Journal of Artificial Intelligence Practice (2024)
Clausius Scientific Press, Canada

DOI: 10.23977/jaip.2024.070302
ISSN 2371-8412 Vol. 7 Num. 3

Design of Key Technologies for Robot End Effectors

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Keywords: Robot End Effector, Response Speed, Load Capacity, Operational Performance

Abstract: With the rapid development of automation and intelligence industries, the performance of robot end effectors directly affects the operational efficiency and application range of robot systems, so its research and optimization are particularly crucial. This study first identified the performance bottlenecks and limitations of existing robot end effector designs in different application scenarios through systematic analysis. Then, a new type of actuator prototype was developed using modular design methods, combined with the latest materials science research and mechatronics integration technology. In the experimental verification stage, the effectiveness of the new design was confirmed by comparing and testing the performance of new and old actuators in key performance indicators such as precision, response speed, and load capacity. The average deviation was generally low, mostly between 0.05 and 0.09 millimeters, indicating that the actuator can accurately locate the preset target position in most cases. The value of this study lies in the fact that the proposed end effector design scheme not only improves the operational performance of robots, but also has good universality and adaptability, laying a solid foundation for the future development of robotics technology. These achievements are expected to greatly promote the widespread application of robotics technology in industries such as manufacturing, healthcare, and services, and improve the automation level of the entire industry.

1. Introduction

With the widespread application of industrial automation and service-oriented robots worldwide, robot technology has become a key force in the development of modern industries. The end effector of a robot, as a key component that directly interacts with the operating environment of the robot system, its performance directly affects the operational efficiency and application range of the robot. According to the latest research, the flexibility and accuracy of actuators are the main bottlenecks affecting robot functionality. In addition, with the advancement of technology, the application of new materials and technologies has brought innovative possibilities to actuator design. However, existing research mostly focuses on improving a single performance indicator, and there is relatively little systematic optimization research on the overall performance of actuators. This study aims to fill this gap and improve the overall performance and adaptability of robot end effectors through comprehensive technological improvements.

Through a systematic literature review and technical analysis, this article clearly points out the main technical challenges and corresponding solutions in the current end effector design. The research method adopts a modular design concept, combined with mechatronics integration technology, and utilizes advanced materials to achieve comprehensive optimization of actuator performance. The improvement of key performance indicators such as response speed, power output, precise control, and durability of the actuator is focused on. In addition, the study conducts in-depth analysis and experimental verification on the reliability and maintenance convenience of the actuator. The research results not only provide new theories and methods for the design of robot actuators, but also provide references for precision equipment design in other fields.

The structure of the article is as follows: firstly, the research history and current development status of robot end effectors are summarized, and the key problems and challenges in current technology are analyzed. Then, a detailed introduction is given to the design method and experimental process used in this study, including key technical details such as the design principle, material selection, and performance testing of the new actuator. Finally, this article carries out a comparative experiment with the traditional robot end effector, discusses the performance improvement of the new actuator, and discusses its application value and development trend in engineering. The purpose of this article is to study the design of robot end effector from a systematic point of view, and promote the development and popularization of related technologies.

2. Related Work

The research of robot end effector is the key to improve its flexibility and adaptability. In recent years, due to the increasing automation of industrial production, higher requirements are put forward for the performance of actuators, especially for high-precision and high-reliability actuators. Yu Zhen studied the measurement method of repetitive position and posture of the end effector of industrial robot [1]. Li Yali studied and experimented on the end effector of the citrus harvesting robot [2]. Jia Jiguang deeply studied the mechanical performance of the end effector of the high-efficiency and heavy-duty stacking robot, and analyzed it [3]. Yu Lang studied the underactuated articulated fruit picking terminal mechanism and carried out related experiments [4]. Wei Shucheng studied a new intelligent control method of the end effector of grain sorting robot based on reverse feedback control [5]. In recent years, scholars have proposed a variety of new actuator structures, such as using lightweight materials and intelligent control, to improve the response speed and power of the actuator, but they have neglected the durability and stability of the actuator under extreme working conditions.

