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Fusion Application of Digital Twin and Internet of Things in Smart Firefighting

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Abstract. This paper investigates the integrated application of digital twin technology and the Internet of Things (IoT) in smart firefighting systems. Traditional firefighting methods primarily rely on manual inspections, whereas smart firefighting achieves interconnectivity among devices and real-time monitoring through the IoT. Furthermore, it employs digital twin technology to construct dynamic simulation models, significantly enhancing the accuracy of fire warnings and the efficiency of rescue operations. From a technical perspective, digital twin technology functions through Building Information Modeling (BIM), computational fluid dynamics (CFD), and artificial intelligence (AI)-based prediction methods; IoT, on the other hand, operates through a layered architecture. Together, these technologies drive the development of real-time visualization, fire scenario simulation, and intelligent emergency response capabilities. This integration points the way toward building a more efficient and precise next-generation fire management system.

Keywords: Digital Twin, Internet of Things, Smart Firefighting

1. Introduction

Since the issuance of the Guiding Opinions on Comprehensively Promoting the Construction of “Smart Firefighting” by the Fire Department of the Ministry of Public Security on October 10, 2017, “smart firefighting” has emerged as a crucial component in building safe and intelligent cities. It has evolved from an initially market-driven initiative into a government-led development model and has become an important part of local governments' efforts to improve public services [1]. With the continuous advancement and refinement of IoT technology in smart firefighting, it has become increasingly efficient to collect operational data on fire protection facilities within buildings during fire investigations. The storage and analysis of these data not only facilitate a comprehensive understanding of equipment performance but also enable the timely identification and elimination of potential safety hazards, thereby significantly enhancing the efficiency and effectiveness of fire investigation and prevention [2]. This paper aims to explore the integration of digital twin and IoT technologies to develop an architecture suitable for smart firefighting systems and their application domains. It also discusses future development trends, with the goal of providing valuable insights for the ongoing construction of modern smart firefighting systems.

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2. Limitations of traditional firefighting and development trends of smart firefighting

2.1. Limitations of traditional firefighting technologies

Traditional firefighting technologies primarily rely on manual patrols, fixed sensor installations, and passive response mechanisms, all of which present significant technical limitations. In terms of fire warning systems, conventional smoke and temperature detectors use threshold-based alarm triggering methods that are susceptible to external environmental influences, making it difficult to distinguish between real fires and false alarms. Monitoring the status of firefighting equipment depends on periodic manual inspections, which are ineffective for timely detection of faults or malfunctions. Furthermore, these inspections are typically documented on paper, resulting in incomplete fire prevention checks and unreliable records [1]. From a data application perspective, subsystems often operate independently, leading to a lack of integration among alarm information, equipment status, and building structure data. This fragmentation hinders emergency decision-making due to insufficient data support. Additionally, current firefighting plans cannot be flexibly adjusted according to changes in building usage. Safety hazard identification still largely depends on personal experience rather than on scientific risk assessment models.

2.2. Development trends in smart firefighting

Smart firefighting technologies are advancing rapidly, aiming to improve the accuracy and efficiency of fire prevention and control through innovative technical approaches. The application of IoT technology has laid a solid foundation in this field by enabling interconnected operations among various firefighting facilities and providing continuous environmental monitoring. This allows for dynamic assessment of potential fire risks and significantly reduces false alarms and missed detections. With the progress of information technology, the combination of artificial intelligence and big data analytics provides more scientific and rational decision-making support for fire warning systems. By analyzing both historical data and real-time information, potential dangers can be predicted, and preventive measures can be implemented in advance. Furthermore, the development of intelligent sensor and image recognition technologies allows the system to quickly locate the fire source and automatically activate appropriate fire suppression procedures, greatly shortening the response time between detection and action. In extreme scenarios, drones and robots are beginning to play key roles in firefighting operations. They not only enhance operational efficiency but also ensure firefighter safety. The adoption of 5G communication technology ensures efficient coordination during command and dispatch, enabling precise allocation of rescue resources.

