Research on the Simulation Platform for Fire Prevention and Control in Highway Tunnels Based on Digital Twin

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Abstract: Aiming at the problems existing in the fire control system of highway tunnels, such as single detection objects, lagging information transmission, and low intelligent level of fire handling, a three-dimensional digital twin model and multi-sensor fusion positioning were constructed based on the theory of fire causes and characteristics and digital twin technology theory. Based on the Unity platform, we designed a fire linkage control system based on digital twins and established a BIM model for tunnels and a visualization simulation platform. Experiments show that this model significantly improves the speed of fire emergency response and the level of digital management, as well as the technical level of safe operation in tunnels.

1. Introduction

The semi-enclosed structure of highway tunnels leads to a high risk of death and rescue obstacles. The traditional monitoring system has a slow response, poor automation level and poor safety prevention effect. It is necessary to study a new type of highway tunnel fire prevention and control simulation platform based on digital twins.

According to the "Outline for the Construction of a Transportation Powerhouse", enhancing the digital control and management capabilities of tunnels has become an important direction for the construction of transportation infrastructure [1]. Countries such as the United States, Japan and Germany have begun to conduct systematic research on tunnel fires. The research points include aspects such as vehicle combustion characteristics, fire spread and temperature distribution [2]. From 1949 to 2016, there were approximately 200 major accident fires in tunnels worldwide, which were low-probability events with serious consequences. The threat posed by accident fires in highway tunnels is much higher than that of ordinary highway fires [3]. Highway tunnels, as key nodes of the transportation network, their fire safety is directly related to public life and property as well as the efficiency of traffic operation. Li Xinxing et al. conducted a technical analysis of the three commonly used types of fire detectors in combination with the full-scale fire test of long tunnels [4]; Tan Xiaomin introduced the application of fiber Bragg grating sensing technology in the tunnel fire alarm system [5], and Ma Chuncheng et al. introduced the design and implementation of the automatic fire alarm system scheme [6]; Yu Lingfeng adopted a multi-sensor gradient data fusion model to monitor tunnel fires, which can more accurately identify the occurrence of fires in the tunnel [7].

In the research on the application of digital twin technology in fire prevention and control as well as tunnels, domestic scholars Wu et al. proposed a digital twin system for intelligent fire protection in tunnels. This system consists of four main components (sensor network, data cloud, artificial intelligence model and user interface), which is used to collect, manage, process and visualize tunnel fire information. It can provide valuable information to help firefighters make decisions [5]. However, the research on the practical application of visualization and intelligence in emergency prevention and control is not in-depth enough.

Based on the actual occurrence of fires in tunnels, this study establishes a three-dimensional digital twin tunnel to link the tunnel fire alarm system with the fire extinguishing system. By using

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multiple perception devices and big data analysis technology, a digital twin tunnel fire prevention and control simulation platform is created.

2. Concept definition and theoretical basis

2.1. Digital twin technology

Digital Twin Technology refers to a method that comprehensively utilizes technologies such as sensors, the Internet of Things, virtual reality, and artificial intelligence to describe and model the characteristics, behaviors, operation processes, and performances of physical objects in the real world. The mapping is completed in the virtual space to reflect the entire life cycle process of the corresponding physical equipment. The essence, structure and dynamic relationship of the system are reflected in the form of virtual modeling, thereby more concentratedly and profoundly reflecting the essence and operation rules of the physical object.

Digital twin technology integrates real-time data, historical data and other sources of data, and uses tools such as principles, mechanisms and process models to create a digital model that accurately and in real time reflects the state of physical objects, and provides real-time feedback and interaction for users.

Core technology: Data collection and synchronization, relying on Internet of Things sensors to collect real-time data such as temperature, location, and operational status of physical entities, and build dynamic mapping relationships. Modeling and simulation, combined with 3D modeling (BIM/GIS), physics engines and algorithms, accurately reproduce the structure and behavior of objects, and support testing and prediction in virtual environments. Artificial intelligence analysis optimizes model parameters through machine learning to achieve decision support such as fault early warning (such as equipment wear prediction) and process optimization (such as improving production line efficiency).

The Binzhou Yellow River Conservancy Bureau has developed a digital twin platform for smart cities, enabling ice formation calculation, automatic drone inspection, and flood control decision-making. The traffic system alleviates congestion through a simulated traffic light scheme. Medical and health care, surgical rehearsals, risk reduction, personalized treatment plans, all realized through the digital model of the human body. In aerospace, NASA simulates the operational status of spacecraft, providing real-time fault diagnosis and remote collaboration.

