Design and Application Verification of an Intelligent Control System for Highway Tunnels Based on "One Click Linkage" Control

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Abstract. To solve the problems of a wide variety of mechanical and electrical equipment in tunnels, independent software systems, lack of emergency response control plans for mechanical and electrical equipment with "one-click linkage" control, and poor operability of emergency response plans, this article relies on the Guangdong Provincial Key Area Research and Development Plan Project "Research and Development of Key Technologies and Equipment for Intelligent Control and Emergency Support of Highway Tunnel Engineering Operation Safety" (Project No. 2022B0101070001) to carry out the research and development of an "intelligent control system for highway tunnels". The system is based on advanced technologies such as the Internet of Things and cloud computing to build a tunnel intelligent control system. The main features of the system are as follows: (1) high-precision base map + rapid apparent image acquisition 3D modeling digital model, based on high-precision base map and tunnel apparent image high-speed acquisition technology to establish a refined modeling of tunnel real-world holographic, to achieve digitalization of tunnel assets and emergency control of mechanical and electrical equipment; (2) real-time safety risk assessment of tunnels, combined with static and dynamic parameters of tunnels to conduct real-time assessment of tunnel operation status, and predict traffic accidents, to achieve feedback from the system and propose measures for tunnel quality improvement and upgrading based on cost-benefit analysis; (3) efficient emergency "one-click linkage" control plan, the system integrates event detection algorithms and mechanical and electrical equipment "one-click linkage" control plans to achieve event detection and "one-click linkage" control at the equipment and facility level within tunnels, streamlining emergency response processes and improving emergency response efficiency and accuracy; (4) emergency training and drills based on MR, the system can achieve daily training and drills for tunnels, equipment operation training, emergency drills, assessment of drills, retrospective of drills, and emergency rescue drills. Relying on the "full-scale tunnel small-scale fire test" conducted in physical tunnels, the "intel-

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ligent control system for highway tunnels" has been tested and verified. Multiple rounds of testing and verification have been conducted in terms of system detection and monitoring analysis capabilities, practical functions, and system stability. The test can achieve second-level alarming for fire and abnormal events, "one-click linkage" control of equipment and facilities, real-time meter-level positioning and physiological monitoring of personnel, event process handling, three-dimensional holographic real-time monitoring of facilities, MR safety emergency drills and training, and other functions. Future improvements can have promotional value.

Keywords: Highway tunnel; tunnel electromechanical; one-click linkage; emergency control

1 Introduction

As an important traffic construction facility, the expressway tunnel plays an important role in shortening the running distance and improving the transportation capacity. At present, the traditional tunnel information construction is relatively insufficient, leading to the increasingly prominent problems such as weak tunnel safety risk perception and low emergency rescue efficiency. If there is a traffic accident or equipment failure in the tunnel, it will have a significant impact on the safety of personnel and transportation in the tunnel. According to relevant data statistics, the death toll of global traffic accidents in China accounts for 18.5% in China, and about 35% occur in high bridge and tunnel ratio sections. Moreover, the tunnel safety accidents are difficult to rescue, have high cost and have great social impact. Strengthening the tunnel information construction and reducing the tunnel traffic accidents are the top priority of tunnel operation.

The expressway tunnel has many mechanical and electrical equipment, the scattered facilities in and outside the tunnel, and the high difficulty of power distribution and lighting system inspection, which brings some difficulties to the daily operation safety control of the tunnel. The traditional tunnel electromechanical subsystems generally include monitoring system, alarm system, ventilation system, fire system, lighting system, broadcasting system, environmental monitoring system, information release system, etc., but each system is independently dispersed and difficult to control [1]. In addition, the characteristics of expressway tunnel are the focus and difficulty of daily operation safety control. The four major systems of ventilation, fire fighting, lighting and power supply and distribution in the tunnel are the top priority of tunnel operation safety. Whether the operation state of the equipment is normal and whether the remote operation instruction of the monitoring center is executed correctly are the focus of attention in the daily operation and maintenance. In tunnel operation condition, need to solve abnormal event detection, mechanical and electrical equipment online status monitoring, mechanical and electrical equipment "a key linkage" control operation management difficulties, effectively improve the management response to safety events, reduce the incidence of secondary accidents, in practice to carry out the wisdom of the highway operation [2].

