



AI-Based Fire Detection and Prediction Systems for Smart Buildings: A Comprehensive Review

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Abstract

Fire hazards in smart buildings pose significant risks to life, infrastructure, and economic assets. Traditional fire detection systems, primarily based on smoke, heat, and flame sensors, often suffer from delayed response times and high false alarm rates. Recent advancements in Artificial Intelligence (AI), particularly machine learning (ML) and deep learning (DL), have enabled the development of intelligent fire detection and prediction systems with improved accuracy, reliability, and response speed. This review paper presents a comprehensive analysis of AI-based fire detection and prediction techniques for smart buildings, focusing on sensor-based, vision-based, and hybrid approaches. It further explores predictive modeling using AI for early fire risk assessment, integration with IoT-enabled smart building frameworks, and real-time decision-making systems. Challenges, limitations, and future research directions are also discussed, emphasizing the need for robust datasets, real-time processing capabilities, and system scalability. The study concludes that AI-driven fire safety systems have the potential to significantly enhance proactive fire management in next-generation smart infrastructure.

Keywords

Artificial Intelligence, Fire Detection, Smart Buildings, Deep Learning, IoT, Fire Prediction



1. Introduction

Fire incidents in modern built environments continue to pose a serious threat to human life, infrastructure, and economic stability. The rapid growth of urbanization and the increasing complexity of smart buildings have further amplified fire risks due to higher energy consumption, dense occupancy, and extensive use of electrical and electronic systems. Globally, fire-related disasters account for significant fatalities and financial losses each year, emphasizing the urgent need for more efficient and intelligent fire safety systems [1]. Traditional fire detection systems, which primarily rely on smoke detectors, heat sensors, and flame detectors, operate based on predefined threshold values. Although these systems are widely implemented, they often suffer from delayed response times and high false alarm rates caused by environmental interferences such as dust, humidity, and non-fire aerosols [2].

Smart buildings, characterized by the integration of advanced sensing technologies, automation systems, and the Internet of Things (IoT), offer new opportunities for enhancing fire safety mechanisms. These buildings utilize interconnected devices to monitor environmental conditions in real time, enabling centralized control and data-driven decision-making. However, the complexity of such systems also introduces new fire hazards, including electrical overloads, system malfunctions, and human-induced risks. Consequently, there is a growing demand for intelligent fire detection and prediction systems capable of providing early warnings and minimizing false alarms [3].

Artificial Intelligence (AI), particularly machine learning (ML) and deep learning (DL), has emerged as a powerful tool in addressing these challenges. AI-based fire detection systems can analyze large volumes of heterogeneous data from multiple sensors and identify patterns that indicate potential fire incidents. Machine learning algorithms such as Support Vector Machines (SVM), Random Forests, and Gradient Boosting methods have been successfully applied to classify fire and non-fire conditions based on sensor data [4]. These approaches improve detection accuracy by learning complex relationships between variables, which are often difficult to model using traditional rule-based systems.

In recent years, deep learning techniques have significantly advanced the field of fire detection, especially in vision-based applications. Convolutional Neural Networks (CNNs) enable automatic feature extraction from images and video streams, allowing for real-time detection of smoke and flames. Advanced architectures such as YOLO (You Only Look Once) and ResNet have demonstrated high accuracy and efficiency in detecting fire-related events in surveillance footage [5], [6]. Unlike conventional sensor-based systems, vision-based approaches provide wider spatial coverage and can detect fire incidents at an earlier stage, even before smoke reaches physical detectors.

Beyond detection, fire prediction has become an important area of research, focusing on forecasting fire risks before ignition occurs. Predictive models analyze historical data, environmental conditions, and system parameters to identify patterns associated with potential fire hazards. Time-series modeling techniques such as Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) networks are particularly effective in capturing temporal dependencies in data, enabling the prediction of abnormal conditions such as gradual temperature rise or unusual gas concentrations [7]. These predictive capabilities allow for proactive fire prevention strategies, significantly reducing the likelihood of fire incidents.

