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Design of Emergency Fire Fighting and Inspection Robot Riding on Highway Guardrail

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ABSTRACT

Based on the problems of untimely Expressway fire rescue and backward traditional fire rescue methods, an emergency fire fighting and inspection robot riding on expressway guardrail is designed. The overall mechanical structure design of emergency fire fighting and inspection robot riding on expressway guardrail is completed by using three-dimensional design software. The target fire detection is realized by using the target detection algorithm of Yolov5; By selecting a variety of sensors and using the control method of multi algorithm fusion, the basic function of robot on duty early warning is realized, and it has the ability of intelligent fire extinguishing. The BMS battery charging and discharging system is used to detect the real-time power of the robot. The design of the expressway emergency fire fighting and inspection robot provides a new technical means for the development of emergency fire fighting equipment, and improves the reliability and efficiency of expressway emergency fire fighting.

Key words: Robot, Expressway Guardrail, Patrol Inspection, Fire Fighting, Emergency Rescue

1. INTRODUCTION

China is in the stage of road traffic development, due to the unique road nature and construction of highways, highways have always been a high-risk areas of traffic accidents, especially in the occurrence of a series of rear-end accidents, it is easy to cause casualties, transport damage, fire outbreaks and rescue difficulties and other problems. At present, the traditional fire rescue method of fire extinguishing robots in China is mainly to set sensors at fixed points, such methods are not only not applicable in highway fire monitoring, but also can only detect whether a fire has occurred, and cannot play the role of pre-disaster environmental monitoring and prevention, as well as the initial pretreatment of fire [1].

This paper designs and develops a highway fire emergency fire fighting and inspection robot, which not only detects the target fire and extinguishes it in time when traffic accidents and vehicle fires occur on the highway, but also can provide a small amount of emergency equipment to ensure the rapid rescue of injured people in accidents; in addition, it can realize real-time monitoring of the robot's power when the robot conducts inspection; this robot The robot combines a variety of new technologies in one, making up for the lack of fire fighting power in the highway, which is a fire-prone area.

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2. COMPOSITION OF ROBOT EQUIPMENT SYSTEM AND ITS WORKING PRINCIPLE

2.1 Composition Structure of Robot Equipment System

The robot is mainly composed of mechanical parts and measurement and control parts, and its system architecture is shown in Fig. 1.

According to the technical requirements of the highway cruising robot and the actual working situation, the overall structure composition and layout of the highway fire rescue and inspection robot is shown in Fig. 2. The total weight of the robot is 120 kg, and the robot box is 900 mm long, 800 mm wide, and 1200 mm high. The design process adopts the idea of modulization, and its overall structure can be divided into five major components: drive unit, monitoring unit, fire fighting unit, transport unit, and energy and configuration unit [2].

2.2 Working Principle of the Robot

The structure of the emergency fire fighting and inspection robot is shown in Fig. 3 [3,4]. The highway emergency fire fighting and inspection robot includes a robot body and a drive unit, a monitoring unit, a fire fighting unit, a transport unit and an energy configuration unit set on the robot body; wherein the robot body is distributed in an upper and lower box structure; the drive unit includes two active drive wheels (12), two clamping wheels (10), two walking wheels (11), and a drive motor (13). travel wheels (11), drive motors (13); the drive system has two, symmetrically set inside the lower side of the box of the robot body, wherein the drive motor (13) is connected to the reducer (14) to drive the movement of the active drive wheels (12) through belt drive; said active drive wheels (12) are set horizontally with the ground, the active drive wheels (12) are made of magnetic

