Design of an Intelligent Monitoring Platform for Guide Robot Dogs in High-Speed Railway Stations

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Abstract

Addressing the issues of dense passenger flow, complex circulation routes, high travel risks for visually impaired passengers in high-speed railway stations, as well as the standalone operation, decentralized management, and weak intelligent coordination capabilities of traditional guide robot dogs, this paper designs an intelligent monitoring platform for guide robot dogs in high-speed railway stations based on multi-agent technology. The platform adopts a core architecture consisting of robot dog execution agents, monitoring and dispatching agents, emergency decision-making agents, and operation and maintenance management agents, integrating five functional modules: situational visualization, equipment monitoring, remote dispatching, alarm handling, and data operation and maintenance. It realizes an integrated management and control mode featuring autonomous collaboration among multiple guide robot dogs, intelligent task allocation, proactive risk warning, and closed-loop fault management. This can provide a reference for the cluster management and control of intelligent service robots in transportation hubs.

Keywords

High-Speed Railway Station; Guide Robot Dog; Multi-Agent; Intelligent Monitoring; Collaborative Scheduling; Emergency Decision-Making.

1. Introduction

With the continuous improvement of China's intelligent transportation and accessible smart service systems, the construction of intelligent convenience services at high-speed railway stations has become a key direction for transportation hub upgrades. High-speed railway stations are characterized by dense passenger flows, complex circulation routes, sudden passenger flow fluctuations, and substantial cross-interference. Visually impaired passengers face numerous safety hazards when traveling independently, including obstacle occlusion, pedestrian interference, and difficulties in orientation recognition. At present, accessible services at high-speed railway stations still rely heavily on manual guidance, which suffers from high labor costs, delayed responses, limited service coverage, and the inability to provide round-the-clock support, making it difficult to meet the safe, efficient, and convenient travel needs of visually impaired passengers. Leveraging intelligent robot technology for accessible guidance has become an important approach to addressing the shortcomings of visually impaired services in public transportation hubs. Current quadruped guide robot dogs have already achieved basic navigation, obstacle avoidance, and guidance capabilities, but they generally operate in standalone modes and lack cluster collaborative control mechanisms. Traditional backend systems only support simple status viewing and manual operation, exhibiting problems such as passive perception, disordered scheduling, delayed emergency response, and low intelligence, which make them inadequate for the complex and dynamic operational scenarios of high-speed railway stations.

Research on guide robots has made notable progress in recent years in terms of system architecture, human-robot interaction, and perception technologies. In system design and navigation, Hwang[1] et

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al. developed a collaborative indoor navigation scheme based on semantic perception through interviews with guide-dog users and trainers, demonstrating navigation capabilities close to those of biological guide dogs. Cai[2] et al. designed the RDog quadruped guidance system, which integrates advanced mapping and navigation technologies and guides users via force feedback and voice feedback. Experiments showed that RDog achieved faster and smoother navigation and reduced cognitive load compared with white canes and smart canes. Yu[3] et al. focused on the characteristic that visually impaired people rely heavily on environmental sounds for navigation, and developed a low-noise walking controller for slow-pace walking, achieving a 50% noise reduction on the Unitree Go1 platform. In the area of physical human-robot interaction, scholars in 2024 proposed a pose estimation algorithm based on IMU data and a user intention detection algorithm, enabling relative pose estimation between the robot and the user in complex environments[6]. In 2026, Kim[4] et al. proposed the PHybrid (Physically Interactive Hybrid) human-robot interaction model, which combines the adaptive guidance capabilities of biological guide dogs with the mechanical reliability of quadruped robots. In perception and tracking, a study published in 2025 presented a fully embedded real-time person tracking scheme that integrates a deep learning-based 2D LiDAR pedestrian detector with a lightweight multi-object tracker, achieving stable operation at 20 Hz on an NVIDIA Jetson Xavier NX and reducing detection latency by 52.38% compared to existing methods[5].

