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TECHNOLOGY-DRIVEN FIRE SAFETY SOLUTIONS IN SMART CITIES: A REVIEW OF INTELLIGENT SYSTEMS AND EMERGENCY MANAGEMENT PRACTICES

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ABSTRACT
The accelerated urbanization process and the growing complexity of constructed environments have aggravated the fire-related hazards in contemporary urban areas and brought the need to develop smarter and more integrated approaches to fire safety. The implementation of modern digital technologies, real-time sensing, and use of data-driven decision-making are important opportunities presented by smart city structures to boost resilience to urban fire. This is a systematic review covering technology-based fire safety solutions in intelligent cities, including intelligent detection and sensing systems, data-driven technologies and prediction, response technologies, including drones, robotics, and automated suppressing systems, and command-and-control technologies built around Building Information Modeling (BIM) and Geographic Information Systems (GIS). Moreover, the paper examines the modern-day emergency management strategies such as integrated command platforms, interagency coordination and community involvement via public alert systems. Comprehending current peer-reviewed literature, standards, and reported examples of smart cities, this review identifies the essential technological achievements, advantages of operation, and challenges that cannot be overcome, including interoperability, cybersecurity, cost, governance, and equitable access. The paper concludes that the identification of the research gaps that are critical and future directions that can be taken to enhance the scalable, secure and inclusive deployment of intelligent fire safety systems within the smart city surroundings.

KEYWORDS*: Smart Cities, Fire Safety, IoT, Machine Learning, Digital Twin, Emergency Management, Drones, GIS, Building Information Modeling.*

1. INTRODUCTION

The high rate of urbanization, rising population density, and a rise in the complexity of built environments are the main causes of the further aggravation of fire-related hazards in contemporary cities [1]. The high-rise buildings, mixed-use projects, underground transport infrastructure and dilapidated infrastructure create environments where a fire outbreak may increase at a high rate leading to the loss of life, economic damages and disruption of some vital services [2]. Older fire safety systems which were mostly reliant on independent detectors, manual checks, and human-centric reaction are still valuable, but prove too insufficient to manage the magnitude, pace, and unpredictability of modern city fire threat. The appearance of intelligent cities provides a new chance to improve fire safety by implementing digital technologies, real-time monitoring, and smart decision-support systems [3]. The Internet of Things (IoT), artificial intelligence (AI), and big data analytics allow detecting the fire early, predicting the threat, monitoring in real-time, and allocating the emergency resources based on the data and moving away the fire safety as the reactive model towards a more proactive and preventative one.

New developments in multisensory fire detectors, vision analytics and distributed IoT networks have enhanced detection precision and minimized false alarms, whereas machine learning and spatio-temporal models can be used to predict fire occurrence and propagation based on environmental, structural and occupancy data [4]. Simultaneously, the response technologies such as firefighting robots, unmanned aerial vehicles, and automated suppression systems provide better response team safety and can intervene fast in the dangerous areas.

Moreover, the combination of Building Information Modeling (BIM), Geographic Information Systems (GIS), and digital twin technologies has enhanced the command-and-control capabilities through the ability to visualize the dynamics of fire in real-time, evacuation routes, and resource deployment. In spite of these developments, issues that surround interoperability, cybersecurity, cost, governance and equal access still exist [5]. Since the extant literature is still scattered across fields, the purpose of the review is to consolidate the latest research on the topic of technology-based fire safety solutions in smart cities, analyze their practical efficiency, and define the gaps in research and areas of future research on enhancing the urban resilience to fires.

2. METHODS

The review is founded on the thorough review of the peer-reviewed journal articles, conference papers, standards documents, technical reports, and documented deployments of smart-city fire-safety published within the past 10-12 years, including the major focus on the studies published in the past five years to reflect the current technological progress. The literature was found in the large academic and technical databases, such as engineering and fire-safety journals, IEEE and ACM conference papers, and official urban-technology white papers [6]. Besides, foreign rules and regulations developed by established bodies like the National Fire Protection Association (NFPA) and the International Organization of Standardization (ISO) were also examined to bring them into conformity with the set regulatory and safety standards.