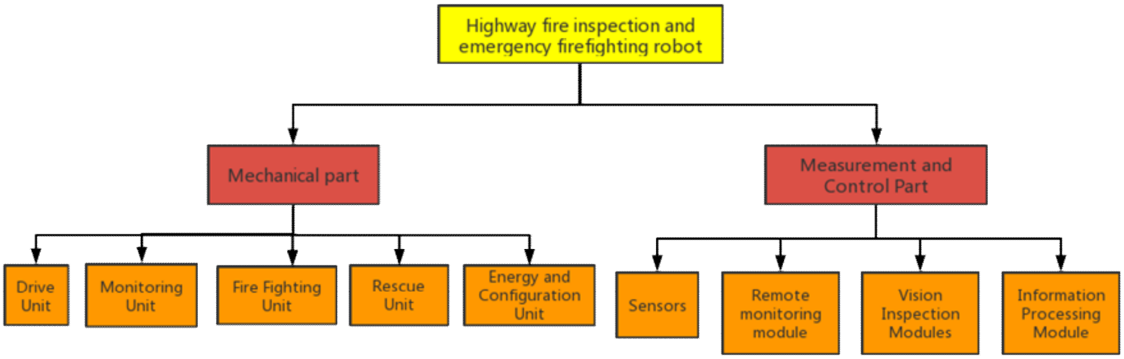

Fig. 1. Block diagram of the structural components of the robot system architecture.

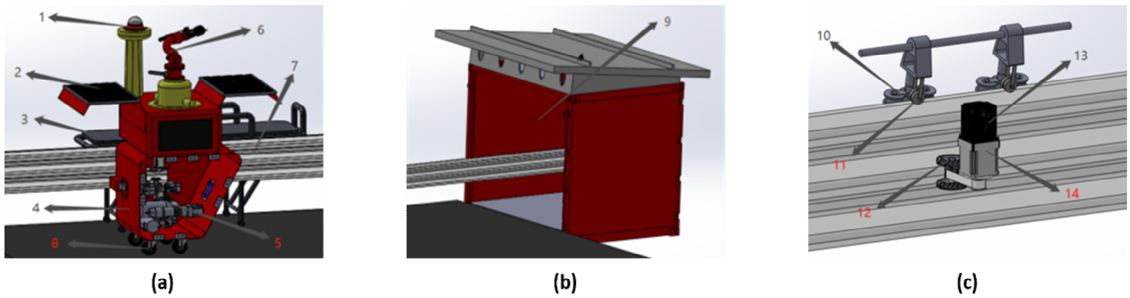

Fig. 2. Emergency firefighting and inspection robot composition. (a) 1–head 2–solar panel 3–stretcher 4–box 5–CAFS device 6–fire water cannon 7–highway guardrail (rail) 8–auxiliary support wheel, (b) 9–charging pile, and (c) 10–clamping wheel 11–walking wheel 12–driving wheel 13–motor 14–reducer.

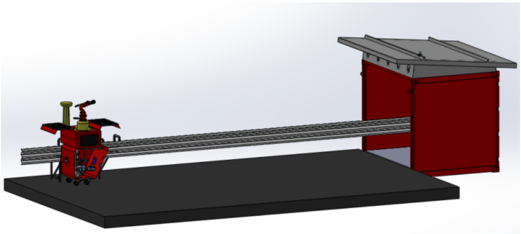

Fig. 3. Emergency fire fighting and inspection robot overall structure diagram.

material and are connected to the highway guardrail (7) magnetic connection, the edge of the active drive wheel (12) is adsorbed in the groove of the highway guardrail (7); four auxiliary support wheels (8) are set on the external lower surface of the box of the robot body, and the auxiliary support wheels (8) are in contact with the ground to ensure the balance stability of the robot movement, and when there is an obstacle in front, the infrared sensor's infrared reflection principle is used to receive the infrared light reflected by the obstacle on the road, and analyze When there is an obstacle in the front, the infrared sensor is used to receive the infrared ray reflected from the obstacle on the road, analyze whether it is the infrared ray emitted by itself, so as to make an obstacle avoidance reaction; the clamping wheel (10) is set at the upper end edge of the highway guardrail, the clamping wheel (10) is set horizontally, and there is a groove structure along the circumference to accommodate the upper end edge of the groove of the highway guardrail (17); the walking wheel (11) is set at the upper platform of the highway guardrail, and the clamping wheel (10) is connected vertically, together Acting on the guide bar and the box connection. Through the magnetic adsorption of the active drive wheel (12), with the clamping wheel (10) and the limit of the walking wheel (11), so that the groove structure of the highway guardrail (17) is sandwiched between the active drive wheel (12) and the clamping wheel (14) and the walking wheel (11), so that the highway emergency fire fighting and inspection robot moves along the highway guardrail (17) and is guided by the highway guardrail (17). The monitoring unit is a gimbal (1), and the gimbal (1) is set at a tab above the box of the robot body for inspecting the surrounding environment and the operation condition of the highway; the fire extinguishing unit includes a CAFS device (5) and a fire water cannon (6), and the CAFS device (5) is set inside the lower side of the box of the robot body, and the fire water cannon (6) is set at a turntable above the box of the robot body, and through the rotation of the turntable said transport unit includes a stretcher (3), the stretcher (3) is set on the outside of the highway guardrail (7), and one side of the stretcher (3) is connected to the outside sidewall of the highway guardrail (7) to move along the highway guardrail (7) with the robot to transport the casualty; the energy configuration unit is located on the outside of the robot body and can be connected to a charging pile (9) set at a fixed location, and The charging pile (9) is set on the outside of the robot, and a fixed male head is installed on the robot body, which can charge the robot in cooperation with the charging stand in the room through the control system to provide energy power for the highway emergency rescue and inspection robot.