The development trend is ecological expansion, extending from single-device modeling to full industrial chain collaboration (such as supply chain logistics optimization). Zero-code platforms have become widespread, and visual tools have lowered the threshold for use. Non-technical personnel can quickly build models (such as dragging and dropping configurations for pre-set algorithm libraries). AI deeply empowers, generative AI accelerates the training of autonomous systems, and physical precise simulation drives a leap in prediction accuracy. Challenges and bottlenecks: Data security risks and the standardization of multi-source heterogeneous data fusion still need to be broken through.

2.2. BIM technology

BIM (Building Information Modeling) technology is a digital tool applied in engineering design, construction and management. Through the integration of digital and information models of buildings, it is shared and transmitted throughout the entire life cycle of project planning, operation and maintenance. It enables engineering and technical personnel to have a correct understanding and efficient response to various building information, provides a basis for collaborative work for the design team and all construction entities including the building and operation units, and plays an important role in improving production efficiency, saving costs and shortening the construction period. BIM is a building and engineering management method based on 3D modeling technology. By integrating all aspects of buildings and infrastructure into a virtual model, it achieves comprehensive coordination, collaboration and management.

Multi-dimensional data integration, taking 3D models as the carrier, integrates information such

as the geometric dimensions, material properties, costs and construction periods of building components, and supports data sharing and traceability throughout the entire process of design, construction and operation and maintenance. Dynamic simulation optimization, through technologies such as energy consumption simulation, structural mechanics analysis, and light prediction, anticipates problems in the design stage, reducing construction changes and resource waste. Full life cycle management, covering all stages from planning, design, construction to operation, realizes closed-loop data management of buildings from "blueprint" to demolition.

3D modeling: BIM can create precise building models with geometric and attribute information by using 3D modeling software. These models can include the structure, equipment, pipelines, electrical systems, etc. of buildings, which can help designers and engineers better understand and visualize the complexity of buildings.

Data Management: BIM not only stores and manages the geometric information of buildings, but can also include detailed component attributes, material information, supplier information, etc. These data can be used in various stages such as architectural design, engineering analysis, cost estimation, and construction scheduling.

Collaboration and coordination: The BIM platform enables collaboration and coordination among multiple participants, promoting good communication and cooperation among various professional teams such as designers, engineers, architects, and construction workers. By sharing models and data, all participants can understand the design conflicts, changes and progress of other teams in real time.

Simulation and Analysis: BIM can support the simulation and analysis of buildings, such as structural analysis, energy efficiency analysis, lighting simulation, etc. This can help designers optimize the design plan, predict the performance of the building, and provide decision support.

Facility management: BIM models can be applied to the maintenance of buildings and facility management. By integrating equipment, systems and maintenance information related to buildings, the automation, intelligence and sustainable development of facility management can be achieved.

2.3. Intelligent fire protection linkage system

The intelligent fire protection linkage system is an intelligent fire protection system that realizes the full-process automatic coordination of fire monitoring, alarm and handling through the Internet of Things, artificial intelligence and automatic control technology. Intelligent perception system: Deploy smoke/temperature detectors, flame recognition cameras, water pressure sensors and other devices to collect environmental data in real time (such as smoke concentration, temperature changes, fire water pressure), and transmit it to the cloud platform through the Internet of Things.

AI decision-making system: Based on deep learning algorithms to analyze multi-source data, the accuracy rate of flame visual recognition is $\geqslant$98%, and an alarm is triggered within 1 second. Coupled analysis of smoke, temperature and electrical parameters filters out 98% of false alarms (such as the "True Alarm Recognition" technology of Tianze Zhilian).

The automatic execution system, in coordination with fire extinguishing devices (sprinkler systems), smoke exhaust equipment, fireproof rolling shutters, emergency broadcasting systems, etc., realizes the full automation of "alarm - handling - evacuation".

Development direction: AI deep empowerment, machine learning optimization of multi-detector coupling models, and improvement of recognition accuracy in complex environments; Generative AI simulates the fire spread path and rehearses the evacuation plan. Cross-system integration, combined with BIM to achieve visualization of building structures (such as the Binzhou flood control platform); Connect with the urban emergency system and share data on transportation and medical resources. By 2025, the closed-loop architecture of "AI perception - digital twin - automatic fire extinguishing" will be widely adopted in newly built tunnels. The policy mandates that 100% of special tunnels (such as oil and gas pipe galleries) be equipped with intelligent linkage systems.