In terms of intelligent monitoring and remote management platforms, current research is still in the exploratory stage. Research by Red Hat has pointed out that autonomous robot dogs currently operate mostly as isolated devices; by offloading heavy computational tasks to the edge, the robot dogs can run as thin clients, significantly extending battery life[7]. Zhang[8] et al. proposed an edge computing framework for guide robots based on the Intel Up-Squared board and Neural Compute Stick, enabling functions such as obstacle avoidance, traffic sign recognition, and voice interaction. In addition, some studies have proposed a fog computing model for guide robots to enable collaborative processing of multi-sensor information including images and voice. The AIBO Monitor project demonstrated the feasibility of using robot dogs as intermediaries for remote home environment monitoring[9]. However, research on a unified intelligent monitoring platform for multiple guide robot dogs in large transportation hubs such as high-speed railway stations-encompassing real-time equipment status monitoring, task scheduling, remote intervention, and emergency management-remains lacking.

Based on the current state of research, the existing technologies and applications still suffer from three core deficiencies: first, the platform's passive management and control mode relies on manual operations and lacks autonomous perception and intelligent decision-making capabilities; second, there is a lack of multi-device cluster coordination mechanisms, resulting in prominent issues such as robot dogs operating independently, task conflicts, and resource wastage; third, there is no specialized emergency closed-loop mechanism tailored to visually impaired services, leading to weak risk warning and handling capabilities. To address the above research gaps and industry pain points, this paper, based on Multi-Agent System (MAS) technology, constructs a hierarchical and collaborative intelligent monitoring platform for guide robot dogs in high-speed railway stations. Through the collaborative interaction of multiple functional agents, the platform realizes autonomous perception, intelligent scheduling, emergency closed-loop management, and intelligent operation and maintenance, thereby solving the problems of insufficient intelligence, poor coordination, and weak scenario adaptability in traditional platforms, and providing a new implementation solution for the cluster management and control of accessible intelligent services in transportation hubs.

2. Fundamental Theories and Key Technologies

2.1 Multi-Agent System (MAS) Theory

Multi-Agent System (MAS) is an important branch of distributed artificial intelligence. Its core idea is to decompose a complex overall system into several sub-agent units that possess the capabilities of autonomous perception, independent decision-making, interactive collaboration, and autonomous

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execution. Each agent does not require full-time control by a central node; it can autonomously complete task solving based on local environmental information, and through inter-agent information communication, cooperative game-playing, and task negotiation, the agents collectively accomplish the overall objectives of the complex system. The structure of a multi-agent system is shown in Fig. 1.