3. MECHANICAL EQUIPMENT STRUCTURE DESIGN FOR ROBOTS

The emergency fire fighting and inspection robot riding on the highway guardrail developed in this paper is composed of five structural modules: drive unit, monitoring unit, fire fighting unit, transport unit (rescue stretcher and related medical equipment), and energy configuration unit (automatic charging device for the robot to return to the hangar), and its main structural modules are designed as shown below.

3.1 Design of the Drive Unit

The drive unit of this robot is divided into four parts, which are active drive wheel, auxiliary support wheel, clamping wheel, and walking wheel.

The transmission system is composed as shown in Fig. 4, which is located at the connection between the robot and the highway guardrail, and its main function is to generate and transmit power. The drive motor, motor reducer and transmission mechanism together form the transmission system equations.

The drive mechanism uses synchronous belt drive, which can ensure the stable driving of the robot, especially the smooth running in the starting and braking stages; the reducer is FABZ-090-L1 precision planetary reducer.

Therefore, the main wheel and guardrail rolling friction is

$$f_1 = \mu_1 S. \tag{1}$$

In the formula (1), S is the magnetic force of the driving wheel, μ_1 is the friction coefficient between the driving wheel and the galvanized guardrail.

Friction between driven wheel and ground is

$$f_2 = \mu_2 mg. \tag{2}$$

In formula (2), μ_2 is the coefficient of friction between the driven wheel and the high-speed road surface, m is the mass of the robot body.

When the robot travels along the guardrail to the bend, centrifugal force is generated during the turn.

$$f_3 = \frac{mv^2}{r} \tag{3}$$

The formula (3), v is the maximum speed of the robot, r is the minimum turning radius of the highway.

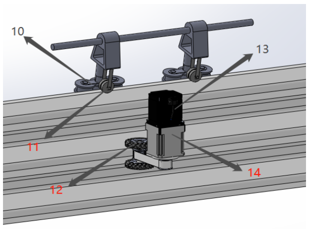

Fig. 4. The components of transmission system. 10-Clamping wheel 11-Walking wheel 12-Driving wheel 13-Motor 14-Reducer.

To carry out the calculation of motor driving force, it is known that the maximum driving speed of this robot $v = 7.2km/h$, the unit conversion is $120m/\text{min}$, the whole vehicle mass of the inspection robot $m = 120Kg$, the maximum mass when carrying the casualty $m = 120Kg$. measured by the experiment $\mu_1 = 0.2$, check the friction coefficient table to know $\mu_2 = 0.63$, assuming that the minimum turning radius of the highway is 4m.

From the formula (3), we can get $f_3 = 220N$. From the formula (1) $f_1 = \mu_1 S = \mu_3$, so $S = 1100N$. By the formula (2) can be obtained $f_2 = 1358.28N$. Traction is

$$F = F_1 + F_2. \tag{4}$$

From the formula (4) can be obtained $F = 1578.28N$. Motor power is

$$P = \frac{1}{60} \cdot F \cdot v \cdot k \cdot \eta. \tag{5}$$

In formula (5), η is the transmission efficiency of the drive motor, k is the safety factor.

From formula(5), we get

$$P = \frac{1}{60} \times 1578.8 \times 120 \times 1.25 \times 0.8 = 4.93kw. \tag{6}$$

Therefore, a 5kw motor can be selected. The K180 DC servo motor produced by Guangzhou Xindemark Company is selected for this design.

