Research on Adaptive Navigation System for Hospital Logistics AMR based on Active Trajectory Prediction

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Abstract

In-hospital logistics is a core link in medical logistics support. Traditional manual delivery has problems such as low operational efficiency, difficult material traceability, and loopholes in hospital infection control. Existing autonomous mobile robots (AMRs) in hospital scenarios with dense pedestrian flow and complex spatial environments have bottlenecks such as insufficient navigation accuracy, weak dynamic obstacle avoidance, and poor spatial adaptability, making it difficult to meet actual needs. Therefore, this paper develops an intelligent AMR logistics system for hospital scenarios: integrating Simultaneous Localization and Mapping (SLAM) navigation technology, fusing YOLACT pedestrian detection and Interacting Multiple Model (IMM) tracking algorithms to achieve dynamic pedestrian perception and trajectory prediction, and combining the Time Elastic Band (TEB) planning algorithm to complete dynamic obstacle avoidance and path optimization, which improves the passage efficiency and navigation robustness in high pedestrian density scenarios; the robot body adopts a fusion design of an omnidirectional chassis and a Stewart parallel platform, taking into account the maneuverability in narrow spaces, realizing pose compensation under extreme working conditions, and reducing transportation losses; a digital twin management platform is built to cover the full process of intelligent scheduling, real-time positioning, and material traceability, and an integrated closed-loop management system is constructed. This system solves the pain points of in-hospital logistics and the technical defects of existing robots, improves the delivery efficiency and hospital infection control level, and provides a feasible solution and practical reference for the intelligent upgrade of hospital logistics.

Keywords

Hospital Logistics; AMR; Adaptive Navigation; Multi-sensor Fusion.

1. Introduction

In-hospital logistics is a key link in the smart hospital's logistical support and infection control. It is responsible for the cross-departmental transportation of medicines, specimens, surgical instruments, sterile consumables and other materials.[1][3] With the expansion of hospital diagnosis and treatment scale and the increasing requirements for refined management[5], the traditional manual delivery model has exposed many shortcomings: nurses undertake a large number of non-nursing delivery tasks[2], resulting in a misalignment of functions; manual contact-based transportation increases the risk of hospital-acquired infections; the lag in material traceability and the difficulty in meeting the urgent needs of emergency and critical care scenarios in terms of delivery timeliness have made it impossible to meet the operational requirements of modern hospitals[4].

Although autonomous mobile robots (AMRs) have been gradually applied to in-hospital logistics, they still face significant technical bottlenecks in hospital scenarios with dense pedestrian flows, narrow corridors, and complex spaces: traditional navigation relies on passive obstacle avoidance, which has poor adaptability to dynamic environments and low passage efficiency; the vehicle chassis has insufficient maneuverability and is restricted in turning in narrow spaces; there is a lack of pose compensation mechanisms in emergency stops and micro-collisions, resulting in insufficient stability in material transportation; and there is a lack of a full-process scheduling and traceability platform, making it difficult to form a closed-loop management. Despite extensive research by scholars at home and abroad in areas such as SLAM navigation[6][7], dynamic obstacle avoidance, and parallel platform control, integrated intelligent logistics solutions tailored to the unique characteristics of hospitals, such as dense pedestrian flows and high safety requirements, are still relatively scarce.

To address these pain points and technical gaps, this paper develops an adaptive navigation system for hospital logistics AMRs based on active trajectory prediction. This system integrates multi-sensor SLAM fusion navigation, combined with YOLACT pedestrian detection, IMM tracking, and TEB dynamic path planning algorithms[7], to achieve active obstacle avoidance and efficient passage in dense pedestrian flow scenarios; it adopts a fusion design of omnidirectional movement chassis and six-degree-of-freedom Stewart platform, balancing maneuverability and transportation stability; and it builds a digital twin management platform to achieve task scheduling, real-time positioning, and electronic traceability of materials. This study aims to solve the efficiency and safety problems in hospital in-hospital logistics and provide feasible technical support and engineering practice references for the intelligent upgrade of hospital logistics.