In view of the above characteristics, this paper relies on the research and development plan project in key areas of Guangdong Province, "Highway network tunnel engineering operation safety intelligent control and emergency security key technology and equipment research and development" (project number: 2022B0101070001) to carry out the research and development of "expressway tunnel intelligent control system", which is also one of the core achievements of the project research and development. Highway tunnel intelligent control system mainly by big data, the Internet of things and other advanced technology as the means, for the tunnel operation management, disaster emergency disposal business requirements, set up software and hardware integration tunnel intelligent control system, realize the tunnel in daily monitoring, accident emergency disposal, safety monitoring and other comprehensive business management, break the barrier between the business system, realize the effective integration of resources, resource sharing, business coordination, centralized data analysis, power tunnel operation management, improve the safety of the tunnel, reduce operating costs [1].

2 System Architecture

2.1 System Hardware Architecture

Fig. 1. Hardware architecture

The hardware architecture of the system includes: field mechanical and electrical equipment layer, core control equipment layer, subsystem layer, and central control integrated platform layer. System hardware architecture is shown in Figure 1.

(1) On-site mechanical and electrical equipment mainly includes: variable information board, lane indicator, traffic signal lights, fan, lighting, COVI, light intensity, rolling shutter door, monitoring, etc.

(2) The core management and control equipment mainly includes: PLC, distributed controller, intelligent operation and maintenance and energy consumption control, intelligent fan control, intelligent dimming control, intelligent gateway, etc.

(3) The sub-systems mainly include: traffic video event system, variable information display system, traffic flow detection system, meteorological detection system, environmental detection system, local control system, fire detection system, lighting control system, power monitoring system, mechanical and electrical maintenance system, safety monitoring system, etc.

(4) The central management and control integration platform mainly integrates all subsystems and equipment to realize integrated management and control.

2.2 System Software Architecture

The system software architecture includes: hardware layer, interface layer, data layer, application service layer and user layer. The system software architecture is shown in Figure 2.

Hardware Layer.

The hardware layer mainly includes: variable information board, lane indicator, traffic signal light, fan, lighting, COVI, light intensity, rolling shutter door, monitoring, etc.

Interface Layer.

Relying on the tunnel electromechanical system, the intelligent gateway products compatible with multiple protocols are adopted to communicate and connect with the regional control units of the tunnel electromechanical subsystem, so as to open up the separate tunnel electromechanical subsystem and establish the Internet of Things perception network [4].

Data Layer.

The data resource layer completes the collection and processing of data. After the data processing, it is stored according to "basic data", "business data", "theme" data "and" shared data ". The classified data is stored locally, and business data is stored on the cloud platform to provide data support for business applications [4].

Application Service Layer.

Through big data flow processing technology, the cloud platform quickly processes and applies the transmitted data, providing a supporting environment for the tunnel safety control system, tunnel mechanical and electrical equipment health monitoring system, and tunnel mechanical and electrical equipment maintenance and management system. The system relies on the public cloud platform to deploy the application system, and uses the virtualization, distributed computing, load balancing and other technologies of the cloud platform to realize the reasonable allocation of computing

and storage resources, and realize the requirements of "energy saving, efficient and simplified management" of tunnel management operation and maintenance [4-5].

User Layer.

System users include highway tunnel operation and management units, scientific research units, etc. Different users have different levels and permissions, and can obtain the corresponding data or services.