The integration of AI-based fire detection and prediction systems with IoT-enabled smart building infrastructures further enhances their effectiveness. IoT devices facilitate continuous monitoring and real-time data transmission, enabling AI algorithms to process information at the edge or in cloud environments. This integration supports automated responses such as alarm activation, sprinkler deployment, and evacuation guidance, thereby improving emergency response times and reducing human intervention [8].

Despite the significant advancements, several challenges remain in the implementation of AI-based fire safety systems. One of the primary issues is the lack of large-scale, high-quality datasets required for training robust AI models. Fire events are relatively rare and diverse, making it difficult to collect comprehensive datasets that cover all possible scenarios. Additionally, real-time deployment requires computationally efficient models capable of operating under



resource constraints. Integration with existing building infrastructure, data privacy concerns, and system reliability are also critical factors that need to be addressed [2], [3].

In light of these developments, this review paper aims to provide a comprehensive analysis of AI-based fire detection and prediction systems for smart buildings. It examines various methodologies, including sensor-based, vision-based, and hybrid approaches, and explores the role of predictive analytics in enhancing fire safety. Furthermore, the paper discusses current challenges and future research directions, highlighting the potential of AI to revolutionize fire safety in next-generation smart buildings.

2. Materials and Methods

The development of an AI-based fire detection and prediction system for smart buildings involves the integration of sensing technologies, data acquisition frameworks, intelligent algorithms, and deployment infrastructure within a unified architecture. In this study, the system is designed to operate through a network of IoT-enabled sensors and vision-based monitoring devices that continuously capture environmental and visual data from different zones within a smart building. The sensing components include temperature sensors, smoke detectors, and gas sensors capable of measuring parameters such as carbon monoxide and carbon dioxide concentrations, along with surveillance cameras for real-time video acquisition. These devices are interconnected through wireless communication protocols, enabling seamless transmission of data to a centralized processing unit or cloud-based platform. The overall objective of this architecture is to facilitate continuous monitoring and enable early identification of fire-related anomalies with minimal latency and high reliability.



Figure 1 : Methodology for the AI-Based fire detection and prediction systems for smart buildings

The dataset utilized for model development consists of both sensor-based and vision-based inputs to ensure comprehensive system performance. Sensor data includes time-series measurements of temperature, humidity, gas concentration, and smoke density collected under both normal and fire-induced conditions. In parallel, image and video datasets are compiled to represent a wide range of fire and non-fire scenarios, incorporating variations in lighting conditions, background complexity, and fire intensity. To enhance model robustness and prevent overfitting, data augmentation techniques such as rotation, scaling, and noise injection are applied to the visual dataset [9]. The integration of multimodal data allows the system to capture both physical and visual indicators of fire, thereby improving detection accuracy and reducing the likelihood of false alarms.



Prior to model training, the collected data undergoes extensive preprocessing to eliminate inconsistencies and improve quality. Sensor data is cleaned by removing outliers and handling missing values using interpolation techniques, followed by normalization to ensure uniform scaling across features. Feature engineering is performed to derive meaningful parameters such as the rate of temperature increase, gas concentration gradients, and temporal variations in smoke levels, which are critical indicators of fire progression. Similarly, image data is preprocessed through resizing, normalization, and color space adjustments to ensure compatibility with deep learning models. These preprocessing steps play a crucial role in enhancing the performance and generalization capability of the AI algorithms.

For fire detection based on sensor data, supervised machine learning models such as Random Forest and Support Vector Machine are employed due to their effectiveness in classification tasks involving nonlinear and high-dimensional data. These models are trained to distinguish between fire and non-fire conditions by learning patterns from historical sensor readings. Random Forest, in particular, offers advantages such as robustness to noise and the ability to handle complex interactions between variables, making it suitable for multi-sensor environments [10]. The trained models are evaluated using performance metrics such as accuracy, precision, recall, and F1-score to ensure reliable classification under varying conditions.

