Research on the Development of Key Technologies for the Mechanical Arm

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Abstract: The technologies employed in robotic arms also need to be constantly updated and iterated to serve humanity better. Mechanical arm technology is one of the key research topics today, and researchers are optimizing the technology for different types of mechanical arms. This article mainly conducts in-depth research and discussion on four key technologies of industrial robotic arms: precise grasping optimization, flexible vibration suppression, intelligent obstacle avoidance control, and visual recognition and positioning. The research results show that the designers have successfully reduced the vibration amplitude of the robotic arm, improved the grasping accuracy, and shortened the obstacle avoidance response time through innovative methods such as approximate inertial manifold reduction, finite element structure optimization, joint space potential field algorithm, and multi-modal sensor fusion. Future researchers can further expand the three-dimensional visual recognition capabilities and develop adaptive control algorithms to achieve goals such as multiple robotic arms working collaboratively. This series of research achievements not only promoted the technological innovation of industrial robotic arms but also provided important technical support for the upgrading of China's intelligent manufacturing industry.

1 INTRODUCTION

With the continuous advancement of the "Made in China 2025" strategy, industrial robotic arms, as the core equipment of intelligent manufacturing, have witnessed an explosive growth in market demand. In this context, the intelligent upgrade of the robotic arm has become a current research hotspot. Among them, the four key technologies of flexible control, precise grasping, intelligent obstacle avoidance, and visual recognition are particularly crucial. Currently, traditional robotic arms have insufficient capabilities in adapting to dynamic environments, the vibration of flexible robotic arms leads to a decrease in positioning accuracy, the cumbersome grasping mechanism affects the operational efficiency, and the two-dimensional visual recognition of robotic arms limits the application scenarios. These shortcomings in technology have restricted the development process of intelligent manufacturing in our country. This article mainly summarizes and analyzes the solutions to current problems and the discussions on future challenges and development for four different types of robotic arms. The research results not only provide technical support for intelligent manufacturing. Still, it can also be applied in special scenarios such as medical assistance and space operations and has significant engineering application value and socioeconomic benefits.

2 INDUSTRIAL GRASPING ROBOTIC ARM

Nanjing Agricultural University has carried out technical optimization in the field of industrial robotic arm (Zhu, 2025) grasping. They established a three-dimensional model of robotic arm using SolidWorks and conducted static analysis and multi-objective design optimization for the robotic arm using ANSYS Workbench. The researchers conducted simulation experiments focusing on the stress and strain characteristics of the mechanical claws and the end effectors under different loads, using the data to

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illustrate the durability and reliability of this design structure (Zhu, 2025). The team also combined the TRIZ contradiction matrix to optimize the size and material of the mechanical claw, etc. They used modeling software to construct the axisymmetric linkage mechanism model of the robotic arm, and through symmetrical design, improved the stability and coordination of the movement. For the mechanical claw section, the researchers conducted static analysis to examine the force conditions. They simulated the stress and strain distribution of the mechanical components under different loads, identified the weak links, and reduced the probability of accidents occurring during the operation process. During the overall design phase, the team employed a multi-objective optimization approach, based on the TRIZ conflict matrix to balance the supporting forces and create new conflicts, and optimized the size and material of the mechanical claw, thereby reducing production costs. For the network division stage, the designer utilized the adaptive function to generate a network consisting of 21,048 elements and 99,603 nodes in ANSYS, aiming to balance the calculation accuracy and efficiency (Gao, Zhu and Tang et al, 2019). The optimized design of industrial grasping robotic arms effectively addresses several shortcomings of traditional robotic arms. Through static stress analysis, the structural reliability of the mechanical claws under different load conditions has been verified, ensuring that the maximum stress is always below the material yield strength and maintaining a reasonable safety margin. The designer adopted a design with holes for weight reduction and a split structure scheme. By reducing the self-weight, this design utilized the symmetrical linkage mechanism to maintain the stability of the grasping process, thereby resolving the contradiction between weight and structural strength. In terms of cost control, by selecting cost-effective materials and applying stress distribution optimization techniques, both performance requirements were met, and material consumption was significantly reduced. The entire design process fully utilized digital tools such as CAD for virtual simulation, significantly shortening the iteration cycle of traditional physical prototypes and achieving simultaneous improvement in design efficiency and product quality. When this robotic arm is applied to actual production, it can stably grasp heavy objects and replace manual labor to complete repetitive tasks, thereby avoiding unnecessary loss of manpower. The robotic arm can be remotely controlled by code programs and can work in high-risk environments, thereby reducing personnel safety risks (Arents and Greitans, 2022). Operators can adjust the grasping angle through the parametric model, which enables them to handle workpieces of different sizes and improves efficiency.

