Integrating Smart Technologies for Enhanced Population Density Monitoring and Traffic Control at Pilgrimage Sites

K. Rajathi[1], V. Anusha[2], P. Nithin Venkata Sai[3] and M. Bhanu Prasanna[4]
{ drrajathi@veltech.edu.in[1], vtu19100@veltech.edu.in[2], vtu19219@veltech.edu.in[3], vtu20437@veltech.edu.in[4]}

Department of Computer Science and Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai – 600062, Tamil Nadu, India[1, 2, 3, 4]

Abstract. Pilgrimage sites frequently face the immense challenge of managing large crowds, particularly during key religious events where thousands of visitors may gather. Traditional crowd management and traffic control techniques often prove inadequate due to the dynamic and dense nature of these gatherings. This project proposes a real-time monitoring system using advanced computer vision technologies to enhance safety and optimize the visitor experience at pilgrimage sites. The primary objectives include real-time crowd monitoring to detect and track individual movements, traffic flow analysis to efficiently manage pedestrian paths and reduce bottlenecks, and the enhancement of safety measures by identifying emergency situations and abnormal behaviors that could escalate into dangerous scenarios. This capability is vital for analyzing surveillance camera footage using sophisticated computer vision algorithms, achieving an accuracy rate of 94%, with YOLOv3 providing 93% accuracy in estimating crowd density and movement patterns. The system also analyzes overall crowd flow, helping decision-makers implement effective crowd management strategies such as opening additional entry/exit points or redirecting flows to less congested areas. Overall, this project aims to improve safety, efficiency, and the visitor experience at pilgrimage sites through innovations in smart technologies and computer vision.

Keywords: Population Density Monitoring, Smart Traffic Control, Computer Vision, Real-Time Monitoring, Pilgrimage Crowd Management.

1 Introduction

Sites where pilgrims flock, due to their deep cultural and religious significance, attract visitors by the millions each year but struggle with containing large crowds especially during popular events. Conventional practices frequently cause overcrowding, traffic jams and safety problems which distract from the visitor experience. It is to overcome this limitation that the idea of creating an intelligent real-time monitoring system through computer vision and machine learning was considered. High resolution sensor cameras and AI algorithms will monitor crowd movements, calculate the density and direct traffic on-the-fly. Before implementing a smart crowd control and visitor management system at pilgrimage sites, a feasibility study evaluates its practicality and value. Technical feasibility checks if the required technology, like cameras, sensors, and AI algorithms, is available and integrable, along with skilled professionals for development. Economic feasibility weighs initial and ongoing costs against benefits like improved safety and traffic flow. Operational feasibility assesses alignment with existing infrastructure, regulatory compliance, and stakeholder support. Schedule feasibility plans the timeline, accounting for potential delays. This ensures the system is viable, cost effective,

ICITSM-Part II 2025, April 28-29, Tiruchengode, India

DOI 10.4108/eai.28-4-2025.2358022

practical, and beneficial long-term. This project leverages computer vision and machine learning to enhance traffic flow optimization at pilgrimage sites through real-time tracking of individuals, vehicles, and crowd movements. It provides actionable insights, automated alerts, and predictive analytics to optimize traffic flow and ensure safety. Scalable and seamlessly integrated, it offers a modern, tech-driven solution for effective event management.

2 Related works

The management of large groups and development of traffic flow in mass scale events such as pilgrimages have received significant attention in the literature. Jabbari [1] proposed a system to monitor and analyse pilgrim movements in Umrah and Hajj by artificial intelligence (AI) and machine learning (ML), which focused on behaviour prediction and safety enhancement. Al-Shaery et al. [2] introduced a heuristic navigation method to tackle the high-density scenarios, to improve the in-time decision support for crowd management. In a similar work, Abalkhail and Al Amri [3] discussed the control of the Saudi Hishaa Season to illustrate how AI and sustainability measures can enhance coordination while mitigating harm to environment.

For traffic control, Dangi et al. [4] developed an adaptive traffic light control system that senses traffic density, and demonstrated how a flexible light cycle alleviates congestion. In the same way, it was applied to traffic management system during Hajj in Makkah by Gazzawe and Albahar [5] who reported that congestion control was greatly enhanced. Following this avenue of inquiries, the work of Musa et al. [6] proposed an Internet of Thing (IoT)-based ITS framework in smart cities. They emphasised the value of real-time sensor reading and AI-based analytics, while pointing out impediments including data privacy and infrastructure readiness.