The active drive wheel is a magnetic wheel, and the drive wheel model is shown in Fig. 5.

Due to the large counterweight of the robot body, the magnetic force of one active drive wheel alone does not maintain the balance, so four sup-

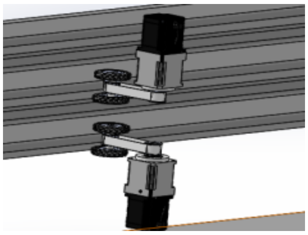

Fig. 5. Active drive wheels.

port wheels need to be placed at the bottom of the robot to assist in supporting the robot box to travel on the highway. The structure of the auxiliary walking wheels is shown in Fig. 6.

The clamping wheel plays an auxiliary clamping function, which can ensure the balance of the robot and prevent it from tipping. The structure of the clamping wheel is shown in Fig. 7.

The walking wheel is connected to the robot box above the rail, and its role is to make the robot sit across the rail as a whole to ensure that the robot can travel along the rail, and the structure of the walking wheel is shown in Fig. 8.

3.2 Design of the Monitoring Unit

The said monitoring unit uses electronic eyes (probes) to inspect the surrounding environment and the operating conditions of the highway, the main purpose of which is to inspect passing vehicles, whether to find accidents and timely fire fighting.

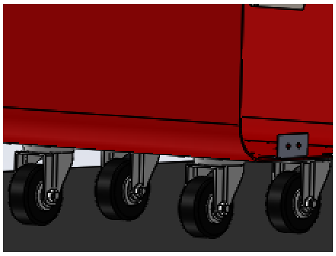

Fig. 6. Auxiliary walking wheels.

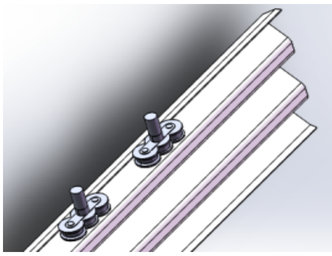

Fig. 7. Clamping Wheels.

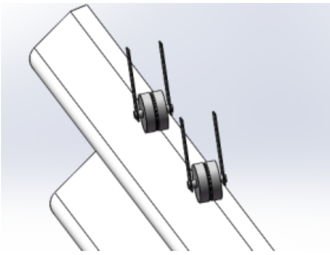

Fig. 8. Traveling Wheels.

3.3 Design of Fire Extinguishing Unit

The fire extinguishing unit consists of a fire water cannon and a compressed air foam system. The water cannon is mounted on a water cannon turntable below and is rotated on the turntable to extinguish highway fires. The water cannon model is shown in Fig. 9.

Compressed air foam system is a new type of fire extinguishing system, which mixes water, foam stock and compressed air in a certain ratio, and fully refines and foams the foam mixture, penetrates deep inside the combustion object or adheres to the surface, which can improve the permeability and adhesion of the foam solution and increase the coverage area of the target area, and plays an important role in the actual fire fighting [6].

The model diagram of CAFS system is shown in Fig. 10.

Fig. 9. Fire Fighting Water Cannon.

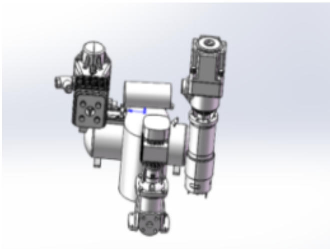

Fig. 10. CAFS device.

3.3 Analysis of the Robot's Working Capacity

When a fire occurs on a highway, it is important to accurately position the jet trajectory of the fire water cannon in different pitch angle situations while aiming the jet at the fire at the first time.

The head of the water cannon on the fire fighting and inspection robot is YST-4NN, with an operating pressure of 689.5kPa, a rated flow rate of 94.625L/s, a head height of 2.1m from the ground, and an equivalent diameter of 57.15mm. the initial velocity of the cannon is

$$v_0 = \frac{4Q}{\pi d^2}. \tag{7}$$

In formula (7), Q is the rated flow rate; d is the equivalent diameter of the gun port.

Taking the highest point of the fire water cannon jet trajectory as the dividing point, the trajectory can be divided into two sections: ascending and descending. The parameters required for the calculation of the trajectory of the fire water cannon under each elevation angle are shown in Table 1.