A thematic review method was applied to the chosen literature, which made it possible to foster a systematic synthesis in various technological and operation fields. The classification of studies was based on their key functional domains within smart-city fire safety systems, such as detection and sensing systems, data analytics and prediction, communication infrastructure, automated actuation and response, and emergency management systems. In each category, aspects of practical deployment that include the integration of the system, scalability, reliability, governance, and equity were analyzed to reveal common trends, strengths, weaknesses, and gaps in the research. It is a highly structured organization that helps to understand the holistic nature of how technology-based fire safety solutions can work in the real-world smart city settings.

3. INTELLIGENT DETECTION AND SENSING SYSTEMS

Smart cities have their basis in intelligent detection and sensing systems as their foundational layer of technology-based fire safety. Opposite to traditional fire detection technology that uses one parameter that is set to a particular threshold, a modern system incorporates various sensors, real time data processing, and network communication in order to enhance the detection capabilities and allow an early response. Sensor fusion, Internet of things (IoT) and artificial intelligence have revolutionized fire detection into a proactive and adaptive safety system that can detect fire related anomalies in their early stages [7].

3.1. Next-Generation Smoke and Flame Detection

Fire detection systems of the next generation incorporate optical sensors of multispectral sensors, gas sensors and temperature sensors to observe various fire indicators. The optical sensors are used to detect smoke and flame properties in visible, infrared, and ultraviolet light, whereas the gas sensors are used to detect by-products of combustion, such as CO, CO_2, and VOCs. Ignition-related abnormal thermal variations are recorded by temperature sensors. The sensor fusion method (in comparison to the solely sensor-based approach) can dramatically minimize the false alarms and enhance detection rates, especially in difficult environment like industrial premises, tunnels and business premises. Due to the low-cost MEMS sensors and embedded edge-processing, the implementation is feasible on a large scale and the local analysis can be fast.

Figure 1: Next-Generation Smoke and Flame Detection [8]

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3.2. Distributed IoT Sensor Networks

Distributed internet of things sensor networks allows fire monitoring in a continuous, wide area across infrastructures in smart cities. Sensor nodes (low-power) installed in buildings and urban corridors use LPWAN technologies (e.g., LoRaWAN and NB-IoT) to transmit information and facilitate long-range and energy-efficient communication. Mesh networking will increase the resiliency of the system, whereas edge computing will minimize the bandwidth needs and provide the possibility of creating alerts in real-time.

3.3. Vision-Based and Video Analytics

Fire detection systems based on vision make use of CCTV cameras, thermal imaging, and computer vision algorithms to detect flames, smoke and abnormal heat signature especially in open areas or large spaces. The deep learning models, particularly, convolutional neural networks, permit early fire detection and estimating the fire spread based on spatial and temporal visual data. These systems can be used together with GIS and emergency management systems to offer improved situational awareness and decision support to ARFs. Figure 2 shows the hierarchical framework of intelligent fire detection and sensing systems used in the smart city set-up.

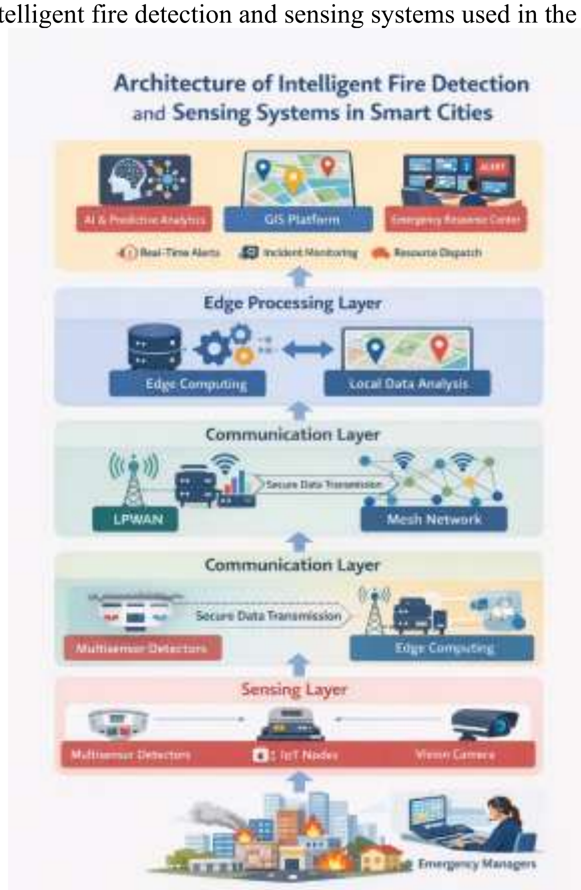

Figure 2: Architecture of Intelligent Fire Detection and Sensing Systems in Smart Cities [9]

Figure 2 illustrates a multi-layered system, which consists of sensing layer (multisensory detectors, IoT nodes and vision-based cameras), a local data analysis layer (edge processing), a communication layer (LPWAN and mesh networks), and analytics and management layer (AI-based models, GIS platform and emergency response system) to provide real-time alerting and action coordination.