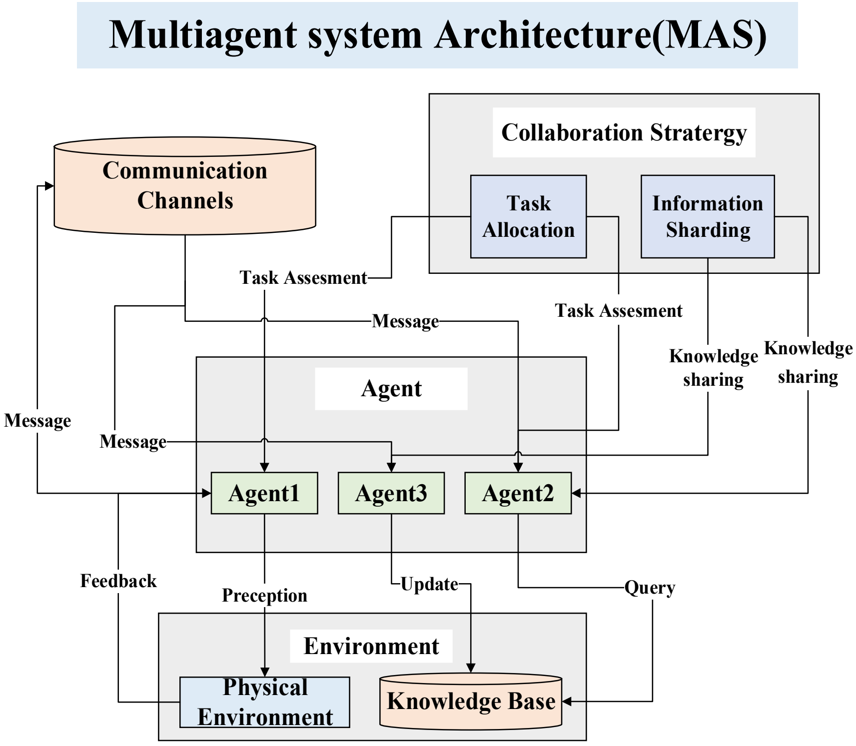

Fig. 1 Architecture of the multi-agent system

Compared with traditional monolithic program architectures, the multi-agent architecture offers four major advantages: autonomy, distribution, fault tolerance, and scalability, making it highly suitable for the complex scenarios of high-speed railway stations, which are characterized by dynamic and changeable conditions, non-linear passenger flow fluctuations, and random and sudden equipment tasks. Based on the MAS hierarchical collaboration theory, the platform in this paper divides the system into four types of agents-execution layer, perception layer, decision-making layer, and operation and maintenance layer-thereby achieving functional decoupling and hierarchical collaboration, and addressing the problems of lag, slow response, and poor coordination in traditional centralized monitoring systems. Table 1 shows a comparison between single-agent and multi-agent systems.

Table 1. Comparison chart of single-agent and multi-agent systems.

Feature	Single-agent System	Multi-Agent System (MAS)
Target	Single objective	Centralized system
Decision-making method	Centralized system	Distributed
Environmental Perception	Single global or local perspective	Multi-perspective
Robustness	System crash caused by a single point of failure	Partial agent failures do not affect the whole system
Complexity	The scale of problems is constrained by individual capabilities	Solving ultra-complex problems through group collaboration

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2.2 Agent Collaborative Scheduling Theory

2.2.1 Problem Description and System Modeling

In heterogeneous multi-agent systems for complex dynamic tasks, each agent not only has differentiated kinematic characteristics and payload capabilities, but also faces practical constraints such as limited communication range and uneven distribution of computational resources. Therefore, the core challenge of collaborative scheduling lies in how to achieve joint optimization of task allocation and execution timing under a decentralized information architecture, while ensuring system robustness to dynamic disturbances.

Suppose the system consists of N agents, denoted as the set $A = \{1,2...N\}$, and needs to complete M independent tasks, denoted as the set $T = \{1,2...M\}$. To characterize the completeness of the scheduling scheme, we introduce binary decision variables $x_{ij} \in \{0,1\}$, where$x_{ij} = 1$ indicates that agent i undertakes task j, and 0 otherwise; we also define continuous variables $t_{ij} \in R^+$ as the time when agent i starts executing task j.

The total scheduling cost of the system consists of two parts: one is the inherent resource consumption (e.g., energy, wear) C_{ij} for task execution, and the other is the delay penalty incurred by deviating from the expected start time e_j of the task. Therefore, the collaborative scheduling problem can be formulated as the following mixed-integer optimization model:

$$\min_{x,t} J = \sum_{i=1}^{N} \sum_{j=1}^{M} [c_{ij} x_{ij} + \gamma_{ij} (t_{ij} - e_j)^+] \tag{1}$$

Where γ_{ij} is the delay weight coefficient.

The above function needs to satisfy three core constraints. First, each task must be assigned to exactly one agent, forming the unique assignment constraint:

$$\sum_{i=1}^{N} x_{ij} = 1, \forall j \in T \tag{2}$$

Secondly, each agent is constrained by its own physical resources (e.g., energy, payload capacity) during task execution. Let w_j denote the resource demand of task j, and W_i denote the total capacity of agent i. Then the load constraint is given as follows:

$$\sum_{j=1}^{M} w_j x_{ij} \le W_i, \forall i \in A \tag{3}$$

Finally, for two different tasks j and k undertaken by the same agent, their start times must satisfy the sequential order and the path transition time $\tau_i(j,k)$. Let D_{ij} denote the duration required for agent i to execute task j, and introduce a sufficiently large positive constant L as a logical constant. Then the temporal constraints can be written as:

$$t_{ik} \ge t_{ij} + D_{ij} + \tau_i(j,k) - L(2 - x_{ij} - x_{ik}), \forall i, \forall j \ne k \tag{4}$$

When $x_{ij} = x_{ik} = 1$, this constraint forces t_{ik} to be no earlier than the sum of the completion time of the previous task and the transition time; otherwise, the constraint is automatically relaxed and becomes inactive.

