Application and optimisation of intelligent control system for home robots

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Abstract. As a significant part of the smart home, intelligent home robots can provide a variety of convenient home services such as automatic cleaning, elderly care, entertainment interaction, etc., which are highly valued and favoured by the majority of home users, and the market scale is expanding. However, the design and optimization of the control system represents a crucial technical challenge to truly realize the intelligence and autonomy of home robots. This paper presents a comprehensive analysis of the design and optimization of automatic control systems for intelligent home robots, which aims to improve the performance and user experience of intelligent home robots and better meet the needs of families. Through collection and analysis of the research on domestic robots and their control technology ,the core technical elements of the control system are summarized and refined, and the hardware structure and software framework of the control system are analyzed. The research results provide valuable insights for improving the performance and capabilities of home robot control systems to better meet the diverse needs and expectations of home users. These innovations provide a solid foundation for advancing the development of intelligent robots in the home. Future trends in control systems may include enhanced perceptual capabilities and decision-making intelligence to enable robots to better understand and meet the needs of home users.

Keywords: Home Robot Design, Technical Architecture, Control Systems, Motion Algorithms.

1. Introduction

The smart home represents a significant area of potential growth and development in the future, and as one of its key components, home intelligent robots have attracted much attention. These robots can provide a variety of convenient home services, which can help improve the quality of family life. At present, major commercial smart home products are equipped with robot service functions, and the market scale is growing rapidly. However, the design and optimisation of the control system of home robots is still a major challenge to achieve real intelligence and autonomy. Existing research has mainly focused on basic technologies, including the mechanical structure of robots, motion planning and sensing systems. However, there is a lack of systematic research on the key technical components of the control system of intelligent home robots and the optimization techniques associated with them, leading to research gaps in autonomous decision-making, human-robot interaction, and other important functions of the robot. Therefore, the paper addresses the design and optimization of the control system of intelligent home robots. Through an exhaustive review of existing research findings, key technical

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components, including precise motion control algorithms, multi-sensor fusion technology, and intelligent decision-making control models, are identified and analyzed. It not only improves the performance and user experience of existing home robots to lay a technical foundation for the future development of smart homes, but also provides a reference for related enterprises and research institutions. Through continuous optimization and innovation, home robots will become an important part of the future smart home, providing residents with a more convenient and comfortable lifestyle.

2. Overview of Home Robots and Intelligent Control Systems

2.1. Overview of the Development of Home Robots

The smart home robots are designed to perform a variety of tasks to provide a range of services in the home environment, which are typically equipped with technologies such as voice recognition, visual recognition, and motion control that enable them to interact with family members through voice commands, recognize the home environment, and provide a range of home services. The China Home Intelligent Robot Industry Market Competitive Situation and Prospective Strategy Research Report 2024-2030 published by Bo Research Consulting shows that the global home intelligent robot market size has been expanding, and the global intelligent home robot market size reached about USD 2.5 billion in 2019, and is expected to reach about USD 11 billion by 2025, with a CAGR of 25% at a rate of around. In the Chinese market, intelligent home robot industry also shows rapid growth [1].

In 1927, Wenzli of the United States of America constructed the inaugural robot “telegraph box,” which was showcased at the World’s Fair in New York. The robot was electric and equipped with a radio transmitter, enabling it to respond to certain queries. However, it lacked the capacity to traverse the environment independently. In 1959, Joseph Ingeborg developed the first industrial robot (programmable, circular coordinates), thereby inaugurating a new era in the field of robotics. In 1970, the U.S. hosted the inaugural International Conference on Industrial Robotics, which contributed to the rapid proliferation of robotics research. In the 1980s, the study of sensing, thinking, decision-making, and the ability to act led to the emergence of intelligent robots and robotics, marking a significant shift in the field's direction. In the 21st century, the study of home robots is becoming an increasingly popular field of research [2].

2.2. Overview of Intelligent Control Systems for Home Robots

Intelligent control systems for home robots are sophisticated technological solutions that integrate sensing, decision-making, and execution capabilities, and are designed to provide intelligent services to home users.Intelligent control of power system refers to the use of artificial intelligence technology to achieve intelligent control of the power system in terms of optimal scheduling, fault diagnosis and recovery, security and stability control. A large amount of data from the system is analysed and learnt in order to improve the operational efficiency, reliability and security of the system.[3] The function of the robot control system is to receive the detection signals from the sensors and drive the motors on the robotic arm in accordance with the specifications of the operational task. The robot must utilize sensors to detect a variety of states. The sensor signals within the robot are employed to reflect the actual motion state of the robotic arm’s joints, while the sensor signals outside the robot are utilized to detect alterations in the surrounding environment. As a result, the robot’s nerves and brain integrate to form a comprehensive robot control system [4]. The four principal components of the robot motion control system are shown in Table 1.