4. DATA-DRIVEN ANALYTICS AND PREDICTION

Analytics based on data is an important part of improving fire safety in smart cities by converting large amounts of heterogeneous sensor and operational data into actionable intelligence. The intensive utilization of IoT sensors, surveillance cameras and digital infrastructure allow the collection of real time and historic data at any moment. Higher analytics, especially machine learning and spatio-temporal modeling, can be used to identify potential hazards early before the fire has escalated, forecast fire behavior and streamline emergency response, thus moving fire management practices to risk mitigation rather than reactive response [10].

✓ **Machine Learning for Anomaly Detection and Prediction**

The use of machine learning techniques (ML) is broad to identify anomalies and forecast a fire incident based on multidimensional data. The normal and abnormal conditions are classified by supervised models being trained on past fire records and the unsupervised techniques include clustering and autoencoders detecting deviations without labeled data. Through a combination of sensor data (temperature, smoke, gas), meteorological data, and building occupancy, the ML models predict the likelihood of ignition and provide high-risk areas. Predictive maintenance algorithms also contribute to better safety as equipment that is likely to fail or overheat is detected and preventive actions, as well as inspections, are taken.

✓ **Spatio-Temporal Modeling and Fire Propagation**

Complex urban environments can be forecasted in terms of fire spread through spatio-temporal models. Physics based modeling such as computational fluid dynamics (CFD) is an accurate computer model of heat transfer and smoke movement at a high cost. Blended methods which involve physics simulations and machine learning have been able to predict faster the spread of fire [11]. These models, when combined with GIS layers, including land use, building materials and population density, can produce dynamic risk maps that are useful in improving situational awareness, evacuation planning, and resourcing first responders.

✓ **Edge Analytics and Federated Learning**

The huge amount of urban sensor networks presents the problem of latency, bandwidth, and privacy of data. Edge analytics handles those problems by computing data on the sensor or the gateway such that it can quickly identify anomalies and even keep on operating in case the network has gone dead. Federated learning also facilitates privacy-preserving intelligence, since one can train distributed models without transferring raw data. Combining edge analytics with federated learning, predictive fire safety systems can be scaled, have low latency, and be secure enough to be used in a smart city setting. Table 1 provides a summary of some of the data-driven analytics methods applied to prediction of fire safety in smart cities.

Table 1: Data-Driven Analytics and Predictive Techniques for Fire Safety in Smart Cities [12]

Analytics Approach	Data Sources Used	Key Capabilities	Application Areas
Supervised ML Models	Historical fire records, sensor data, weather data	Fire risk prediction, anomaly classification	Urban buildings, industrial facilities
Unsupervised ML Models	Real-time sensor streams	Detection of abnormal patterns without labeled data	Early-stage fire detection
Physics-Based CFD Models	Building geometry, airflow, thermal data	Accurate fire spread simulation	High-rise buildings, tunnels
Hybrid ML–Physics Models	Simulation outputs, real-time sensor data	Fast and accurate fire propagation prediction	Urban-scale fire modeling
GIS-Based Risk Mapping	Land use, building materials, weather inputs	Spatial risk visualization, decision support	Emergency response planning
Edge Analytics	Local sensor data	Low-latency anomaly detection	Time-critical fire scenarios
Federated Learning	Distributed local models	Privacy-preserving collaborative learning	Residential and public environments