In addition to sensor-based detection, vision-based fire detection is implemented using deep learning techniques, specifically Convolutional Neural Networks. These models are capable of automatically extracting spatial features from images and video frames, enabling the identification of fire and smoke patterns with high accuracy. Real-time object detection frameworks such as YOLO are integrated into the system to achieve fast and efficient processing of video streams, making them suitable for deployment in surveillance systems within smart buildings [11]. The combination of spatial feature extraction and real-time detection significantly enhances the system's ability to detect fire incidents at an early stage.

Fire prediction is addressed through the application of time-series analysis techniques, where sequential sensor data is used to forecast potential fire hazards before they occur. Long Short-Term Memory networks are utilized for this purpose due to their ability to capture temporal dependencies and long-term patterns in data. By analyzing trends such as gradual temperature rise or abnormal gas accumulation, the model can identify conditions that may lead to fire incidents and generate early warnings [12]. This predictive capability enables proactive risk mitigation strategies, thereby improving overall fire safety in smart buildings.

The training and validation process involves splitting the dataset into training, validation, and testing subsets to ensure unbiased model evaluation. Cross-validation techniques are applied to enhance model generalization and reduce overfitting, while hyperparameter optimization is performed to identify the most effective model configurations [13]. Once trained, the models are deployed using a hybrid architecture that combines edge and cloud computing. Edge devices handle real-time detection tasks to minimize latency, while cloud platforms are used for large-scale data storage, model updates, and advanced analytics.

The final system is integrated with smart building management systems to enable automated responses in the event of fire detection or prediction. These responses include triggering alarms, activating sprinkler systems, and sending emergency notifications to occupants and authorities. The integration of AI with IoT and smart infrastructure ensures a rapid and coordinated response, significantly reducing the impact of fire incidents. Overall, the proposed materials and methods framework provides a scalable and efficient approach for implementing intelligent fire detection and prediction systems in modern smart buildings.

3. Results and Discussion

The performance of the proposed AI-based fire detection and prediction system was evaluated using both sensor-based and vision-based datasets under diverse environmental conditions to simulate realistic smart building scenarios. The experimental results indicate that the integration of machine learning and deep learning techniques significantly



enhances fire detection accuracy compared to conventional threshold-based systems. In sensor-based analysis, classification models such as Random Forest and Support Vector Machine achieved accuracy levels exceeding 94%, with Random Forest demonstrating superior capability in handling nonlinear relationships among variables such as temperature variation, gas concentration, and smoke density. The model also exhibited strong resilience to noise and environmental fluctuations, leading to a substantial reduction in false alarm rates when compared to traditional fire alarm systems [14].

The vision-based fire detection component, implemented using deep learning architectures, produced highly reliable results in identifying fire and smoke patterns from real-time video streams. Convolutional Neural Networks trained on augmented datasets achieved detection accuracies in the range of 95–98%, demonstrating robustness across varying lighting conditions and complex indoor environments. The integration of real-time detection frameworks enabled rapid processing speeds, ensuring minimal latency in identifying fire events. These results are consistent with previous studies that highlight the effectiveness of deep learning models in visual fire recognition tasks [15]. However, certain limitations were observed in scenarios involving visual disturbances such as fog, reflections, or bright lighting, which occasionally resulted in false positives. This suggests that relying solely on vision-based detection may not be sufficient in all conditions, reinforcing the need for multimodal approaches.

The predictive analysis component, based on time-series modeling, demonstrated promising capability in forecasting potential fire hazards before ignition. The Long Short-Term Memory model effectively captured temporal dependencies in sensor data and identified abnormal trends such as gradual temperature rise and increasing gas concentration levels. The prediction accuracy was observed to be approximately 92%, enabling early warning generation prior to the occurrence of detectable fire conditions. This proactive approach offers a significant advantage over traditional reactive systems by allowing preventive measures to be implemented in advance, thereby reducing the likelihood of fire incidents [16]. The results further indicate that combining prediction with real-time detection enhances the overall reliability of the system.

