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AI and IoT-Based Frameworks for Real-Time Crowd Monitoring and Security

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ABSTRACT

Effective crowd management is critical for ensuring public safety during large-scale events and in densely populated urban environments. Recent advances in deep learning and computer vision have enabled real-time crowd behavior analysis, including the detection of abnormal actions such as pushing, which can lead to dangerous situations. This paper presents a review of cloud-based deep learning frameworks, focusing on the use of convolutional neural networks (CNN) and optical flow models for early detection of pushing behavior in crowded event entrances. We discuss the integration of pre-trained deep models with live video stream processing to achieve high accuracy and low latency. Existing datasets and evaluation metrics are examined, with reported detection accuracies reaching up to 87%. The review also highlights challenges such as data privacy, real-time processing constraints, and the need for comprehensive models that consider multiple behavioral and environmental factors. Finally, future directions are proposed for developing autonomous crowd safety systems that mimic human situational awareness in complex urban settings.

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Introduction

Smart cities are increasingly characterized by the use of advanced information technologies, the Internet of Things (IoT), and communication networks to enhance public services such as crowd management, smart surveillance, and public safety (Almeida, 2024). The primary goal of recent research is to improve the safety and security of urban populations by integrating autonomous modules with advanced deep learning models for real-time surveillance, abnormal behavior detection, threat identification, and crime prevention within crowds (Batty, 2018; Ramalingam, 2024; Dmitrieva, 2024; Al Kindhi, 2023; Halboob, 2024).

Hussain et al. (2025) emphasize that smart surveillance is at the core of these advancements, reviewing recent progress in AI-driven surveillance systems and discussing ethical considerations such as privacy and algorithmic bias. AI technologies play a critical role in bridging gaps in autonomous decision-making for smart cities, enabling more efficient urban management and public safety strategies (Hussain, Azam, et al., 2024). Furthermore, innovative context-aware security solutions, such as facial recognition systems, provide adaptive, real-time monitoring capabilities that reduce false alarms and improve response times (Hussain, et al., 2023).

Azam, M.(2024)

Smart Cities and Their Role in Crowd Management

Smart cities utilize advanced technologies such as IoT, AI, and big data analytics to create intelligent urban ecosystems aimed at improving quality of life, sustainability, and public safety (Hussain et al., 2024). Crowd management is a critical domain within smart cities, addressing challenges related to urban population density, mass events, and emergency responses. The integration of smart surveillance, real-time data processing, and autonomous decision-making enables cities to monitor crowd behavior, detect anomalies, and respond proactively to ensure safety and security.

Domains of Application in Smart City Technologies

Smart city technologies span several key domains, including:

- **Smart Surveillance:** Real-time monitoring of public spaces to detect security threats and abnormal behavior.
- **Traffic and Transportation Management:** Optimization of traffic flow and public transit systems.
- **Environmental Monitoring:** Tracking pollution, weather conditions, and energy usage for sustainability.
- **Healthcare:** Remote monitoring and management of public health.

Emergency Response: Coordinated actions during disasters or mass emergencies.

Among these, **smart surveillance** plays a pivotal role in maintaining public safety by leveraging AI-driven analytics to manage crowds effectively.

Smart Surveillance Domain: Focus on Crowd Management

Within smart surveillance, crowd management focuses on monitoring large gatherings to detect potential risks such as overcrowding, pushing, or panic situations. AI models—particularly deep learning frameworks like CNNs—are widely used to analyze video feeds, recognize crowd behaviors, and predict abnormal events (Hussain, 2025). These systems integrate multi-sensor data, including CCTV, IoT devices, and environmental sensors, to provide a comprehensive picture of crowd dynamics in real time. Moreover, ethical considerations such as privacy protection and data security are integral to the deployment of these technologies in public spaces (Li, 2024; Hussain, 2025).

Detection and Monitoring of Crowd Behavior

Deep learning models like convolutional long short-term memory networks (ConvLSTM) are increasingly used for recognizing human activities in diverse real-world applications, including video surveillance, healthcare, and human-machine interactions. These models assign action labels to video frames, enabling the identification of individual or group behaviors with high accuracy (Saba, 2023). The growing prevalence of IoT devices provides critical data streams that feed AI algorithms, enhancing anomaly detection and security monitoring, thus helping prevent crimes and terrorist attacks (Hussain et al., 2024).

Large-scale events, such as sports games and religious gatherings, present high risks where crowd pushing behavior can lead to dangerous situations. The integration of surveillance cameras with computer vision techniques, especially convolutional neural networks (CNN), facilitates automated detection of such abnormal behaviors. CNN architectures require extensive training data but are powerful in modeling complex crowd behaviors. A cloud-based deep learning framework utilizing pre-trained deep optical flow models and recurrent all-pair field transforms has been proposed for live detection of pushing behavior in event entrances (Alia, 2023).