2.3. Concepts and integration value of digital twin and IoT

The 20th National Congress of the Communist Party of China emphasized the importance of promoting digital transformation in education, highlighting the irreplaceable role of digital technologies in driving innovation and development. Among them, Digital Twin technology refers to the creation of dynamic digital replicas of physical entities in virtual environments. These replicas reflect the real-time state, behavior, and performance of the physical systems and optimize their operational efficiency through data analysis and simulation. Meanwhile, the Internet of Things (IoT) leverages sensors, communication networks, and data processing technologies to connect various physical devices, enabling functions such as environmental monitoring, information gathering, and remote control.

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The integration of these two technologies yields significant complementary advantages. Digital twin technology relies on the real-time data streams provided by IoT to ensure that virtual models stay synchronized with actual environments, thus improving prediction accuracy and decision-making efficiency. Conversely, the sensing layer of IoT is enhanced by the powerful simulation capabilities of digital twins, enabling optimized equipment management and early fault detection. In the context of smart firefighting, IoT sensors monitor indoor temperature, smoke concentration, and gas levels, while the digital twin model dynamically simulates the spread of fire to support the development of the most effective evacuation plans and firefighting strategies. This integration also facilitates remote maintenance, intelligent diagnostics, and optimal resource allocation. It plays a critical role in the digital transformation of industrial production, smart city construction, and energy management systems, thereby improving overall system reliability, safety, and operational efficiency.

3. Technical foundations of digital twin and IoT

3.1. Core technologies of digital twin

As a key enabling technology of the intelligent era, digital twin has evolved in close synergy with advances in virtual reality (VR), augmented reality (AR), and mixed reality (MR). Through the convergence and innovation of VR/AR/MR technologies, digital twin systems have achieved significant improvements in immersive interaction and multidimensional perception. The core mechanism of this technology lies in constructing a real-time mapping channel between physical entities and their virtual models, relying on IoT sensor networks. By dynamically collecting data from physical objects and their environmental parameters via multi-source heterogeneous sensors and synchronously transmitting them to the digital twin system, two-way data interaction and state coordination between the physical and virtual spaces can be realized.

In the field of smart firefighting, digital twin technology is deeply integrated with Building Information Modeling (BIM) to create a high-precision 3D information model that includes building geometry and topology, thermal performance of materials, and operational data of fire protection facilities. Coupled with computational fluid dynamics (CFD) simulations, the system can numerically model complex physical phenomena such as smoke dispersion and temperature field evolution under fire conditions. Furthermore, artificial intelligence (AI) algorithms are incorporated to mine and analyze historical fire data and real-time monitoring information. This integrated approach fully leverages the digital foundation of BIM, the physical simulation capabilities of CFD, and the intelligent decision support of AI. It promotes the transformation of smart firefighting systems from traditional passive response modes to proactive risk prevention strategies, effectively enhancing system operational efficiency and disaster early warning capabilities.

3.2. Iot application framework in firefighting

The application framework of IoT technology in the field of fire safety adopts a layered design, consisting of four levels: perception, transmission, application, and presentation. As shown in Figure 1 [3], the perception layer deploys various smart monitoring devices including smoke detectors, temperature sensors, and electrical fire monitoring units. These are paired with high-definition cameras to form a comprehensive, around-the-clock environmental monitoring network that collects data and image information from the scene. The transmission layer is responsible for data exchange between field equipment and cloud servers [4]. The collected data are then applied to fire alarms,

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firefighting equipment management, and system monitoring. All relevant parameters are ultimately displayed on computers or mobile devices. This structured framework ensures the timeliness and accuracy of firefighting monitoring operations while also providing a solid technical foundation for subsequent data analysis and remote control.