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2.2.2 Distributed Consensus and Alternating Optimization Mechanism

Although the above centralized model has a clear structure, the complexity of mixed-integer programming increases dramatically as the number of agents N and the number of tasks M grow. Moreover, it is difficult to obtain global state information in practical scenarios. To address this, this paper adopts the Alternating Direction Method of Multipliers (ADMM) to decompose the original problem in a distributed manner, transforming the coupled global assignment constraints into local subproblems that can be solved in parallel by each agent.

An auxiliary consensus variable z_{ij} is introduced to represent the global average estimate of the final assignment status of task j across all agents. To convert the unique assignment constraint from a hard constraint into separable penalty terms, the augmented Lagrangian function of the original problem is constructed as follows:

$$\mathcal{L}_p = \sum_{i=1}^{N} J_i\,(X_i, T_j) + \sum_{j=1}^{M} \lambda_j\,(\sum_{i=1}^{N} x_{ij} - 1) + \frac{\rho}{2}\sum_{j=1}^{M}(\sum_{i=1}^{N} x_{ij} - 1)^2 \tag{5}$$

Where λ_j is the Lagrange multiplier (corresponding to the scarcity of assignment for task j), and $\rho > 0$ is the quadratic penalty parameter.

2.2.3 Convergence Conditions

For the above distributed iterative process, the primal-dual residuals are adopted as the convergence criterion. The primal residual r^k and the dual residual s^k at the kk-th iteration are defined respectively as:

$$r^k = \sum_{j=1}^{M} \left\| \sum_{i=1}^{N} x_{ij}^k - 1 \right\|_2^2 \tag{6}$$

$$s^k = \sum_{j=1}^{M} \left\| z_j^k - z_j^{k-1} \right\|_2^2 \tag{7}$$

When both are respectively below the preset thresholds ϵ^{pri} and ϵ^{dual}, the algorithm is considered to have reached an acceptable near-optimal state, that is:

$$r^k \leq \epsilon^{pri} \tag{8}$$

$$s^k \leq \epsilon^{dual} \tag{9}$$

The scheduling scheme obtained at this time satisfies the global uniqueness of task assignment, and no agent can significantly reduce its local cost by unilaterally changing its own strategy.

3. Multi-Agent-Based Platform Design

3.1 Overall Platform Design

The core innovation of the platform in this paper lies in its multi-agent hierarchical collaborative architecture, which abandons the traditional single data monitoring mode and decomposes the system into multiple agent units equipped with perception, judgment, execution, and interaction capabilities. Each agent operates autonomously, interacts in real time, and collaborates in a coordinated manner. The platform mainly comprises four core agents: robot dog execution agents, situational awareness agents, scheduling and decision-making agents, and operation and maintenance emergency agents, corresponding to five functional modules respectively, forming a fully intelligent workflow chain of

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"terminal perception → intelligent decision-making → execution scheduling → emergency closed-loop → data iteration."

Each agent possesses independent task processing capabilities and can exchange information across units. It can autonomously adjust its working strategies according to changes in passenger flow, equipment status, and emergent risks at high-speed railway stations, without requiring full-time manual intervention. The platform as a whole satisfies the agent design principles of autonomy, collaboration, real-time performance, and fault tolerance, adapting to the dynamic and complex operating environment of high-speed railway stations, and achieving intelligent management and control of guide robot dog clusters.

