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Exploration on the Empowerment of Digital Twin and AI Early Warning for Smart Fire Protection Based on BIM Technology

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Abstract: Against the background of accelerated urbanization and diversified architectural forms, the passive and lagging shortcomings of the traditional fire protection model have become increasingly prominent. As a core part of smart city construction, smart fire protection relies on AI early warning and machine learning algorithms to mine risk patterns from multi-source data, upgrade fire early warning and response prediction, and provide systematic solutions for smart fire protection. Based on the digital foundation of BIM technology and focusing on digital twin and AI early warning as two core technologies, this paper analyzes the technical integration path in the field of smart fire protection, expounds the empowered application scenarios from the dimensions of risk perception, emergency command and operation & maintenance management, discusses the current challenges and future development directions, so as to provide theoretical reference and practical reference for the construction of smart fire protection system.

Keywords: Digital Twin; AI Early Warning; Smart Fire Protection; BIM.

1. Introduction

Fire protection is an important defense line to ensure urban public security, which is directly related to people's life and property safety and social stability. With the continuous emergence of complex scenarios such as super high-rise buildings, large commercial complexes and chemical industrial parks, the traditional fire protection mode relying on manual inspection and fixed-point monitoring has problems such as untimely hazard identification, delayed fire response and experience-dependent command and decision-making, which can hardly meet the needs of modern fire safety management [1]. Fire IoT data, GIS spatial data, meteorological and environmental data are stored separately in different systems, lacking a unified integration standard and collaborative analysis mechanism, forming "data islands", resulting in insufficient early warning accuracy and scientific decision-making.

Accelerating the digital and intelligent transformation of emergency management and building a smart emergency system has emerged as the times require. Its core lies in realizing the full-factor and full-process intelligent management of fire safety through IoT, big data, artificial intelligence and other technologies. Digital twin technology developed based on BIM can construct a mapping relationship between the physical world and the virtual world, providing a visual and deducible digital foundation for fire management [2]; AI early warning technology realizes accurate identification and early prediction of risks with its powerful data processing and analysis capabilities [3]. The in-depth integration of the two has become a key driving force to promote the upgrading of smart fire protection and is of great practical significance for improving fire safety governance capacity.

2. Technical Integration of Digital Twin and AI Early Warning

2.1. Connotation of Related Technologies

Digital twin is a virtual model constructed based on digital technology and fully mapped with physical entities. It realizes the synchronous evolution of the virtual model and physical entities by collecting real-time status data of physical entities [4]. In the field of smart fire protection, the construction of a digital twin model needs to rely on Building Information Modeling (BIM) and Geographic Information System (GIS) technologies, integrate multi-dimensional data such as building structure, fire protection facility layout, personnel distribution and environmental parameters to form an equal-scale 3D visualization model, providing a digital sandbox for fire management [5].

AI early warning technology takes machine learning, deep learning and other algorithms as the core, conducts intelligent analysis on multi-source data collected by IoT sensors, identifies hidden risk features behind the data, and realizes the leap from data monitoring to risk prediction [6]. Common algorithms include Convolutional Neural Network (CNN) for image recognition of flames and smoke, Long Short-Term Memory (LSTM) network for trend prediction of time-series data such as temperature and current of electrical equipment, and Reinforcement Learning (RL) for evacuation route optimization [7].

2.2. Technical Integration Path

The integration of digital twin and AI early warning is essentially the collaborative operation of "virtual model + intelligent algorithm", forming a closed-loop system of data collection, model mapping, intelligent analysis and decision output. The specific integration path is divided into three levels:

1.Integration of perception and transmission layer. On-

site dynamic data are collected by "fixed + mobile" IoT sensors and transmitted to the digital twin platform in real time through 5G/4G + LPWAN heterogeneous network; AI algorithms clean and extract data features and feed them back to the model to improve its accuracy [2].

2.Integration of data platform layer. Heterogeneous data such as sensor data, BIM/GIS data and video data are integrated, and AI algorithms are embedded in the digital twin model to dynamically simulate and predict fire, smoke and evacuation through the engine and intelligent agent. The AI physics engine simulates fire spread and predicts damage to load-bearing components combined with building structure data [8].

3.Integration of application and presentation layer. Based on the BIM-integrated digital twin and AI model, applications such as risk early warning, emergency command and operation & maintenance management are developed, and information visualization and interaction are realized through multiple terminals, converting data analysis into intuitive interfaces and executable instructions to achieve deep integration of technology and business [9].

3. Empowerment of Smart Fire Protection by Digital Twin and AI Early Warning

3.1. Pre-Incident Risk Perception and Early Warning

Pre-incident prevention is the core goal of smart fire protection. The integration of digital twin and AI early warning breaks the limitations of traditional fixed-point monitoring and realizes global, dynamic and accurate risk identification [3].