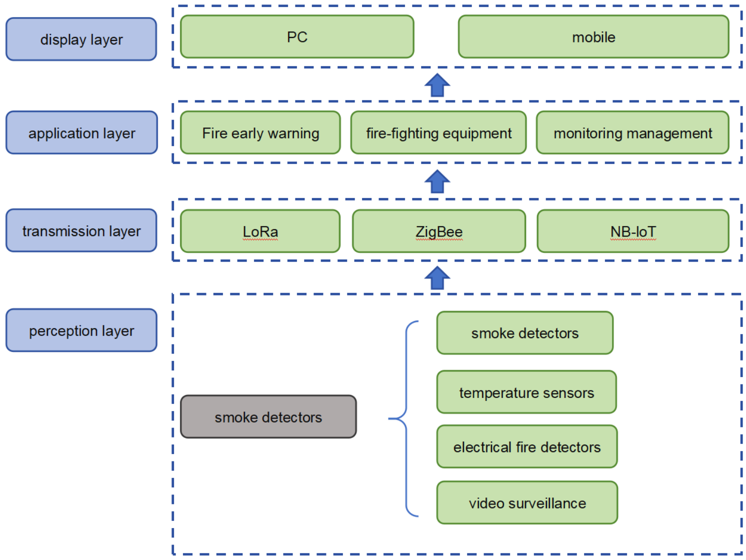

Figure 1: Schematic diagram of the fire IoT architecture

With ongoing technological advancement, the application of IoT in smart firefighting is becoming increasingly widespread and has gradually become a mainstream direction in the development of the firefighting industry. By integrating technologies such as sensors, embedded systems, cloud computing, and big data, IoT enables the remote acquisition, transmission, processing, and sharing of information. The construction of smart firefighting systems allows for full utilization of these technological tools in fire safety management, accelerating the speed of hazard detection and response. Furthermore, the application of IoT technology provides robust technical support for smart firefighting, promoting the transition of firefighting systems toward greater intelligence and automation, thereby improving the overall safety and stability of the system.

4. Integration scenarios of digital twin and IoT

4.1. Real-time monitoring and dynamic visualization

By collecting real-time physical-world data via IoT sensors and leveraging high-speed transmission networks, digital twin models can be instantly updated, ensuring synchronized mapping and interaction between the virtual model and its corresponding physical object. This technological integration significantly enhances the accuracy and responsiveness of system status monitoring and demonstrates strong application potential in building fire safety management. The smaller the gap between a digital twin and its physical counterpart, the more accurately the digital twin reflects the actual situation. Therefore, minimizing this difference is a key design consideration, with the primary goal of digital twin construction being the realization of high-fidelity simulations [5].

In the building fire safety system, the deployment of IoT sensors—such as temperature and smoke detectors—along with 3D modeling and real-time data visualization technologies, allows for the creation of spatiotemporally consistent digital twin models. These enable comprehensive visual representation of fire hazards. The core component of a city-wide building fire safety management system is a security system based on IoT, which ensures effective communication channels between connected users and municipal fire control centers. Under normal conditions, fire command centers can use this IoT platform to provide connected users with timely, accurate, and rapid fire alerts and other safety information [6]. The spatiotemporal consistency of digital twin models enhances the performance of IoT systems. This integration not only enables the monitoring of firefighting equipment operational status but also employs visualization tools such as heatmap analysis and smoke spread simulations to clearly illustrate the spatial distribution and evolution of potential threats. It thereby offers multidimensional support for early warnings and real-time emergency decision-making.

4.2. Fire simulation and predictive analysis

By combining real-time environmental data gathered from IoT sensors with historical fire incident data, digital twin technology can construct highly realistic fire simulation scenarios. Using AI techniques such as machine learning and deep learning, the model can dynamically predict fire spread trends. Furthermore, based on real-time monitoring data of combustible gas leaks, and aided by CFD simulations and AI-based prediction tools, digital twin systems can simulate the specific diffusion paths, concentration distributions, and potential explosion risks of gases under different conditions. This provides a solid scientific basis for disaster early warning and emergency response. Studies have shown that data generated through real-time computation can be converted into renderable formats and visualized via the OSG (OpenSceneGraph) 3D rendering engine [7]. Such research has developed a relatively complete platform for forest fire development simulation and firefighting training by implementing specific data structures and core algorithms. This comprehensive application not only improves the accuracy of fire risk assessment but also enhances the proactivity and intelligence of disaster prevention measures.

