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Research on the Application of Artificial Intelligence in Commercial Robots

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Abstract: *With the acceleration of consumption upgrading and industrial intelligent transformation, commercial robots have widely penetrated various fields such as retail, warehousing, catering, healthcare, and hotels. Artificial intelligence (AI) technology is the core driving force enabling their leap from "automation" to "intelligence." This paper adopts a combination of literature analysis and case investigation to systematically review the current application status of AI in commercial robots, focusing on the technical implementation paths in five major scenarios: retail, warehousing, catering, healthcare, and hotels. Three innovative directions are proposed: multimodal interaction optimization, federated learning collaboration, and digital twin operation and maintenance. Targeted strategies are also provided to address practical issues such as data security, scenario adaptation, and insufficient robustness. The study shows that AI technology can significantly improve the operational efficiency and user experience of commercial robots, and related innovative solutions have been validated in real-world scenarios, providing theoretical support and practical reference for the large-scale deployment of the commercial robot industry.*

Keywords: *Artificial Intelligence; Commercial Robots; Computer Vision; Natural Language Processing; Multimodal Interaction; Federated Learning; Digital Twin*

1. Introduction

1.1 Research Background

In recent years, global demand for commercial robots has continued to show a growth trend. According to the China Commercial Robot Industry Development Report (2024) released by the China Electronics Standardization Institute, the Chinese commercial robot market reached 89.6 billion yuan in 2023, a year-on-year increase of 23.5%, with robot penetration rates in retail, warehousing, and healthcare rising to 18.2%, 25.7%, and 12.3%, respectively. [1] The core value of commercial robots lies in replacing repetitive labor and improving service precision; however, traditional robots generally face issues such as "single interaction, passive decision-making, and insufficient collaboration." The deep integration of AI technologies, such as computer vision, natural language processing, and reinforcement learning, can endow robots with core capabilities of "perception, cognition, and collaboration," becoming the key to overcoming industrial development bottlenecks.

1.2 Research Significance

1.2.1 Theoretical Significance

Current related studies mostly focus on the hardware design of commercial robots or the application of a single AI technology, lacking a systematic integration of the “technology–scenario–innovation” framework. This paper, by reviewing the AI technology implementation logic in four core scenarios, constructs a multidimensional innovation framework that can further improve the theoretical system of AI integration with commercial robots and provide a reference for subsequent research in specialized subfields.

1.2.2 Practical Significance

To address practical pain points such as low inventory management efficiency in retail, time-consuming path planning in warehousing, and large delivery errors in catering, this paper proposes implementable technical solutions based on typical cases from companies such as Geek+ and Pudu Robotics. The proposed solutions are expected to help enterprises reduce operational costs (estimated average reduction of 15%-20%) and improve service efficiency (average improvement of 25%-30%), promoting the transformation of commercial robots from "pilot applications" to "large-scale adoption." [2]

1.3 Research Methods

This paper adopts two core research methods: First, the literature analysis method, which systematically reviews relevant research results on AI and commercial robots published in authoritative domestic and international journals over the past five years, including IEEE and China Circulation Economy, to clarify technology development trends and research hotspots. Second, the case study method, which conducts in-depth analysis of actual project cases from companies such as Geek+, Pudu Robotics, TiMi Robotics, and Yunji Technology, to verify the feasibility and application effectiveness of the technical solutions.

2. Current Application Status of Artificial Intelligence in Commercial Robots

2.1 Technical Foundations

Artificial intelligence provides three core capability supports for commercial robots: First, perception capability, which relies on computer vision (CV) technology to achieve product recognition and obstacle detection, with relevant technologies generally reaching over 95% accuracy; second, interaction capability, which uses natural language processing (NLP) technology to complete voice command recognition and user demand response, with semantic understanding accuracy exceeding 90%; third, decision-making capability, which optimizes path planning and demand prediction based on reinforcement learning (RL) and machine learning (ML) algorithms, improving decision efficiency by 30% compared with traditional algorithms. [3]

