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Research on Application of Dual-arm Cooperative Robot in Oil Drilling Field

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Abstract:This paper reviews the application of dual-arm collaborative robots in the assembly and disassembly of derricks (drilling derricks). First, the basic concepts and technical background of dual-arm collaborative robots are introduced, and then its specific applications in the assembly and disassembly of derricks and the challenges it faces are discussed. Finally, the progress of current research is summarized and future development directions are proposed.

Keywords:Dual-Arm Collaborative Robot, Derrick, Assembly And Disassembly, Disassembly, Industrial Automation

I. INTRODUCTION

With the rapid development of industrial automation, the application scope and depth of robotics in various fields are constantly expanding. Whether in manufacturing, healthcare, agriculture, or service industries, robotics is gradually changing the traditional way of working and improving efficiency and quality. In this context, dual-arm collaborative robots, as an advanced device that can simulate the coordinated movements of human hands, have shown unprecedented potential. This type of robot can not only perform complex operating tasks, but also achieve a high degree of interaction with the environment and objects through precise synchronization control and force feedback mechanisms.

In the oil drilling industry,Derrick(Drilling rig)DisassemblyDisassembly is a critical and challenging task.DerrickofDisassemblyThe installation and disassembly process involves a large number of heavy parts and high-precision operations, which requires workers to have rich experience and a high degree of coordination. However, the traditional manual operation method has obvious shortcomings in terms of efficiency and safety. Inefficiency will not only lead to longer operation time and increased costs, but may also have a negative impact on the overall drilling progress. In a high-risk working environment, the safety of workers is difficult to be fully guaranteed, and they are often faced with the threat of personal injury and accidents.

Based on this, this paper aims to explore the application of dual-arm collaborative robots inDerrick disassembly and assemblyThrough a review of existing technologies and analysis of specific application cases, this paper will demonstrate the significant advantages of dual-arm collaborative robots in improving operational efficiency, ensuring operational safety, and reducing labor costs. At the same time, this paper will also discuss the technical challenges and solutions that dual-arm collaborative robots may face in practical applications, providing a reference for future research and development. Through such discussions, we hope to provide new ideas and effective technical support for the automation process of the oil drilling industry.

II. BASIC CONCEPTS AND TECHNICAL BACKGROUND OF DUAL-ARM COLLABORATIVE ROBOTS

The dual-arm collaborative robot is an advanced robotic system designed to simulate the movements of human hands through the coordinated operation of two robotic arms to complete complex tasks. Compared with single-arm robots, dual-arm collaborative robots have significant advantages in flexibility and operational capabilities, and can demonstrate greater coordination and efficiency in industrial tasks such as assembly, handling, and welding.[1-4].

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Figure 1. Development of collaborative robot system

The core concept of dual-arm collaborative robots lies in collaborative control. Through complex control algorithms, this type of robot can achieve precise synchronization and coordinated movements between the two arms, enabling it to operate independently or collaboratively at the same time, thereby completing tasks that traditionally require the collaboration of human hands. Collaborative control usually involves a combination of position control, speed control, and force control to ensure the accuracy and stability of the operation.[5-7].

In terms of technical background, the dual-arm collaborative robot is composed of a variety of advanced hardware and software systems. The first is the robotic arm part. Each robotic arm usually has 6 to 7 degrees of freedom, which enables it to move and operate freely in three-dimensional space. This high degree of freedom design allows the robotic arm to imitate the movements of human arms and perform complex operating tasks. The second is the end effector, which is a tool installed at the end of the robotic arm for direct interaction with the operating object. There are various types of end effectors, including grippers,Ejectiontool,TightenTools, etc. can be selected and replaced according to different operation requirements. In addition, the dual-arm collaborative robot is equipped with an advanced sensor system, which is used to monitor the state of the environment and the operation object in real time, providing the necessary data support for precise control.[8]Force feedback control is one of the key technologies. Through the force feedback sensor, the robot can sense and adjust the force applied by the robotic arm in real time, thereby making dynamic adjustments.[13], ensuring the safety and precision of the operation. Force feedback control not only improves the reliability of the robot when handling complex tasks, but also greatly reduces the potential damage to the object being operated and the surrounding environment.