The cross-sectional area of the ascending section is given by

$$S_M = A_0(1 + aln(1+x)). \tag{8}$$

In the formula (8), A_0 for the nozzle cross-sectional area; a for the rising section cross-sectional area change factor, x for the horizontal direction of the fire water cannon range;

The formula for the cross-sectional area of the descending section is

$$S_M = A_0(1 + bln(1 + y_0 - y)). \tag{9}$$

In formula (9), y_0 is the shot height of the highest point of the jet; b is the coefficient of change of

Table 1. Required Parameters for Calculation of Jet Area at Each Elevation Angle.

Angle	a	b	k1	k2
30°	159	4.98	1.05	1.65
45°	259	4.32	1.18	1.56
60°	299	3.65	1.196	1.45
75°	323	3	1.2	1.38

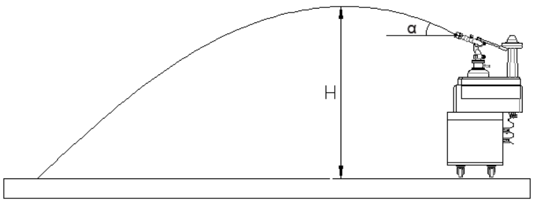

Fig. 11. Fire Fighting Water Cannon Jet Trajectory.

the cross-sectional area of the descending section; y is the shot height of the vertical direction of the fire water cannon.

The above parameters are substituted into the jet trajectory model to determine the fire extinguishing area of the fire water cannon jet trajectory under different elevation angle conditions [8].

Calculated with $a = 45$ degrees angle launch jet height.

According to the formula (8) and (9) calculated from the rising section cross-sectional area is 1.63, falling section cross-sectional area is 0.05.

Vertical component is

$$v_t = vcos45^\circ. \tag{10}$$

By the formula,

$$2gS = V_t^2. \tag{11}$$

Calculations can be obtained $v_t = 26.08m/s$, $S = 33.8m$; indicating that when the spraying angle is 45 degrees, plus the robot's own height, the spraying height is 3 5 m.

When the spraying angle is 30 degrees, the maximum height that can be sprayed at this time is $2gH = V^2$, $H = 51.2m$, plus the robot's own height, the maximum spraying height can reach 53 m [2].

4. INTEGRATED DESIGN OF ROBOT MEASUREMENT AND CONTROL SYSTEM

The measurement and control system and control system of the robot include the following modules: robot sensor, vision detection module, information processing module, communication module, fire extinguishing control module, and remote monitoring module.

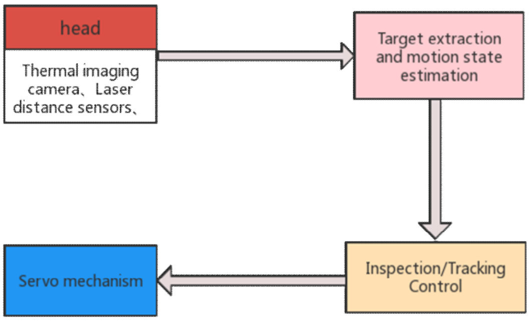

Fig. 12. Active Vision System Architecture.

4.1 Design of Visual System

In the event of a highway fire, the temperature in the center of the flame will be much higher than the ambient temperature, and a large amount of smoke will be generated at the same time. To address this feature, the vision system in this design will detect both flame and smoke in the background of the highway. A visible camera is used to acquire images of the fire scene, which are fed into the target detection frame to obtain the position envelope of the flame and smoke.

This design uses an active vision system, which simulates human eyes through the thermal camera and laser range sensor, and the gimbal simulates human neck, driving the thermal camera to make horizontal and pitch angle movements to expand the detection range and autonomously select and track the gazed target objects, as shown in Fig. 12.

In the target recognition part, deep learning is used for simultaneous recognition of flame and smoke. The target detection framework of YOLOv5d is selected as the main detection framework.

The structure of YOLOv5 network is shown in Fig. 13 below, which mainly consists of three main components, Backbone, Neck, and Head.

This design will collect fire images from highways and other scenes by itself and manually label them to generate a smaller fire smoke detection dataset. YoloV5 [9], a model with small network depth and feature map width, is used for training on the Pytorch platform, and migration learning is used in the training process to select some fully connected layers on the currently available fire detection initialization network [10].