2. Overall System Design

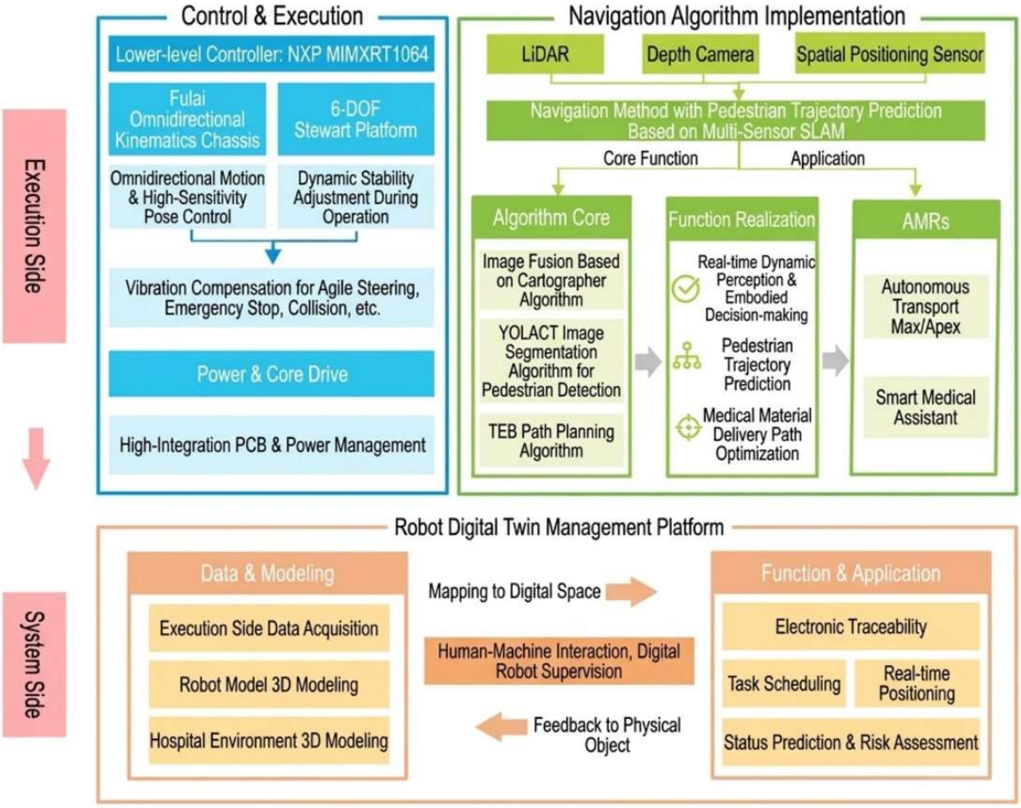

Fig. 1 Design Diagram of Smart Medical Logistics System

This system adopts a dual-layer architecture design of "execution end + system end", which is in line with the operational characteristics and management requirements of hospital logistics within the premises, forming a closed-loop system covering the entire process from "perception - decisionmaking - execution - traceability".[10] The execution end is the AMR robot itself, which is the core execution unit for material transportation, mainly responsible for real-time environmental perception, dynamic autonomous navigation, and stable transportation of medical supplies, and is suitable for narrow and complex spaces such as hospital corridors, elevators, and wards. The system end is a digital twin management platform, serving as the intelligent control center of the entire logistics system, focusing on functions such as intelligent multi-machine task scheduling, real-time positioning and monitoring of robots, and electronic traceability of the entire supply chain of medical supplies, breaking down the data interaction barriers between the physical and virtual ends. The overall system takes active trajectory prediction navigation as the core technological breakthrough point, integrating mechanical structure optimization and cloud-based intelligent control, precisely adapting to the special scenarios of hospitals with dense pedestrian flow, high safety control, and high-time efficiency delivery. It also takes into account the efficiency of logistics distribution, the safety of material transportation, and the hard requirements of hospital infection control. The overall system architecture is shown in Fig. 1.

3. Core Technology and Function Implementation

3.1 Multi Sensor Fusion Active Navigation Technology

In response to the characteristics of variable lighting and dense human flow in hospital environments, this system integrates RPLIDAR C1 LiDAR, Intel RealSense D435i depth camera, and T265 tracking camera to construct a multi-source heterogeneous SLAM navigation framework.[6] The T265 camera relies on visual inertial odometry to compensate for the positioning shortcomings during dynamic occlusion, and the complementary coupling of the three overcomes the perception defects of a single sensor.