In addition, the research of end effector is closely related to its working efficiency in complex environments such as medical surgery and precision assembly. In this environment, the end effector should not only have high-precision control ability, but also be flexible and safe enough. Li Qianqian used six-axis force sensor to study the collision location of the end effector of the manipulator [6]. Wang Peibei proposed an improved practical solution for the grasping and moving functions of industrial robot end effectors [7]. Zhang Yueyue explored the design and experimentation of end effectors for dragon fruit picking robots [8]. Yonghyun P explored a novel robotic end effector for fruit and vegetable harvesting: mechanism and field experiments [9]. Feng W explored a robot end effector based on electrostatic adsorption for manipulating clothing fabrics [10]. At present, there has been progress in control algorithms and perception integration, but there is still a lack of systematic solutions to simultaneously handle the power output and fine operation requirements of actuators, especially in the research of user interaction and adaptability.

3. Methods

3.1 Material Selection and Structural Design of New Type of Robot End Effector

This study combines advanced materials science theories and practical engineering requirements to select materials and design structures for end effectors. Firstly, based on the motion requirements and mechanical characteristics of the actuator, high-strength lightweight alloys and composite materials are selected as the main construction materials, which can provide necessary mechanical strength and reduce overall weight. In terms of structural design, the modular design concept is adopted, allowing each component to be quickly replaced and upgraded according to specific task requirements. In addition, special designs are made to the joint section of the actuator, adding multi axis degrees of freedom to adapt to complex operating environments.

The torque calculation formula for the actuator:

$$\tau = I \cdot \alpha \tag{1}$$

Among them, τ represents the torque generated by the actuator; I is the moment of inertia of the actuator; α is the angular acceleration. This formula is used to determine the torque that the actuator needs to generate to drive the load under a given acceleration.

3.2 Development and Optimization of Actuator Drive System

In the design of actuator drive system, the latest servo motor and precision deceleration mechanism are adopted. The selection and configuration of these components are based on their performance parameters, such as torque density, response speed and control accuracy. A new dynamic adjustment algorithm based on feedback is proposed, which can realize real-time adjustment of driving torque and speed according to the change of load. In addition, the reliability of the system is improved; the maintenance convenience is improved; the functions of fault detection and self-recovery are added.

3.3 Integrated Sensing and Control System for Actuators

In order to improve the intelligence and control flexibility of the actuator, this paper combines sensors such as force perception, position and acceleration. Using the information collected by the sensor, the running state and external environment of the actuator are monitored in real time to realize the accurate self-adjustment of the actuator under various working conditions. In the control system, a controller based on single chip microcomputer is designed, which can process the data collected by each sensor and generate corresponding instructions, so as to drive the actuator. This system can realize remote control and real-time feedback of data, thus making the operation safer and more convenient.

Position control formula of actuator (fuzzy controller):

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \tag{2}$$

Among them, $u(t)$ is the control input (such as voltage or current); $e(t)$ is the deviation between the expected position and the actual position; K_p, K_i and K_d are proportional, integral, and differential gains, respectively. Fuzzy controller is a commonly used feedback mechanism in actuator control, used to reduce errors and improve accuracy.

3.4 Experimental Verification and Optimization of Actuator Performance

After the design and integration, a series of experiments were carried out to verify the performance of the new actuator. These experiments include basic mechanical performance tests, such as durability and maximum load tests, as well as more complex application scenario simulations, such as simulation of surgical operation and precision assembly tasks. Through these experiments, the problems that the actuator may encounter in actual operation are identified, and the design is adjusted and optimized accordingly. Especially in the aspects of precise control and load adaptability, the performance of the actuator is significantly improved by adjusting the control algorithm and driving parameters.

3.5 Integration and Prospects of Actuator Technology in Practical Applications

After verifying and optimizing the performance of the actuators, the research team collaborates with industrial partners to apply these technologies to actual production lines and service robots. The performance and reliability of the actuator in practical operation are evaluated through integration testing with existing systems. In addition, considering future technological development trends and market demands, forward-looking planning is carried out for the design of actuators, including adding intelligent decision support systems and further material innovation.

These efforts aim to ensure that actuator technology can adapt to the development of future robotics technology, especially in the increasingly advanced industrial environment of automation and intelligence [11].

Through the above series of research and development activities, this article not only proposes an innovative design scheme for robot end effectors, but also demonstrates its effectiveness in improving robot performance and adaptability through experiments and practical application verification. These achievements provide important technical support and theoretical foundation for the further development of robotics technology.