1.Early warning of electrical fires. Electrical faults are the main cause of fires. Traditional monitoring can only display real-time data but cannot predict trends. Sensors deployed at key parts such as power distribution cabinets collect time-series data and transmit them to the digital twin platform, and the LSTM algorithm analyzes trends to identify abnormalities such as equipment overload. In electrical fire prevention, when data deviates from the threshold, the system automatically issues an early warning, marks the risk point in the digital twin model, displays equipment information and abnormal parameters, and notifies relevant personnel in a timely manner.

2.Status monitoring and predictive maintenance of fire protection facilities. Traditional fire protection maintenance relies on regular inspections, which is prone to over-maintenance or under-maintenance. The operation data of fire protection equipment are collected by IoT, and the location and parameters of equipment are mapped in real time combined with the BIM digital twin model. AI algorithms analyze the data to establish a fault prediction model. When the operation parameters of fire equipment are abnormal, the system predicts the fault risk, generates a maintenance work order combined with maintenance records and pushes it to managers to realize on-demand maintenance.

3.Intelligent identification of "video surveillance + AI visual analysis". Cameras are deployed in key areas, and the CNN algorithm is used to analyze videos in real time to identify behaviors such as blocking fire passages and illegal hot work [6]. The system automatically captures and obtains evidence of violations, locates them in the digital twin model, and pushes alarms to managers, replacing manual prevention with technical prevention. When the smoke concentration is low but the temperature rises abnormally, the system can accurately judge the fire risk and issue an early warning by combining sensor data and historical cases.

3.2. Intelligent Command and Evacuation Optimization

Rapid and accurate emergency disposal in case of fire directly affects casualties and losses. The integration of digital twin and AI early warning provides visual, deducible and optimizable decision support for command.

1.Fire situation deduction. In case of fire, IoT sensors collect data such as smoke and temperature in real time and transmit them to the BIM digital twin platform. The AI physics engine simulates the spread path of fire and smoke combined with building structure and combustible data. The digital twin model presents the fire point, fire scope, smoke diffusion and component damage in 3D visualization, assisting commanders to dynamically grasp the fire scene. Compared with traditional manual reports, this technology realizes real-time and accurate presentation of fire situation and provides scientific support for decision-making.

2.Dynamic evacuation route planning. Traditional evacuation routes are fixed and cannot adapt to changes in fire scenes. The system displays personnel positions in real time through positioning technology, and the AI algorithm dynamically generates the optimal evacuation route combined with factors such as fire, smoke and passage status [7]. The evacuation route guides personnel to avoid danger through mobile APP, broadcast and indicator lights. The decision-making system links fire protection equipment to realize automatic fire operations.

3.Multi-department collaboration to break information barriers. In fire rescue, the traditional command mode has problems such as poor information and low resource allocation efficiency. The digital twin platform integrates multi-department data, displays fire situation and rescue force distribution in real time, and AI algorithms assist in generating allocation plans and automatically issue instructions. The system quantitatively assesses fire risk, dispatches the nearest fire brigade, plans the optimal route and coordinates traffic diversion, providing a basis for fire decision-making.

4.Collaborative operation of fire-fighting robots and drones. When personnel are difficult to enter the fire scene, AI-controlled fire-fighting robots and drones can extinguish fires autonomously. Drones take aerial photos of the fire scene through thermal imaging and transmit images to the digital twin platform, and AI algorithms identify the fire location; fire-fighting robots autonomously avoid obstacles and spray extinguishing agents according to the fire location positioning in the model [5]. The digital twin model feeds back equipment status in real time to assist remote control.

3.3. Accident Analysis and Plan Optimization

Summary of fire accidents is an important method to improve fire safety management. The combination of digital twin and AI early warning can provide accurate and comprehensive data support for accident assessment.

1.Whole-process restoration of fire. Traditional accident investigation relies on on-site investigation and witness testimony, which is highly subjective and lacks sufficient evidence. The BIM digital twin platform stores all data before

and after the fire. Through AI algorithm analysis, the digital twin model can reproduce the whole process of fire. Investigators can trace each link with the help of the model to accurately determine the cause of fire and responsibility.

2.Effectiveness verification and optimization of emergency plans. Traditional emergency plans are mostly lack of practical verification. Various fire scenarios can be simulated in the digital twin model, and AI algorithms are used to evaluate the evacuation efficiency and rationality of resource allocation of the plans to find bottlenecks. For example, simulating a fire in a garage, it is found that the original evacuation routes are concentrated and easy to cause congestion. The routes are optimized by AI and exits are added to improve the effectiveness of the plan.

