS) regulations. Personal Protective Equipment (PPE) specifically safety helmets, high-visibility vests, and safety shoes serves as the last line of defense in minimizing injury severity. While regulations such as the Ministry of Manpower Regulation No. 5 of 2018 mandate PPE usage, non-compliance remains a pervasive issue due to limitations in supervision.

Traditional monitoring methods rely heavily on manual inspections by safety officers. This approach is limited by field of view, officer fatigue, and the inability to continuously monitor large areas. Consequently, violations are often missed due to sporadic inspections [6]. This situation has encouraged the use of computer vision and deep learning to automate safety monitoring [7].

Earlier methods, such as HOG, are less effective in dynamic environments, while CNN based deep learning models have proven more accurate and reliable [4]. Object detectors consist of two stage (Faster R-CNN) and on stage (YOLO, SSD) methods. Faster R-CNN is less suitable for real time because of its high computational cost, while YOLO has become the industry standard because it balances speed and accuracy. Review by [8] shows that the latest version of YOLO is increasing effective in detecting small objects, such as shoes and gloves.

Recent studies have adopted newer YOLO iterations to improve performance. Introduced YOLOv7 with trainable bag-of-freebies, setting a new benchmark for real-time detectors. The YOLO model continues to be developed, for example, YOLOv5, with its attention mechanism that improves helmet detection accuracy under occlusion [9], and a modified YOLOv8 that is more effective in dealing with complex backgrounds in industrial environments [10].

However, a gap remains between object detection and its presence verification. Most systems only detect the presence of PPE, such as helmets, without analyzing their relationship to the worker [11],[12],[13]. This results in the "separated object" problem, where PPE is detected but not associated with an individual. Furthermore, studies that examine the overall PPE adequacy for each worker are still limited. The regularity of complete PPE sets (helmets, vests, and boots) is often overlooked for individual workers.

The challenge lies not only in detection but also in spatially associating PPE items with workers to accurately assess compliance. Despite the advancement of deep learning based PPE detection, most studies still view it as general object detection, simply recognizing items like helmets or vests without ensuring correct and complete use by each worker. As a result, detected PPE objects are often not spatially associated with specific individuals, leading to false compliance interpretations.

To clarify this research gap, Table 2 summarizes representative PPE detection studies and highlights their limitations in terms of completeness verification and spatial association. This comparison demonstrates the necessity of a verification-oriented framework rather than detection-only solutions.

**Table 1. Comparison of PPE Detection and Compliance Verification Approaches**

Study	Method	Classes Detected	Completeness Verification with Spatial Association Logic
Nath et al. (2020)	YOLOv3	Helmet, Vest	No
An et al. (2023)	Improved YOLOv5	Helmet	No
Songn et al. (2024)	Improved YOLOv8	Helmet	No
Samperante et al. (2025)	YOLOv8	Helmet, Vest, Shoes	No
Proposed Method	YOLOv11l + Logic	Helmet, Vest, Shoes	Yes

*Note: successfully detected shoes but treated them as independent objects without binding them to the worker ID for verification.*

Moreover, existing detection systems fail to account for the anatomical correctness of PPE placement. A helmet detected in the frame does not guarantee it is worn on the worker's head it could be carried in hand or placed on a table. Similarly, a vest might be draped over equipment rather than worn on the torso. Spatial reasoning limitations can lead to verification errors, as PPE cannot simply be detected; it must also meet standards.

This research proposes a YOLOv11l based system with spatial association logic linking PPE to workers to improve the accuracy of individual assessments. Its contributions include: (1) reliable multi class detection for small and obstructed objects; (2) zone based verification that ensures the completeness and accuracy of PPE positioning; and (3) comprehensive performance evaluation to ensure system reliability for automated audits.



to ensure standardized PPE placement, going beyond simple global IoU based object detection.