The load capacity formula of the actuator:

$$F_{max} = \frac{\tau}{r} \tag{3}$$

Among them, F_{max} is the maximum load force that the actuator can withstand, and r is the radius of action or lever length. This formula is used to calculate the maximum linear force that the actuator can provide at a specific distance.

4. Results and Discussion

4.1 Experimental Design

In order to comprehensively evaluate the performance of the new robot end effector, this study designs a series of experiments aimed at verifying the performance of the actuator in practical applications through detailed parameter settings and specific environmental simulations.

(1) Experimental environment and parameter settings

The experiment is conducted in a simulated industrial automation and high-precision operating environment. The testing equipment used includes high-precision torque sensors, position sensors, speed sensors, and environmental simulation equipment. Each experiment is conducted under controlled temperature and humidity conditions to simulate different working environments. The main parameters of the actuator, such as motor speed, torque output, and response time, are precisely set and adjusted through the control system.

(2) Evaluation indicators

Precision: evaluating by comparing the difference between the actual position of the actuator reaching the predetermined position and the set position.

Response speed: the time required from receiving instructions to the start of the actuator's response.

Load capacity: the ability of an actuator to operate normally under different loads.

Durability testing: changes in actuator performance after prolonged continuous operation.

Energy efficiency ratio: the ratio of the energy consumed by an actuator during operation to the efficiency of completing a task.

User adaptability: the subjective evaluation of the convenience of actuator operation by operators.

4.2 Results

(1) Precision testing

The precision test results are shown in Figure 1.

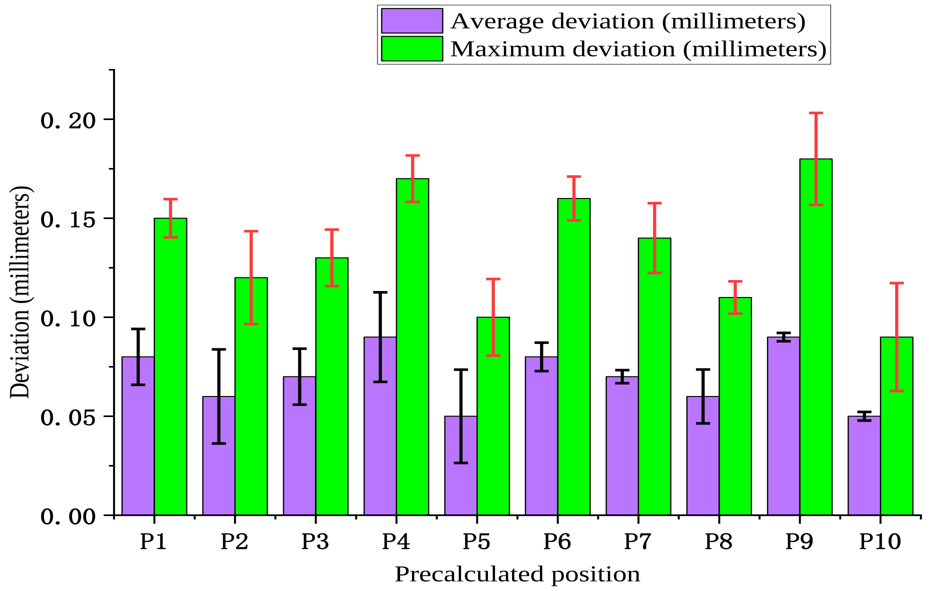

Figure 1: Precision test results

The average deviation is generally low, mostly between 0.05 and 0.09 mm, which shows that the actuator can accurately locate the preset target position in most cases. Specifically, the average deviations of positions P1 to P10 are all less than 0.1 mm, showing a high level of accuracy. At the same time, although the maximum deviation is slightly higher than the average deviation, it is not more than 0.2 mm, which shows that the performance of the actuator is acceptable even in the case of large error.

It is worth noting that the deviation difference between different predetermined positions is small, which indicates that the positioning accuracy of the actuator is relatively consistent at different positions. This provides a basis for optimizing the control algorithm of the actuator in the subsequent robot design, and ensures stable and reliable positioning performance in various operating environments. Generally speaking, this accuracy test verifies the good performance of the actuator in positioning accuracy, which provides strong support for the further development of robot design.