2.1 Current Development Status of Dual-Arm Collaborative Robots

As an advanced technology that can simulate the coordinated operation of human hands, dual-arm collaborative robots have been widely studied and applied in many fields in recent years. Its rapid development in industrial automation, medical health, service robots, etc. indicates that this technology is gradually maturing. In the field of industrial automation, dual-arm collaborative robots have begun to emerge in many high-precision and complex tasks. For example, in industries such as automobile manufacturing, electronic assembly and precision machining, dual-arm collaborative robots are used to perform tasks such as assembly, handling, welding and inspection. These robots can perform complex operations in a small space and improve production efficiency and product quality through collaborative work. Many industrial robot manufacturers, such as ABB, KUKA and Fanuc, have launched a number of dual-arm collaborative robot products, which have achieved good results in practical applications. In the field of medical health, dual-arm collaborative robots also show great potential. Surgical robots are one of the most representative applications. By precisely controlling dual-arm collaborative robots, surgeons can perform minimally invasive surgery, significantly reducing patient trauma and recovery time.[9]For example, the da Vinci surgical robot system has been widely used in various types of surgeries around the world. In addition, dual-arm collaborative robots are also used for rehabilitation therapy and nursing assistance.[10-11], providing patients with personalized rehabilitation training and daily care services. The technical progress of dual-arm collaborative robots is mainly reflected in the following aspects. First, the continuous development of intelligent control algorithms has made dual-arm collaborative robots more intelligent and efficient in task planning and execution. Control algorithms based on artificial intelligence and machine learning enable robots to make autonomous decisions and adjust operation strategies in complex and dynamic environments.[12]. Secondly, the advancement of sensor technology provides dual-arm collaborative robots with more accurate environmental perception capabilities. By integrating high-precision force sensors, visual sensors, and tactile sensors, the robot can perceive changes in the surrounding environment in real time, thereby performing more delicate and safe operations. In addition, the development of human-computer interaction technology has also made dual-arm collaborative robots easier to operate and manage. Through natural language processing, gesture recognition, and virtual reality technology, users can interact with robots more intuitively and efficiently, improving the convenience and safety of operation.

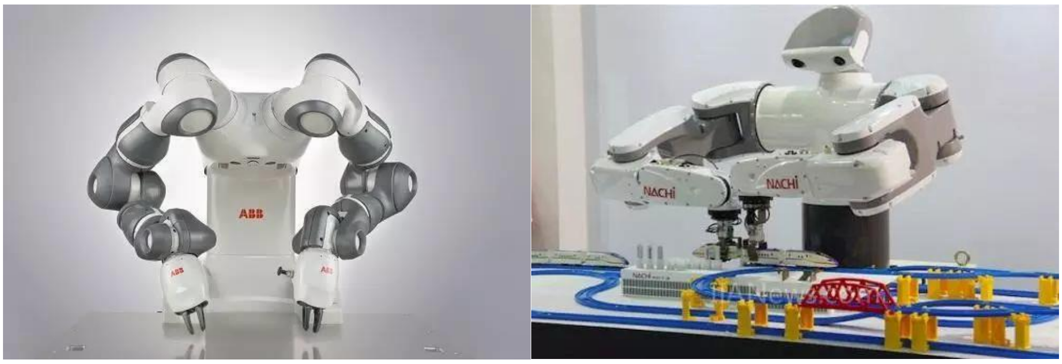


Figure 2. Top collaborative robots on the market

III.CHALLENGES IN DERRICK ASSEMBLY AND DISASSEMBLY

Derrick(Drilling rig)DisassemblyDisassembly and removal is a critical and complex task in oil drilling[14]As shown in Figure 3The complexity and high risk of manual work have brought many challenges to the operation. The traditional manual operation has obvious deficiencies in efficiency, safety and precision, so it is urgent to introduce automated solutions to improve the overall level of operation.Derrick disassembly and assemblyThe main challenges faced during the disassembly process.

Figure 3.1 Actual scene of derrick disassembly and assembly

3.1 Task Complexity

DerrickofDisassemblyThe robot arm is performing a large number of heavy parts and complex operation processes. These tasks require the precise execution of multiple steps, each of which requires a high degree of coordination and accuracy.DisassemblyWhen disassembling, it is necessary to handle large-sized, heavy-weight and various-shaped components, which places extremely high demands on the flexibility and control accuracy of the robot arm.DerrickofDisassemblyInstallation and disassembly usually need to be carried out at high altitude, which increases the difficulty and risk of the operation.

