https://doi.org/10.62836/emi.v4i3.451 Global Science Publishing

EMI
Economics & Management Information
https://ojs.sgsci.org/journals/emi

Article

Design and Research of Pharmacy Management Robot Based on Artificial Intelligence

Hui Cheng, Ming Sun, Hai-Ling He *, Shi-Qing Huang, Rui Feng and Yong-Qiang Wang

School of Economics and Management, Zhaoqing University, Zhaoqing 526061, China

Abstract: In order to solve the problems of long queuing time, low efficiency of manual dispensing and high risk of errors in traditional hospital pharmacies, this study designed and developed a pharmacy management robot system integrated with artificial intelligence technology. Through the integration of automatic robotic arm, AI visual recognition and Internet of things perception technology, the system innovatively realizes the intelligent management function of the whole drug process: It includes high-precision drug visual recognition and two-dimensional code scanning, accurate cover opening and drug distribution of multi-axis manipulator, omnidirectional mobile chassis driven by ROS robot operating system, and multi-sensor fusion navigation system based on laser radar and depth camera. Among them, the intelligent packaging module developed by the product solves the problem of insufficient opening accuracy of existing pharmacy robot medicine bottles through the precise lid opening technology of mechanical arm, effectively optimizes the efficiency of drug distribution and the quality of medical service, and becomes an innovative breakthrough in the field of intelligent pharmacy management.

Keywords: artificial intelligence; pharmacy management; automated sorting

1. Introduction

With the acceleration of the aging process of the global population, medical and pharmaceutical services are upgrading in the direction of "precision + intelligence", and patients' requirements for pharmacy services have changed from basic supply to whole-process optimization. However, the traditional pharmacy's manual model is limited by the pharmacist training cycle and technical bottlenecks, making it difficult to cope with these surges. The new generation of pharmacy management robot technology provides a key breakthrough to solve the above challenges by integrating heterogeneous drug intelligent identification and autonomous navigation systems, deeply integrated medical information systems, and applying edge computing and federated learning technology, aiming to build a fully automated link of drug storage, sorting and distribution, realize the real-time synchronization of prescriptions, inventory and distribution instructions, and optimize resource scheduling under the premise of ensuring data security.

In view of the common pain points of patients in traditional hospital pharmacies, such as long queuing time, low manual dispensing efficiency and high risk of errors, this paper focuses on the development and application of pharmacy management robots. Specifically, this study aims to develop a smart pharmacy management system by integrating automated robotic arms, AI visual recognition and Internet of Things (IoT) technologies. The

Received: 15 June 2025; Accepted: 30 June 2025.

* Corresponding: Hai-Ling He (2648380698@qq.com)

system is committed to achieving accurate and rapid sorting and distribution of prescription drugs, optimizing dynamic inventory monitoring and replenishment warning, and supporting multi-threaded processing of prescription review, medication consultation and logistics scheduling tasks, thereby effectively reducing manual load and improving the accuracy of drug dispensing. In this paper, we focus on the research and development of automated drug dispensing mechanical systems (including mobile chassis, visual recognition and robotic arms), as well as the development of intelligent collaborative management systems (including cluster control, scheduling algorithms and data interfaces), so as to solve the core problems of drug whole-process automation and efficient collaborative operation of multiple robots in the pharmacy scenario.

2. Literature Review

2.1. The Development Status of Pharmacy Robots in Foreign Countries

The robot technology of international pharmacies presents the following characteristics: automated pharmacies in Europe, the United States, Japan and other countries have formed a technical system with AI visual recognition and edge computing as the core, which greatly improves the efficiency of drug distribution [1] and effectively shortens the waiting time of patients through automated drug dispensing systems [2]. Foreign equipment is mainly divided into four categories: manipulator type, drug storage tank type, bulk type and rotary type, and the core functions focus on efficient drug dispensing and precise drug storage [3]. The manipulator system of ROWA in Germany adopts multi-axis robotic arm and three-dimensional positioning technology, and the daily processing volume of prescriptions reaches 3000 cases, and the error rate is <0.01%, but the hardware maintenance cost accounts for 35% of the investment. The storage tank system of APOTEKA in France combines gravity sensing and RFID technology, and the dispensing speed is 8 s per order, but the manual replenishment process leads to a 18% reduction in system efficiency. The metering accuracy of TOSHO's powder subcontractor is 98.7%, but the upper limit of processing is 120 packs/hour, which is difficult to meet the demand of 5000+ prescriptions per day. Hanel's swing system in Germany has a space utilization rate of 85% [4], but it is only suitable for standard pharmaceutical containers. At present, the coverage rate of international equipment in small and medium-sized medical institutions in developed countries is 72%, but its algorithm and hardware are designed for the scenario of 2000 prescriptions per day. If it is directly applied to China's tertiary hospitals (8000+ prescriptions per day), due to the lack of high concurrency processing capacity and mechanical durability defects, the system delay rate may rise to 12%, and the operation and maintenance cost may increase by 40%, so it is necessary to optimize the multi-machine collaboration algorithm and consumption-resistant hardware architecture.