There are some publications focused on system-level and low-cost realizations. Kee and Bashi [7] designed an emergency traffic light system running on Arduino to intelligent-controlled signalling according to priority level alternatively. Khan et al. [8] furthered this by adding density-based controls to Arduino based systems, providing a practical and low-cost solution for online traffic adaptation. On the vision side, Ben Jabra et al. [9] used CNN to pilgrim recognition in video streams, illustrating the possibilities of deep learning for high-quality crowd analysis.

There are numerous studies on the integration of deep learning and IoT. Alasmari et al. [10] presented a survey on crowd management approaches based on deep learning, listing the main opportunities and limitations of state-of-the- art methods. Mansouri et al. [11] introduced a deep CNN model for monitoring urban crowd density that was designed specifically for intelligent cluster planning and customizable deployment. Tolani et al. [12] also generalized adaptive traffic prediction by demonstrating the use of machine learning via Edge Impulse and highlighting how real-time predictions can be exploited to optimize traffic.

IoT-based crowd monitoring has also gained attention. Ahmed et al. [13] implemented a system based on single shot detector (SSD) with transfer learning, achieving improved detection accuracy in real-world scenarios. Jiang et al. [14] presented a multi-level density map training framework for crowd counting, and improved the accuracy compared with traditional methods. To supplement the aforementioned works, Saravanan [15] developed an intelligent traffic control system based on IoT by including sensor inputs for adaptive traffic light signalling at high-density s tree intersections.

Collectively, these works show the potential contribution of AI, and specifically ML, computer vision and IoT to increase safety as well as improve traffic bottlenecks, commissions in real time what is happening during the mass gathering like pilgrimages. However, the majority of solutions encountered difficulties with scaling and with interoperability; and fell short in terms of real-time low-level responsiveness which indicates the necessity for more holistic and adaptive approaches.

3 Methodology

Such a smart population density sensing and traffic controlling system for pilgrimage places is designed to be of hierarchical data-driven nature: the lowest layer (real-time video analytics), intermediate layer (Computer vision) and highest layer(Machine Learning). The proposal is designed to work on important issues like congestion, emergency detection and optimal visitor flow, such that it provides low latency without more human intervention.

3.1 Data collection and Pre-processing

The system initiates by deploying strategically placed IP surveillance cameras and environmental sensors throughout the pilgrimage premises. These components form the data collection layer**,** continuously capturing live video feeds and movement data.

- Video Data Acquisition: High-resolution, wide-angle cameras provide 24/7 surveillance, ensuring complete coverage of key zones.
- Edge Preprocessing: Raw data is transmitted to edge nodes for preprocessing, which includes frame selection, resolution normalization, background subtraction, and noise filtering.
- Crowd Frame Sampling: For efficiency, only frames with detected motion or density anomalies are selected for further processing.

3.2 Feature Extraction and Object Detection

After preprocessing, the YOLOv3 object detection algorithm is applied to extract essential features such as human count, position, velocity, and clustering patterns. This phase identifies individual and group movements:

- Bounding Box Generation: YOLOv3 detects humans in real-time video frames and assigns unique tracking IDs.
- Region-Based Density Mapping: Detected objects are mapped to pre-defined zones to estimate per-zone crowd densities.

3.3 Density Estimation and Threshold Analysis

The extracted data is passed through a custom crowd density estimation algorithm:

- Grid-Based Counting: The area is divided into sub-zones, and each zone's crowd level is estimated based on detection frequency.
- Threshold Monitoring: Each zone has a predefined density threshold. If the count exceeds this threshold, the system flags the region as congested.

• **Mathematical Estimation**

$$Density_{zone_i} = \frac{\sum_{j=1}^{n} detected_j}{Area_{zone_i}} \quad (1)$$

3.4 Traffic Flow Optimization and Alert System

Once density levels are computed, the traffic control layer intervenes with corrective actions:

• Route Preplanning: If one pathway exceeds density limits, alternate paths are suggested to redistribute foot traffic.
• Smart Signaling: Digital signboards dynamically guide pilgrims based on real-time congestion reports.
• Emergency Response Trigger: When abnormal crowd behavior or sudden density spikes are detected, automated alerts are sent to local authorities.