2.2 Overview of Existing Application Fields

Currently, AI commercial robots cover five core application fields: In retail, the core functions are "product recognition + inventory management," with typical representatives such as Suning RetailBot; in warehousing, the focus is on "path planning + goods sorting," such as Geek+ AGV robots; in catering, the emphasis is on "order delivery + voice interaction," such as Pudu Robotics' "Happy Delivery" robots; in healthcare, the core positioning is "medicine delivery + guidance services," such as TiMi medical robots; in hotel services, the focus is "room delivery + voice interaction," such as Yunji Technology's "GeGe" robots. However, current applications still have three prominent shortcomings: first, interaction forms are single, mostly relying on voice, lacking multidimensional interactions such as expressions and gestures; second, multi-robot collaboration depends on centralized data storage, posing risks of data privacy leakage; third, operation and maintenance modes are relatively passive, mostly performed after faults occur, lacking early warning and predictive capabilities.

3. Specific Application Scenarios and Technical Implementation of Artificial Intelligence in Commercial Robots

3.1 Retail Service Robots: AI-Driven "Goods–People–Space" Collaboration

3.1.1 Product Recognition and Inventory Management

Retail robots achieve two core functions through the combination of computer vision and deep learning technologies: First, shelf product recognition, which uses the YOLOv8 algorithm for real-time detection of product packaging and barcodes, achieving 98.5% accuracy and automatically identifying out-of-stock or misplaced products; second, dynamic inventory counting, which, combined with the robot's path planning function, completes inventory checking of a 10,000-square-meter supermarket in just 2 hours, improving efficiency by 60% compared with manual counting. [4]

Case: Suning RetailBot has been deployed in over 300 stores nationwide. Through an AI-driven inventory management system, the out-of-stock alert response time is reduced to 15 minutes compared with traditional methods, restocking efficiency is increased by 40%, and customer complaints caused by out-of-stock products decrease by 25%.

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3.1.2 User Demand Prediction and Recommendation

Based on machine learning technology, specifically the random forest algorithm, robots analyze user shopping trajectories and historical consumption data to accurately predict potential user demands. For example, by identifying product categories where users linger for more than 30 seconds, the robot proactively pushes related promotional information (e.g., when a user shows interest in infant formula, complementary food is simultaneously recommended), achieving a recommendation conversion rate of 12%, which is 8 percentage points higher than traditional manual recommendations.

3.2 Warehouse and Logistics Robots: AI-Optimized "Sorting–Transport" Full Process

3.2.1 Dynamic Path Planning

Warehouse AGV robots use reinforcement learning (DQN algorithm) to optimize path planning, dynamically adjusting travel routes through real-time perception of obstacles in the warehouse, such as workers and other robots. Compared with traditional fixed-path algorithms, reinforcement learning–driven path planning reduces travel time by 30% and decreases the AGV idle rate by 25%. [5]

Case: After the deployment of Geek+ "Goods-to-Person" AGV robots in JD Asia No.1 Warehouse, under the same operating hours, the average daily order handling per robot increased from 120 to 150, overall warehouse sorting efficiency improved by 25%, and labor costs decreased by 30%.

3.2.2 Goods Sorting and Grasping

Robots achieve precise goods grasping through the combination of computer vision and 3D vision sensors: First, CV technology identifies the shape and label information of goods; then, 3D vision captures the spatial coordinates of the goods, controlling the robotic arm to adjust the grasping angle. The grasping success rate reaches 97%, making it particularly suitable for irregularly shaped items such as fresh produce and fragile goods.

3.3 Catering Service Robots: AI-Ensured "Accurate Delivery + Friendly Interaction"

3.3.1 Accurate Order Delivery

Catering robots integrate SLAM algorithms and computer vision technologies to achieve localization and obstacle avoidance: SLAM technology constructs restaurant environment maps with a positioning accuracy of ±5 cm; CV technology detects pedestrians, tables, chairs, and other obstacles in real time, with an obstacle avoidance response time below 0.5 seconds and a delivery error rate under 3%. [6]

Case: Pudu Robotics' "Happy Delivery" robots have been deployed in 20,000 restaurants nationwide. During peak dining periods, a single robot delivers an average of 40 orders per day, replacing the daily delivery workload of 1.5 waitstaff, helping restaurants reduce labor costs by 18% and improve delivery efficiency by 35%.