2.2. The Development Status of Domestic Pharmacy Robots

The development of domestic pharmacy robot technology presents the following characteristics: compared with the international level, domestic R&D started late but developed rapidly, and the clinical application coverage rate has increased from 23% in 2023 to 41% at present. Chen et al. (2024) [5] improved the processing efficiency of mixed-line prescriptions by 37% and reduced the frequency of pharmacist intervention to 0.8 times/100 prescriptions by optimizing the dynamic sorting algorithm. According to the research of Wei Menglin [6] and Jiang Tingting [7], the imported third-generation system shortens the average waiting time of patients in tertiary hospitals to 4.2 min, and the error rate of drug dispensing <0.05%, but the annual operation and maintenance cost still accounts for 18–22% of the initial investment.

Breakthroughs have been made in the field of independent research and development: the bionic robotic arm system developed by Tian Maojun's [8] team has achieved a grasping accuracy of 50 mg ± granular traditional Chinese medicine, and the success rate of grasping special-shaped packaging has increased to 93%; Zhao Xianglong (2024) [9] designed a double-helix dispensing mechanism that compresses the single-slot dispensing cycle to 1.8 s, which is 62% better than that in 2023. The elastic separation module developed by Jiang Tingting [7] has been verified in tertiary hospitals in 17 provinces and cities, and the pass rate of the composite pill box channel has reached 99.6%.

At the industrial level, a complete supply chain has been formed in China, and the fourth-generation system of the leading enterprise integrates flexible scheduling and edge computing technology, supports the processing of 8000+ prescriptions in a single day, and the equipment localization rate is 81%. In 2024, the market size will increase by 49% year-on-year, and the technology iteration speed will be 2.3 times that of the international period, and the competitiveness will continue to be strengthened under the policy and market drive.

3. Smart Pharmacy Robot Design

3.1. Overall Design of the Robot

The overall design architecture of this pharmacy management robot takes the robot ontology as the core, and builds a collaborative system composed of four key modules. As the intelligent center, the ROS layer is responsible for core data analysis and computing tasks, including robot motion path planning based on A* algorithm and DWA algorithm, ACML positioning system, robot scheduling, sensor information collection and calculation, upper control of the robotic arm, and machine vision processing. Depth information sensors (including lidars that provide 2D plane information and depth cameras that provide three-dimensional spatial information) are responsible for sensing environmental depth information and providing basic data for navigation and operation. The cloud server platform undertakes cloud control and cloud monitoring functions, realizes remote control of the robot and obtains its sensor information in real time. The bottom control layer is responsible for the physical execution and basic perception of the robot, covering the motion control driven by the motor, the bottom action execution of the robotic arm driven by the servo, and the sensor information collection through the nine-axis gyroscope, temperature and humidity sensor, smoke sensor, etc. These four levels work closely together to form a complete functional system of pharmacy management robots (as shown in Figure 1).