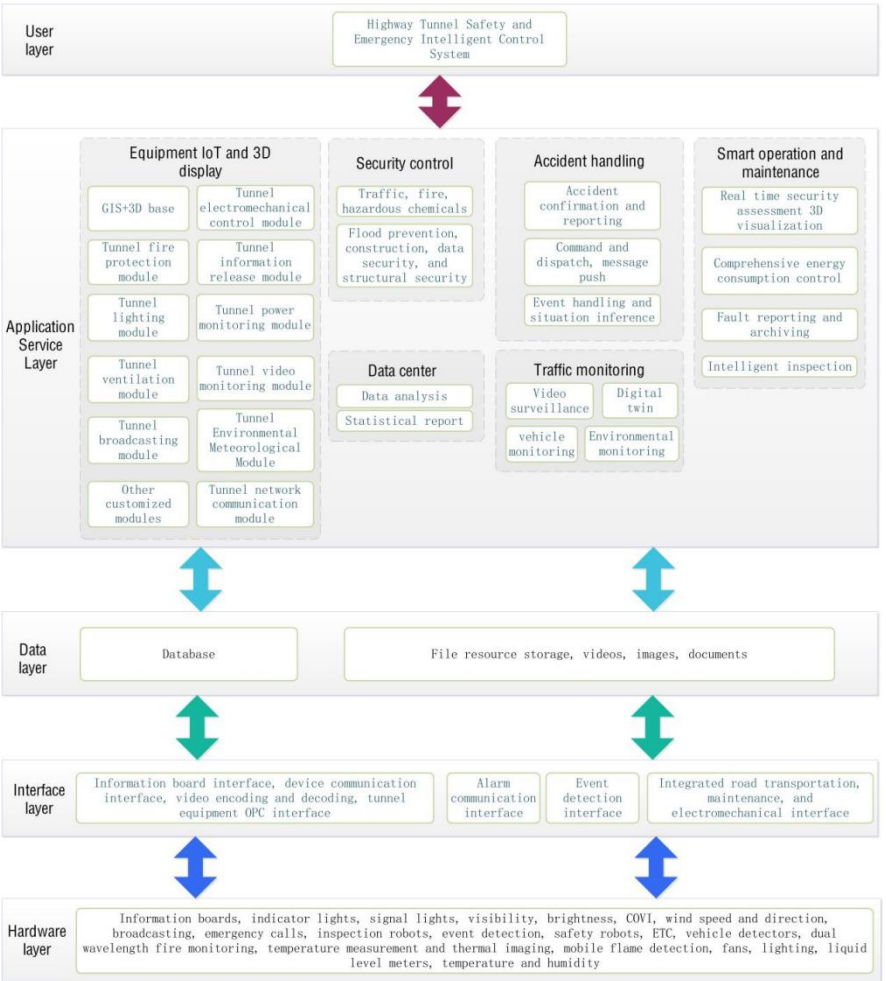


Fig. 2. Software architecture

2.3 System Technical Architecture

The front end of the tunnel intelligent control system is developed with jQuery +

Html5 + modular framework, Ajax technology is used for asynchronous data loading, and the one-to-one digital modeling demonstration of the tunnel is combined with the high-precision three-dimensional base engine. The back end adopts MVC (Model + View + Control) + multi-layer decoupling architecture. The user sends the request to the front-end controller through the PC browser, transmits the relevant control instructions and data to the back-end application, the back-end application communicates with the service layer through the MQ message queue and API interface, the service layer interacts with the device, the feedback signal of the device or data processing goes back to the application processing program and then returns to the front-end controller, and then rendering and displays them in real time. The front-end function page is simple and friendly, and the background realizes the standardization of basic data, control and management process and informatization. The system technical architecture is shown in Figure 3.