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Table 1. Four Main Components of A Robot Motion Control System

Executing Agency	Servo motors or stepper motors
Drive Mechanism	Servo or stepper drives
Control Mechanism	Motion controllers that do algorithmic algorithmic control of path and motor linkage
Control Method	If there is a fixed way to execute the action, program the fixed parameters to the motion controller; if there is a vision system or other sensors, according to the sensor signals, program the unfixed parameters to the motion controller.

As one of the most core components of the robot, the robot controller plays a decisive role in the performance of the robot, which affects the development of the robot to a certain extent. The embedded main controller is the core of the control system, using the STM32F407 chip as the processor controller, with a variety of peripheral interfaces, such as RS232, RS485, UART, CAN, DI, DO and PWM [5]. In order to ensure that the system has enough computing and storage capacity, the current robot controller is mostly composed of chips with high computing power, such as Arm series, DSP series, POWER PC series, and Intel series

3. Design and Optimization of the Control System

3.1. Control System Architecture Analysis

The perceptual system is referred to as the “middle control system,” the decision-making system as the “upper control system,” and the execution system as the “lower control system.” In order to meet the needs of environment perception, robots are often equipped with many cameras, LiDAR, millimetre wave radar, ultrasonic and other sensors, under which, along with V2X and 5G network technologies, multi-source information can be acquired in real time to provide support services for decision-making and planning. Currently, there are two technical routes for environment sensing technology, one is a multi-sensor fusion solution dominated by cameras, typically represented by Tesla. The other is led by LiDAR, with other sensors as auxiliary solutions, with typical enterprise representatives such as Google and Baidu.

As one of the more common sensors, the camera has the advantage of being able to distinguish colors and is more suitable for scene interpretation. Distinguished formally, panoramic cameras are broadly categorized as single-lens and those consisting of multiple lenses, with the single-lens panoramic camera generally referred to as a fisheye camera [6]. Despite their advantages, panoramic cameras also have some inherent limitations. First, the camera lacks a “depth” dimension and has no stereoscopic vision to determine the distance between an object and the camera. Second, the camera is more sensitive to light, too dark or too strong light and the rapid shear between the two will have a serious impact on its imaging. According to the different lenses and arrangements, cameras can be roughly categorized into four types, monocular cameras, binocular cameras, trinocular cameras and ring-view cameras. Monocular cameras are mainly used for scene judgment, while binocular or even multinocular cameras use two cameras to capture objects at close range, with information such as object pixel offset, camera focal length, and the actual distance between the two cameras, based on which the distance to the object can be converted.

Common technical architectures in the field of decision planning can be categorised as hierarchical, reactive and hybrid hierarchical architectures. Hierarchical stepwise can be understood as a series structure, each module is arranged in a straight line, the content of the previous module will be directly into the next stage, the advantage of hierarchical stepwise is that the order of the modules is clear, the hierarchical structure allows each module to deal with the scope of the work is gradually narrowed down, the accuracy of the processing problem is gradually increased, it is easier to realise the high level of intelligent control.

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3.2. Control Algorithm

Currently, there are three main types of behavioral decision-making algorithms in common use, as shown in Table 2.

Table 2. Main Types of Behavioral Decision-Making Algorithms

Neural network-based	Neural networks are mainly used to determine specific scenarios and make appropriate behavioral decisions
Rule-based	Engineers come up with all possible combinations of “if-then rules”, and then program the decision-making system using a rule-based technology route
Hybrid route	Combines the above two decision-making approaches, optimized by a centralized neural network and refined by “if-then rules”. The hybrid approach is the most popular technical approach.

In the chip field, there are two main types of mainstream chips in common use. The first is the Mobileye® EyeQX™ series of in-vehicle computing platforms, developed by Intel-Mobileye. The second is the NVIDIA Drive PX series of in-vehicle computing platforms, developed by NVIDIA. Mobileye was founded in 1999 with the aim of developing and promoting visual assistance systems for the transport sector. For example, Mobileye’s latest chip, EyeQ5, delivers 12 Tera per second of computing performance and supports up to 20 external sensors (camera, radar or lidar). Furthermore, the EyeQ5 incorporates heterogeneous, fully programmable accelerators, with the four integrated types of accelerators all exhibiting algorithmic optimization, facilitating the attainment of “sensor fusion.” Traditional control methods mainly include Proportional-integral-derivative (PID) control, fuzzy control, optimal control, and sliding mode control (predictive model control MPC). PID control algorithms are widely used in robot control tasks because of their simplicity and robustness [7]. However, in practical applications, it usually requires tedious parameter tuning and accurate system modelling to ensure the control effect. Common parameter tuning methods include the critical ratio method and the decay curve method [8].

The biggest difference between intelligent control methods and traditional control methods is the heightened emphasis on the utilization of control object models and the integration of information learning. Common intelligent control methods include model-based control, neural network control, and deep learning methods, among which neural network control allows the control problem to be viewed as a pattern recognition problem, where the identified patterns are mapped to “behavioral” signals of “change” signals. It is achieved by constantly modifying the connection weights between neurons and storing them discretely in a network of connections, and is very effective for the control of nonlinear systems and systems that are difficult to model.