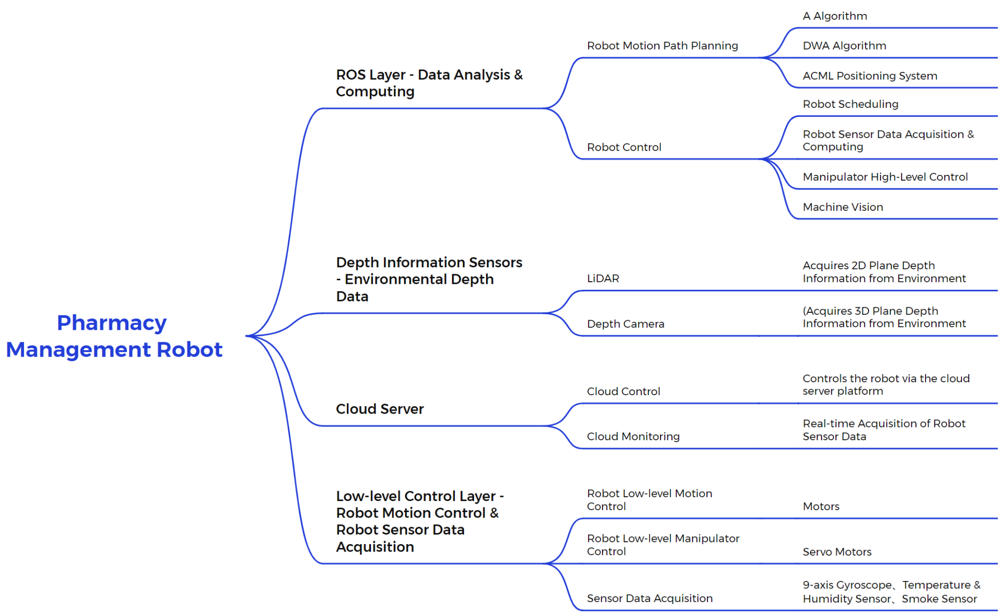

Figure 1. Pharmacy Management Robot System Architecture Diagram.

3.2. Design of Robot Operation Structure

This solution focuses on the precise control of the robotic arm, and the core lies in the application and integration of the stepper motor driver. As a conversion actuator from electrical pulse to angular displacement, the stepper motor driver is controlled to rotate at a fixed angle (step angle) by receiving pulse signals, so as to realize the precise positioning and movement of each joint of the robotic arm. The controller contains a microprocessor and drive circuitry that interprets external instructions and converts them into motor signals, while monitoring the motor status for timely adjustments.

The optional DM542 and OK2D 4020A drives drive five and one specific motors of the robotic arm, respectively, to ensure efficient and stable operation. The DM542 uses advanced DSP technology and built-in micro-segmentation for smooth operation and low noise, automatic parameter tuning and multiple protection functions.

In terms of control strategy, MoveIt is introduced as a software framework for robotic arm motion planning and control. Based on ROS, MoveIt supports a variety of controllers and interfaces, provides RRT, PRM and other algorithms to achieve motion planning, and uses 3D simulation tools for trajectory simulation and optimization to ensure accurate and efficient actual operation. The process using MoveIt includes ROS/MoveIt installation configuration, robotic arm modeling and description, motion planning and path optimization, final motion control and real-time monitoring.

To sum up, this solution provides a solid technical support for the accurate and efficient control of the robotic arm through the integrated application of advanced stepper motor drive technology and MoveIt software framework.

The system framework is shown in Figure 2.

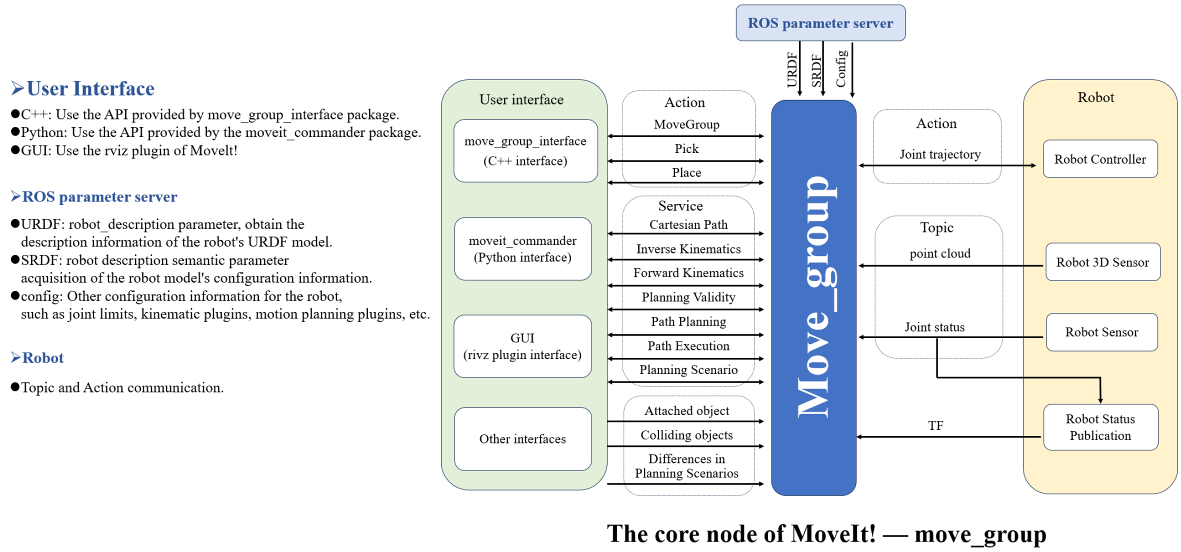

Figure 2. MoveIt System Framework.