## Regional Zone Partitioning

For each detected Person bounding box  $B_P = (x_p, y_p, w_p, h_p)$ , where  $h_p$  is the height of the person, the system defines three distinct zones:

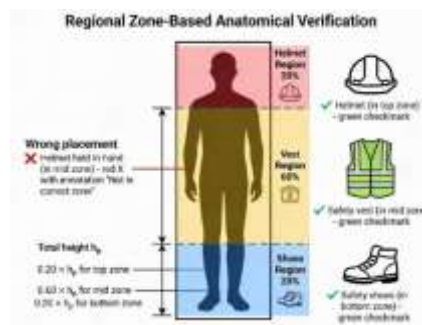
$$Z_{top} = (x_p, y_p, w_p, 0.20 \times h_p)$$

$$Z_{mid} = (x_p, y_p + 0.20 \times h_p, w_p, 0.60 \times h_p)$$

1. Top Zone (Helmet Region): Occupies the upper 20% of the person's bounding box, representing the head area.
2. Mid Zone (Vest Region): Occupies 60% of the bounding box, spanning from shoulder to waist, where high-visibility vests are typically worn.
3. Bottom Zone (Shoes Region): Occupies the lower 20% of the bounding box, corresponding to the foot area.

$$Z_{bottom} = (x_p, y_p + 0.80 \times h_p, w_p, 0.20 \times h_p)$$

**Figure 3** . Regional Zone Partitioning for Anatomical PPE Verification



This partitioning is grounded in anthropometric principles and reflects the physical requirements of OHS regulations, ensuring that PPE detection is not only spatially associated but also positionally valid.

## Zone-Specific IoU Computation

For each detected PPE item, the system computes the Intersection over Union (IoU) specifically with its corresponding anatomical zone:

$$IoU_{zone}(B_{PPE}, Z_{region}) = \text{Area}(B_{PPE} \cap Z_{region}) / \text{Area}(B_{PPE} \cup Z_{region})$$

PPE item is considered correctly associated with the worker only if:

1. Helmet:  $IoU(B_{helmet}, Z_{top}) \geq T_{helmet}$
2. Vest:  $IoU(B_{vest}, Z_{mid}) \geq T_{vest}$
3. Shoes:  $IoU(B_{shoes}, Z_{bottom}) \geq T_{shoes}$

Where  $T_{helmet}$ ,  $T_{vest}$ ,  $T_{shoes}$  are empirically determined IoU thresholds. Based on validation experiments, we set  $T_{helmet} = 0.5$ ,  $T_{vest} = 0.4$ , and  $T_{shoes} = 0.3$ , accounting for the varying sizes and occlusion patterns of each PPE type.

A worker is classified as "COMPLIANT (Safe)" if and only if all three conditions are satisfied simultaneously:

$$\begin{aligned} \ast & \text{ Status} = \text{COMPLIANT} \text{ if } (\text{Helmet} \in Z_{top}) \text{ AND } (\text{Vest} \in Z_{mid}) \text{ AND } (\text{Shoes} \in Z_{bottom}) \ast \\ & \text{ Status} = \text{NON-COMPLIANT} \text{ otherwise} \end{aligned}$$

If any PPE item is missing or detected outside its designated zone, the worker is flagged as "NON-COMPLIANT (Unsafe)" with a visual annotation indicating which item is absent or misplaced.

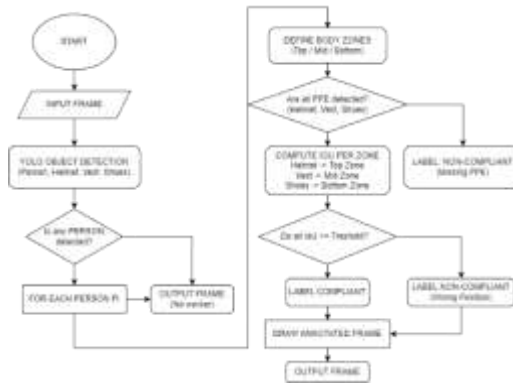
## Advantages of Regional Zone Verification

This approach offers several advantages over global IoU:

1. Prevents Misuse: PPE that is simply carried, not worn, cannot fool the system because the zones check for anatomical placement.
2. Reduces False Positives: Objects detected outside the zone, such as a helmet on a desk, are not associated with the worker.