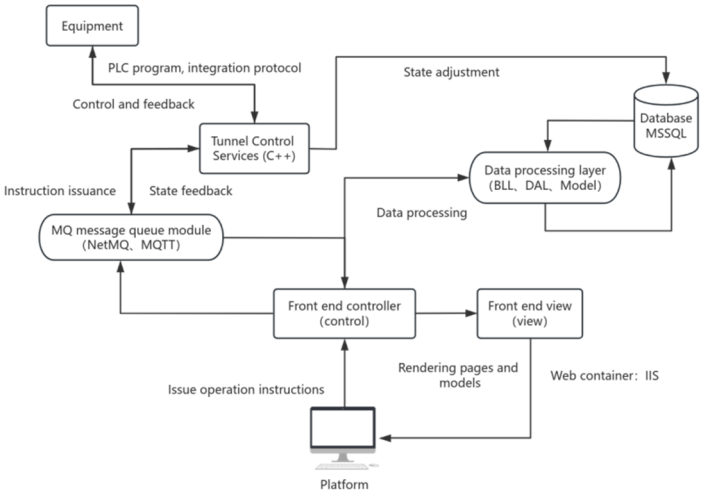


Fig. 3. Technical Architecture

3 System Function Highlights

In view of the problems of the tunnel electromechanical system, complex composition, mutual independence, and restricting the development of the tunnel intelligent level, a unified tunnel 3 d safety and emergency intelligent control system is established, which integrates the comprehensive collection, analysis, control and display of the tunnel data. Tunnel 3 d holographic display, equipment distributed intelligent monitoring, security real-time dynamic assessment, digital traffic monitoring, MR safety drills and training, mechanical and electrical facilities under the event "a key linkage" control, personnel positioning and physiological monitoring, intelligent operations, etc., to build more efficient, safe tunnel intelligent emergency control system, improve the tunnel traffic safety traffic capacity.

The main functions of the system include: (1) GIS + 3 D tunnel digital model; (2) equipment Internet, data integration and display; (3) safety control; (4) emergency control; (5) traffic monitoring; (6) intelligent operation and maintenance; (7) training and drill.

The main functional components of the system are shown in Figure 4.

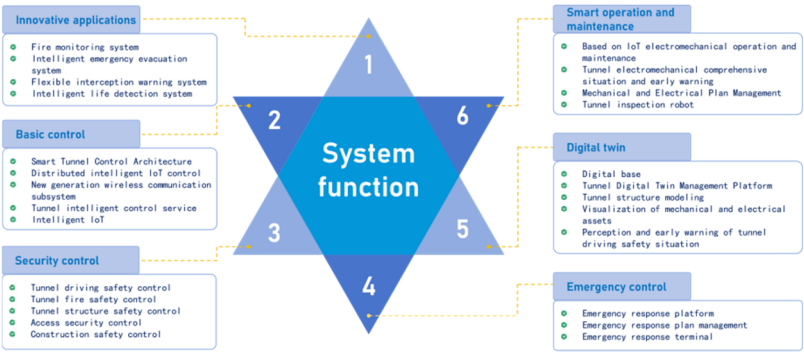


Fig. 4. Main functional composition of the system

In addition, the core features of the system are as follows:

High-Precision Base Map + Fast Apparent Image Acquisition Three-Dimensional Modeling Digital Model.

The fined modeling of tunnel real scene based on high-precision base map and tunnel apparent image. Secondary development in the 3 D base engine to build a tunnel digital model based on GIS + 3 D model. At present, the equipment assets included in the 3 D base engine include fan, indicator light, information board, etc. In the secondary development, other equipment assets should be digitized, superimposed and marked into the tunnel through the open platform provided by the base, and support equipment control through the 3 D model panel. Display the equipment online status, online rate, traffic service level of the whole line, traffic flow, alarm information status, tunnel environment information status, energy consumption data status, risk source information and surrounding road network, so as to realize the emergency control of tunnel equipment and facilities.

Real-time Tunnel Safety Risk Assessment.

Real-time safety risk assessment module contains large traffic highway tunnel operation safety risk source identification and assessment method, combined with the tunnel alignment, mechanical and electrical facilities configuration and static parameters such as traffic volume, speed, equipment integrity rate dynamic parameters of tunnel operation assessment, and traffic accident prediction, real-time in the tunnel intelligent control system feedback, through the cost benefit method evaluation quality upgrading measures, used to guide the tunnel facilities renovation and management means.