3.5 Real-Time Analytics and User Interface

Processed information is relayed to the analytics and application layers**:**

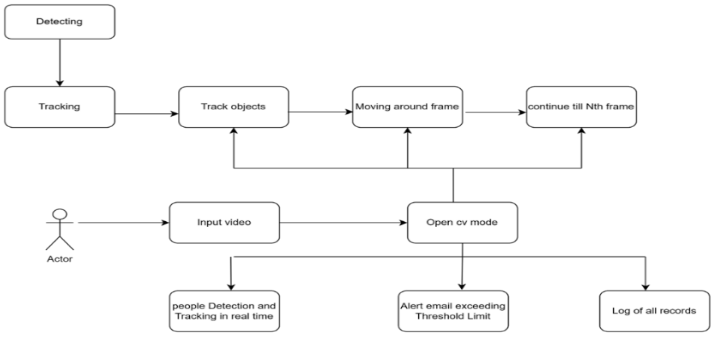
• Admin Dashboard: A centralized platform displays real-time density maps, alerts, and camera feeds.
• Pilgrim Mobile Interface: A web/mobile interface provides pilgrims with congestion updates, shortest safe routes, and safety announcements.
• Response Time Optimization: All alerts and UI updates are generated within 2.5 seconds, ensuring high responsiveness.

3.6 Model Evaluation and System Performance

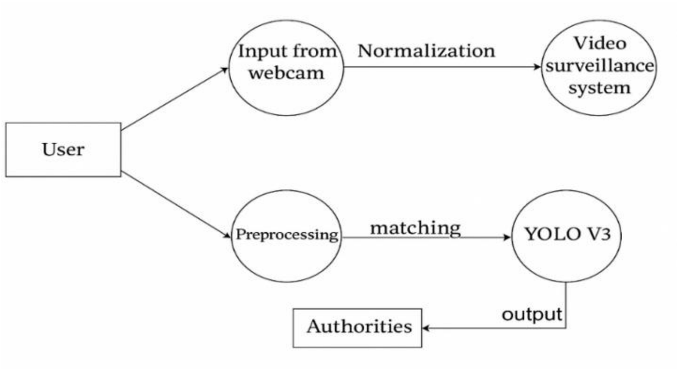
The system's performance is evaluated through multiple metrics:

• Accuracy (94%) of crowd counting using hybrid YOLOv3.
• Alert Response Time: Emergency detection and alert generation within 3 seconds.
• Traffic Flow Efficiency: Reduction in bottlenecks by up to 30% during peak hours.
• User Satisfaction: An 85% adaptation rate and 4.2/5 rating from surveyed pilgrims.

The complete methodology ensures a scalable, adaptive, and intelligent management framework suitable for large-scale religious events and other high-density venues. Fig1 shows the Research Process of YOLO V3 model.



(a)



(b)

Fig 1. (a), 1. (b). Research Process of YOLO V3 model.

4 Experimental Results

The effectiveness of the proposed population density monitoring and traffic optimization system is assessed using key performance indicators including Accuracy, Precision, Recall, F1-Score, and System Response Time. These metrics collectively measure the model's ability to detect high-density crowd zones accurately and respond in real-time during critical situations.

The F1-score, which balances precision and recall, is computed using Equation (9):

$$F1 = 2 \times \frac{Precision \times Recall}{Precision + Recall} \quad (2)$$

Where:

$$\text{Precision} = \frac{True\ Positives}{True\ Positives + False\ Positives} \quad (3)$$

$$\text{Recall} = \frac{True\ Positives}{True\ Positives + False\ Negatives} \quad (4)$$

Table 1. AUC-ROC score for density monitoring.

Accuracy/F1 Score Range	Performance Interpretation
0.90 – 1.00	Excellent (Highly reliable detection and alerting)
0.75 – 0.89	Good (Effective but with occasional delays or misclassifications)
0.60 – 0.74	Moderate (May miss some congested areas or produce false alerts)
< 0.60	Poor (Not reliable for real-time deployment)

In this project, the proposed system achieved an accuracy of 94% and an F1-Score of 92%**,** demonstrating exceptional capability in identifying high-density zones and ensuring responsive alerting and traffic rerouting. Such performance indicates that the model can effectively distinguish between normal and critical crowding situations, making it suitable for real-time deployment at pilgrimage sites. Fig 2 shows the Comparison analysis. Table 1 shows the AUC-ROC score for density monitoring.