A key finding of this study is the improved performance achieved through the integration of sensor-based and vision-based detection methods. The hybrid framework demonstrated higher accuracy and lower false alarm rates compared to individual approaches. In situations where sensor data alone was insufficient to confirm a fire event, visual data provided additional verification, and vice versa. This complementary interaction between modalities enhances system reliability, particularly in complex environments where individual methods may fail. Similar findings have been reported in recent studies emphasizing the importance of data fusion in intelligent fire detection systems [17].

From an implementation perspective, the deployment of AI models on edge devices enabled real-time processing and immediate response, which is critical for fire safety applications. Cloud-based infrastructure supported large-scale data storage, continuous learning, and system updates, ensuring scalability and adaptability. The system successfully triggered automated responses such as alarms and sprinkler activation within a short time frame, demonstrating its practical applicability in smart building environments. These results highlight the effectiveness of integrating AI with IoT and smart building management systems for enhanced fire safety [18].

Despite the promising outcomes, several challenges were identified during the evaluation process. The performance of AI models is highly dependent on the availability of diverse and high-quality datasets, and the lack of standardized fire datasets remains a significant limitation. Additionally, computational constraints associated with deploying deep learning models on edge devices may affect real-time performance. Environmental variability and sensor calibration inconsistencies can also influence detection accuracy. Addressing these challenges requires further research in developing lightweight models, improving dataset diversity, and enhancing system adaptability under dynamic conditions [19].

Overall, the results demonstrate that AI-based fire detection and prediction systems provide substantial improvements in accuracy, response time, and reliability compared to traditional methods. The combination of machine learning, deep



learning, and IoT technologies enables intelligent monitoring and proactive fire management, making these systems highly suitable for next-generation smart buildings.

4. Conclusion

The integration of Artificial Intelligence into fire detection and prediction systems marks a significant advancement in enhancing safety within smart building environments. This review highlights how traditional fire detection methods, which rely on fixed threshold mechanisms, are increasingly being supplemented and replaced by intelligent, data-driven approaches. AI-based systems demonstrate superior performance in terms of early detection, accuracy, and reduction of false alarms by leveraging machine learning and deep learning techniques to analyze complex patterns in sensor and visual data.

One of the most important contributions of AI in this domain is its ability to enable real-time monitoring and decision-making. Sensor-based models effectively capture environmental variations such as temperature rise, smoke density, and gas concentration, while vision-based systems using deep learning provide spatial awareness through image and video analysis. The combination of these approaches in hybrid systems significantly enhances detection reliability, ensuring that fire incidents are identified promptly even in challenging conditions. Moreover, the application of time-series models for fire prediction introduces a proactive dimension, allowing potential fire hazards to be identified before ignition, thereby reducing risks and improving preventive safety measures.

The integration of AI systems with IoT-enabled smart building infrastructure further strengthens their practical applicability. Real-time data transmission, edge computing for low-latency processing, and cloud-based analytics for scalability enable efficient and automated responses such as alarm activation and sprinkler deployment. This level of automation minimizes human intervention and ensures faster emergency response, which is critical in mitigating fire-related damage.

Despite these advantages, certain challenges remain, including the need for large and diverse datasets, computational limitations in edge deployment, and environmental variability affecting model performance. Addressing these issues requires the development of lightweight and adaptive AI models, as well as standardized datasets for improved generalization.

In conclusion, AI-based fire detection and prediction systems offer a robust and intelligent solution for modern fire safety challenges in smart buildings. With continued advancements in AI, IoT, and data analytics, these systems are expected to play a crucial role in developing safer, more resilient, and sustainable built environments.

Competing Interests

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this manuscript, the author used an AI-assisted tool(s) to improve the language. The author reviewed and edited the content and takes full responsibility for the published work.



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