4.2 Construction of Remote Monitoring System

The remote monitoring system mainly includes the 4G communication module and the backup WLAN communication module, which are connected to the remote monitoring platform via wireless network.

1. Communication module selection

The 4G communication module adopts USR-G780 4G DTU data transmission unit to realize wireless long-distance data transmission, which can quickly realize the remote control function of serial devices.

As the WLAN module is limited by the signal range of the wireless router, multiple router sites

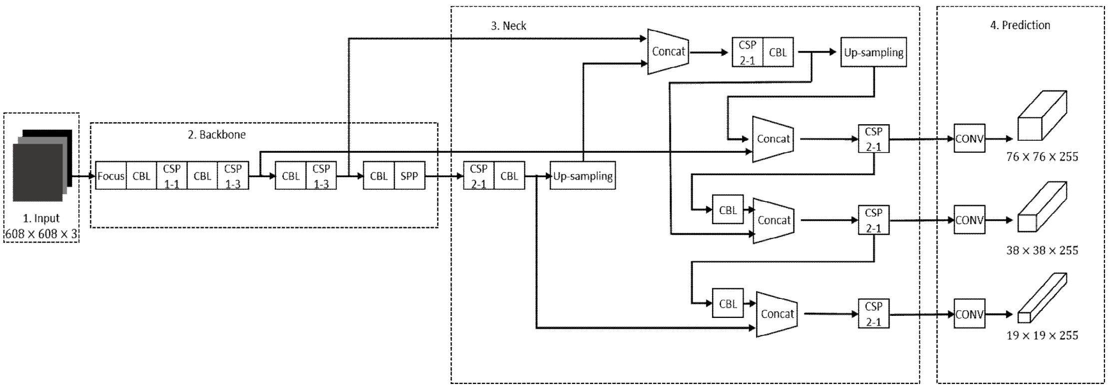

Fig. 13. Yolov5 Overall Architecture Diagram.

need to be set up in the midway section of the highway. As an alternate communication solution for 4G-DTU communication, the MIMO WiFi SKW92A module from Sky Control is selected for this design.

2. Rescue center monitoring platform design [11]

The hardware system of the rescue center monitoring platform consists of PC and human-computer interaction equipment. The software system includes video monitoring unit, ROS robot control unit, and the upper computer graphical interface.

The rescue center is deployed in a control room set up near the highway, and the data exchange between the robot communication module and the monitoring center is completed through a 4G wireless network. Image data are deployed by the computer to the image detection unit, processed by the OpenCV computer vision library, and finally the processing results are displayed in real time in the human-machine interface.

The rescue center inferred the working status of the robot and the fire situation at the scene based on the robot sensor data. To prevent the robot from disconnecting when 4G fails or power supply is insufficient, a joint 4G-WLAN communication network is constructed as shown in Fig. 13, and multiple router sites are set up in the midway section of the highway to save the robot's sensor data and send alarm signals to the rescue center at any time instead of the DTU.

4.3 Information Processing System Design

The traditional fire detection system uses a single sensor, which has the disadvantage of low detection efficiency. Therefore, this design uses multi-sensor information fusion technology, which can realize the timely detection and alarm of fire.

1. Sensor selection

The rotating head is equipped with various monitoring devices such as visible light camera, infrared thermal camera, gas sensor, infrared thermometer, ultrasonic obstacle avoidance sensor, radar velocimeter, laser distance sensor [12].

The rotating head uses a brushless motor (model DYS-4108-130T) to drive its rotation, where the motor control system is connected to a PC-based host system, which can control it, thus realizing remote control of the head rotation.

The infrared thermal imager is selected from the TOSEEN M640A infrared thermal imaging module of Grove UX, which can meet the requirements of fire source detection on the highway road.

After the relative position of the fire source is determined by the infrared thermal image, the relative distance between the robot and the fire source needs to be measured to achieve accurate fire source positioning. According to the environmental requirements of the highway, the TF40 laser rangefinder from North Wake Photonics was selected to complete the laser range finding task.

The role of the infrared thermometer is mainly to monitor the surrounding temperature, here the Glass5.2 infrared temperature sensor produced by GasDNA of Korea is selected.