The dual insurance centralized control system combines manual control with intelligent control. It is a system that centrally controls, displays and uniformly manages all fire protection facilities in

the system through the fire control room. Usually, the detection, communication and alarm systems, fire pumps, supply fans, smoke exhaust and ventilation fans, some fireproof rolling shutters and automatic fire extinguishing control devices, etc. are centrally controlled and uniformly managed in the fire control room. For large and scattered control systems such as smoke exhaust and ventilation fans and fire door release devices, on-site decentralized control can be adopted.

3. The composition of the tunnel fire prevention and control system

3.1. Tunnel fire detection and alarm technology

Fire detection and alarm system: The working mechanism of the highway tunnel fire detection and alarm system mainly involves installing corresponding detection instruments inside the tunnel and monitoring various fire-related parameters through different detection methods. Once an abnormal situation is detected, the automatic fire alarm system will issue an alarm signal and transfer the fire location to the monitoring screen in the tunnel monitoring center. After confirmation by the on-duty personnel, the fire control, traffic signal, ventilation, lighting, broadcasting and other linkage procedures shall be implemented, and the relevant departments shall be notified to take corresponding measures to quickly control the fire, enhance the efficiency of fire fighting work and reduce the losses caused by the fire. At present, the fire detectors applied in tunnels are mainly divided into three categories: photosensitive fire detectors, temperature-sensitive fire detectors and smoke detectors.

Fire location technology: As fire incidents that occur in tunnels are usually caused by vehicle fires, and vehicle fires are typically moving fires, there is a certain distance error from the discovery of a vehicle fire to its cessation. During this period, multiple fire detectors on the side walls of the tunnel may send out alarm signals, but they cannot provide accurate information on the location of the fire source. Therefore, how to accurately locate the fire source point, correctly associate the corresponding fire protection facilities of the fire source point, and reduce the adverse risks caused by linkage failure and incorrect associated positions is a key issue that needs to be urgently solved at present. The fire location scheme proposed in this paper achieves precise location of the fire source points in the tunnel through flame detectors + fiber Bragg grating fire detection equipment, combined with the fire locator on the tunnel track robot. This scheme can quickly and accurately determine the pile number where the fire occurs within the fire occurrence area, thereby ensuring the correct triggering of the corresponding rain valve group for fire extinguishing and avoiding the occurrence of untimely and insufficient fire extinguishing. Compared with the dual-spectrum thermal imaging image-based fire detector, the image-based fire detector has higher positioning accuracy and shorter response time. The image-based fire detector is selected as the precise fire source detection equipment to be installed on the tunnel rail-mounted robot. By using rail-mounted robots equipped with image-based fire detectors, accurate detection and timely response to fire sources in tunnels can be achieved, thereby enhancing the safety of tunnels and the ability to deal with accidents.

3.2. Tunnel fire protection technology

Tunnel fire protection technology: The construction of undersea tunnels is highly challenging and the safety requirements are relatively high. In China, rain-based fixed water-based fire protection systems (automatic fire extinguishing systems) are generally installed in undersea tunnels to enhance safety guarantees. Considering the importance of tunnel fire prevention and control, this study will focus on developing a simulation platform for tunnel fire prevention and control based on the role of an automatic fire extinguishing system. In order to ensure the practicability and pertinence of this platform, a domestic submarine immersed tube tunnel with a rectangular cross-section will be adopted as the research object to demonstrate and optimize the fire control strategy and effectively evaluate the system performance. The foam-water spray fire extinguishing system forms a protective foam layer covering the surface of the burning object by spraying foam liquid, isolating the burning object from contact with oxygen and suppressing the generation of flames and

heat. This approach can more effectively suppress the fire and reduce the damage caused by the fire to the tunnel structure. On the other hand, since submarine immersed tube tunnels are usually large in size and closed in space, when a fire occurs in a submarine immersed tube tunnel, a large amount of thick smoke is produced, which brings great difficulties to personnel evacuation and rescue. The foam-water spray fire extinguishing system can effectively suppress the diffusion of smoke through the covering effect of foam liquid, reduce the impact of smoke on personnel, and improve the efficiency of personnel evacuation. In conclusion, the selection of foam-water spray fire extinguishing systems for submarine immersed tube tunnels can effectively control and extinguish fires in the submarine environment, ensuring the safety of personnel and the integrity of the tunnel structure.