3.Immersive training and drills. A VR/AR training system is built by using digital twin to simulate real fire scenarios and provide sensory experiences such as high temperature and smoke. Plan deduction is carried out through the digital platform, and Pyrosim is used to simulate fire and smoke diffusion; firefighters practice fire-fighting tactics in the Pathfinder environment, and employees conduct escape training to master correct methods [4]. The system fire model optimizes the plan through simulation, helping fire departments determine the best response strategy and resource allocation, and providing support for plan revision and training.

4. Challenges in Technical Implementation

The application of digital twin and AI early warning technologies in smart fire protection requires interdisciplinary talents who understand both fire protection business and information technology, and the shortage of such talents restricts the development of technologies.

4.1. Inconsistent Data Fusion Standards

Digital twin and AI early warning require massive data, but there are "information islands" in data collection in the current fire protection field. The data formats of equipment from different manufacturers are inconsistent, and the interfaces between BIM and GIS data are incompatible, making it difficult to share and integrate data [1]. The data sharing mechanism of management departments is imperfect, and cross-department collaboration is difficult, affecting the accuracy of digital twin models and the analysis effect of AI algorithms.

4.2. High Cost of Complex Scene Modeling

Digital twin modeling of complex scenarios needs to integrate a large amount of data, and BIM modeling is complex and time-consuming. The simulation of physical processes such as fire spread requires high-precision physics engines, with high algorithm difficulty and cost, which limits the popularization of technology.

4.3. Insufficient Generalization Ability of AI Models

Most current AI early warning models are for specific scenarios with weak generalization ability. In the fire protection field, it is necessary to clarify the early warning basis of the model to obtain the trust of personnel and guide actions. For example, the fire early warning model of commercial complexes has significantly reduced accuracy in chemical industrial park scenarios [6]. AI model training relies on labeled data, fire scenario data is difficult to obtain, and model training effect is limited [7].

4.4. Security and Privacy Risks

Digital twin and AI early warning systems involve sensitive data, and data security and privacy protection face challenges. If the system is attacked, it will lead to data leakage and model tampering, affecting management operation. The collection and use of personnel location data may infringe on privacy, and a sound security protection mechanism needs to be established.

5. Technical Development Countermeasures

Deepen the application of AI large models in fire prediction and develop industry pre-training models. Collect fire data for targeted training to improve fire risk prediction ability; use various types of data to predict fire occurrence probability and spread trend. Apply digital twin technology to build virtual BIM models to support fire prevention and control. Explore an open smart fire protection ecosystem, integrate 5G to realize real-time communication of equipment, and integrate blockchain to ensure data security and credibility. Promote cooperation and sharing through an open ecosystem and drive the innovation of smart fire protection technology.

5.1. Establish Unified Data Fusion Standards

Accelerate the formulation of data standards in the fire protection field, unify equipment data formats, and realize seamless connection of sensors, BIM and GIS data. Establish a cross-department data sharing mechanism to break information islands and provide data support for the integration of digital twin and AI early warning.

5.2. Promote the Lightweight Development of Modeling Technology

Develop lightweight digital twin modeling technology to reduce cost and difficulty. Use AI algorithms and image recognition to automatically generate building models and reduce manual work; develop modular physics engines to realize rapid scene adaptation and promote the application of technology in small and medium-sized scenarios.

5.3. Improve the Generalization Ability of AI Models

Based on Federated Learning (FL) technology, realize joint training of multi-scenario data and improve the generalization ability of AI models [8]. Federated learning can integrate multi-party data to train general models while protecting privacy. At the same time, digital twin is used to generate virtual fire data to supplement the shortage of real data and improve training effect.

5.4. Strengthen Data Security and Privacy Protection

Establish a sound data security and privacy protection mechanism, use encryption technology to protect sensitive data and prevent data leakage [9]. At the same time, formulate data usage specifications, clarify the scope and authority of data collection and use, and balance the relationship between data utilization and privacy protection.

6. Conclusion

The fire digital twin system maps temperature data to the 3D model, displays equipment status with colors, and realizes virtual-real integrated monitoring. Managers can view the BIM model and real-time video simultaneously to improve situation awareness efficiency. The system can display the status of fire equipment and passage information, and support multi-user collaborative operation. The AI fire early warning system realizes intelligent identification and analysis through multi-dimensional perception, early warning and automatic linkage, reduces fire incidence and false alarm rate, and promotes the transformation from passive fire fighting to active prevention and control, such as the ESMap solution. The in-depth integration of digital twin and AI early warning can accurately identify and warn in advance, support emergency decision-making in the event, and optimize analysis plans after the event. Although facing challenges such as inconsistent data standards, with the progress of technology, the two will become the core support of smart fire protection and ensure urban safety.

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