5. RESPONSE TECHNOLOGIES: ROBOTICS, DRONES, AND AUTOMATED ACTUATORS

Although early detection and prediction is paramount, the success of fire safety systems in smart cities is in the end tied to the rapidity, accuracy, and synchronization of response systems. The increase in robotics, unmanned aerial systems and automated actuation technologies have greatly increased the operational capacity of emergency response systems [13]. These technologies improve human visibility of hazardous conditions, improve situational awareness, and allow quick and precise measures to be taken. The response technologies in the smart city setting are becoming more and more integrated with the smarter and more intelligent detection systems and centralized emergency platforms to allow coordination of firefighting activities and their adaptation.

a) Aerial Drones for Situational Awareness and Payload Delivery

Unmanned aerial vehicles (UAVs) have emerged as useful devices to provide real-time situational analysis to fire incidents. Drones are fitted with thermal cameras, gas sensors, and high-resolution optical sensors which allow quick overhead views of the fire location, intensity, and spread, especially those areas that are either challenging or unsafe to reach [14]. They are highly adaptable in terms of altitude and mobility and are thus suitable in the detection of buildings of the high rise, industrial sites and highly populated cities. Besides reconnaissance, new drone platforms also enable limited payload deliveries in the form of fire-retardant dispersal teams, emergency communication relays, which can be useful in containing the fire and restoring communications during early response operations.

b) Ground Robots for Hazardous Interior Operations

Firefighting robots will have the capability of working under extreme conditions of high temperatures, poisonous smoke, and uncertain buildings. These robots are also provided with thermal, gas, and visual sensors, which allow them to conduct reconnaissance operations, search, and suppress victims in a building and underground areas. Tethered robots are used due to the fact that they offer uninterrupted power and dependable communication over extended periods of operation whereas untethered platforms offer extended movement in highly complicated layouts. Robotic systems with smart city emergency response models enhance the safety and effectiveness of the responders to the high-risk fire incidents.

c) Smart Suppression Systems and Automated Actuation

Smart suppression systems allow localized and instant control of fire by automation of actuation on real-time sensor data. Fire detection and analytics platforms are linked to networked sprinklers, intelligent misting systems, and remotely controlled valves that would allow swift and focused suppression. Smart suppression also reduces the destruction of water and resources wasted unlike in the traditional systems since the focus is laid on the affected areas [15].

Combination with building management and city emergency platforms also contributes to the effectiveness of the response because it allows such functions as fuel isolation and intelligent ventilation of smoke to be performed. Table 2 gives a reference-based summary of response technologies that have been addressed in the literature on smart city fire safety and emergency management.

Table 2: Response Technologies for Fire Safety in Smart Cities: Literature-Based Overview

References	Response Technology	Primary Function	Key Benefits
Érces et al. (2023) [16]	Aerial Drones (UAVs)	Situational awareness, reconnaissance, payload delivery	Rapid assessment, access to inaccessible areas, real-time data
Costa et al. (2022) [17]	Firefighting Robots	Hazardous interior operations, suppression, search	Reduced risk to human responders, operation in extreme conditions
Elvas et al. (2021) [18]	Smart Suppression Systems	Automated fire control and containment	Early intervention, reduced water damage, efficiency
González-Villa et al. (2024) [19]	Integrated Emergency Platforms	Coordination and decision support	Faster response, improved inter-agency coordination

6. DIGITAL TWIN, BIM, AND GIS FOR COMMAND AND CONTROL

The smart cities require effective command and control in order to handle fire emergencies in a complex and rapidly changing situation. Digital twin technologies, Building Information Modeling (BIM), and Geographic Information Systems (GIS) constitute a unified spatial and operational environment, which improves situational awareness, coordination, and decision-making [20]. These technologies facilitate responsive and proactive fire management response measures in real-time by connecting sensor information and detailed digital models of cities and buildings.

➢ ***Building Information Modeling (BIM) Integration***

BIM is an overarching computer-aided database of building planning, materials, layout, and installed security systems. BIM, when intertwined with live information of fire-detection, acts as a real-time digital twin, allowing the responders to see the positions of the fires, smoke patterns, occupancy, and escape routes. Such integration enhances efficiency in operations, has facilitated anticipation of hazards, safer navigation and also prioritization of rescue operations especially in complex structures like high rise buildings and large community facilities.

➢ ***Urban-Scale Digital Twins and GIS Layering***

Urban-scale digital twins duplicate these functions to the city scale combining transportation systems, utility systems, population density, and environmental data via GIS. The emergency management systems superimpose fire messages, weather, traffic, and availability of resources on the geospatial maps, forming a single operational image. These GIS based systems enable optimal path routing of firefighters and dynamic evacuation modeling, which improves inter-agency communication during fire incidents.