3. OHS Complaint: Verification assesses actual compliance, ensuring PPE is worn correctly, not simply present in the worker's vicinity.
4. Pose Adaptive: Percentage based zones adjust to the pixel size of each worker supporting flow is shown in Figure 3.

**Figure 4 . Flowchart**



The overall verification process can be summarized as follows. For each input frame, the YOLOv11 detector first localizes all relevant objects (persons, helmets, vests, and shoes). For every detected person, the corresponding bounding box is partitioned into three body regions (top, middle, and bottom), and each PPE item is associated with its designated region using zone-specific IoU thresholds. A worker is labeled Compliant only if a helmet, vest, and shoes are all detected and correctly positioned in their respective zones; otherwise, the worker is labeled NonCompliant due to missing or misplaced PPE. Finally, the system renders an annotated frame with color-coded person bounding boxes (green for compliant, red for noncompliant) and textual feedback indicating the required PPE status.

## Evaluation Metrics

System performance was evaluated using standard object detection metrics :

- Precision (P): Accuracy of positive predictions. •
- Recall (R): Ability to find all positive instances.
- Mean Average Precision (mAP@50): The average precision across all classes at an IoU threshold of 0.5. •
- F1-Score: The harmonic mean of Precision and Recall, providing a balanced view of performance.

## Result and Discussion

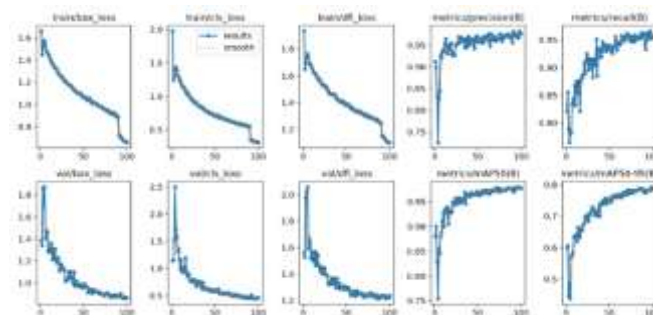
The experimental results validate the efficacy of the proposed system in both quantitative detection metrics and qualitative verification scenarios.

### Result

#### Training Convergence

The training process over 100 epochs showed stable convergence. As illustrated in Figure 4, the box loss (*train/box\_loss*) and classification loss (*train/cls\_loss*) decreased consistently, while the precision and recall metrics improved, indicating that the model successfully learned the feature representations of the PPE items without overfitting.

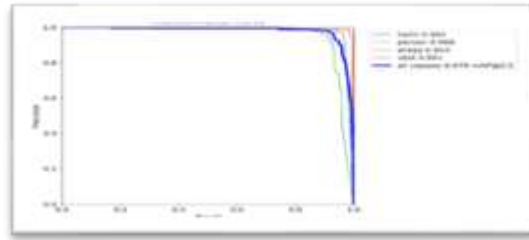
**Figure 5 . Training Data Evaluation Results**



#### Detection Performance

The quantitative evaluation reveals exceptional detection accuracy. The Precision-Recall (PR) curve in Figure 5 demonstrates an overall mAP@50 of 0.979.

**Figure 6 . Precision-Recall Curve Achieving mAP@50 of 9,79**



To visually demonstrate the model's detection capabilities on unseen data, Figure 6 displays sample predictions from the validation batch. The model accurately localizes multiple PPE items (helmets, vests, shoes) simultaneously across different worker poses and lighting conditions.