Fig. 2 Heterogeneous Sensor Fusion Architecture

The laser radar provides anti-interference 2D geometric point cloud data, and the depth camera and tracking camera work together to form a machine vision perception system. The complete operating logic is shown in Fig. 3; The combination of two types of visual sensors completes the scanning of unknown space RGB-D information and depth point cloud texture.[4][6] The scanning visualization effect is shown in Fig. 4, which can greatly improve the robot's exploration and collision avoidance ability in complex environments. The T265 camera relies on visual inertial odometry to compensate for the positioning shortcomings during dynamic occlusion, and the complementary coupling of the three overcomes the perception defects of a single sensor in low light, texture loss, and reflective scenes.

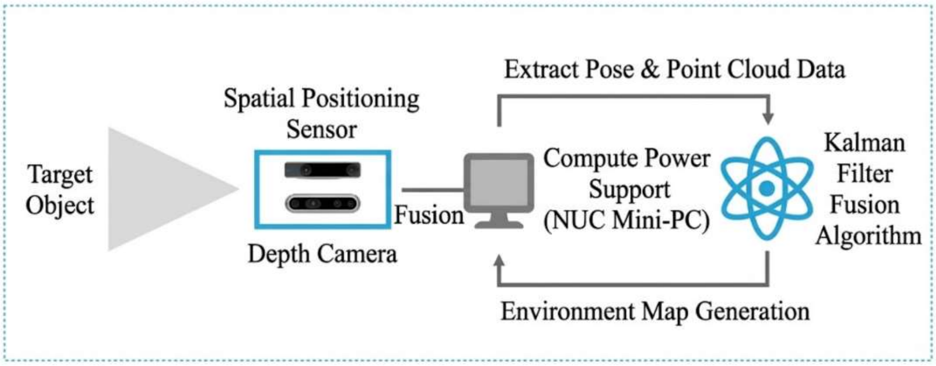

Fig. 3 Machine vision perception system operating logic

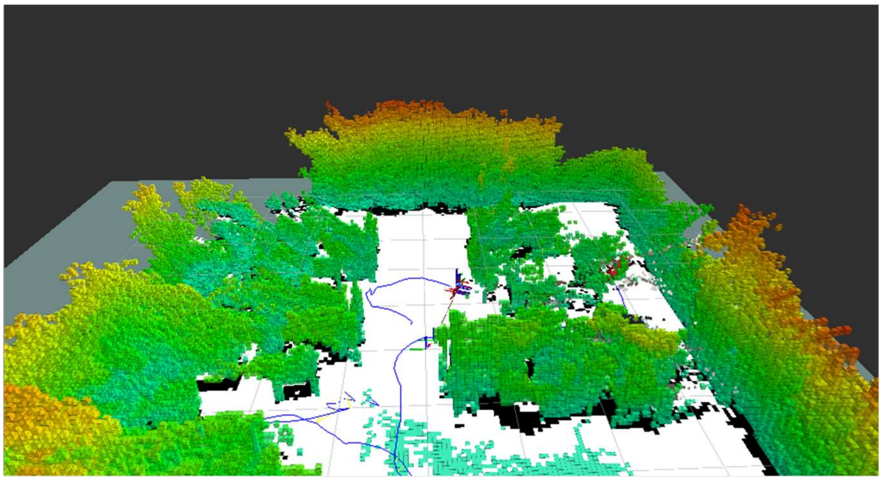

Fig. 4 Visualization of point cloud scanning in unknown space

Multi sensor data fusion is based on the Cartographer algorithm and adopts a hierarchical grid fusion strategy. The specific fusion process framework is shown in Fig. 5.