Efficient Emergency "One-Key Linkage" Control Plan.

Due to a variety of tunnel accidents, tunnel fire or traffic accident space limit, personnel and vehicle evacuation escape difficult, mechanical and electrical equipment emergency "one key linkage" control plan to tunnel fan, horizontal hole, shaft, lane indicator, broadcast, monitoring section for reference, partition section write "one key linkage" control plan. The event detection algorithm and the "one-key linkage" control plan are integrated into the tunnel intelligent control system to realize the event detection in the tunnel and the "one-key linkage" control of the equipment and facilities layer, streamline the emergency disposal, improve the efficiency and accuracy of emergency response, and ensure the safe evacuation of tunnel personnel.

Emergency Training Drill Based on MR.

For the lack of professional, system, emergency drill high cost, poor training effect, and in the tunnel construction based on MR highway tunnel safety and emergency training system, and layout personnel positioning and physiological characteristics collection system, for the emergency plan, emergency evacuation and rescue plan verification and emergency drill training conditions. The MR-based highway tunnel safety and emergency training system can be integrated into the tunnel intelligent control system, in the system of tunnel daily training drill, equipment operation training, emergency drill training, drill assessment, drill backtracking, emergency rescue drill deduction can be realized.

4 System Application Verification

4.1 System Fire Verification Content

Fig. 5. Small scale fire test of foot tunnel

Relying on the "full-scale tunnel small-scale fire test" carried out in the physical tunnel, mainly verifying the intelligent tunnel control system: (1) verifying the effectiveness of the tunnel fire monitoring system; (2) verifying the effectiveness of the "one-button linkage" control plan for tunnel mechanical and electrical equipment; (3) verifying the response speed and emergency disposal process of the intelligent tunnel control system; (4) verifying the stability of the intelligent tunnel control system.

The main test content of the tunnel intelligent control system test is divided into three parts: detection, monitoring and analysis ability, practical function, and system stability. Small scale fire test of foot tunnel is shown in Figure 5.

Detection, Monitoring and Analysis Capability.

Detection and analysis ability refers to whether the system can detect and automatically discover fire events in time and accurately, and the corresponding test indicators include capture rate, accuracy and timeliness. In addition, there are tunnel test field environmental monitoring, equipment (such as fan, gun ball machine) status monitoring, etc.

In addition to the fire event detection, the rescue and escape monitoring and positioning of the fire test personnel were also carried out to verify the accuracy and stability of the positioning track of the positioning system.

Practical Functions.

Practical function refers to the related functions of the monitoring center using the operation control system for fire emergency response, including: event detection, event alarm, event confirmation, start plan (equipment control and emergency response), event reporting, event recovery, etc. The following is the relevant meaning explanation:

① Event detection: the detection equipment located in the tunnel detection field.

② Event alarm: control system can alarm event information automatically pop window display, and provide the key information of the event (must contain event type, occurrence time, tunnel name, line direction, camera gun number, camera gun pile number, ball machine automatic rotation, lane, vehicle type, casualties and other corresponding images and video records).

③ Event confirmation: conduct manual confirmation after the control system alarms, and automatically record the system alarm time and manual response time.

④ Start-up plan: After the alarm information of the control system is manually confirmed, the system will automatically match the emergency plan, and after the start-up plan is manually confirmed, the manual response time will be automatically recorded. Synchronize records whether the field equipment is actually on / off.

⑤ Event reporting: confirm the event information, manually report the corresponding event according to the management requirements, and automatically record the manual response time.

⑥ Event recovery: After the completion of the on-site disposal of the event, the event will be resumed after manual confirmation, and the normal operation (or traffic control) traffic plan will be resumed, and the manual response time will be automatically recorded. Synchronize records whether the field equipment is actually on / off.

System Stability.

Stability refers to whether the control system can maintain normal service for a long time, and the more times and longer the system breaks, the failure, and the lag, the worse the stability.