3.3. The tunnel fire prevention and control system is linked and controlled

We should establish a complete fire alarm linkage control system to ensure that an alarm can be issued promptly when a fire occurs and effective measures can be taken for fire extinguishing and evacuation. The specific control process is as follows: Apply the specification "Code for Design of Automatic Fire Alarm System" (GB 50116-2013), and design three types of fire alarm system (FAS) linkage logics to be selected in the tunnel vehicle lane. That is, three types of fire alarm signals: The alarm signals of the flame detector, the fiber Bragg grating and the manual button are regarded as three logical points. They need to simultaneously trigger two sets of signals to activate the foam sprinkler valve groups at the corresponding positions in the tunnel and carry out foam sprinkler fire extinguishing in the corresponding areas. However, if there is only one trigger signal alarm in the same alarm area, the system will determine that the linkage conditions are not met. In order to prevent the system from causing linkage failure due to misjudgment or missed judgment, this linkage control system introduces a tunnel track-type fire location alarm robot and adds a new linkage control logic. That is, in the same alarm area, any one of the flame detector, fiber Bragg grating, or manual alarm button triggers an alarm signal. It will then activate the nearby fire location and alarm robot to go to the fire site to locate the fire source and control the fire extinguishing system in a coordinated manner. We need to design digital tunnels and precisely connect the building automation system (BAS) equipment through a digital dual-tunnel fire control platform to nip fires in the bud and enhance the tolerance for tunnel fire conditions.

4. Research on Digital Twin Method for Tunnel Fire Prevention and Control

4.1. Construction of BIM model for tunnels

The core process and technical key points of tunnel BIM model construction, modeling process and technical route: Basic route design, using Civil 3D to create the spatial centerline of the tunnel (route plane and longitudinal design), and generate the three-dimensional reference path. A three-dimensional surface model is constructed through topographic mapping data (elevation points, contour lines) as the geological basis. The cross-sectional formwork library was established. The cross-section of the tunnel was split into independent components (such as initial support, lining, drainage ditches, etc.), and a parametric cross-sectional formwork library was created using the CSD tool. The shield tunnel requires the pre-installation of standard ring/turning ring segments, and automatic assembly is achieved through parametric programs.

Model generation and assembly: Tunnel body model : Scan the cross-section template along the centerline to generate the main structure of the tunnel. Complex nodes (such as shafts, inclined shafts) : Revit+Dynamo fine modeling is used for curved sections of irregular structures. Geological integration : Sectioning geological bodies with stratigraphic profile data and fusing them with tunnel structure models.

4.2. Construction of BIM model for tunnel fire protection

Data collection: BIM model of the main structure of the tunnel (civil construction), geological report, design code (fire protection special edition), equipment manufacturer data (fire hydrant, fire

extinguisher, detector, alarm equipment, pump, fan parameters, etc.), relevant standard atlas. Reference and coordinate setting: Take the main structure model of the tunnel as the basic reference. We should establish a unified coordinate system and elevation reference, set up a clear elevation and shaft grid system (especially in complex areas such as ramps and connection channels), and ensure the precise positioning of each fire protection system model.

Fire protection system component modeling: Piping system modeling: Fire protection water supply system, main pipe (ring network), branch pipe, fire hydrant (including box), pump coupling, valve (gate valve, butterfly valve, check valve, pressure reducing valve, relief valve), pressure gauge, flow meter, pipe support/hanger. Water spray/foam system (if any), nozzles, piping, control valve assembly, foam tank and related equipment.

Equipment modeling: Fire extinguishing equipment, fire extinguisher boxes (including fire extinguishers), fixed fire extinguishing system equipment (such as dry powder, high-pressure fine water mist devices). Alarm and detection equipment, fire detector (smoke, temperature, flame, linear temperature, etc), manual alarm button, sound and light alarm, fire telephone jack, emergency broadcast loudspeaker, area alarm controller/module box. Smoke control and exhaust equipment, tunnel jet fan, axial fan (opening), damper (fire damper, smoke exhaust damper, regulating damper), duct (if any). Power supply and emergency lighting, fire power distribution box, emergency lighting fixtures, evacuation indication lights. Other, fire pump room/fire water tank equipment (if in a tunnel or opening).