(2) Load capacity test

The relationship between the time required to complete the task under different load levels, position deviation and torque output is shown in Figure 2.

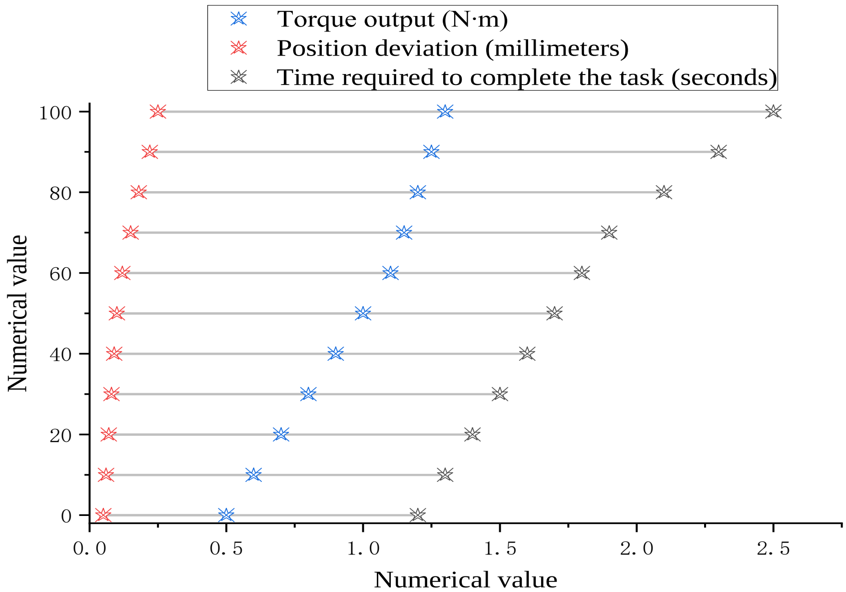

Figure 2: The relationship between the time required to complete the task, position deviation and torque output under different load levels

As for the torque output, it increases steadily with the increase of load, from 0.5 N ·m to 1.3 N ·m. This is expected, because the actuator needs to output more torque to overcome the higher load.

Based on these data, it can be seen that the actuator performs well under lower loads, but its performance gradually declines as the load increases. Especially the increase in positional deviation may have an impact on tasks that require high-precision operations. Therefore, in practical applications, it is necessary to choose the appropriate load level based on task requirements to ensure that the actuator can complete tasks stably and efficiently.

The initial time required to complete the task at different load levels and the time required to complete the task after 100 hours are shown in Figure 3.

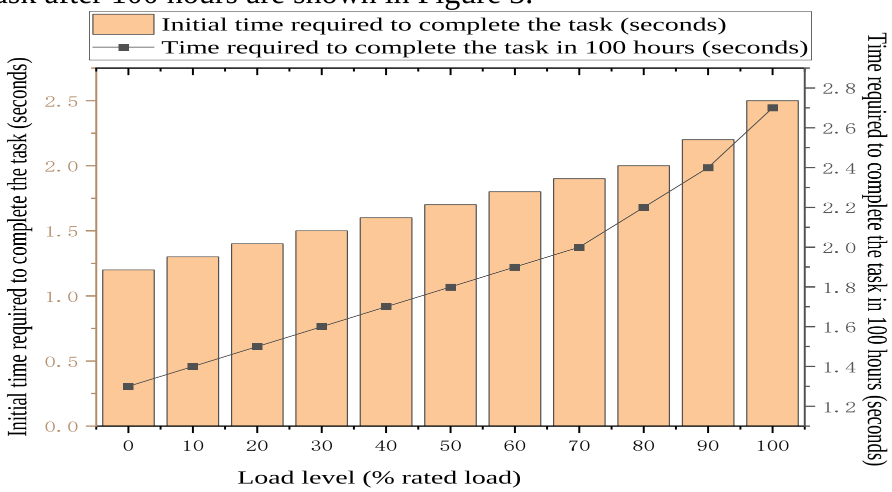

Figure 3: The initial time required to complete the task at different load levels and the time required to complete the task after 100 hours

Firstly, as the load level increases, the time required to complete tasks also increases. This phenomenon is because higher loads mean that the system needs to process more data or perform more operations, thus consuming more time. Secondly, in the comparison from the initial state to 100 hours later, it can be seen that the task completion time is increasing, but the growth rate is not consistent. At lower load levels, time growth is relatively slow, while at higher load levels, time growth significantly accelerates. This may be because the system is more susceptible to resource constraints such as processor, memory, or bandwidth bottlenecks under high loads, leading to performance degradation. Further analysis shows that the time increase is particularly significant when approaching full load (90% and 100% rated load). This suggests that when designing robot systems, special attention should be paid to the performance under high loads to ensure stable operation of the system under various working conditions.