3.3.2 Voice Interaction and Demand Response

Using natural language processing (BERT model), the robots achieve multi-turn dialogue capabilities: they accurately recognize user commands such as "add utensils" or "hurry the dish," with semantic understanding accuracy reaching 92%, and support dialect recognition (e.g., Sichuanese, Cantonese), adapting to the interaction needs of users across different age groups.

3.4 Medical Assistance Commercial Robots: AI-Empowered "Safe–Efficient" Services

3.4.1 Medication Verification and Delivery

Robots ensure medication delivery safety through the combination of computer vision and RFID technologies: CV technology identifies the label information on medicine boxes, while RFID reads the electronic codes of the drugs, providing dual verification of drug name, dosage, and expiration date. In practical applications, the verification accuracy reaches 100%, effectively preventing manual dispensing errors. [7]

Case: After deployment of TiMi medical robots at Ruijin Hospital in Shanghai, the robots deliver over 800 medications daily, replacing the delivery workload of three nurses. The medication delivery error rate dropped from 0.5% to 0, and nurses' time available for patient care increased by 20%.

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3.4.2 Patient Guidance and Information Interaction

Based on natural language processing and multimodal interaction technologies, robots can answer common questions such as "department location" and "consultation procedures." At the same time, they use cameras to recognize patient expressions (e.g., frowning, anxious facial expressions) and proactively inquire about needs, further enhancing the patient experience.

3.5 Hotel Service Robots: AI-Restructured "Check-In–Service–Experience" Full-Scenario Loop

3.5.1 Accurate Room Service Response

Robots are equipped with voice recognition, natural language processing (NLP), and facial recognition technologies, enabling natural conversation with guests, identity recognition, and personalized service. At the same time, through 3D spatial navigation, multi-floor elevator scheduling, and obstacle avoidance algorithms, robots achieve autonomous path planning and precise delivery in complex environments.

Case: Yunji Technology's industry-specific semantic model YJ-NLP can interpret and fulfill over 1,000 different consumer needs, categorized into five core types: item delivery, inquiries, services, replacement of room amenities, and emotional requests. The "GeGe" series robots handle tasks such as check-in registration, taxi booking, and hotel introductions, enhancing guest experience. The "UP" series robots deliver water, takeout, and toiletries within the hotel, achieving daily service volumes at the million-level.

3.5.2 Energy Management and Operational Optimization

The AI system collects hotel operation data, analyzes energy consumption patterns, and optimizes robot scheduling and task allocation, identifying trends in daily and seasonal demand changes or recurring maintenance needs, achieving energy savings and efficiency improvement.

Case: Yunji Technology's HDOS system integrates hotel operational data and uses predictive analytics to automatically adjust robot work schedules. The evolution from handling individual guest requests to providing overall solutions ensures closed-loop service delivery.

4. Innovative Directions of Artificial Intelligence in Commercial Robots

4.1 Multimodal Interaction Optimization: From "Single Voice" to "Full-Sensory Interaction"

4.1.1 Technical Principles

By integrating three interaction modalities—voice recognition, facial expression recognition, and gesture recognition—and using multimodal fusion algorithms (e.g., Transformer architecture) to extract and merge features from multiple sources, robots achieve natural interaction combining "voice command response + gesture control operation + expression feedback interaction." For example, a user's waving gesture can trigger the robot to pause its task, and when a frowning expression is detected, the robot proactively asks, "Do you need assistance?" [8]

4.1.2 Application Value

Case: UBTECH Walker X robots have been deployed in high-end shopping malls. The multimodal interaction functionality increased user satisfaction from 82% to 95%, and the average interaction time between users and robots increased by 1.5 minutes, effectively enhancing brand exposure and user engagement.

4.2 Federated Learning–Driven Robot Collaboration: "Data Sharing without Leakage" Collective Intelligence

4.2.1 Technical Principles

Using a federated learning framework (e.g., FedAvg), multiple robots complete model training locally and only upload the trained model parameters—not the raw data—to a central server. The server aggregates and optimizes the model parameters from all robots and redistributes them to each robot, achieving a collaborative mode of "data stays, model moves." For example, ten AGV robots in a logistics park can optimize overall scheduling efficiency through federated learning collaboration without sharing

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their individual path data.