The sports chassis design features Mecanum wheels, as shown in Figure 3. The Mecanum wheel is designed to move in all directions with an innovative design that uses a 45-degree angle of the rollers in contact with the ground for omnidirectional flexibility. Its unique structure enables the car body to move forward, traverse, oblique and rotate, and adapt to narrow space operations. Although the structure is compact and flexible, the torque efficiency is low, the cost is high, and the wear resistance is insufficient, which is suitable for smooth ground and the durability is weakened in complex terrain.

Figure 3. Mecanum Wheel.

As shown in Figure 4, the core of the sports chassis main control scheme uses STM32F103ZET6 as the main control MCU, which is extremely powerful, integrating rich resources such as 64KB SRAM and 512KB FLASH, and supporting a variety of peripheral interfaces, including 2 DMA controllers, 3 SPI, 2 IIC, 5 serial ports, etc., and 112 general-purpose IO ports, which is very suitable for complex control needs. Most importantly, its external bus (FSMC) efficiently expands SRAM and drives LCDs, significantly increasing the display refresh rate, making it the top model in the STM32F1 series.

Figure 4. STM32 main control chip.

In terms of attitude perception, the Witt intelligent WT9011G4K gyroscope is selected as the posture sensor module, as shown in Figure 5. The module integrates a high-precision gyroscope, accelerometer, and geomagnetic field sensor, and uses advanced algorithms to achieve accurate attitude solving in dynamic environments, with an accuracy of up to 0.01 degrees and excellent stability. It has a built-in voltage stabilization circuit, supports 3–6 V working voltage, is compatible with 3.3 V/5 V systems, and provides serial port and IIC interface options to meet diverse connection needs. The module also supports high-speed data transmission to ensure real-time performance, which is ideal for improving the accuracy of robot movements.

Figure 5. Wit Smart WT9011G4K Gyroscope.

3.3. Design of Manipulator for Taking Medicine

3.3.1. Visual Library Selection

This project uses OpenCV as the core vision processing library, which provides rich image processing algorithms and efficient computer vision functions, including image filtering, edge detection, feature extraction, etc. For the QR code recognition task, OpenCV can complete image preprocessing and preliminary positioning, but in order to further improve the recognition accuracy and speed, this project combines Zbar library for QR code decoding. ZBAR is a lightweight, high-performance barcode/2D code scanning library that supports a variety of encoding formats and is able to quickly parse QR code information. After image preprocessing via OpenCV, the ROI (region of interest) is passed to Zbar for efficient and stable 2D code recognition.

3.3.2. QR Code Scanning Process

1. Pre-processing stage: First, the BGR image collected by the camera is converted into a grayscale image to reduce the amount of calculation. Subsequently, the Laplacian operator was used for edge enhancement to highlight the contour features of the QR code. Due to the possible noise interference in the actual environment, a further mathematical morphological operation (corrosion first and then expansion) was used to remove fine noise while preserving the structural integrity of the QR code.

2. Boundary extraction and positioning: The contours in the image are detected by the cv2.findContours() function, and the candidate areas that conform to the geometric characteristics of the QR code (such as the corner distribution of the quadrilateral) are screened out. In order to improve the positioning accuracy, the minimum external rectangle of the contour was calculated, and the affine transform was used to correct it into a standard square to ensure that the QR code area was free of distortion and convenient for subsequent recognition.

3. Recognition and decoding: input the preprocessed image area into the Zbar scanner, configure the scanning parameters (such as coding format, scanning accuracy, etc.), and call the scan() method to parse the QR code data. If the identification is successful, the drug number or location information will be extracted; If it fails, an error is reported and a rescan mechanism is triggered to ensure robustness.

3.3.3. Object Detection Optimization

1. Dataset construction: The YOLOv5 model is used for drug target detection, and the training data is uniformly scaled to 640 × 640 pixels to balance computing efficiency and detail retention. By randomly cropping and scaling the original drug image, the data diversity can be expanded while avoiding the training burden caused by excessive resolution.