Collision detection and coordination optimization: We integrate the fire protection model with the tunnel structure model as well as the mechanical and electrical (ventilation, lighting, power and weak current conduits) models, and set up running collision detection to identify spatial collisions (hard collisions, soft collisions, gap collisions) between fire protection pipes/equipment and the structure, as well as other pipes. Based on the collision report, design optimization and adjustment (such as adjusting pipe elevations, orientations, and optimizing equipment positions) is one of the greatest values of BIM in tunnel engineering, which can significantly reduce construction rework.

Analysis and Simulation: Evacuation Simulation: with fire facility layout, simulate the evacuation time and route of people in a fire scenario.

We conduct flue gas flow simulation to verify the effectiveness of flue gas control and exhaust system design (professional software such as PyroSim and FDS are required).

Hydraulic calculation verification: Use the pipeline information in the model to perform hydraulic calculations to check if the pressure and flow rate at the least favorable point meet the requirements.

4.3. Model mapping method

We utilize the BIM model of the tunnel to demonstrate its fire resistance performance, present the digital twin model of the tunnel's fire resistance performance, and clarify the logical relationship of the mapping of the tunnel's fire resistance performance.

The objects of the digital twin of the tunnel fire prevention and control mapping include: The location and status mapping of fire detection and alarm facilities, the location and status mapping of fire source points, and the location and status mapping of fire extinguishing facilities are designed based on the proportional relationship between the real tunnel and the digital tunnel coordinates. According to the mapping relationship of tunnel fire prevention and control and the initial coordinates of the tunnel on the virtual platform, the corresponding relationship between the pile numbers of fire prevention and control facilities and the coordinates of the virtual platform is designed, including the positions of flame detectors and foam-water spray groups.

Fire source point mapping: To obtain the precise location of the fire source point (the pile number of the fire source point and the position of the lane where it is located) in the digital twin platform, it is necessary to correspond the world coordinates of the virtual platform with the tunnel pile number in the real world. In this paper, Unity3D is used to build a virtual simulation platform, and the corresponding fire zones are divided through the relative positions of the flame detectors in the tunnel in the virtual platform. To accurately read the location of the fire source, it is necessary to

connect to the database, obtain certain parameter inputs, and map the location of the fire source based on the set calculation conditions. The specific steps are as follows: In Unity, we introduce the MySQL database plugin; we write code in C# to connect to the database and perform data reading and writing operations; we use SQL statements to query the location of fire sources in the database; we convert the query results into the data structure in Unity and use Vector3 to represent the position information in the three-dimensional coordinate system; we apply the position of the fire source to the rendering scene of Unity using the particle system in the scene.

Linkage control mapping of fire protection facilities: According to the designed linkage control process of the fire prevention and control system, combined with the virtual platform coordinates of the digital tunnel, the linkage relationship between each area in the digital tunnel and the foam-water spray group is measured and calculated. The position of the foam-water spray group is mainly related to the X and Z axis coordinates of the foam-water spray group in the digital tunnel. The X coordinate determines whether the opening position of the foam-water spray is in the left tunnel or the right tunnel, and the Z coordinate determines the position of the pile number of the opened foam-water spray group. To achieve the linkage of water spray equipment, two data tables, water_sprinklers and sprinklers, need to be established first. The water_sprinklers data sheet stores the foam-water spray device activation combinations and their corresponding Z-axis coordinate ranges of the digital tunnel when the fire source points occur at different positions within the tunnel.

5. Development of a simulation platform for Tunnel Fire Prevention and Control

5.1. Model Platform Design

Overall design: The overall system architecture is divided into four levels: the model layer, the data layer, the analysis layer, and the service layer. (1) The model layer mainly includes the tunnel model, the fire detector model, the fire protection model, and the track robot model built inside the tunnel. (2) The data layer includes equipment location data, equipment status data, fire monitoring data and emergency zoning data. (3) The analysis layer is the core of the system. It is mainly responsible for realizing the linkage of tunnel fire prevention and control equipment, monitoring the status of equipment, and managing fire sections, etc., and analyzing and calculating various information of the system. (4) The service layer mainly targets the operation and maintenance management personnel of the tunnel, including system management, data dashboards, and the combination of the results from the analysis layer with BIM models to achieve visual display of tunnel fire prevention and control.