3.2 Design of Core Platform Functional Modules

Based on the multi-agent collaboration mechanism, this paper designs five core functional modules, each driven by its corresponding agent, thereby realizing an operational mode in which "modules carry functions and agents drive decisions." The modules work collaboratively to accomplish intelligent management and control of the entire guide robot dog cluster within the station.

3.2.1 Global Situational Awareness Visualization Module

This module is responsible for data aggregation and situational assessment by the situational awareness agent, serving as the core of the platform's global intelligent perception. The agent collects in real time the positioning data, status data, and environmental data of all robot dogs within the station, integrates them with the indoor and outdoor electronic maps of the high-speed railway station, and dynamically updates equipment locations and operating status. Through autonomous classification and assessment by the agent, color-coded icons are used to distinguish four operating conditions-normal service, standby, low battery, and fault-replacing the traditional passive mode of manual refresh and viewing.

Meanwhile, the situational awareness agent can autonomously compile core data such as the number of online devices, service count, and alarm quantity, dynamically refresh the list of abnormal events, and proactively push situational change information to management personnel, achieving active perception, intelligent presentation, and dynamic early warning of the overall station operation status.

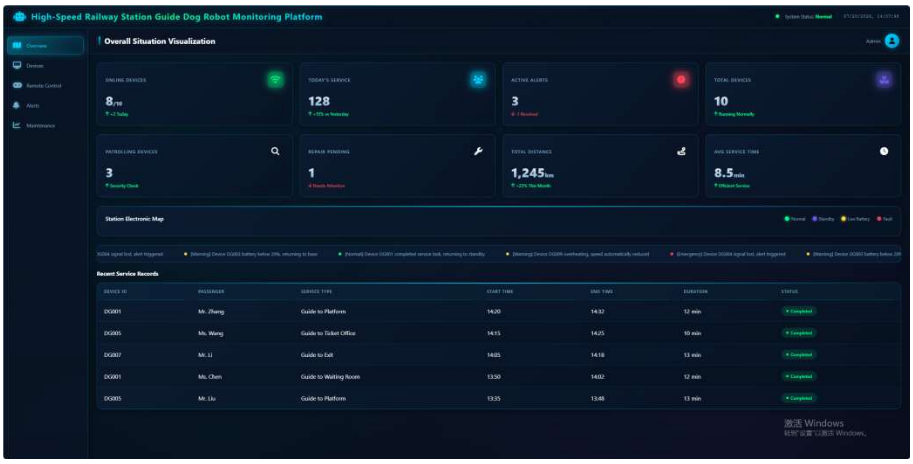

Fig. 2 Architecture of the global situational awareness module.

3.2.2 Real-time Equipment Status Monitoring Module

The data source for this module is the terminal execution agent carried by each guide robot dog. Each robot dog agent possesses autonomous perception capabilities, enabling it to collect in real time its own operational data including battery level, signal strength, temperature, radar obstacle avoidance data, video feeds, and positioning coordinates, and proactively upload these data to the platform to establish a unified equipment ledger. Compared with traditional monitoring, the agent can

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autonomously complete status self-inspection and anomaly identification without requiring platform polling.

When the terminal agent identifies issues such as device offline, temperature anomalies, or signal fluctuations, it proactively reports anomaly flags to the platform. The platform automatically highlights and prioritizes these alerts, achieving autonomous fault detection, proactive reporting, and early warning, thereby significantly enhancing the intelligence level of equipment monitoring.