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Figure 3: Urban-Scale Digital Twins and GIS Layering [21]

➢ ***Human–Machine Interfaces and Augmented Reality***

Dashboard, wearable devices and augmented reality (AR) systems are human-machine interfaces that convert complicated digital data into actionable insights that can be used by the responders. The AR headsets and handheld devices have the capability of superimposing building plans, area of danger, and thermal images on top of reality, even when visibility is low. These interfaces are less cognitive, enhanced situational awareness, and made firefighters safer and more effective when coupled with digital twin platforms [22].

7. EMERGENCY MANAGEMENT PRACTICES AND INTEGRATION

Making smart cities effective with regards to fire safety goes beyond fire detection and fire response technologies to incorporate coordinated practices of emergency management. Complex fire incidents require integration of high-level information systems, standard process, and community participation to manage them. Current emergency management systems focus on the aspects of interoperability, real-time data exchange, and collaborative decision-making, which help the smart cities to improve preparedness, effectiveness of response, and general resilience to fire emergencies [23].

✓ **Integrated Command-and-Control Platforms**

Smart cities rely on the use of integrated command-and-control platforms during an emergency. The emergency operation centers (EOCs) consolidate the information of fire sensors, CCTV systems, weather services, traffic platforms, and resource databases to generate a common operating picture. This integration enables emergency managers to evaluate the changing situations in a short period and make wise decisions. Application programming interfaces (APIs) and standardized messaging protocols, visualization dashboards, and geospatial decision-support tools also minimize the response time and enhance the situational awareness in fire incidents.

✓ **Interagency Coordination and Mutual-Aid Automation**

Fire emergencies in cities are usually situations in which various agencies, utilities, and other non-state actors have to cooperate [24]. Smart city emergency management sites facilitate interagency response by automated workflow and notification systems that trigger set response routines. Mutual-aid plans, online checklists, and resource lists built into command systems standardize operations, increase accountability, and make intervention scalable in responses to major fire incidences or across many sites.

✓ **Community Engagement and Public Alerting**

The community involvement is a very important aspect in efficient crisis management. To promptly send out evacuation and safety information, various communication means like mobile alerts, SMS, public address systems, and social media are employed by the public alerting systems to dispatch the information on time. More sophisticated platforms also facilitate two-way communication where the citizens can exchange real-time data such as pictures and location with the responders. This community participation will help in better situational awareness, build trust and resilience of urban areas. The important emergency management practices and integration mechanisms in smart cities fire safety models are summarized in table 3.

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Table 3: Emergency Management Practices and Integration Mechanisms in Smart Cities [25]

Practice Area	Key Components	Functional Role	Benefits
Command-and-Control Platforms	Data integration, dashboards, APIs	Centralized monitoring and decision-making	Faster response, improved situational awareness
Interagency Coordination	Automated workflows, mutual-aid protocols	Multi-agency collaboration and resource sharing	Scalable response, reduced coordination delays
Public Alerting Systems	Mobile alerts, SMS, PA systems, social media	Risk communication and evacuation guidance	Enhanced public safety, reduced panic
Community Reporting Tools	Two-way communication, crowdsourced data	Real-time situational feedback	Improved data validation, citizen engagement

8. CONCLUSION

This review proves that technology-based fire safety solutions are the need of the hour to improve the resilience, efficiency, and preparedness of smart cities. The convergence of intelligent detection and sensing technologies, data analytics, response technologies, and digital twin-enabled command and control solutions help to transition from a reactive firefighting approach to a proactive risk management strategy. Technologies like IoT sensor networks, machine learning algorithms, drones, robotics, BIM, and GIS help to improve early warning detection, situational awareness, firefighter safety, and decision support during fire emergencies. However, the effective adoption of these technologies requires not only technological innovation but also strong system integration, cybersecurity, standardized frameworks, interagency collaboration, and governance. Overcoming challenges in interoperability, data privacy, cost, and equity remains essential for large-scale adoption. This study emphasizes the importance of adopting a holistic, human-centric, and policy-friendly approach to leverage the full potential of intelligent fire safety solutions, thus making smart cities safer, more sustainable, and resilient.

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