Database design: Firstly, the coding design is carried out. The location code is the pile number of the location where the tunnel fire prevention and control facilities are located, and the code length is 6 digits. The coding of facility types and the location coding of fire prevention and control facilities are based on the types of fire prevention and control related electromechanical facilities inside the tunnel, and the electromechanical facilities are coded in the left and right tunnels of the tunnel and on the left and right sides inside the tunnel. According to this code, all the electromechanical facilities related to fire prevention and control in the tunnel can be precisely located. The lane position code indicates the specific lane position where the fire source point is located, and the relative position code indicates the specific position of the fire source point on the left and right tunnels of the tunnel. According to this coding method, the position of the fire source point in the tunnel can be precisely located. We should establish fire source point information tables, fire detection and alarm information tables, and fire protection system data tables, including the position information of flame detectors and alarm equipment. We should establish a flame detector data table, which should include the detector name, digital tunnel coordinates and pile number. We should establish an information management database, including the startup device information table, the abnormal device information table, and the logged-in personnel information table. The start-up facility information table contains the equipment names, location information and status information of the tunnel fire prevention-related facilities. For the abnormal facilities found during the inspection of tunnel facilities, we should store their facility codes in the abnormal facility

information table. The login personnel information table contains the name, employee number and login time of the logged-in personnel.

System Function module Design: The research purpose and design process of the digital twin fire prevention and control system for tunnels are analyzed. The main functional requirements of the system are information management of fire and fire prevention and control facilities within the tunnel, visualization of the fire extinguishing scene, visualization of the entire tunnel zoning, and system management. Therefore, the integrated system functional requirements are classified into three categories: fire prevention and control data information management, visualization management, and system management. The fire prevention and control data management function module helps users query the specific locations of fire sources in the tunnel. The visualization management function module, in order to display the occurrence and extinguishing of tunnel fires more intuitively, combines the mapping methods of fire source points and the linkage control mapping of fire protection facilities to set up the Particle System (Particle System) in the tunnel BIM model to create the visualization effects of fire source points and foam-water spray systems. The system management function module mainly manages the information of personnel logging into the system and the abnormal prevention and control facilities existing in the tunnel.

5.2. Function display and release deployment

User Interface: Based on the Unity platform, we can design an intuitive and user-friendly interface through its visual editor, powerful GUI system, multi-platform support, and third-party plugins and resources, providing a good user experience. This system mainly designs a three-layer structure of the login interface, the main interface and the result display interface.

Visual function interface: When a fire breaks out in a tunnel, the location information of the fire source point at the real tunnel fire scene is synchronatively mapped in the digital twin tunnel through the tunnel integrated management system. On the platform, users can choose whether to activate the fire protection facilities. When the fire-fighting facilities are activated, the digital model of the tunnel will display the fire-fighting scene and, through the tunnel's comprehensive management system, activate the fire-fighting facilities and open the corresponding foam water spray groups.

When setting up the information release for the tunnel digital system, in the "Settings" function, we select the scenario to be released and make the settings in the scenario setting column. Secondly, in the platform column, we should choose "Publish using WEBGL". Finally, in the player settings, we set the parameters that need to be modified.

The key visual outputs during the construction process (which can be understood as the specific manifestations of the "construction diagram"), these views are the direct embodiment of the construction process and the final outcome: the three-dimensional overall model view, which visually presents the overall layout and interrelationships of the fire protection system (pipelines, equipment) within the tunnel space. Uses: macro coordination, presentation and display, spatial perception. Visualization key points: Distinguish different system colors (such as red water supply, yellow alarm, blue smoke exhaust), model fineness (LOD 300/400).

Fire protection system schematic diagram: While traditionally it is drawn in two dimensions, in the BIM environment, can automatically generate or assist in drawing more accurate system schematic diagrams (especially piping system diagrams and alarm system topology diagrams) based on the logical connection relationships in the model. Purpose: To understand the working principle of the system, logical relationship, device linkage sequence. Visualization points: Symbol standard, flow clear, hierarchy distinct.

The core of the "BIM Model Construction Diagram for Tunnel Fire Protection" : refers to the process of building a digital model of the tunnel fire protection system that is information-rich, geometrically accurate, logically related, and coordinately error-free , as well as its key visualization results. Key value: Reduce collision rework and resolve most spatial conflicts before construction. To enhance the design quality, we optimize the design through 3D visualization and reduce errors by integrating information. 3D visualization optimization design can enhance

construction efficiency, enabling precise material cutting and prefabrication, and providing visual guidance for installation. Auxiliary operation and maintenance: A complete information model is the cornerstone of intelligent operation and maintenance.