Figure 3.2 Examples of large-size components used at the derrick disassembly and assembly site

3.2 Environmental Complexity

The oil drilling site environment is usually very complex, including harsh climatic conditions and changeable working environment. These environmental factors pose challenges to the stability of equipment and the reliability of operation. The dual-arm collaborative robot needs to have strong environmental adaptability and be able to work normally under conditions such as extreme temperature, strong wind, high humidity and dust. At the same time, the drilling site has limited space and complex equipment layout, requiring the robot to be able to operate flexibly in a narrow space and avoid collisions with other equipment.

Figure 3.3 Work site in heavy rain

3.3 Security

The assembly and disassembly of derricks are high-risk operations, and workers are vulnerable to dangers such as heavy objects falling and equipment out of control. The safety of traditional manual operations is difficult to guarantee, and the introduction of automated equipment can reduce human operating errors, but it also faces the risk of equipment failure and accidents. The dual-arm collaborative robot needs to be equipped with advanced safety protection systems, such as force feedback control and collision detection functions, to ensure that the operation can be stopped in time under abnormal circumstances to protect the safety of equipment and personnel.

3.4 Force control requirements

During the assembly and disassembly of the derrick, force control is a key factor in ensuring successful operations and equipment safety. When robots are handling and installing heavy components, they must precisely control the force they apply to avoid damage or danger to the components. Force feedback control systems can achieve dynamic adaptation and precise control of complex tasks by monitoring and adjusting the force applied by the robot arm in real time. However, the development of high-precision, high-response speed force feedback control systems remains a technical challenge that requires continuous optimization and innovation.

3.5 Collaborative Operation

The assembly and disassembly of derricks often requires the coordinated operation of multiple devices and multiple workers to ensure that each step can be seamlessly connected. When performing tasks, the dual-arm collaborative robot not only needs to coordinate with other robots or equipment, but also needs to cooperate with manual operations. This places high demands on the communication and coordination capabilities of the robot system. Achieving efficient collaborative operations requires advanced task planning and scheduling algorithms, as well as reliable communication and control systems.

Figure 3.4 Collaborative work between ground personnel and crane

IV. Application verification of dual-arm collaborative robot in derrick assembly and disassembly

4.1 System Design

4.1.1 Hardware Structure

4.1.1.1 Robotic Arm

In a dual-arm collaborative robot system, the choice of the robot arm is key. The robot arm should have a high degree of freedom to enable flexible operation and adaptability to complex working environments.[15]Specifically, six-degree-of-freedom robotic arms are an ideal choice because they provide a wealth of kinematic freedom, allowing the robot to perform complex operations and posture adjustments. Six-degree-of-freedom robotic arms typically include three rotational joints and three translational joints, enabling them to achieve arbitrary posture movements in three-dimensional space. This flexibility is particularly important for well site operations that require operations in narrow spaces.

In addition, the structural design of the robot arm also needs to consider parameters such as its load capacity, accuracy and speed. The load capacity determines the weight of the object that the robot arm can carry, the accuracy affects the performance of the robot arm when performing delicate operations, and the speed is directly related to the work efficiency of the robot arm. When selecting a robot arm, these factors need to be considered comprehensively to ensure that it can meet the requirements of a specific task.

Figure 4.1 Actual picture of the designed six-degree-of-freedom robotic arm

4.1.2 Sensors

Sensors play a vital role in the dual-arm collaborative robot system. The main function of the sensor is to monitor the environment and task progress in real time and provide necessary data support for the control system. Common sensor types include position sensors, torque sensors, visual sensors, and tactile sensors.[16].

Position sensors are used to detect the angles and positions of the joints of the robot arm, thereby achieving precise motion control. Torque sensors can detect the force and torque applied to the end effector of the robot arm, helping the robot sense the weight and resistance of objects when performing grasping and handling operations. Visual sensors, such as cameras and depth sensors, can capture images and three-dimensional information of the environment to help robots identify and locate objects. Tactile sensors are used to sense the surface characteristics and contact force of objects, enhancing the robot's tactile feedback capabilities in fine operations. In order to improve the robustness and reliability of the system, a combination of multiple sensors is usually used to form a multimodal sensing system. In this way, the robot can obtain environmental information from multiple dimensions, make comprehensive judgments and decisions, and improve the accuracy and efficiency of task execution.

Figure 4.2 The robotic arm equipped with an arm-mounted visual sensor

4.1.3 End Effector

The end effector is the part of the dual-arm collaborative robot system that directly interacts with the task object, and its selection and configuration have a significant impact on the system performance. The end effector needs to have the ability to grasp, carry and perform fine operations, and needs to be configured accordingly according to the specific task objectives. In addition, the control system of the end effector also needs to have high precision and high response speed to ensure that it can accurately execute the predetermined operation trajectory. In some complex tasks, it may also be necessary to configure multiple end effectors to achieve multi-functional collaboration.Based on the derrick disassembly and assembly tasks, a total of 9 corresponding end actuators were designed for this experiment.