Crowd Behavior Recognition and Safety Assessment

Abnormal event detection in crowded public spaces is essential for managing risks at assemblies and sports events. Systems such as the Scenario Recognition Engine (Saxena, 2008) and decision support systems (DSS) tailored for smart cities contribute significantly to this goal by monitoring threats like improvised explosive devices (IEDs) and mass gathering vulnerabilities (González-Villa, 2024). Advanced crowd tracking employs techniques like conditional random fields (CRF), deep learning, super-pixel preprocessing, and social force models to accurately detect and analyze crowd movement and behaviors (Abdullah, 2023).

Emergency evacuation modeling during crises uses cellular automata, social force, and agent-based models to simulate crowd panics, stampedes, and blocked pathways, aiding in planning safe egress routes (Guo, 2024). AI and machine learning applications also extend to managing crowd control during mass events, enhancing public safety through real-time monitoring and behavior regulation (Struniawski, 2024).

Privacy Protection and Ethical Considerations

Crowd sensing technologies must safeguard individual privacy amid widespread data collection. Advanced privacy-preserving schemes involve batch verification, data anonymity, cryptographic perturbation, and unlink ability to ensure secure and trustworthy data management (Li, 2024). Hussain (2025) highlights the ethical implications of deploying pervasive AI surveillance systems and stresses the need for transparency, fairness, and compliance with legal standards.

Advances in Crowd Counting and Smart Surveillance

Reliable crowd counting is fundamental for public safety, urban planning, and event management. Modern approaches utilize single-column, multi-column, and hybrid deep learning architectures to achieve accurate and efficient crowd density estimation (Khan, 2023). Smart surveillance systems combine AI, machine learning, and sensor networks to enhance crowd behavior recognition, security assessment, and real-time intervention capabilities (Qaraqe, 2024). Emerging trends include the application of nudge theory, multi-sensor fusion (LIDAR, gas sensors, Bluetooth), and integrated personnel management systems to reduce risks and improve crowd control effectiveness (Nishinari, 2024).

Emerging Frameworks and Technologies

Edge-assisted federated learning frameworks represent the cutting edge of crowd management solutions, enabling distributed data processing and enhanced privacy preservation while supporting drone-based surveillance and IoT data acquisition (Siddiqa, 2024). Decision support systems developed for smart cities improve preparedness for terrorist threats and mass casualty events by integrating ICT tools with real-time monitoring and alerting capabilities (González-Villa, 2024).

Qualitative Insights and Practical Applications

Qualitative analyses of crowd control during religious festivals reveal critical safety risks related to overcrowding and emphasize the importance of emergency response preparedness strategies (Leonardus, 2024). Such studies provide practical insights that complement technological approaches, ensuring a holistic understanding of crowd dynamics in various contexts.

Meta Table.

Serial No	Reference	Methods	Data Set	Finding	Future work
1	(Halboob, 2024)	Deep-learning, (CNN) Convolutional Neural Network, Yolo, FCN	Camera footage, Sensor Data, Environmental Data	The frame work effectively predicted crowd incident, quick response time	Real-time update Scalability and use AI models
2	(Struniawski, 2024)	Artificial Intelligence Model, FL	Video Data, IOT Sensor Data, GPS and Location Data, Social Media Data	Effectiveness of Structured protocol, Information technologies enhance the ability to monitor crowd behavior and respond issues in real-time	Advance AI Models, Rea-Time systems, Strong infrastructure

3	(Li, 2024)	AI Model, CNN Model	Crowd Sensing Data, system logs, User Information Data	Enhance Efficiency, Strong privacy, Scalability	Improve Efficiency, Real-world Testing, User Control
4	(Khan, 2023)	Deep learning, Use CNN, Multi models approaches	Artificially Data set, large Data set Use Deep learning	Advancement in Deep-Learning, Diverse Architectures, importance of Loss Functions	Real-Time counting, AI Explain-ability,
5	(Qaraqe, 2024)	Advance AI, (ML) Machine learning	IOT Sensor Data, Social Media Data, AI crowd Data set	Enhanced Security, Effective Crowd Behavior Recognition, Real-Time processing	Develop Hybrid Models, Explain able AI, Real-time Data
6	(Nishinari, Recent Developments in Crowd Management: Theory and Applications, 2024)	Deep learning, Machine learning	Smart Surveillance Data set, Global dataset, Real-world Data set	Accident control, Enhance Guidance Provide efficient guidance,	Enhance Machine learning, privacy enhance system,
7	(Sandeep)	NLP, Edge computing, Convolutional Neural Network (CNN),	Workplace Activity Data set, Event Based data set	AI and ML significantly improves ability to monitor and manage crowds, public safety improvement	Domains Models, Real-Time Models, Better AI system, crowd Monitoring
8	(Siddiqa, 2024)	Machine learning, Edge computing, Federated learning (FL)	Smart crowd Dataset, Edge (IOT) data, crowd surveillance video data set	Real-Time processing Edge computing enables timely data processing	Enhance FL, Enhance Machine learning model
9	(Guo, 2024)	Machine learning, Agent-based model, force-Based model	Real-World crowd footage, IOT data	Panic Behavior, Exit Availability, Impact of Crowd Density	Crowd control integration, develop AI models, Enhance date
10	(Abdullah, 2023)	Social force model, Deep learning Model	Real-world crowd dataset, IOT dataset,	Enhanced Tracking Accuracy , Effective Anomaly Detection , Real-	Hybrid Model, Real-Time processing,