The development of future industrial grasping robotic arms still faces numerous challenges and opportunities. In terms of hardware, it is necessary to further enhance the adaptive capability of the end effector and develop flexible grippers with variable stiffness to be able to grasp workpieces of different shapes and materials. Meanwhile, how to reduce the weight of the robotic arm while ensuring its structural strength requires more in-depth material research. Furthermore, issues such as the safety of human-machine collaboration, the reliability of long-term use, and cost control all require continuous research. With the development of Industry 4.0, grasping mechanical arms needs to be better integrated into the intelligent manufacturing system and achieve seamless connection with technologies such as AGV and digital twins. The resolution of these challenges will drive the development of industrial grasping robotic arms towards greater intelligence, greater flexibility, and greater reliability.

3 RIGID-FLEXIBLE ROBOTIC ARM

The team from Central South University studied a model reduction method for flexible-rigid mechanical arms based on the Approximate Inertial Manifold (AIM) approach (Piras, Cleghorn and Mills, 2005) and proposed a feedforward control strategy based on Particle Swarm Optimization (PSO). The researchers conducted theoretical modeling, simulation analysis, and experimental verification, integrating rigid and flexible arm mechanical systems, and adjusting the coupling effect of rigidity and flexibility as well as the nonlinear distributed parameter system, to achieve efficient reduction of the model order for the robotic arm and effective suppression of the residual vibration at the end. The researchers employed an approximate inertial filtering technique to project the infinite-dimensional (Xu, Deng and Lin et al, 2022) flexible-rigid mechanical arm vibration equation into a finite-dimensional space composed of the eigenorthogonal decomposition (POD) modes. They utilized the Galerkin method to simplify the system (Shi, Yang and Wang, 2023), retaining the interactions between high-order and low-order modes, thereby constructing a reduced model. At the same time, the particle swarm optimization algorithm is employed to adjust the signal parameters, approximating the input signal as a combination of a finite number of sine functions. The amplitude is then adjusted through PSO to minimize the target position error and end-point vibration. Regarding the sensors and feedback loops, the designers did not add any additional equipment. Instead, they directly suppressed the vibrations by optimizing the input signals, thus simplifying the control structure. Finally, the researchers set up a hardware experimental platform and used resistance strain gauges and half-bridge circuits to measure the deformation. This verified the effectiveness of the reduced-order model and control strategy. The dynamic model of the flexible-rigid mechanical arm is a nonlinear and strongly coupled infinite-dimensional system, and traditional methods are difficult to solve directly for it. By using the AIM method, the model is explained as a finite-dimensional one, significantly reducing the computational complexity. The feedforward control strategy proposed during the design process effectively suppressed the vibration by optimizing the input signal, while avoiding the complexity of sensors and feedback loops in traditional closed-loop control (Yavuz, Mıstıkoğlu, and Kapucu, 2012). These advantages solved the problem of residual vibration generated by the flexible robotic arm during movement, which affected the positioning accuracy. The traditional Galerkin method may lose important characteristics during modal truncation, while the AIM method, by retaining the interactions between high and low order modes, reduces the dimensionality while maintaining the model accuracy. By effectively suppressing the end-point vibrations, the positioning accuracy of the robotic arm has been significantly improved, enabling it to handle high-precision tasks such as medical surgeries and precision manufacturing. Because the feedforward control strategy has been innovated, there is no need to rely on additional sensors. This not only reduces the hardware cost but also simplifies the overall system architecture. Finally, the researchers adopted a combined rigid-flexible design for the robotic arm, which combines the adaptability of traditional flexible robotic arms with greater load-bearing capacity. This design enables it to perform better in special scenarios such as space exploration and operations in dangerous environments. Meanwhile, the optimized flexible structure effectively reduces the motion inertia and energy consumption of the robotic arm, aligning with the current trend of green manufacturing. It achieves the dual goals of performance improvement and energy conservation, and environmental protection.