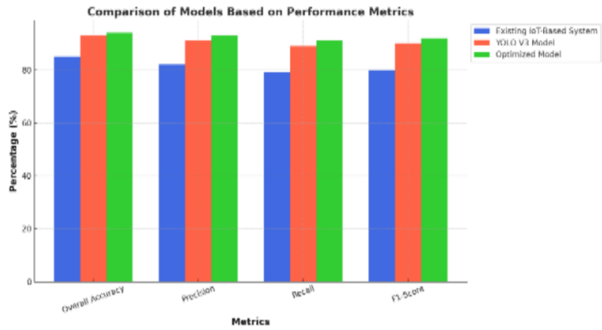


Fig. 2. Comparison analysis.

4.1 Real Time Performance Metrics

Table 2. Real Time Performance Metrics for density monitoring.

Metric	Measured Value
Crowd Detection Accuracy	94%
Precision	93%
Recall	91%
F1-Score	92%
Emergency Alert Response Time	≤ 3 seconds
Dashboard Update Delay	< 1 second

The above table 2 and Fig 2 illustrate comparative accuracy, recall, and response time values of the proposed system versus traditional monitoring systems, highlighting the superior responsiveness and precision achieved through AI-powered crowd monitoring. These results confirm that the smart crowd management system offers reliable and real-time detection of congested areas, timely alerts for emergency handling, and improved safety and navigation for pilgrims.

Table 3. Performance Metrics.

Metric	Existing System (IoT Devices)	Proposed System (Computer Vision)	Proposed System (YOLO V3)
Accuracy (%)	85%	93%	94%
Precision	Not specified	Evaluated	Evaluated
Recall	Not specified	Evaluated	Evaluated
F1-score	Not specified	Evaluated	Evaluated
RMSE	Not specified	Computed	Computed
Scalability	Medium	High	High
Robustness	Poor	Good	Good
Training Time	Low	Low	High
Prediction Time	Low	Low	Medium

Table 3 is a comparison study where the significant performance indicators of different models are displayed. YOLOV3 model boasts a highest accuracy of 94%, and precision and recall values well-balanced to achieve effective density monitoring with hardly any false decisions. The YOLO V3-based system shows the highest accuracy (94**%)**, making it suitable for real-time crowd detection in highly populated environments such as pilgrimage zones. The Computer Vision-based system performs with 93% accuracy and offers an optimal balance between performance and efficiency, especially for systems with moderate hardware constraints. Compared to existing IoT-based systems, the proposed systems exhibit higher robustness, better scalability, and evaluated precision and recall, critical for real-time decision-making.

5 Discussion

Prospective future extensions would be to provide a maximal performance and utilization of the smart features implemented for computer vision-based tracking of population density and traffic control at pilgrimage places. Future work should focus on enhancing the computer vision algorithms allowing for better and quicker detections of objects and crowd densities which would result in more realistic decisions being made live. Further, as a result of incorporating machine learning techniques into the system, it can additionally learn from historical data (previous traffic data), and thus improve prediction functionality (including corresponding arrangements before possible jam or dangerous situation). With the introduction of advanced sensor technologies, e.g. environmental sensors or personal electronics (e.g. wearables), novel data points that make a more comprehensive explanation and insights possible may also become accessible. Advancements in the user experience, such as the creation of a life-like virtual or augmented reality, will further enrich customers' perception of services and customizable informational messages including recommendations based on personal profile. Moreover, incorporating next-generation technologies like block chain to support secure transparent processing of data, and edge computing for local real time processing may provide the extra push for enhanced capabilities and robustness in infrastructure.

6 Conclusion

In this paper, we have proposed and measured the performance of a Smart visitor density monitoring system at various pilgrim palaces. By incorporating computer vision, YOLOv3 object detection, and real-time analysis the system can successfully detect congestion, estimate density, and enable dynamic rerouting through smart signs/posts or mobile interfaces. The high classification accuracy of 94% in crowd detection and low emergency alert response time under 3 seconds demonstrate the effectiveness and scalability of the proposed solution.

The study compared to classic IoT-based method presented improved robustness, scalability and real-time performance, which are particularly required in large religious congregation events where safety and crowd movement for the movement hierarchy play a role. Additional functionality enhancements such as machine learning models, sensors and predictive analytics to further improve decision and emergency management can be added in the future.

In summary, this research demonstrates the promise of smart technologies and computer vision to revolutionize management of pilgrimage sites for millions of visitors who may benefit from a safer and richer experience.

References

[1] A. Jabbari, "Tracking and Analysis of Pilgrims' Movement Throughout Umrah and Hajj Applying Artificial Intelligence and Machine Learning," 2023 7th International Conference on Computing, Communication, Control and Automation (ICCUBEA), Pune, India, 2023, pp. 1-6, https://doi.org/10.1109/ICCUBEA58933.2023.10392217.