4.2 Evaluation Criteria for System Fire Verification.

The tunnel intelligent control system has been verified by the "small scale tunnel fire test", and the overall evaluation criteria of the system are shown in Table 1.

Table 1. Overall evaluation criteria of the system

order number	test items	Decision rules / criteria	Determine the result	remarks
one		**Detection and analysis ability**		
1	Fire detection	**The laroccurred within 10s**	Satis/ unsatisfied. Accuracy = accurate alarm times / (accurate alarm times + wrong alarm times)	
2	Equipment detection	**Online status of the equipment and its normal operation**	Whether the status of the equipment in the system is consistent with the actual situation	
two		**Practical function**		
1	Event alarm	The control system can automatically display the alarm event information and provide the key information of the event (it must include the corresponding pictures and video records of the event type, occurrence time, tunnel name, line direction, camera gun number, camera gun pile number, automatic rotation of ball machine, lane, vehicle type, injury and death, etc.). Record the alarm method	Satis/ unsatisfied. Reliability = times of all correct information / (times of all correct information + times of not all correct information), reliability greater than 90% is satisfied.	The hardware-unsupported detection function of the default system can meet the requirements

2	Event confirmation	After the alarm of the control system, the manual confirmation shall be conducted, and the system alarm time and manual response time shall be automatically recorded. **OK to perform the next step after confirmation**	Satisfied / Unsatisfied	
3	Start-up preplan (equipment control and emergency response)	After the alarm information of the control system is manually confirmed, the system automatically matches the emergency plan, and after manually confirming the start plan, the manual response time is automatically recorded. **Synchronize to record whether the field equipment is actually started / off, such as fan, etc**	Satis/ unsatisfied. Reliability = number of devices actually on or off / Plan Configure number of devices on or off. Reliability is 100% satisfied	Hardware reasons cause the device to start up or close as the plan
4	Event submitted	After the event information was confirmed, the corresponding event was submitted according to the management requirements, and the manual response time was automatically recorded	Satisfied / Unsatisfied	
5	Event recovery	After the on-site disposal, the event shall be resumed after manual confirmation, and the normal operation (or traffic control) traffic plan shall be resumed, and the manual response time shall be automatically recorded. **Synchronize records whether the field equipment is actually started / off**	Satis/ unsatisfied. Reliability = number of devices actually on or off / Plan Configure number of devices on or off. Reliability is 100% satisfied	Hardware reasons cause the device to start up or close as the plan
three	**system stability**			
1	Can maintain the normal service for a long time	Number of system outage, disconnection, lag and other failures	Satisfied / Unsatisfied	System failure due to hardware causes does not count as the number of system failures

4.3 System Fire Detection and Monitoring Results

Fire Detection Method.

Active fire detection method The current tunnel only supports two temperature gratings and dual-wavelength fire detectors. Ignition detection is recorded in Table 2.

Table 2. Ignition detection record

Site	Alarm location	event type	Event time	Report to the police details
Long-term safety entity testing site for tunnel engineering	K0+100	fire	2024/4/16 17:43:02	Long-term safety entity test site of tunnel engineering: K0 + 100 (temperature grating 6) occurs alarm
Long-term safety entity testing site for tunnel engineering	K0+240	fire	2024/4/16 17:40:01	Long-term safety entity test site of tunnel engineering: K0 + 240 (dual-wavelength fire detection synthesis Disc) alarm
Long-term safety entity testing site for tunnel engineering	K0+100	fire	2024/4/16 17:39:05	Long-term safety entity test site of tunnel engineering: K0 + 100 (temperature grating 1) occurs alarm
Long-term safety entity testing site for tunnel engineering	K0+200	fire	2024/4/16 17:39:03	Long-term safety entity test site of tunnel engineering: K0 + 200 (temperature grating 7) occurs alarm
Long-term safety entity testing site for tunnel engineering	K0+200	fire	2024/4/16 17:39:01	Long-term safety entity test site of tunnel engineering: K0 + 200 (temperature grating 2) occurs alarm