In the future, this research can be further expanded to cover multiple fields. It can integrate thermal and electrical effects from multiple physical fields to explore the dynamic characteristics of flexible and rigid robotic arms in more complex environments. Researchers can also incorporate deep learning or reinforcement learning to enhance the real-time performance and adaptability of the control strategies, integrate flexible-rigid mechanical arms into the intelligent manufacturing system, and achieve more flexible automated production. This research provides new ideas for the modeling and control of flexible-rigid mechanical arms. It demonstrates the theoretical value and practical significance of the spacing concept. In the future, it is expected to be widely applied in multiple fields.

4 REAL-TIME OBSTACLE AVOIDANCE MECHANICAL ARM

Huazhong University of Science and Technology mainly studied a real-time obstacle avoidance motion planning algorithm for industrial robotic arms based on the improved artificial potential field method (APF) in joint space (Chen, Chen and Ding et al,2023). The research subject is a six-degree-of-freedom robotic arm (such as the ROCRE robotic arm), and its main objective is to address the shortcomings of traditional APF methods in terms of real-time performance, local minimum value issues, and handling of singular configurations. The research team verified the effectiveness of the algorithm through theoretical modeling, simulation comparison (using Matlab/Simscape), and physical experiments (Zhang, Wang and Wu,2023). The team adopted the joint space artificial potential field method, directly calculating the attractive and repulsive forces in the joint space, avoiding the need for the inversion of the Jacobian matrix required by the traditional Cartesian space APF, and significantly improving the real-time performance (Chen, Chen and Ding et al,2023). The researchers adjusted the dynamic learning rate and, through relevant formulas, dynamically adjusted the step size of gradient descent to balance the obstacle avoidance accuracy and speed. This robotic arm employs a virtual obstacle mechanism. When the robotic arm gets stuck at a local minimum, virtual obstacles are automatically generated, enabling it to break free from the stagnant state without the need for external input. The researchers also employed the sphere envelope method to simplify the distance calculation. They used a sphere to envelop the complex obstacles, converting the shortest distance from the joint to the obstacle into the distance between the center of the sphere and the radius, thereby reducing the computational complexity. Because the traditional APF requires frequent calculation of the potential field function or the inverse of the Jacobian matrix, which is cumbersome, an improved algorithm is adopted. In each cycle, only the potential field needs to be calculated once, and the time consumption is extremely short. Compared with the Cartesian space APF, it is much faster. The robotic arm, through the virtual obstacle mechanism, can autonomously break free from the stagnant state without human intervention, thus solving the problem of local minimum traps. Regarding the problem of singular configuration failure, the direct calculation in joint space avoids the situation where the Jacobian matrix becomes non-invertible during the Cartesian space mapping. When the obstacles are complex and diverse, the ball envelope method simplifies the irregular obstacles into a combination of spheres, which is compatible with the common obstacle types such as conveyor belts and shelves found in factories. The improved robotic arm can quickly plan paths in dynamic environments and meet the high-speed production demands of the 3C industry. Furthermore, in terms of hardware costs and safety performance, this robotic arm can avoid obstacles solely by relying on the encoder of the base joint, which reduces the budget and improves the variation of joint angles in the APF by 62% compared to the genetic algorithm. The movement is more stable and reduces mechanical wear and accidental collisions (Chen, Huang and Sun et al, 2022).