2. Annotation and data augmentation: Use the LabelImg tool to accurately label the drug bounding box and generate a labeling file in PASCAL VOC format. Data augmentation strategies include random rotation, translation, brightness/contrast adjustment, simulating the difference of lighting and placement angle in the pharmacy, and improving the generalization ability of the model.

3. Category imbalance treatment: In order to solve the problem of uneven distribution of drug categories, category weights are introduced into the loss function, and the weights are dynamically adjusted according to the occurrence frequency of each category in the training set to avoid the model biased towards high-frequency categories. For example, the weight coefficient of low-frequency drugs is set to 1.5~2 times that of high-frequency drugs to ensure the fairness of testing.

4. Model lightweight: Fine-tuning based on the pre-trained YOLOv5s (small version), combined with channel pruning (Pruning) to remove redundant convolution kernels, and INT8 quantization is used to reduce model storage and computing overhead. The inference speed is increased by more than 30% to meet the real-time requirements of the robotic arm.

5. Tuning and evaluation: 5-fold cross-verification is used to evaluate the stability of the model, and hyperparameters such as learning rate and anchor box size are adjusted through Grid Search. The final indicators include mAP@0.5 (average accuracy) and FPS (frame rate) to ensure that the model achieves the optimal balance between accuracy and speed, and realizes the fast and accurate positioning of drugs.

3.4. Robot Control System Design

3.4.1. Primary Controllers

In this study, the ESP32 module is used to realize the real-time video transmission control. Developed by Espressif Systems as an upgraded version of the ESP8266, the module integrates a dual-core processor, Bluetooth and Wi-Fi capabilities, and is designed for IoT devices. Its built-in high-efficiency processor and large-capacity memory support multitasking, which can be adapted to smart home, wearable devices and other application scenarios. At the technical level, ESP32 supports Bluetooth 5.0 protocol and Mesh networking, expands GPIO interfaces and is compatible with USB-OTG communication, and combines low-power consumption characteristics with development frameworks such as Arduino and ESP-IDF, significantly reducing the threshold for IoT device development. The hardware-accelerated H.264/MJPEG video encoding capability can meet the needs of real-time transmission, and has been applied on a large scale in remote monitoring, medical equipment and other fields.

3.4.2. Overall Architecture

In addition to the real-time transmission of video, coupled with the security detection of the environment, the monitoring effect of the Internet of Things design can be achieved. Therefore, in addition to the mentioned ESP32, build the IoT system architecture: perception layer and application layer. The perception layer is responsible for collecting information, and the application layer is responsible for providing a secure and reliable platform for connectivity, interaction, and sharing (see Figure 6).

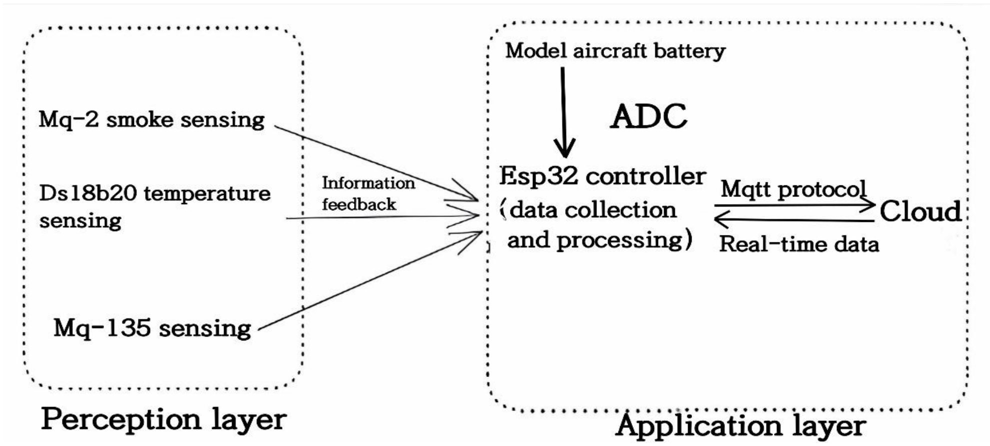

Figure 6. IoT architecture diagram.