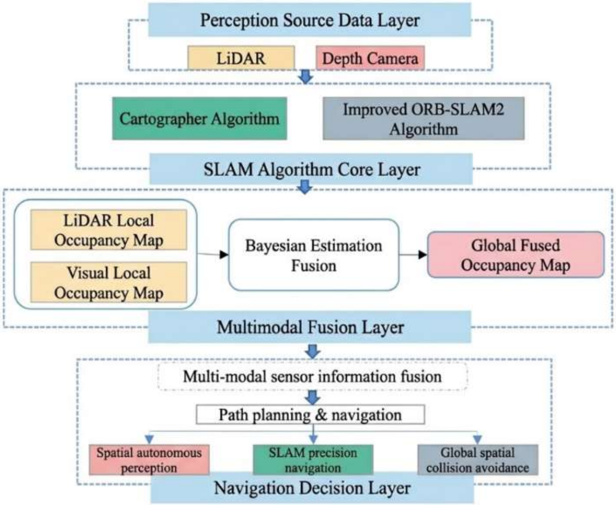

Fig. 5 Fusion architecture

For the undetermined state of laser and visual grid, Bayesian estimation method is used to achieve the fusion of grid occupancy probability. The core formula is:

$$p^{\circ} = \frac{p\_lp\_d}{p\_lp\_d + (1 - p\_l) + (1 - p\_d)} \tag{1}$$

In the formula, p_l is the probability of the laser radar grid, and p_d is the probability of the RGB-D camera grid. The obstacle detection threshold T is set to 0.5. If the probability value is higher than the threshold, the grid is determined to be occupied, otherwise it is considered idle. Through the above strategy, the system has achieved complementary advantages between laser point cloud and depth information. The mapping effect of laser radar alone is shown in Fig. 6, the 2D mapping result of depth camera 3D mapping is shown in Fig. 7, and the high-precision 2D map after the fusion of the two is shown in Fig. 8. The fused map outperforms single sensor mapping in both accuracy and scene coverage, ultimately resulting in a high-precision, full scene coverage hospital environment map.

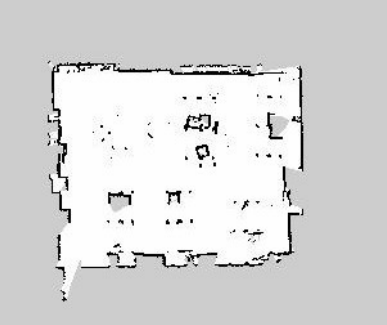

Fig. 6 Lidar mapping results

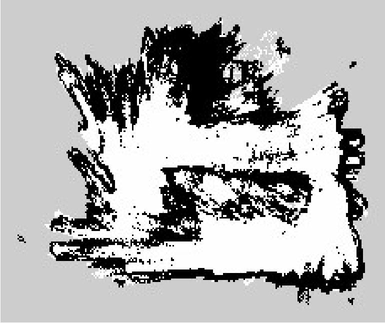

Fig. 7 2D Mapping of Depth Camera 3D Mapping

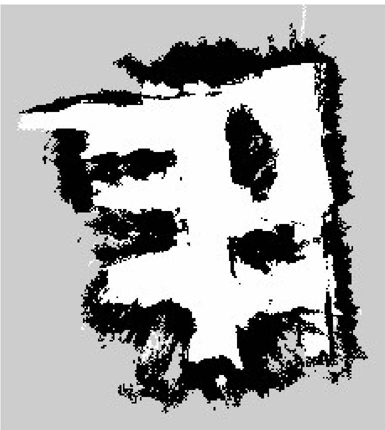

Fig. 8 Fusion of LiDAR and depth camera for mapping

To achieve active obstacle avoidance in dense pedestrian flow scenarios, the system adopts a multi-level processing architecture for pedestrian perception and trajectory prediction: based on the YOLACT algorithm, real-time instance segmentation of pedestrians is achieved, accurate extraction of pedestrian mask information and allocation of unique identifiers; Combining IMM interacting multi model algorithm, integrating three motion models of uniform speed, uniform acceleration, and steering, dynamically adjusting model weights to adapt to the complex motion state of pedestrians, and achieving continuous and stable pedestrian tracking.

Building a pedestrian trajectory prediction model based on the Kalman filter algorithm, the state equation and observation equation are:

$$\begin{aligned} X_k &= A \bullet X_{k-1} + B \bullet U_{k-1} + W_{k-1} \\ Z_k &= H \bullet X_k + V_k \end{aligned} \tag{2}$$