The development of future obstacle-avoiding robotic arms faces several key challenges. Firstly, there is the issue of real-time performance in dynamic obstacle avoidance. The existing algorithms still have computational delays in complex and changing environments, and it is necessary to optimize the path planning algorithm to enhance the response speed. Secondly, the obstacle avoidance strategy in multi-obstacle scenarios needs to be improved. Particularly, the success rate of obstacle avoidance in narrow spaces needs to be enhanced. In terms of the perception system, how to reduce the cost of 3D vision sensors and lidar while maintaining measurement accuracy is an important issue. Furthermore, the multi-sensor data fusion technology still needs to be further developed to enhance the accuracy of obstacle recognition. In terms of control algorithms, although AI methods such as deep reinforcement learning have shown potential, the stability and generalization ability of these algorithms still need to be verified. Meanwhile, the energy optimization of the robotic arm during the obstacle avoidance process is also a key research direction in the future. With the development of 5G and edge computing technologies, cloud-based collaborative obstacle avoidance systems will become the trend, which places higher demands on communication latency and algorithm deployment. The resolution of these issues will facilitate the wider application of the obstacle-avoiding robotic arm in fields such as intelligent manufacturing and warehouse logistics.

5 OBJECT RECOGNITION MECHANICAL ARM

The Chinese company Yachen Planning and Designing Co., Ltd. mainly studied a mechanical arm system based on image recognition and remote control (Li, 2023). The research adopts a modular design to divide the system into the remote control end and the robotic arm end. It uses a camera to capture the image of the target object, and transmits it via WiFi to the remote control end for image processing. After calculating the target coordinates, it generates control instructions to drive the three-degree-of-freedom robotic arm to complete the grasping task (Li ,2023). The system also integrates ultrasonic distance measurement and temperature sensors to ensure operational safety and environmental adaptability. This research employed a series of key technologies to achieve target recognition and automatic control: Firstly, using MATLAB image processing algorithms, the camera image was subjected to color segmentation and binarization processing, enabling precise identification of the target's center position; Then, an ESP8266 wireless module is utilized to establish a WiFi connection (Zinkevich, 2021), enabling remote control and data transmission between devices like how a mobile phone connects to a router. The entire system is coordinated and controlled by the Arduino motherboard as the "brain". It can not only drive the stepper motor to rotate, but also read the data from the temperature sensor and ultrasonic distance measurement device in real time. A mechanical arm movement calculation formula has been specially designed, which can convert the screen coordinates into the motor rotation angle. Finally, a computer control interface was made using LabVIEW software, allowing for intuitive data viewing and command sending. This research effectively addressed several key challenges in the practical application of industrial robotic arms: By using WiFi wireless transmission and an efficient MATLAB image processing algorithm, the delay of control instructions was reduced to the millisecond level, which was faster than the common Bluetooth response. It is also equipped with an ultrasonic distance measurement sensor and a temperature monitoring module, enabling the robotic arm to perceive changes in the surrounding environment just like a human, ensuring stable operation even in complex conditions. It replaces the cumbersome manual debugging steps required by traditional methods with its automatic target location recognition function, significantly reducing the operational difficulty. The entire system is built using affordable Arduino development boards and ESP8266 communication modules. Coupled with a flexible modular design, the overall cost is only a fraction of that of commercial industrial robotic arms. This makes high-performance automation technology more accessible and practical. These innovations have enabled the robotic arm to not only be quick in response and adaptable, but also easy to operate and cost-effective, providing a new option for small and medium-sized enterprises to achieve intelligent production. The practical benefits brought by this research are obvious: In the factory, this system can precisely perform repetitive tasks such as circuit board grasping and goods sorting, When working in a high-temperature workshop or a hazardous environment with radiation, the operator controls the robotic arm and remotely operates it to perform tasks from a safe location via WIFI. This research combines image recognition and wireless control technologies to provide cost-effective automated solutions for small and medium-sized industries. Its core advantage lies in the open-source nature of the hardware and the lightweight nature of the algorithms (Bowman, 2023). In the future, through the integration of three-dimensional perception and intelligent algorithms.

This research has provided a cost-effective automated solution for small and medium-sized industrial scenarios through an innovative combination of "image recognition and wireless control”. Its core advantage lies in the open-source nature of the hardware and the lightweight nature of the algorithm. In the future, through the integration of 3D perception and intelligent algorithms, it is expected to further expand its application scenarios.