5.3. Tunnel Digital Twin Fire Prevention and Control Simulation Platform

In recent years, tunnel fire accidents have occurred frequently around the world. In early 2024, a major fire broke out in a tunnel in France due to an electrical failure. These painful lessons exposed the fatal shortcomings of the traditional fire protection system, including delayed early warning, slow response and difficult coordination. Hunan Changsha Zhijia Group has successfully established the world's first "heaven, earth and man" three-dimensional tunnel fire protection system, reducing the fire warning time from the traditional 30 minutes to 90 seconds and increasing rescue efficiency by 300%. It has truly achieved "early detection, quick response and zero casualties".

The intelligent fire protection solution for tunnels, through a "space-air-ground" three-in-one monitoring network, builds a fire prevention and control system covering all scenarios: it adopts sub-meter satellite remote sensing technology to monitor abnormal heat sources within a 5-kilometer radius around the tunnel in real time. By comparing historical data models, potential risks such as vegetation withering and mountain seepage can be automatically identified. We have data linkage with the meteorological department and can issue extreme weather warnings such as lightning strikes and high temperatures 72 hours in advance.

Dual monitoring system: Distributed optical fiber temperature measurement system (DTS) deployed at intervals of 50 meters. Residual current type electrical fire monitoring detectors covering all electromechanical equipment. The intelligent linkage device automatically shuts down the ventilation system when a fire occurs to prevent the spread of the fire, activates the foam water spray combined fire extinguishing system, and suppresses open flames within 30 seconds.

The "superpower" of AI large models: The DeepSeek fire protection large model independently developed by Tezhijia has demonstrated astonishing performance in this solution: intelligent diagnosis, automatically identifying abnormal conditions of equipment by analyzing over 100,000 historical fault data. Behavior prediction: Based on vehicle traffic data, predict the risk level of hazardous chemicals transport vehicles. Decision optimization: In the simulation exercise, the efficiency of rescue route planning was increased by 40 times compared with manual operation.

Shenzhen Tanglangshan Tunnel (Guangdong's first digital twin platform) : Centimeter-level vehicle twin positioning technology, tracking hazardous chemical vehicles throughout the journey, and giving a one-minute early warning to high-risk vehicles at the tunnel entrance. Incidents such as fires and scattered objects can be identified within milliseconds, and the emergency response time has been reduced from 5 minutes to 3 seconds. The management has been upgraded, changing manual inspection to 24-hour real-time online monitoring, with the accuracy rate of equipment failure prediction reaching 91%.

The direction of technological evolution involves in-depth collaboration among multiple systems. For instance, the Tanglangshan Tunnel in Shenzhen integrates "dumb devices" such as fire water pressure early warning and distribution room monitoring, achieving full control over the entire area's equipment. Ai-driven decision-making upgrades: In the Changsha case, the DeepSeek large model was adopted to optimize fire prediction, increasing the efficiency of rescue decision-making by 40 times. Low-cost transformation solution, lightweight "edge-cloud" architecture compatible with existing facilities (such as the Wuhan project), reducing the cost of intelligent transformation..

6. Conclusion

The new tunnel fire prevention and control linkage control system reduces the probability of linkage failure and false alarm rate. It achieves precise fire source location (with an error of less than 1 meter) through a multi-level positioning scheme of "fixed detector + track robot", optimizes the emergency linkage process and high-precision positioning technology, and improves the efficiency of emergency response and the scientific nature of decision-making.

We design a virtual-real mapping algorithm for BIM models and digital twins, and establish an automatic control mechanism for fire protection facilities, which can achieve full-process linkage of fire detection, alarm and extinguishing, significantly improving the speed of emergency response.

We have formulated coding rules for tunnel facilities, modular data architectures and system function designs, which can build fire prevention databases and information management modules, and divide them into three major functional modules: data management, visualization and system management, providing structured theoretical support for system development.

We developed a cross-platform visualization simulation system, built a B/S architecture digital twin platform based on the Unity 3D engine, integrated WEBGL remote access and dynamic rendering technologies, to achieve visualization of the fire scene, monitoring of facility status and early warning of emergency areas, significantly improving the efficiency of tunnel operation and management.

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