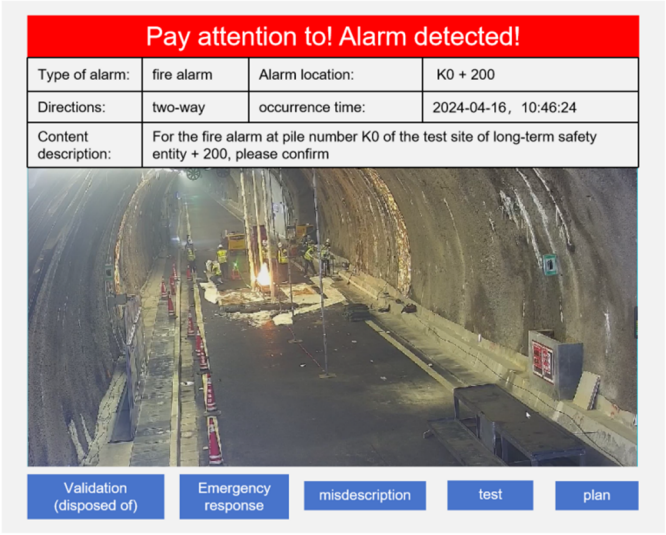
Fire Detection Speed.

According to the video analysis of multiple rounds of fire test, the average time from ignition to fire detection by the system is about 30 seconds, which is first detected by warm grating and delayed by double-wavelength detection. The preliminary analysis of the lag reason is that only one set of equipment is installed in pile K0 + 255 in the tunnel. The fire test is in the K0 + 200 position, and the detection radius of the dual-wavelength fire detector in the tunnel is about 50m, so the detection results have certain influence.

4.4 Fire Emergency Disposal Process of the System

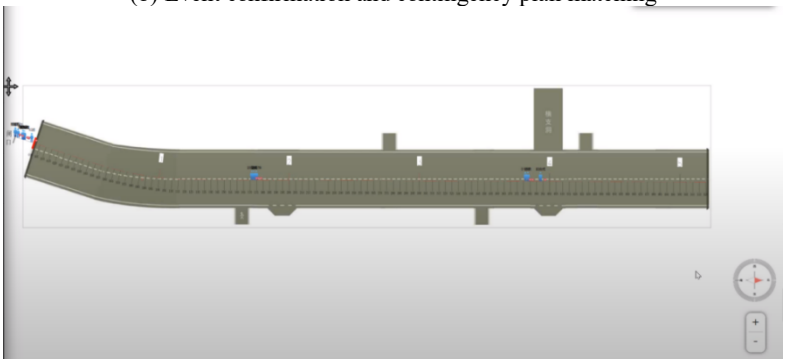
In view of the "one-key linkage" control plan of mechanical and electrical equipment under the test condition of "small scale fire test", the "one-key linkage" control of mechanical and electrical equipment was well implemented in the fire test. The fire event emergency disposal process is shown in Figure 6.

The personnel positioning system is used to monitor the positioning and physiological characteristics of the personnel in the tunnel in real time to understand the evacuation of fire personnel, and to ensure the safety of personnel during the fire test and emergency drill.



(a) Event discovery

(b) Event confirmation and contingency plan matching



(c) Personnel positioning and collection of physiological characteristics (The blue label indicates the location of personnel inside the tunnel)

Fig. 6. Emergency Handling process of fire incidents

4.5 Effectiveness of the "One-button Linkage" Control Plan for Fire Mechanical and Electrical Equipment

The ignition position of the "Full-scale tunnel small-scale fire test" is in K0 + 200 position, which is automatically matched to the "one-key linkage" control plan of tunnel fire mechanical and electrical equipment belonging to K0 + 200 section. After confirming the event information by the monitoring center, the operation of the plan is confirmed. After the system clicks the confirmation, the "one-button linkage" controls the tunnel information board, broadcast, lane indicator, fan, lighting and other mechanical and electrical equipment, and carries out emergency disposal and control of the tunnel fire in time. The "one-key linkage" control of the system can achieve millisecond response and second response.