The gas sensor is an important part of this robot sensing system [13][14], which is used to obtain the gas information in the environment. The MQ series semiconductor gas sensor is used in this design, which has a variety of models that can be used to detect gases.

2. Design of fire detection system with multi-sensor information fusion [15].

The highway fire detection and alarm system uses multi-sensor information fusion technology, which collects and pre-processes the data information, as well as the extraction of features, and finally fuses and calculates the data obtained from multiple sensors to produce fusion results.

According to the analysis of the highway fire detection system ideas and the application of multi-sensor information fusion technology, a fire detection alarm system is designed: first of all, the fire detection module is connected to the ATD module built into the main control board, which can

Fig. 14. Rescue Center Monitoring Platform Physical Diagram.

transfer the data information collected by each sensor such as temperature, gas and smoke to the core control board, and provide working voltage for the main control board through DC power supply, buzzer, monitoring platform display When the detection value reaches a certain height, the buzzer will alarm, and the detection data can be displayed through the monitoring platform.

For the shortcomings of the traditional single sensor system, this design uses multi-sensor information fusion technology, through the selection and research of the IPC, sensors and other modules, the design of multi-sensor information fusion of highway fire detection and alarm system to improve the accuracy of fire detection.

The control host is the core component of the system and needs sufficient communication interfaces to meet the access of multiple devices such as infrared thermal camera, PTZ, PLC controller and CAFS system. The robot directly adopts 4UIPC-610H-XS-KD331 IPC as the main information processing unit.

The robot is equipped with fire fighting water cannon, main drive wheel and CAFS system to be controlled and realized by PLC, which is connected to the IPC and accepts the commands sent from the serial port of the IPC at any time and executes the control logic according to the program. The PLC controller used in this design is the EM AM03 module of Siemens S7-200 SMART series, with SINAMICS V90 drive to complete the motor drive control of each execution unit.

When the buzzer input is high, the triode will be on and the buzzer will beep; when the input is low, the triode will cut off and the buzzer will stop beeping.

In order to ensure that the robot has sufficient range during the inspection process, there are solar panels installed on both sides of the robot box in this design, which can charge the robot battery under sunny conditions.

As the robot is charged and discharged in the inspection task, it is necessary to monitor the battery system in real time, and make early warning or control the charging and discharging according to the power situation, so as to guarantee the continuous use of the robot and extend the battery life, so the battery management system (BMS) is used to monitor and manage the battery, so as to realize the protection of the battery and improve the comprehensive performance of the battery.

This design uses the EVBCM-8133 power lithium battery master control module from Gaotek Electronics as the core of the BMS system. According to the monitoring data of the battery module, the power detection program of the battery charging process is designed as shown in Fig. 15 [16].

5. CONCLUSION

In order to solve the problem of the sudden fire situation of running vehicles on the highway and the resulting inability to achieve emergency rescue, this paper designs a highway fire emergency res-

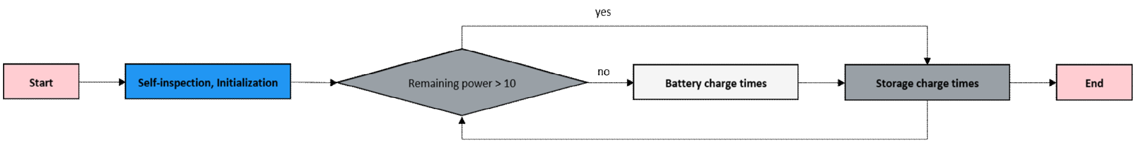

Fig. 15. Power Detection Program.

cue and inspection robot (has declared a national invention patent), and some of its component equipment should be verified by application (such as: walking robot, CAFS, water cannon device, etc., with the cooperation of Dalian G.I. Rescue Equipment Co. Science and Technology Innovation Award issued by the Fire Department), relying on the highway guardrail (rail).

It can realize the round-trip riding along the highway and autonomous cruise and other functions, its equipment and system relying on the information technology platform integrated with a variety of high-tech and one, intact to achieve the efficiency of on-site firefighting, the diversity of inspection functions, the rapidity of emergency rescue and other functions, providing a new solution for intelligent firefighting applications.

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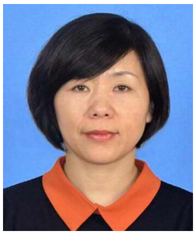

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