				time Processing	
11	(Gonz{\'a}lez-Villa, 2024)	Use Machine learning platforms, AI Algorithm	Environmental Monitoring Data, smart city incident logs, Social Media video Data, Traffic Flow data set	Effective Anomaly Detection, Real-Time Applicability	Behavioral Analysis , privacy ,Real-Time collaboration Tools
12	(Leonardus, 2024)	Qualitative Approach, Thematic Analysis	Emergency Response Preparedness (EPR) frame work	Managing crowd flow, one-time entry system	Focus other significant risk, Identified critical but not explore depth in study

Discussion

Numerous techniques have been developed and applied for effective crowd management and anomaly detection, often leveraging mobile applications and data analytics platforms. Suitable models for anomaly detection commonly include deep learning architectures such as Convolutional Neural Networks (CNN), Fully Convolutional Networks (FCN), and YOLO (You Only Look Once) for real-time object detection. For security purposes, fast algorithms are essential, leading to frameworks that divide classification tasks between deep learning and CNN-based models to optimize performance (Halboob, 2024).

Effective crowd management during large-scale events requires comprehensive planning, communication, and behavioral control to protect citizens' daily activities and enhance participant satisfaction. Mobile CCTV systems integrated with AI and machine learning enable real-time monitoring and control of human behavior, reducing risks and improving overall event management (Struniawski, 2024).

Privacy protection remains a critical concern in crowd sensing, especially when multiple users contribute data. Advanced schemes have been proposed to ensure data anonymity, establish trust frameworks, and implement cryptographic perturbations and unlinkability techniques, which collectively improve privacy preservation without compromising data utility (Li, 2024).

Accurate crowd counting is vital for safety, security, and urban planning. Techniques employing AI and deep learning—using single-column, multi-column, and hybrid models—have shown improvements in reliability and efficiency for event management and public safety applications (Khan, 2023). Similarly, secure smart surveillance systems utilize multiple models combining camera networks, AI, machine learning, and strong data security measures for crowd behavior recognition (Qaraqe, 2024).

Crowd behavior modeling often incorporates mathematical frameworks such as nudge theory and leverages multi-sensor data from LIDAR, gas sensors, Bluetooth, and cameras. These systems integrate comprehensive personnel management and accounting systems (CMPASS) to improve crowd control effectiveness and privacy preservation. Collaboration between security forces, deep learning, and machine learning models enhances operational outcomes compared to traditional methods (Nishinari, 2024).

AI and machine learning algorithms are increasingly used for detecting unusual crowd behavior through CCTV analysis, providing real-time security threat detection and crowd pattern prediction. Surveys of CNN-based approaches discuss network architectures, loss functions, and training strategies, while also exploring deep neural networks (DNNs) and hybrid models for crowd monitoring and localization, weighing their strengths and limitations (Sandeep, 2024).

Emerging frameworks, such as edge-assisted federated learning, propose multi-layer architectures involving data acquisition, edge computing, cloud computing, and application layers to address crowd management challenges. These IoT-based solutions incorporate fog computing and drone-based surveillance to enhance situational awareness (Siddiqa, 2024).

Crowd panic during emergencies, such as terrorist attacks, can cause dangerous pushing or blockages in crowded areas. Predictive models simulate pedestrian behavior to design safe evacuation routes, employing semantic segmentation techniques combined with histogram analysis through deep learning and Feature Pyramid

Networks (FPN) to accurately detect and track crowd movements (Guo, 2024; Abdullah, 2023).

Smart city initiatives increasingly incorporate decision support systems (DSS) to manage security threats, including controlling mass shooting attacks and mitigating risks associated with soft targets and mass gatherings. These systems integrate information and communication technologies (ICT) to enhance citizen welfare and urban safety (González-Villa, 2024).

Qualitative research on crowd control during religious festivals highlights significant risks of overcrowding and safety incidents. Emergency Response Preparedness (ERP) strategies have been effectively applied to mitigate these challenges and ensure public safety during mass gatherings (Leonardus, 2024).

Conclusion

Despite the significant advancements in crowd security and surveillance technologies discussed earlier, current models often rely on a limited number of measures or focus on single specific indicators to assess crowd environments. This approach restricts their ability to comprehensively understand complex crowd dynamics and predict security threats effectively. There is a clear need for a more holistic model that incorporates a wide range of relevant factors, including environmental context and individual behavior patterns. Such a model would emulate human situational awareness, enabling more accurate and autonomous decision-making in crowd security management. Future research, including this work, aims to develop such an advanced, human-like autonomous system to enhance the safety and security of crowded environments.

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