In the formula, X_k is the pedestrian position and velocity state vector at time k, and Z_k is the observation vector. Based on this model, short-term trajectory prediction can be completed based on pedestrian historical motion data, and potential collision risks can be identified in advance. To achieve the unity of robot coordinate system and camera perception coordinate system, and eliminate the coordinate deviation of multi-sensor data fusion, this paper introduces the coordinate conversion formula between robot and camera:

$$P_{\mathrm{robot}} = R \bullet P_{camera} + T \tag{3}$$

In the formula, R is the rotation matrix and T is the translation vector, achieving accurate mapping of pedestrian three-dimensional positions. Transforming the predicted trajectory into time-varying obstacle constraints and utilizing the TEB time elastic band algorithm for dynamic path planning, the multi-objective optimization function is:

$$J = \sum_{i=1}^{N} (w_1 \bullet d_{path}(i)^2 + w_2 \bullet d_{obstacle}(i)^2 + w_3 \bullet \triangle v(i)^2) \tag{4}$$

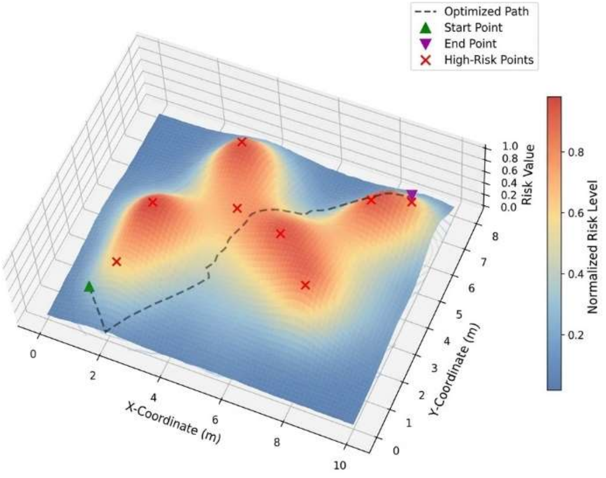

Fig. 9 Visualization of 3D Risk Perception Path Planning

In the formula, w_1, w_2, and w_3 are weight coefficients, d_{path} is trajectory deviation, $d_{obstacle}$ is obstacle distance, and $\triangle v$ is velocity change. Through optimization, active obstacle avoidance and smooth passage are achieved. The actual effect of 3D risk aware path planning is shown in Fig. 9, effectively improving the problems of traditional robot passive obstacle avoidance lagging and low efficiency.

3.2 Integrated Body Structure Design

In response to the characteristics of high foot traffic, narrow corridors, and limited space in hospitals, the robot body adopts a deeply integrated design of an omnidirectional motion chassis and a six-degree-of-freedom Stewart parallel platform[8][9], which balances the maneuverability in narrow spaces and the stability of material transportation. The omnidirectional kinematic chassis structure of this design is shown in Fig. 10; it adopts a Omni wheel structure with three-degree-of-freedom motion characteristics, enabling flexible movements such as in-situ rotation and lateral translation, and thus perfectly adapting to narrow-space scenarios including corridor turns and elevator entrances and exits.

Fig. 10 Kinematic chassis

To realize precise speed solution and control for the omnidirectional chassis and guarantee its flexible motion performance in complex hospital scenes, an inverse kinematics control model is established for the designed chassis, and the model is expressed as follows:

$$\begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix} = \frac{1}{R}\begin{bmatrix} 1 & 0 & r \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & r \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & r \end{bmatrix}\begin{bmatrix} \mathrm{v}_x \\ v_y \\ w \end{bmatrix} \tag{5}$$

In the formula, w_1, w_2, and w_3 are the rotational speeds of each wheel, R is the wheel diameter, and v_x, v_y, and w are the chassis linear and angular velocities.[7] Through this model, accurate calculation of chassis velocity can be achieved. The omnidirectional kinematic calculation principle of the Omni wheel is shown in Fig. 11. Compared with traditional differential chassis, it greatly improves the efficiency of passing through complex spaces.