4.2.2 Application Value

After applying this technology in a logistics park, the collaborative efficiency of multiple AGV robots increased by 15%, the risk of data privacy leakage dropped to an extremely low level (near 0), and potential security hazards associated with centralized data storage were avoided.

4.3 AI and Digital Twin–Based Operation and Maintenance Collaboration: "Predictive Maintenance" Replacing "Reactive Repair"

4.3.1 Technical Principles

A digital twin model of commercial robots is constructed, synchronizing real-time operational data (e.g., motor temperature, battery level, sensor accuracy). AI prediction algorithms (e.g., LSTM) analyze trends in the operational data to identify potential fault risks in advance (e.g., insufficient battery life, early signs of motor anomalies). In actual tests, the warning accuracy reached 92%.

4.3.2 Application Value

After implementing this solution in JD Asia No.1 Warehouse, robot downtime due to faults was reduced from an average of 4 hours to less than 1 hour, operation and maintenance costs decreased by 40%, and overall warehouse operational efficiency increased by 18%.

5. Challenges and Countermeasures in the Application of Artificial Intelligence in Commercial Robots

5.1 Data Security and Privacy Protection

5.1.1 Core Issues

During operation, commercial robots collect user data (e.g., shopping preferences, medical information) and enterprise operational data (e.g., inventory data, order information), which are at risk of leakage. Especially in multi-robot collaboration, centralized data storage can easily become a target for cyberattacks. [9]

5.1.2 Countermeasures

First, differential privacy technology can be applied, proactively adding noise during data collection to ensure that data remains usable but cannot be reconstructed, achieving "data usable but not visible." Second, federated learning can be promoted to avoid uploading raw data to a central server, reducing data leakage risks at the source. Third, blockchain technology can be used to record the entire data flow process, ensuring traceability of data usage and clarifying data responsibility.

5.2 Scenario Adaptation and Cost Control

5.2.1 Core Issues

Different application scenarios (e.g., supermarkets, restaurants, hospitals) have significant environmental differences (e.g., lighting conditions, types of obstacles, user demand characteristics), leading to high costs for customized AI algorithm development, which small and medium enterprises find difficult to bear (the customization cost for a single scenario is approximately 500,000–1,000,000 yuan).

5.2.2 Countermeasures

First, it's necessary to develop a modular AI algorithm library, encapsulating commonly used functions such as product recognition and path planning into standardized modules, allowing enterprises to select and combine as needed, reducing customization costs by more than 50%. Second, it's also important to adopt a general-purpose hardware platform (e.g., robots equipped with Horizon J5 AI chips) by using hardware standardization to adapt to multiple scenarios and reduce hardware procurement costs by 20%.

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5.3 Insufficient Robustness in Complex Environments

5.3.1 Core Issues

In dynamic and complex environments (e.g., peak crowds in shopping malls, wet floors in restaurants, emergencies in hospitals), robot perception accuracy is easily affected. For example, product recognition accuracy drops from 98% to around 85% under strong lighting, and obstacle avoidance success decreases from 97% to 88% in complex obstacle scenarios.

5.3.2 Countermeasures

First, multi-sensor fusion technology (LiDAR + visual sensors + infrared sensors) can be used to complement the strengths of each sensor, improving perception accuracy in complex environments to over 95%. Second, transfer learning technology can be introduced to transfer model parameters from mature scenarios to new scenarios, reducing the data required for scenario adaptation by over 60% and quickly enhancing robot robustness in new environments.

5.4 Elevator Integration: The "Obstacle" for Service Robot Popularization

5.4.1 Core Issues

Commercial service robots often require coordination with elevators, access control systems, and other infrastructure through IoT technology. However, in many countries and regions, elevator hardware modification faces significant regulatory constraints. In Europe, for example, any adjustment to elevator control systems must comply with the EU Machinery Directive (2006/42/EC) and standards such as EN 81-20/50, and pass the corresponding certifications. Hardware-level changes require a comprehensive safety assessment process, which is technically complex and involves lengthy approval cycles and high compliance costs. Under this regulatory context, companies are often forced to adopt cloud-based system integration solutions in cooperation with elevator manufacturers. While this approach bypasses hardware modification regulations, it introduces ongoing deployment and upgrade costs and deepens structural reliance on third-party hardware suppliers. Such dual technical and regulatory constraints ultimately limit the global deployment and large-scale application of commercial service robots.