**Figure 7 . Visual detection results on validation batch showing**



**precise bounding boxes for all classes**

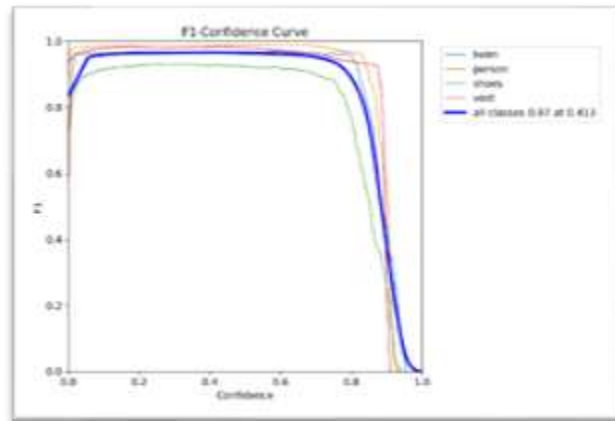
Detailed performance metrics for each class are summarized in Table 1. As shown, the model achieves high precision across all classes. The "Safety Vest" class performs best (mAP 0.992) due to its distinct visual features and high contrast colors. Even for the most challenging class, "Safety Shoes," the model maintains a robust mAP of 0.958, proving the effectiveness of the YOLOv11 architecture for small object detection.

**Table 2. Validation Results**

Class	Precision (P)	Recall (R)	mAP50	mAP50-95
Safety Helmet	0,981	0,963	0,985	0,812
Safety Vest	0,991	0,987	0,992	0,854
Safety Shoes	0,954	0,921	0,958	0,725
Person	0,988	0,978	0,991	0,865
All Classes	0,976	0,954	0,977	0,787

The F1-Confidence curve (Figure 7) indicates that the model operates optimally at a confidence threshold of approx. 0.413, achieving a peak F1-Score of 0.97. This suggests a very strong balance between precision (low false alarms) and recall (low missed detections).

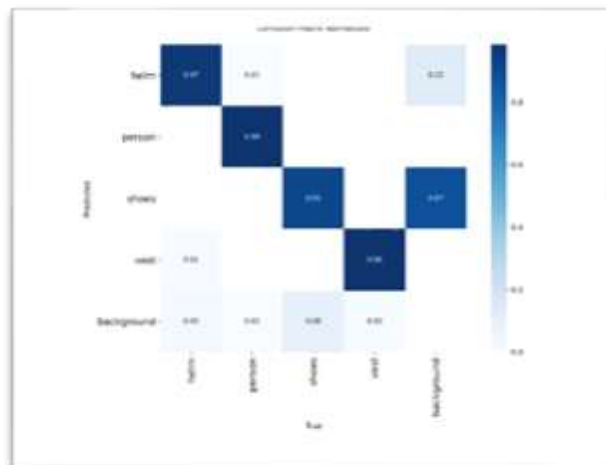
**Figure 8** .F1-Confidence Curve Peaking at 0,97



### Confusion Matrix Analysis

The normalized confusion matrix (Figure 7) further elucidates the classification accuracy. The model achieves 99% accuracy for identifying persons and 98% for vests. The primary source of error is in the "Shoes" class, where 8% of instances were misclassified as background (false negatives). This is a known challenge in computer vision for small, ground-level objects, yet the 91% true positive rate for shoes remains sufficient for effective safety auditing.

**Figure 9.** Confusion Matrix Normalize



### Qualitative Verification

The spatial association logic was tested on inference data. The system successfully distinguished compliant and noncompliant workers. Figure 8 demonstrates four scenarios: (A) a fully equipped worker detected as compliant, (B) a worker correctly identified as noncompliant due to a missing vest, (C) a worker wearing only safety shoes and a vest, which is classified as noncompliant because the helmet is absent, and (D) a worker detected with shoes and vest while holding a helmet in the hand, which is also labeled noncompliant since the helmet does not lie in the designated head region.

**Figure 10** . Verification result: (a) Compliant worker detected with full PPE; (b) Non compliant worker detected with missing vest alert.