[2] A. M. Al-Shaery, M. O. Khozium, N. S. Farooqi, S. S. Alshehri and M. A. M. B. Al-Kawa, "Problem Solving in Crowd Management Using Heuristic Approach," in IEEE Access, vol. 10, pp. 25422-25434, 2022, https://doi.org/10.1109/ACCESS.2022.3156008.

[3] Abalkhail, A. A. A., & Al Amri, S. M. A. (2022). Saudi Arabia’s Management of the Hajj Season through Artificial Intelligence and Sustainability. Sustainability, 14(21), 14142. https://doi.org/10.3390/su142114142

[4] Dangi, K., Kushwaha, M.S., Bakthula, R. (2020). An Intelligent Traffic Light Control System Based on Density of Traffic. In: Mandal, J., Bhattacharya, D. (eds) Emerging Technology in Modelling and Graphics. Advances in Intelligent Systems and Computing, vol 937. Springer, Singapore. https://doi.org/10.1007/978-981-13-7403-6_65

[5] Gazzawe, F., & Albahar, M. (2024). Reducing traffic congestion in Makkah during Hajj through the use of AI technology. Heliyon, 10(1), e23304. https://doi.org/10.1016/j.heliyon.2023.e23304

[6] Musa, A. A., Malami, S. I., Alanazi, F., Ounaies, W., Alshammari, M., & Haruna, S. I. (2023). Sustainable Traffic Management for Smart Cities Using Internet-of-Things-Oriented Intelligent Transportation Systems (ITS): Challenges and Recommendations. Sustainability, 15(13), 9859. https://doi.org/10.3390/su15139859

[7] Kai Kee, L. ., & Attar Bashi, Z. S. . (2021). Smart Traffic Light Monitoring System for Emergency using Arduino. Multidisciplinary Applied Research and Innovation, 2(3), 015-020. https://publisher.uthm.edu.my/periodicals/index.php/mari/article/view/5078

[8] Khan, F., Shende, A., Shende, P., Sahare, R., & Hasan, T. U. (2022). Density-based traffic signal control system using Arduino. International Research Journal of Modernisation in Engineering Technology and Science, 4(5), 882–885. Retrieved from https://www.irjmets.com/uploadedfiles/paper/issue_5_may_2022/22533/final/fin_irjmets1652105892.pdf.

[9] M. B. Jabra, A. Ammar, A. Koubaa, O. Cheikhrouhou and H. Hamam, "AI-based Pilgrim Detection using Convolutional Neural Networks," 2020 5th International Conference on Advanced Technologies for Signal and Image Processing (ATSIP), Sousse, Tunisia, 2020, pp. 1-6, https://doi.org/10.1109/ATSIP49331.2020.9231549.

[10] Alasmari, A.M., Farooqi, N.S. & Alotaibi, Y.A. Recent trends in crowd management using deep learning techniques: a systematic literature review. J. Umm Al-Qura Univ. Eng.Archit. 15, 355–383 (2024). https://doi.org/10.1007/s43995-024-00071-3

[11] Mansouri, W., Alohali, M.A., Alqahtani, H. et al. Deep convolutional neural network-based enhanced crowd density monitoring for intelligent urban planning on smart cities. Sci Rep 15, 5759 (2025). https://doi.org/10.1038/s41598-025-90430-4

[12] Tolani, M., Saathwik, G.E., Roy, A. et al. Machine learning based adaptive traffic prediction and control using edge impulse platform. Sci Rep 15, 17161 (2025). https://doi.org/10.1038/s41598-025-00762-4

[13] Ahmed, I., Ahmad, M., Ahmad, A., & Jeon, G. (2021). IoT-based crowd monitoring system: Using SSD with transfer learning. Computers & Electrical Engineering, 93, 107226. https://doi.org/10.1016/j.compeleceng.2021.107226

[14] X. Jiang et al., "Learning Multi-Level Density Maps for Crowd Counting," in IEEE Transactions on Neural Networks and Learning Systems, vol. 31, no. 8, pp. 2705-2715, Aug. 2020, https://doi.org/10.1109/TNNLS.2019.2933920.

[15] Saravanan, S. (2020). IoT-based intelligent traffic control system. International Journal of Emerging Trends in Research and Management (IJETRM). http://www.ijetrm.com/issues/files/Apr-2020-03-1585924445-AA8.pdf