3.3. Trajectory Planning and Optimization

Trajectory planning is the process of determining the path of motion in an automated control system, where algorithms and techniques are used to plan the trajectory of a machine or vehicle to achieve a specific task or goal. The process involves the consideration of environmental constraints, dynamical conditions, and performance metrics to ensure that the system completes the task safely and efficiently during actual motion . Problems such as discontinuous robot acceleration, reduced motion accuracy, trajectory shifts caused by end jitter during pointing, or even damage to mechanical components due to impact.

The categorization of trajectory planning depends on the planning space utilized, which can be classified as either joint space trajectory planning or Cartesian space trajectory planning [9]. In the context of joint space trajectory planning, it is essential to utilise the inverse kinematics solution method when the given condition (trajectory planning position) is expressed in Cartesian space. This approach enables the conversion of the robot's endpoint path points in Cartesian space to the joint path points of each joint. Subsequently, a suitable function can be fitted for the corresponding joint path points, taking into account the motion requirements (velocity, acceleration, etc.) of each joint, which allows for the description of the motion of each joint from the starting point trajectory. The function describes the trajectory of each joint from the starting point through the path points and finally reaches the target point. The Cartesian space trajectory planning takes the endpoint trajectory of the robot as the planning goal, and the endpoint trajectory is obtained according to the demand planning, and then the endpoint trajectory is mapped to the joint space through the kinematic inverse solution to obtain the trajectory curve of each joint.

In the practical application of robots, not only the task requirements and motion effects, but also the energy consumption, work efficiency and smoothness of robots should be considered. Therefore, in order to obtain a trajectory that meets the above requirements, many scholars at home and abroad have carried out research on optimal trajectory planning from the aspects of time optimisation, energy optimisation and smoothness optimisation. Elias et al. planned the robot motion trajectory through a cubic B-spline curve, and optimized the time by taking into account the kinematic constraints (velocity and acceleration) of the robot [10]. Ding Yang et al used five times non-uniform B-spline curves to construct the motion trajectories of each joint of the robot and then utilized a Quantum-behaved Particle Swarm Optimization (QPSO) algorithm to identify the optimal trajectory, achieving a shorter time than that obtained by the Differential Evolutionary Algorithm (DEA) and the Standard Particle Swarm Algorithm (SPA) [11].

4. Future Developments

4.1. Personalized Service Capabilities and Security and Privacy Protection Mechanisms

The home robot will accurately recognize and understand the user's personal preferences, schedule, and living habits through voice interaction, face recognition, and other technologies to provide tailored service suggestions and life planning. With its ability to learn and remember users' behavioral patterns, it can optimize and improve personalized services over time to maximize user satisfaction. In addition, it can provide personalized care, assistance and interactive services, such as reminding users to take medication regularly and arranging rehabilitation training, based on the user's age, health status, physical condition and other characteristics. Advanced technologies such as biometrics and encryption algorithms are employed to ensure the security of robot identity verification and data transmission, preventing information leakage and system intrusion. With perfect privacy information management function, users can independently control the access rights of the robot to the family' private data. Intelligent fault diagnosis and remote maintenance functions, can be timely found and repair system failures, to ensure 24-hour stable and reliable operation.

4.2. Multi-Functional Composite Design

In the future, the robot can perform a multitude of tasks simultaneously, including household cleaning, entertainment accompaniment, health monitoring, and education counseling, which markedly enhance the efficiency of life [12]. The incorporation of modular mechanical structure and intelligent control system enables the rapid switching of functional modules in accordance with the specific requirements of the task at hand. Furthermore, the robot can be furnished with voice interaction, gesture control, touch screen display and other sophisticated human-computer interaction methods, accommodating the diverse usage preferences of users across age groups. Through wireless network connection, it can interconnect and control with intelligent devices at home, including lighting, air conditioning, and security systems, which can sense and analyze the home environment data in real time, intelligently plan the working status and operation mode of each device, and realize home energy management and life optimization. In addition, it provides users with one-stop home management, life services and remote control, which greatly improves the intelligent level of family life [13].

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5. Conclusion

In this paper, through extensive analysis of existing technological achievements, three core elements of an intelligent home robot control system have been refined, i.e., precise motion control algorithms, multi-sensor fusion technology, and intelligent decision control models. The study concluded that future home robots will evolve from single-function devices to multi-function devices, from passive services to active learning and optimization, and from isolated operation to deep integration with home systems. Additionally, it suggests that these robots will continue to enhance their security and privacy protection capabilities. However, there are some limitations to this study, particularly with regard to the core functions of the robot, such as decision-making ability and human-robot interaction, which require further investigation. Future research will focus on the following directions to continuously optimize and innovate: first, to further improve the autonomous decision-making ability of the robot; second, to strengthen the research of human-machine interaction technology; and third, to explore the control system of cloud and network. It is postulated that through unceasing technological innovation, the family intelligent robot will become an indispensable and significant support for the smart home, providing unprecedented convenience and comfort to the majority of users.

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