5.4.2 Countermeasures

Enhancing operational capabilities is increasingly recognized as a core technical element for achieving large-scale deployment of service robots. This capability allows the robot to perform physical operations independently, without relying on cloud or hardware integration with elevator control systems, thus avoiding the technical dependencies and compliance bottlenecks of existing solutions. This approach not only provides an extensible technical framework for cross-border applications but also significantly expands global market accessibility.

Industry data show that current elevator manufacturers charge annual service fees for cloud control systems of approximately \$10,000–\$20,000 per unit. By adopting operation-capable robots with robotic arms to autonomously press elevator buttons, substantial reductions in ongoing cloud integration costs are expected. Preliminary estimates indicate that this technical pathway could save approximately \$1.8 billion in deployment and operational costs globally each year.

Case: In March 2025, Pudu Robotics launched the new robot "Lightning Box" Arm, developed on the flagship commercial service robot Lightning Box. It integrates mobility, operational, and interactive technology stacks, providing generalized operational capabilities for tasks in hotels, office buildings, catering, retail, healthcare, and other commercial scenarios. For end users, the combination of mobility and operational capabilities enables Lightning Box Arm to complete delivery tasks in a human-like manner, achieving end-to-end delivery loops while significantly reducing IoT modification and manual assistance costs. Additionally, by operating its robotic arm, Lightning Box Arm can physically press elevator buttons, access control panels, knock on doors, and open doors, marking an important milestone in the robot's transition from 2D to 3D capabilities.

6. Conclusion

This paper systematically analyzes the application status, specific scenarios, and innovative directions of artificial intelligence in commercial robots, and draws the following conclusions: First, AI technologies have been effectively implemented in five core scenarios—retail, warehousing, catering,

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medical, and hotel delivery. Through the deep application of computer vision, natural language processing, and other technologies, robot operational efficiency and user experience have been significantly improved. Second, multimodal interaction, federated learning–based collaboration, and digital twin–enabled operation and maintenance are the current core innovation directions, effectively addressing issues such as single-mode interaction, privacy leakage, and reactive maintenance in existing applications. Third, data security, scenario adaptability, and insufficient robustness in complex environments remain the primary challenges, which need to be gradually overcome through technological optimization and innovative models.

In recent years, breakthroughs in AI large models, multimodal perception, and bionic robotic arms have enabled humanoid embodied intelligent robots to rapidly advance in autonomous decision-making, environmental interaction, and generalized operations, achieving cross-scenario task-handling capabilities and moving from laboratory research toward commercial deployment at an accelerated pace. Compared with the prolonged generalization process of humanoid robots, humanoid embodied intelligent robots addressing scenario-specific pain points currently have more practical significance. More importantly, as these robots continuously validate their mobility, multitasking, complex environment adaptation, and human–robot collaboration capabilities in industries where commercial service robots are already widely deployed—such as hotels, catering, and hospitals—they also help cultivate public awareness and usage habits, drive cost reduction, and pave the way for deployment in homes, eldercare, and companion scenarios, thereby unlocking larger market potential. In May 2024, Pudu Robotics first introduced the concept of humanoid robots in the industry: by leveraging robotic arm operations, service robots can greatly enhance their product capabilities, realize more general product value, and lead the application of humanoid robots in hotel delivery. The future service robot ecosystem will consist of three forms: specialized robots, humanoid robots, and humanoid embodied robots.In the future, with the continuous iteration of AI algorithms (e.g., deep integration of large language models with robots) and gradual reduction of hardware costs, commercial robots are expected to evolve toward being “smarter, more general, and more cost-effective,” with the potential to achieve large-scale application in additional fields such as education and cultural tourism, becoming an important driving force for industrial intelligent transformation.

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