3.4.3. Overview of the Perception Layer

As the basis of the IoT system, the perception layer integrates a variety of sensor modules, such as the MQ-2 smoke sensor and the DS18B20 temperature sensor. The MQ-2 sensor provides timely warning of fire risk by detecting changes in smoke concentration, and its operating principle is based on changes in the conductivity of tin dioxide semiconductor materials. DS18B20 is a high-precision digital temperature sensor that provides stable and accurate temperature readings and supports single-bus communication for easy system integration and expansion. In addition, the MQ-135 gas sensor is used to monitor harmful gases in the air, such as ammonia, hydrogen sulfide, etc., and its high sensitivity and wide applicability make it ideal for pharmacy environmental monitoring. Together, these sensors form the perception layer of the Internet of Things, providing rich environmental data support for the system.

3.4.4. MQTT Communication Protocol

This project uses the MQTT protocol as the IoT communication protocol, which is known for its lightweight, high reliability, flexibility, and security, which is very suitable for data exchange between IoT devices. Through the MQTT protocol, the pharmacy environmental data and robot status can be uploaded to the cloud in real time, and control commands can be received at the same time to achieve remote monitoring and management, which greatly improves the intelligent level of pharmacy management.

3.5. Robot Scheduling Design

3.5.1. ROS Robot Operating System

ROS (Robot Operating System) is an open-source software framework designed for robot development, which simulates the core functions of the operating system, such as hardware abstraction, device control, inter-process communication and package management, and integrates a variety of robot-specific functions, such as navigation, visual processing and speech recognition. ROS aims to improve the reusability and collaborative operation ability of robot software, and realize seamless data exchange and service sharing between different program modules through standardized communication protocols. It supports cross-language (e.g., C++, Python, Java) and cross-platform (e.g., Linux, Windows, Mac OS) development, which greatly facilitates the prosperity of the robotics software ecosystem.

The core architecture of ROS is built around the concept of “nodes”, where each node represents an independent software module that communicates with each other through a messaging mechanism to form a flexible network structure. This loosely coupled design model simplifies the process of developing, managing, and maintaining the system. ROS also provides a wealth of functional libraries and development tools, including simulation environments, data visualization interfaces, graphical user interfaces, and data logging and analysis tools, to fully support the R&D and testing needs of robots.

3.5.2. ROS Data Processors

In this project, NVIDIA’s jetson nano 01 was selected as the core hardware platform for ROS data processing. Jetson nano 01 is a high-performance embedded development board from NVIDIA for AI and robotics applications. It is equipped with a GPU based on the NVIDIA Maxwell architecture, a quad-core ARM Cortex-A57 processor, high-performance memory and storage system, and supports a variety of video codec formats and high-speed interfaces, making it easy to handle complex robot vision processing and data processing tasks. By integrating the NVIDIA JetPack SDK, jetson nano 01 not only provides acceleration support for advanced technologies such as deep learning and computer vision, but also ensures stable and efficient operation of the software environment. In the ROS environment, jetson nano 01 can take full advantage of its GPU acceleration and multi-version compatibility, bringing more superior performance and flexibility to robotics applications.

3.5.3. Pharmacy Management Robot Control Logic

Figure 7 shows how an automated system improves the efficiency of a pharmacy through robotics, especially during peak periods, by quickly responding to medication requests, reducing wait times, and ensuring the accuracy of drug distribution. By optimizing the medication distribution process, pharmacies can better manage resources and enhance patient satisfaction.

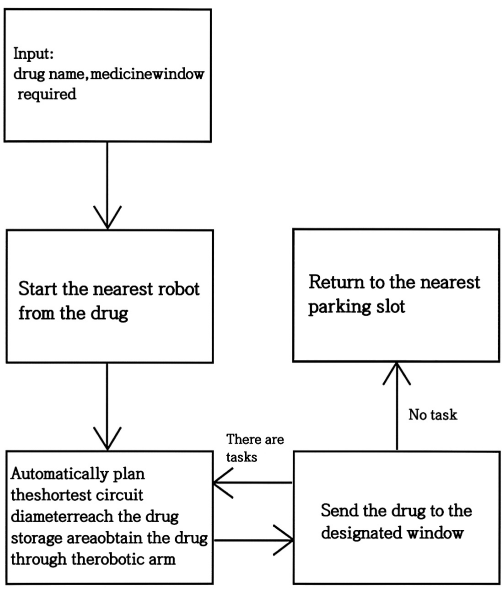

Figure 7. Logic diagram of pharmacy management robot control technology.