6 CONCLUSIONS

This study analyzed and discussed four types of robotic arms. Firstly, based on the reduced-order modeling method of approximate inertia manifold (AIM), the ten-order nonlinear system of the flexible robotic arm was successfully simplified to a three-dimensional model. While maintaining a certain level of accuracy, the computational efficiency was significantly improved, providing a theoretical basis for real-time control. Secondly, the improved joint space artificial potential field (APF) algorithm, through the sphere envelope method and the virtual obstacle mechanism, reduces the obstacle avoidance planning time to 0.35 seconds, thereby solving the failure problem of traditional algorithms in singular configurations. Thirdly, the lightweight grasping mechanism design has been verified through finite element analysis. Under different load conditions, stress and strain can be monitored promptly, thereby enhancing the safety factor. Finally, the image recognition system based on color threshold segmentation achieved a positioning accuracy of ±1.5mm. Combined with a WiFi remote control, a complete perception-decision-execution closed loop is built. These technological innovations have had a significant impact on the field of industrial automation. The AIM reduction method and the joint space APF algorithm provide new ideas for the modeling and control of complex electromechanical systems, especially the design paradigm of multi-sensor fusion architecture, which offers a reference for the research on the environmental adaptability of intelligent equipment. Future research can extend to the study of the ability of perception when it is confronted with different dimensions. Multiple sensors or depth cameras can be utilized to overcome the limitations of a single level. In addition, researchers can add multiple linked working modules to the robotic arm, enabling interconnection between the robotic arms. Through the Internet, they can control to achieve the goal of collaborative operations, etc. These future features may drive industrial robotic arms towards a more intelligent, more flexible, and more efficient direction.

REFERENCES

Arents, J., & Greitans, M. (2022). Smart industrial robot control trends, challenges and opportunities within manufacturing. Applied Sciences, 12(2), 937.

Bowman, R. W. (2023). Improving instrument reproducibility with open source hardware. Nature Reviews Methods Primers, 3(1), 27.

Chen, X., Huang, Z., Sun, Y., Zhong, Y., Gu, R., & Bai, L. (2022). Online on-Road Motion Planning Based on Hybrid Potential Field Model for Car-Like Robot. Journal of Intelligent & Robotic Systems, 105(1), 7.

Chen, Y., Chen, L., Ding, J., & Liu, Y. (2023). Research on real-time obstacle avoidance motion planning of industrial robotic arm based on artificial potential field method in joint space. Applied Sciences, 13(12), 6973.

Gao, Y., Li, C., Zhu, Y., Tang, J., He, T., & Wang, F. (2019). Deep adaptive fusion network for high performance RGBT tracking. In Proceedings of the IEEE/CVF International Conference on Computer Vision Workshops (pp. 0–0).

Li, K. (2023). A mechanical arm based on image recognition and remote control. Journal of Physics: Conference Series, 2649(1), 012031.

Piras, G., Cleghorn, W. L., & Mills, J. K. (2005). Dynamic finite-element analysis of a planar high-speed, high-precision parallel manipulator with flexible links. Mechanism and Machine Theory, 40(7), 849–862.

Shi, B., Yang, J., & Wang, J. (2023). Forced vibration analysis of multi-degree-of-freedom nonlinear systems with the extended Galerkin method. Mechanics of Advanced Materials and Structures, 30(4), 794–802.

Xu, L., Deng, H., Lin, C., & Zhang, Y. (2021). Approximate Inertial Manifold - Based Model Reduction and Vibration Suppression for Rigid - Flexible Mechanical Arms. Complexity, 2021(1), 8290978.

Yavuz, H., Mıstıkoğlu, S., & Kapucu, S. (2012). Hybrid input shaping to suppress residual vibration of flexible systems. Journal of Vibration and Control, 18(1), 132–140.

Zhang, W., Wang, N., & Wu, W. (2023). A hybrid path planning algorithm considering AUV dynamic constraints based on improved A* algorithm and APF algorithm. Ocean Engineering, 285, 115333.

Zhu, Z. (2025). Design and Analysis of an Industrial Grasping Robot Arm. Advances in Engineering Technology Research, 13(1), 1012–1012.

Zinkevich, A. V. (2021). ESP8266 Microcontroller Application in Wireless Synchronization Tasks. 2021 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM) (pp. 670–674). IEEE.