4.3. Intelligent emergency response and decision-making

By creating a digital replica that mirrors the real firefighting environment and incorporating IoT technology to collect real-time, multi-dimensional data—such as temperature, smoke concentration, and personnel location—a smart firefighting system based on the integration of digital twin and IoT technologies can conduct high-fidelity emergency drills in virtual environments. This system uses big data analytics and algorithmic models to process both historical fire data and real-time monitoring information, simulating the evolution of fire conditions under various rescue strategies and generating scientifically optimized emergency response plans. Additionally, the AR navigation and command platform developed through the integration of digital twin and IoT technologies enables key information—such as evacuation routes, danger zones, and the locations of trapped individuals—to be presented visually in augmented reality to frontline firefighters, facilitating precise positioning. Studies have noted that replacing traditional point cloud technology with visible light–based AR positioning for 3D visualization and interaction with BIM models not only improves positioning accuracy but also leverages visible light communication principles. In this approach, LED light sources serve as data carriers and act as optical communication base stations. Since these base stations do not emit radio waves, they avoid interference with surrounding radio signals, thereby offering excellent anti-interference performance and ensuring stability and reliability during data transmission [8]. This enables firefighters to access critical information quickly in complex and dynamic fire scenes. At the same time, command centers can use first-hand information collected by

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IoT devices, together with digital twin models, to dynamically supervise and coordinate the entire rescue operation. This greatly enhances the speed and accuracy of decision-making during fire emergencies, providing a new intelligent pathway for modern emergency firefighting response.

5. Challenges and issues

5.1. Technical challenges

In practical engineering applications, smart firefighting systems face numerous technical obstacles, with data accuracy and sensor reliability being the most critical. Environmental disturbances constitute major technical barriers—extreme temperature and humidity gradients, dense smoke, and electromagnetic interference during fire scenarios can cause significant deviations in readings from temperature, humidity, and gas concentration sensors. Additionally, coordinating multi-source heterogeneous sensor networks poses inherent complexity. Devices such as infrared thermal imagers, smoke particle detectors, and barometric pressure sensors vary in sampling frequency, measurement accuracy, and spatial calibration dimensions, creating bottlenecks in building high-fidelity digital twin models—especially in ensuring spatiotemporal consistency of data. From a long-term operational perspective, sensor performance degradation is also a non-negligible issue. Prolonged exposure to dusty or corrosive gas environments leads to a gradual decline in monitoring sensitivity, which traditional manual calibration mechanisms are ill-equipped to detect in real time.

Furthermore, the integration of digital twin and IoT technologies into intelligent firefighting systems imposes high demands on computational power due to real-time monitoring and immediate feedback requirements. At present, digital twin applications in firefighting remain in early stages and require further in-depth research and development. Specifically, more efforts are needed to improve the accuracy, stability, and reliability of the models. Current smart firefighting systems commonly face difficulties in data processing, struggling to efficiently analyze and extract meaningful insights from vast volumes of information. This shortcoming in data handling directly impacts the system's ability to identify fire hazards and predict accident trends accurately and promptly [9]. Real-time data analysis also encounters limitations in computational resources, particularly when millisecond-level response speeds are required. The limited processing capacity of edge devices becomes a major constraint, while network transmission delays further hinder data preprocessing and model update efficiency. In addition, system security remains a potential threat. IoT nodes may be vulnerable to attacks such as data tampering or false signal injection, which can undermine the foundation upon which the digital twin system makes accurate decisions.

To address these challenges, edge computing technology can be employed. By deploying data processing and analysis functions closer to the data generation point, it effectively meets the need for real-time responsiveness and significantly reduces network latency. In industrial production scenarios, this technology can process massive volumes of data generated by various devices in real time, resulting in more precise analytical outcomes [10].

5.2. Management challenges

To promote the horizontal development and practical application of intelligent firefighting systems based on digital twin and IoT technologies, cross-departmental data sharing and standardized protocols are particularly crucial. However, due to the siloed operations of various government agencies—such as fire services, emergency management, housing and urban development, and public security—business systems are built independently, resulting in incompatible data formats and interface standards. Moreover, the lack of clear definitions regarding data access permissions and sharing scopes among departments, combined with concerns over the security of sensitive information and the urgent needs of fire warning systems, contributes to challenges in data collection. After cross-departmental data exchange, the ambiguity surrounding responsibility for data security, along with the absence of clear procedures for handling sensitive materials, severely limits the efficiency of coordinated operations in smart firefighting systems. If stakeholders hesitate to support data openness due to unclear responsibility demarcation, this could lead to delays in updating critical IoT node information, thereby compromising the accuracy of digital twin models.