4. Conclusions and Prospects

4.1. Conclusions

The pharmacy management robot developed in this study has the following core advantages:

(1) Convenient adaptation and deployment: The intelligent grasping technology is used to adapt the existing drug shelf structure for drug access, which is highly efficient and can achieve aseptic operation, without the need for large-scale transformation of pharmacy infrastructure, and significantly reduces the complexity of deployment;

(2) Flexible cost control: support stand-alone independent operation and multi-machine collaboration mode, small and medium-sized hospitals can adopt a phased deployment strategy, gradually complete intelligent upgrades, and effectively control the initial investment cost;

(3) Optimization of the efficiency of the whole process: the operation efficiency is significantly higher than that of traditional manual operation, and at the same time, the repetitive work of medical personnel in the drug management link is reduced, so that they can focus more on patient communication and medication guidance, and systematically improve the efficiency and quality of pharmaceutical services.

4.2. Future Prospects

On 5 January 2025, the State Council promulgated the “Action Plan for Promoting Large-scale Equipment Renewal and Trade-in of Consumer Goods”, and China’s medical and health institutions are accelerating the intelligent upgrading, among which the construction of “smart pharmacies” has become a key path to optimize drug services. The goal of seamless connection between the prescription system and the dispensing system proposed by the National Health Commission and other institutions has laid a policy foundation for the application of pharmacy management robots. At present, although the domestic pharmacy automation equipment market is in a period of rapid growth, there is still a significant gap between the technical maturity of existing products and the surging demand for prescription processing and precision drug dispensing in the medical market, especially in the high-load scenario of more than 6000 prescriptions per day in tertiary hospitals, the coverage rate of automation equipment is less than 35%. This contradiction between supply and demand continues to drive the iteration of pharmacy management robot technology, which is deeply coupled with the pharmaceutical process through artificial intelligence algorithms, and gradually realizes the intelligent reconstruction of the whole process in the links of prescription review, drug sorting and medication guidance, which is expected to become the core breakthrough point for improving the quality and efficiency of the medical industry.

Funding

This research was funded by the 2025 Zhaoqing University University-Level Undergraduate Innovation and Entrepreneurship Training Program Project: Pharmacy Management Robot Utilizing Artificial Intelligence, grant number X202510580014.

Author Contributions

Writing—original draft, H.C., M.S., H.-L.H., S.-Q.H., R.F. and Y.-Q.W.; writing—review and editing, H.C., M. S., H.-L.H., S.-Q.H., R.F. and Y.-Q.W. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

References

1 Svirsko AC, Norman BA, Hostetler S, *et al*. Optimizing the Medication Distribution Process for Inpatient Units. *Journal of Medical Systems* 2022; **46**: 1–10.

2 Das S, Dey R, Nayak AK. Artificial Intelligence in Pharmacy. *Indian Journal of Pharmaceutical Education and Research* 2021; **55**: 304–318.

3 Chen C. *Research on Intelligent Drug Dispensing System for Automated Pharmacy Based on Binocular Vision*; Zhejiang University of Science and Technology: Hangzhou, China, 2023.

4 Wu W, Liu T. Design and Analysis of Pharmacy Sorting Robot Handling System. *Precision Manufacturing and Automation* 2020; **2**: 5–11.

5 Chen P, Shu Y, Lv Y, *et al*. Construction of Management Model of Unattended Smart Surgical Pharmacy Based on PDCA Cycle Method. *Chinese Journal of Hospital Pharmacy* 2024; **44**: 847–852.

6 Wei M, Dou D, Zhang D, *et al*. The Effect and Problem Analysis of Large-Scale Use of Automated Dispensing Machines in Outpatient Pharmacy. *Modern Hospital* 2019; **19**(**04**): 518–521.

7 Jiang T, Xian Q, Li C. Analysis on the Application Effect of Automated Drug Dispensing System in Hospital Outpatient Pharmacy. *China Pharmaceutical Industry* 2023; **32**: 15–18.

8 Tian M. *Research on Key Technologies of Automated Pharmacy for Granular Traditional Chinese Medicine*; Beijing University of Posts and Telecommunications: Beijing, China, 2023.

9 Zhao X. *Design and Research on the Quantitative Dispensing System of Chinese Herbal Medicines in Pharmacy*; Beibu Gulf University: Qinzhou, China, 2024.