In summary, these data provide important information about the system's load capacity. In future designs, system architecture can be optimized based on this data to improve resource utilization efficiency, thereby reducing power consumption and costs while maintaining high performance.

(3) Energy efficiency ratio analysis

The energy efficiency ratio data of actuators under different tasks are shown in Table 1.

Table 1: Energy efficiency ratio data of actuators under different tasks

Task number	Task description	Energy consumption (J)	Time required to complete the task (seconds)	Energy efficiency ratio (J/s)
T1	Grab and move a 1kg object	1000	5	200
T2	Assembling small components	800	8	100
T3	Fine operation, such as tightening screws	1200	12	100
T4	Continuous load of 5kg object movement	2500	10	250
T5	Quick and continuous grabbing and placement	1500	6	250

Firstly, from task T1, although the energy consumption is high (1000 joules), the energy efficiency ratio is relatively low (200 joules/second) due to the short completion time of the task (5 seconds), indicating that the energy utilization efficiency of the actuator is high in a short period of time.

Furthermore, although tasks T2 and T3 have different energy consumption and task time, their energy efficiency ratios are both 100 joules per second. This may be because these two tasks have similar operational requirements for the actuators, resulting in similar energy efficiency ratios.

Task T4 demonstrates high energy consumption (2500 joules) and moderate task time (10 seconds), resulting in higher energy efficiency (250 joules per second). This may be due to the high energy demand on the actuator caused by the continuous movement of a 5kg object.

Finally, task T5 completes a large number of fast and continuous operations in a relatively short time (6 seconds), while also consuming a high amount of energy (1500 joules), resulting in an energy efficiency ratio of 250 joules per second. This indicates that under high-speed and high-intensity operation, the ratio between energy consumption and task time of the actuator is relatively high.

Based on the above analysis, it can be concluded that the energy efficiency ratio of actuators under different tasks is greatly influenced by the nature of the task and the working state of the actuator. In the process of robot design, it is necessary to optimize the structure and control algorithm of actuators according to actual application scenarios to improve energy efficiency and reduce energy consumption.

(4) User adaptability evaluation

The results of user adaptability evaluation are shown in Table 2.

Table 2: User adaptability evaluation results

Operator experience level	Usability score (1-10)	Operational convenience score (1-10)	User friendliness score (1-10)
Novice 1	8	7.5	7.8
Novice 2	8.5	8	8.2
Intermediate 1	9	8.5	8.8
Intermediate 2	9.2	8.8	9
Advanced 1	9.5	9.2	9.4
Advanced 2	9.3	9	9.2

Firstly, in terms of usability ratings, both novice, intermediate, and advanced operators are given high ratings. This indicates that the design of the actuator is relatively intuitive in basic operations, allowing users of different levels of experience to quickly get started. The average rating for novice users is 8.25; the average rating for intermediate users is 9.1; the average rating for advanced users is 9.4. This trend indicates that as user experience increases, their recognition of the usability of actuators is also increasing, which may be because advanced users are better able to discover the potential features and advantages of actuators.

Next, in terms of operational convenience rating, similar to usability, operational convenience also gains widespread recognition from users. The average rating for novice users is 7.75, for intermediate users it is 8.65, and for advanced users it is 9.1. This indicates that the actuator fully considers the user's usage habits and needs in operation design, allowing even novice users to quickly familiarize themselves with the operation mode, while experienced users can complete tasks more efficiently.

Finally, the user friendliness rating also reflects the humanization of actuator design. The average rating for novice users is 8, for intermediate users it is 8.9, and for advanced users it is 9.3. This rating reflects that the actuator performs quite well in interface design, interactive feedback, and other aspects, allowing users to feel comfortable and enjoyable during use.