(a)

(b)

**Figure 11**. Verification result: (c) Non compliant worker detected without helmet; (d) Non compliant worker detected



(a)

(b)

## RESULTS AND DISCUSSION

The experimental results indicate that the proposed system functions effectively not only as a PPE detection model but as a comprehensive compliance verification framework. While the high detection accuracy achieved by the YOLOv11 backbone confirms the robustness of the model, the primary contribution of this study lies in the integration of spatial association logic that enables per-worker PPE completeness assessment. This shows that the system is not only oriented towards technical performance, but also towards practical relevance in the context of implementing occupational safety in the field. Deep learning techniques have increasingly been adopted for construction safety monitoring due to their ability to automatically detect unsafe conditions and worker behaviors .

Unlike detection-oriented systems that infer compliance based solely on the presence of PPE objects in an image, the proposed approach explicitly enforces anatomical correctness through region-based verification. This system aligns detected PPE with defined body zones, preventing false compliance, such as PPE simply being carried or placed near the worker. This approach increases the validity of the results by ensuring verification under real world conditions, aligning with OHS standards.

Zone based partitioning provides a computational alternative to efficient pose estimation or keypoint methods. By dividing the PPE region proportionally within the worker's bounding box, the system adjusts for height, posture, and camera perspective while still enabling realtime processing, critical for resource constrained construction operations.

Unlike conventional PPE systems that simply detect items individually, this framework combines multi class detection with spatial verifications logic, resulting in more accurate and structured pass/fail decision, making it an automated safety audit tool rather than a passive detection tool.

Despite its high overall performance, safety footwear remains challenging due to occlusion and poor visual conditions, the system prioritizes a conservative principle, where false negative errors are safer than permitting risky behavior.

Limitations also arise in condition of heavy occlusion or low lighting. Integrating temporal tracking or additional context could improve detection consistency without changing the core design. Although tested in construction, this framework can be applied to other sectors such as manufacturing, mining, and logistics that have similar safety standards. When directly compared to previous research, this approach demonstrates more comprehensive conceptual advantages. Most previous studies based on YOLO or object detection only detect the presence of PPE without verifying its use thus risking presence bias. This study addresses this issue with body zone based spatial verifications, minimizing misinterpretation of improperly applied PPE.

Compared to pose estimation methods, this approach is simpler and computationally efficient, suitable for real time implementation on construction sites. In addition to detection, this framework generates explicit decisions (pass/fail), making it more contextual for safety evaluation. However, performance can degrade when helmet occlusion occurs, vests blend into the background. Pr when worker density is high. Computationally, while zoning is less demanding than pose estimation, evaluations such as FPS and memory usage are still necessary to ensure performance.

In terms of implementation, this system has the potential to be integrated with CCTV cameras and IoT-based safety management systems or web dashboards. However, implementation faces challenges such as lighting variations, hardware limitations, camera calibration requirements, and user acceptance. Therefore, its implementation requires not only technical readiness but also adequate operational support and safety policies.

## CONCLUSION

This study presents an automated PPE compliance verification system that extends conventional object detection into a structured, per-worker safety assessment framework. By integrating the YOLOv11 deep learning architecture with anatomically grounded spatial association logic, the proposed system verifies not only the presence of PPE items but also their correct placement and completeness for individual workers.

The system demonstrates strong detection performance, achieving an overall mAP@50 of 0.979 and a peak F1-score of 0.97, while effectively reducing false compliance cases through region-based verification. Unlike conventional detection, this framework supports consistent compliance with OHS standards and is suitable for continuous, low bias safety audits, with a safety first approach. Although shoe detection is still hampered by occlusion and low lighting the system's performance remains adequate for field monitoring.

Further development will focus on integrating temporal tracking, expanding the dataset to nighttime and extreme environments, and adding a real time alert system to enhance safety management. These enhancements are expected to further strengthen the applicability of the proposed system for automated construction safety supervision.

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