6. Future development directions

6.1. City-level firefighting digital twin platform

Currently, the interconnectivity among buildings within smart firefighting systems remains underdeveloped. With the advancement of technology and wider adoption in practice, these systems are expected to evolve into city-level firefighting digital twin platforms capable of constructing comprehensive urban fire protection models. By leveraging wide-coverage IoT networks based on 5G-A/6G technologies, centimeter-level positioning accuracy can be achieved, alongside the deployment of tens of millions of intelligent sensor nodes. Additionally, advances in multi-scale modeling will further facilitate the deep integration of Building Information Modeling (BIM) with Geographic Information Systems (GIS), significantly improving the accuracy of fire spread predictions, effectively containing the spread of fires, and optimizing rescue routes. Urban-scale smart firefighting cloud platforms show tremendous development potential and signal a major shift in regulatory models. Although smart firefighting is still in a developmental phase, future platforms will undoubtedly evolve toward greater openness, enhanced security, and higher levels of intelligence. As application scenarios and management demands continue to change, the platform will adapt accordingly, gradually integrating data from various firefighting business information systems. This includes linking detailed information about target structures—such as their location, overview, structural features, and fire protection facilities—thereby providing robust data support for remote monitoring and emergency response, and paving the way for a next-generation urban smart firefighting system [11].

6.2. Immersive command system

With the construction of accurate and real-time updating models and parameter feedback mechanisms, it is anticipated that light field display technology will enable 1:1 scale holographic projections of fire scenes in the future. This technology would support free zooming from multiple perspectives and achieve high-precision rendering of smoke particles. Moreover, when combined with Mixed Reality (MR), physical environments and virtual scenes can be seamlessly integrated into an expanded interactive space where real and virtual objects coexist and allow for immediate user interaction [12]. Through gesture recognition technology, commanders could adjust rescue strategies in real time, significantly improving the efficiency of tactical deployment. To address the current issue of low user engagement in mixed reality interactions, one solution is to adopt a HoloLens-based platform that uses real-world objects as interactive media, establishing a hybrid interaction framework in which physical items can influence digital content [12]. This approach not only enables virtual images to be accurately positioned within the physical world but also allows them to be viewed and interacted with from different angles as if they were real objects. HoloLens devices can superimpose computer-generated virtual elements or holograms onto the real environment, allowing users to see and manipulate virtual content while simultaneously perceiving their physical surroundings. The built-in sensing system can map the local physical space (i.e., perform holographic rendering) and track user movements [13].

Once technical barriers are overcome and computational requirements are met, digital twin systems are expected to achieve a high degree of synchronization with the real world. Through big data analysis and simulation, such systems will support the pre-execution and verification of firefighting commands. Additionally, pressure sensors integrated into firefighters' safety gear could provide tactile warning signals (e.g., vibrations) when approaching hazardous zones, thereby enhancing safety during rescue operations.

7. Conclusion

7.1. The core value of combining digital twin and Internet of Things (IoT)

The integration of digital twin technology with IoT technology creates a dynamic replica of the fire protection system through real-time data support and virtual simulation methods, thereby achieving precise correspondence between the real environment and the digital model. The sensor networks within the IoT continuously collect information about environmental conditions and facility status, providing the digital twin with the most up-to-date data foundation. The digital twin then utilizes computational fluid dynamics simulations and artificial intelligence predictive algorithms to analyze fire development trends, optimizing escape routes and rescue plans. This cooperative model overcomes the information silos and response delays present in traditional fire protection systems, greatly enhancing the effectiveness and accuracy of fire prevention and control measures.

7.2. Transition from passive firefighting to active disaster prevention

Future intelligent fire protection systems will provide robust support for monitoring, regulation, and improvement of the real world through the deep integration of digital twin technology and IoT [14], enabling a shift in fire protection work from post-incident handling to pre-incident prevention. Urban-level fire digital twin platforms can integrate multi-source information and perform multi-layered modeling to achieve dynamic prediction and intuitive visualization of fire risks. Meanwhile, immersive command and control systems combined with augmented reality/mixed reality technologies empower rescue operations with simulation validation capabilities. With the widespread development and adoption of 5G-A/6G communication networks and edge computing technologies, the system's response time is expected to shorten to the millisecond level, thereby establishing a comprehensive proactive fire prevention system that covers risk assessment, intelligent early warning, and precise rescue operations. This will significantly reduce property damage and casualties caused by fires.

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