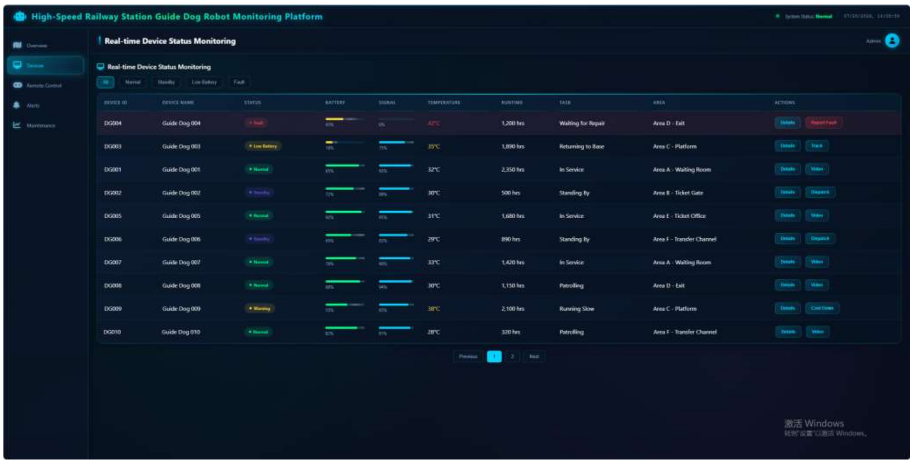

Fig. 3 Equipment monitoring module diagram

3.2.3 Remote Dispatching and Control Module

This module is led by the scheduling and decision-making agent, serving as the core decision-making unit for the platform's intelligent services. Traditional dispatching mostly relies on manual assignment, whereas the agent can autonomously complete optimal device matching, path planning, and task allocation based on passenger demands, equipment locations, remaining battery levels, and regional passenger flow density, enabling coordinated scheduling of multiple robot dog clusters and avoiding task conflicts and resource idleness.

At the same time, the scheduling agent supports a human-machine collaborative mechanism. In complex scenarios such as extreme passenger flows or path deviations, it can receive manual intervention commands and cooperate in performing remote joystick control, emergency braking, voice reassurance, and other operations. After manual intervention, the agent can re-plan routes autonomously and resume independent operation, realizing a dual-guarantee mechanism of "intelligent autonomous scheduling + manual assisted intervention."

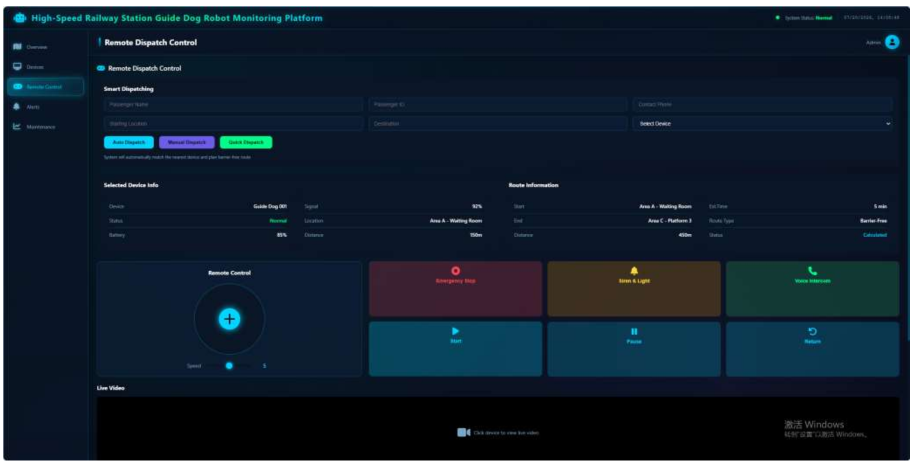

Fig. 4 Architecture of the remote dispatching module.

3.2.4 Alarm Emergency Response Module

This module relies on the emergency decision-making agent to achieve autonomous risk assessment and closed-loop response. The emergency agent can receive in real time anomaly information reported by terminal agents, including faults, collisions, boundary violations, and passenger assistance requests, and autonomously perform risk grading, distinguishing three levels: emergency alarms, warnings, and general notifications. Compared with traditional fixed-threshold alerting, it offers stronger scenario adaptability.

Once an anomaly is triggered, the emergency agent can autonomously execute a series of coordinated operations including pop-up alerts, device positioning, video retrieval, message pushing, and broadcast integration. It automatically tracks response progress, updates statuses among pending, in-process, and closed, and retains complete logs and video recordings throughout the entire process, realizing an intelligent emergency system featuring autonomous risk identification, linked incident response, and automatic process closure.