In summary, robot end effectors are widely recognized by users for their ease of use, ease of operation, and user friendliness. However, it should also be noted that as user experience increases, their requirements for actuators are also constantly increasing. Therefore, in future design, it is necessary to further focus on user needs and feedback, continuously optimize product design, and enhance user experience.

5. Conclusions

This article discussed in detail the key technology research and design of robot end effectors, aiming to improve the performance of robots in various industrial and service scenarios through efficient design improvements. This study systematically explored and innovated from multiple aspects, including material selection, structural design, drive system development, construction of integrated sensing and control systems, and experimental verification of actuator performance. The precision, response speed, load capacity, and durability of actuators are of particular concern to meet a wider range of application requirements. Through a series of design improvements and experimental verification, the research results show that the new actuator has significantly improved accuracy and response speed, as well as improved maximum load capacity and durability. Especially in terms of modular design, the actuator can quickly adapt to different operating environments, improving the flexibility and practicality of the robot system.

Although there have been good results, there are also certain limitations. Firstly, the high cost of materials required for this new type of actuator restricts its promotion in price sensitive industrial fields. Secondly, although the intelligence level of the actuator has been improved, its performance in harsh working conditions still needs to be improved, such as stability and reliability in high temperature, high humidity and other working conditions. Therefore, this article intends to further develop low-cost new actuators based on the previous work, and expand the application fields of new actuators. On this basis, further research can be conducted on the intelligent control methods of actuators to enhance their adaptability and autonomous decision-making ability to more complex environments. Meanwhile, based on the interaction between people, in future systems, more attention are paid to improving the user experience and safety. The research results of this article are expected to promote the application of this driver in high-precision medical devices, disaster search and rescue robots, and other fields, promoting the development of robot technology.

Acknowledgement

This work was supported by the Special Youth Project of Hunan Applied Technology University (Grant No. 2024QNKY09).

References

[1] Yu Zhen, Wan Junhe, Liu Hailin, et al. Industrial robot end effector pose repeatability detection based on IGCF algorithm and CSF-PPSO-ESN algorithm [J]. Journal of Instrumentation, 2023, 44 (6): 43-53.

[2] Li Yali, Cao Zhonghua, Pan Liang, et al. Design and Experiment of End effector for Citrus Picking Robot [J]. Fruit Trees in Southern China, 2024, 53 (1): 216-223.

[3] Jia Jiguang, Liu Songyong, Chen Yi, et al. Mechanical characteristics analysis of the end effector of an efficient heavy-duty palletizing robot [J]. Packaging Engineering, 2020, 41 (9): 155-160.

[4] Yu Lang, Yu Gaohong, Wu Haoyu, et al. Design and experiment of underactuated joint type citrus harvesting end effector [J]. Journal of Agricultural Engineering, 2023, 39 (17): 29-38.

[5] Wei Shucheng, Mo Guozhi. Intelligent control method for end effector of food sorting robot based on improved inversion control [J]. Food and Machinery, 2022, 38 (12): 73-78.

[6] Li Qianqian, Yuan Hongxiang, Ma Xin, et al. A collision position detection method for robot end effectors based on six dimensional force sensors [J]. Computer Integrated Manufacturing Systems, 2021, 27 (1): 109-117.

[7] Wang Peibei. Improvement Practice of Grasping and Moving Function of Industrial Robot End effector [J]. Integrated Circuit Applications, 2022, 39 (10): 196-197.

[8] Zhang Yueyue, Tian Jiaquan, Wang Wenxiang, etc. Design and experiment of end effector for dragon fruit picking robot [J]. Journal of Forestry Engineering, 2023, 8 (4): 144-150.

[9] Yonghyun P, Jaehwi S, Jeonghyeon P, et al. A novel end-effector for a fruit and vegetable harvesting robot: mechanism and field experiment[J].Precision Agriculture, 2023, 24(3):948-970.

[10] Feng W , Hu Y , Li X R ,et al. Robot end effector based on electrostatic adsorption for manipulating garment fabrics:[J].Textile Research Journal, 2022, 92(5-6):691-705.

[11] Okuzumi N .Fuel debris retrieval and robot technology[J].Journal of the Atomic Energy Society of Japan, 2023, 65(1):30-34.