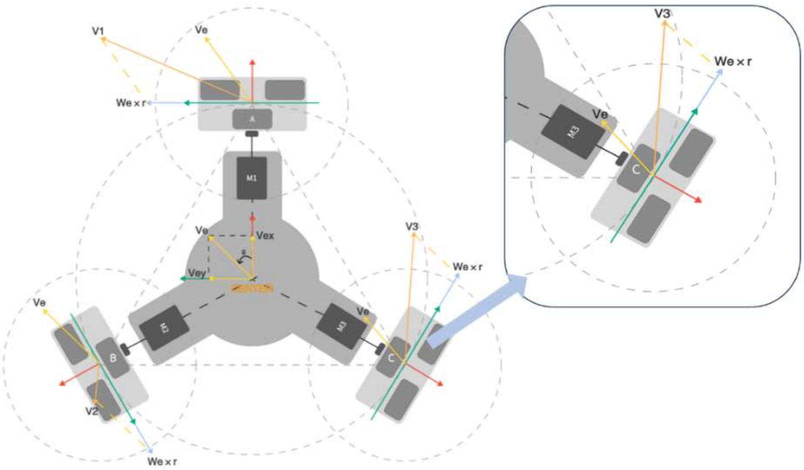

Fig. 11 Omni omnidirectional kinematic solution

To solve the problem of material shaking under emergency stop, collision, floor height difference, slope passage and other working conditions, a six degree of freedom Stewart parallel platform is installed above the chassis, and a pose compensation model is constructed based on vector loop constraints. The core equation is:

$$a_i + d_i s_i = p + b_i \tag{6}$$

In response to parameter disturbances and nonlinear disturbances in platform motion, a fuzzy PID adaptive control scheme is adopted. The specific control process is shown in Fig. 12, which can achieve precise pose compensation. The platform can adjust its posture in real time, always keeping the bearing surface level, effectively avoiding problems such as drug overturning and specimen damage, and balancing the mobility of the vehicle with the safety and stability of medical material transportation.

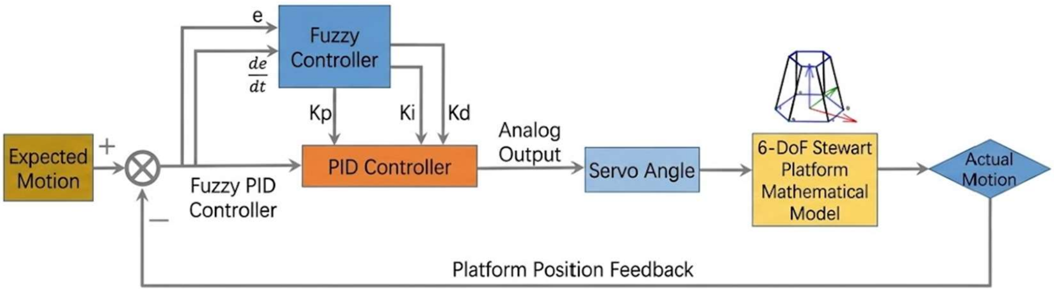

Fig. 12 control flow

3.3 Digital Twin Control Platform

The construction of real-time monitoring and intelligent scheduling system is the core technical support for achieving efficient logistics in the medical delivery robot system. By using IoT technology to build a robot digital twin management platform, the platform can accurately obtain key information such as real-time robot location, power status, material flow data, and task progress, forming a closed-loop management system for the entire process.

The robot scheduling system designed in this project establishes a real-time communication channel between the robot and the scheduling monitoring host, achieving key functions of human-computer interaction and material traceability. The system synchronously presents three types of core information through a visual interface: the dynamic position and operating status of the robot, the temperature and humidity parameters of the transport box, and the batch and circulation records of materials. Operators can view the delivery path, handover time, and responsible person information of sensitive materials such as sterilization packages and drugs in real time, achieving full digital supervision throughout the process.

4. Conclusion

This article focuses on the shortcomings of manual delivery in hospital logistics and the technical deficiencies of existing AMR robots. A self-adaptive navigation logistics system based on active trajectory prediction has been developed. The system has broken through the bottleneck of navigation efficiency in dense pedestrian flow scenarios through multi-sensor fusion SLAM and pedestrian trajectory prediction technology; By integrating an omnidirectional chassis with a six degree of freedom stable platform design, it balances the maneuverability of narrow spaces with the stability of material transportation; Through the digital twin platform, closed-loop control of the entire logistics process has been achieved, effectively improving the efficiency of in-hospital delivery, reducing hospital infection risks, and optimizing the allocation of medical resources. This system can provide practical technical solutions for the intelligent and refined upgrading of logistics in smart hospitals, and has strong engineering application value. In the future, the multi machine collaborative scheduling algorithm can be further optimized to expand its adaptability to special scenarios such as emergency departments and operating rooms.

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