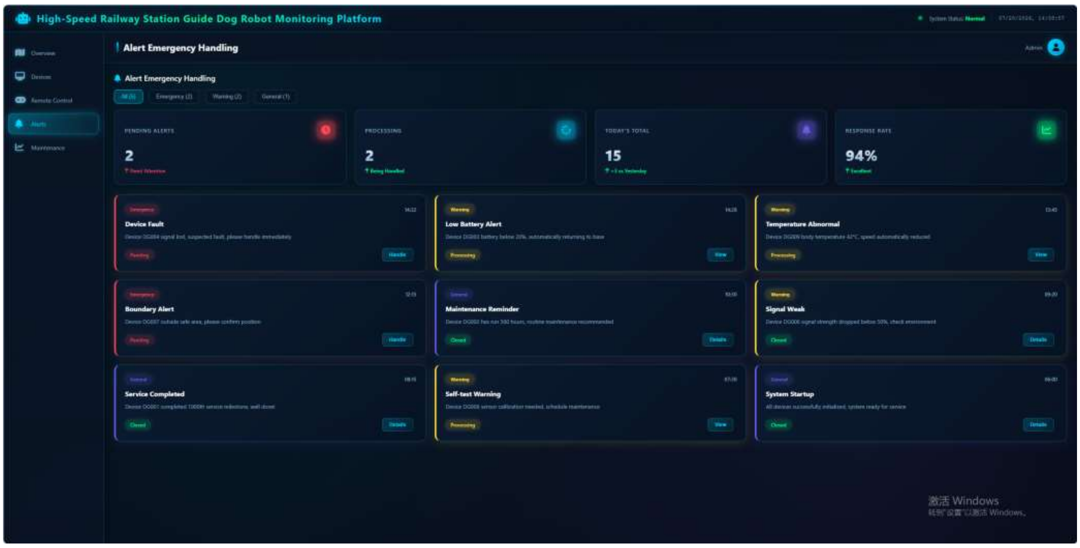

Fig. 5 Alarm emergency response module diagram

3.2.5 Operation, Maintenance and Data Statistics Module

Fig. 6 (a) Operation and maintenance statistical diagram

Fig. 7 (b) Operation and maintenance statistical diagram

Fig. 8 (c) Operation and maintenance statistical diagram

This module is supported by the operation and maintenance management agent, which provides backend intelligent support. The operation and maintenance agent continuously records and analyzes the operational data, fault patterns, and maintenance cycles of each robot dog, autonomously establishes electronic equipment profiles, and automatically pushes maintenance and repair work orders based on operating duration and fault status, achieving full-lifecycle intelligent operation and maintenance of equipment and replacing traditional manual ledger recording.

At the same time, the operation and maintenance agent can autonomously aggregate service data, alarm data, and equipment status data, intelligently generate visual statistical charts and reports, and provide data support for station service optimization and equipment assessment. Combined with an intelligent permission management mechanism, it automatically differentiates operational permissions for different roles, ensuring the safe, standardized, and intelligent long-term operation of the platform.

4. Summary

This paper, based on multi-agent technology, designs an intelligent monitoring platform for guide robot dogs in high-speed railway stations, constructing four types of cooperative functional agents paired with five major business modules to achieve full-process management and control of robot dog cluster situational awareness, status monitoring, intelligent scheduling, emergency response, and intelligent operation and maintenance. The platform addresses the industry pain points of insufficient intelligence, poor coordination, and delayed emergency response in traditional guide equipment

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management and control, effectively enhancing the safety and intelligence of accessible services in high-speed railway stations.

Future research can further optimize multi-agent collaborative algorithms to improve the autonomous obstacle avoidance, dynamic task allocation, and collaborative operation capabilities of multiple robot dogs in high-density passenger flow scenarios. Combined with deep learning techniques, the risk prediction capabilities of agents can be strengthened, further promoting the improvement and practical deployment of intelligent management and control systems for service robot clusters in transportation hubs.

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(2) College-level Research Platform of Yibin Vocational and Technical College (ybzy20kypt04).

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