The implementation of the electromechanical equipment in the "small scale fire test" is shown in Table 3.

Table 3. Control plan of "one-button linkage" for mechanical and electrical equipment

order number	device class	device name (internal number)	Execute the operation	remarks
1	Camera	QCA02	Aim at the section of the accident and return the scene video	
		QCA01, QCA03	Start the video storage backup and increase the rotation saccade frequency	
2	Lane Indicator	LI01, LI02	The traffic sign is changed to prohibited traffic	
3	Variable information board	HCMS 01	Display the content "Tunnel fire, not allowed in"	
4	Fan	AFN01	Turn on the fan for smoke exhaust	
5	Lighting	all fronts	Full-line lighting adjustment to the maximum	
6	broadcasting	LDS01	Broadcast "in a fire, no entry"	Outside the hole
		LDS02, LDS03, LDS04, LDS05, LDS06, LDS07, LDS08, LDS09	Broadcast "If there is a fire, please leave the tunnel as soon as possible"	
		LDS10, LDS11	Broadcast "if there is a fire, please evacuate to the horizontal passage"	

Through the start of the "one-key linkage" control plan of mechanical and electrical equipment, the flue gas generated by the tunnel fire is well controlled, and the flue gas is discharged downstream of the tunnel. The comparison before and after the start of the tunnel electromechanical equipment "one-button linkage" control plan is shown in Figure 7.

(a) Before the start of the "one-key linkage" control plan for the tunnel electromechanical equipment (the flue gas is not discharged from the tunnel)

(b) After the "one-key linkage" control plan of tunnel electromechanical equipment is started (flue gas discharge tunnel)

Fig. 7. Comparison before and after the launch of the "one-key linkage" control plan for tunnel mechanical and electrical equipment

4.6 System Stability

The "small scale fire test" lasted 3 days and carried out more than 10 kinds of fire test conditions. The intelligent tunnel intelligent control system operated stably without any abnormality. At the same time, the system uses the site to check the operation of the mechanical and electrical equipment in real time, and the mechanical and electrical equipment operates normally.

4.7 Overall System Evaluation

Tunnel emergency control system can realize the fire and abnormal event second level alarm, equipment facilities "a key linkage" control, real-time positioning and physiological monitoring, event disposal, facilities 3d holographic real-time monitoring, MR safety drills and training, and other functions, after perfect, the system can be combined with specific tunnel conditions in the highway operation management.

5 Conclusion

Based on the current situation of tunnel information construction and management, this paper studies, designs and realizes the intelligent tunnel control system from the aspects of system structure and system function [3]. And the system was verified in the "full-scale tunnel small-scale fire test". This result is summarized as follows:

(1) At present, the control software of the electromechanical system of the expressway tunnel is independent, so it is difficult to realize the automatic linkage control between the systems and the unified monitoring and early warning of the equipment status. This paper combines the development trend of expressway and the requirements of the transformation of management mode, according to the transformation trend of "construction, management and maintenance", relying on cloud computing, big data and other technologies, and builds the tunnel intelligent control system [4], Tunnel 3 d holographic display, equipment distributed intelligent monitoring, security real-time dynamic assessment, digital traffic monitoring, MR safety drills and training, mechanical and electrical facilities under the event "a key linkage" control, personnel positioning and physiological monitoring, wisdom operations, and other functions of innovative applications, promote the progress of the highway tunnel management and service level and update [4].

(2) The existing tunnel emergency plan research mainly for a single tunnel and only for tunnel of mechanical and electrical equipment, although from the current operation of the tunnel, the tunnel of the possibility of major traffic accident, accident through system "a key linkage" other such as traffic police, fire protection, medical departments also exist data barriers and information island, but in the long term development, form a set of mature and complete tunnel community mechanical and electrical facilities and management organization safety emergency linkage control plan is the overall trend [4].

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