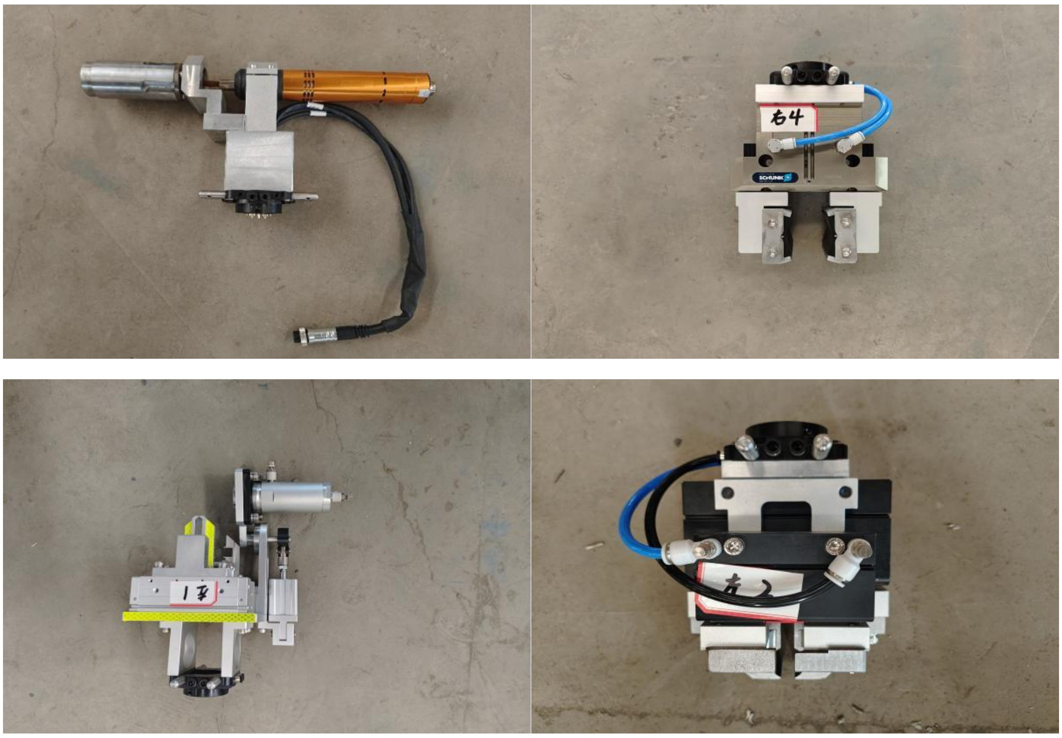


Figure 4.3 Examples of corresponding actuators designed for different functions

4.2 Control System

In the design of a dual-arm collaborative robot system, the realization of the control system is the key to ensure that the robot can perform tasks accurately, coordinated and safely. The control system includes two parts: synchronization control and force feedback control.

4.2.1 Synchronous control

Synchronous control ensures coordinated movements between the two arms to achieve synchronous operation of the target object or task. The system adopts a master-slave control strategy, in which one robotic arm serves as the master arm to perform the main operation task, and the other robotic arm serves as the slave arm to cooperate with the movements of the master arm. The motion trajectory of the master arm is generated by a preset path planning algorithm, and the slave arm is synchronously adjusted according to the real-time position and posture of the master arm. Path planning uses the A* algorithm or the RRT algorithm to generate the optimal path from the initial position to the target position for each robotic arm, avoiding collisions and minimizing energy consumption. Trajectory generation uses polynomial interpolation or spline interpolation methods to generate a smooth motion trajectory for each joint, ensuring smooth and continuous movement of the robotic arm. The system uses high-speed communication protocols such as EtherCAT or CAN bus to ensure real-time data transmission between the controller and the sensor[17]The status information (position, speed, acceleration) of each joint is fed back to the controller in real time through sensors. The controller dynamically adjusts the control parameters according to the feedback information to ensure the synchronization and coordination of the two arms.

Figure 4.4 Schematic diagram of the robot control software panel

4.2.2 Force feedback control

Force feedback control ensures the accuracy and safety of operation by real-time detection and feedback of force information. The system installs a six-dimensional force/torque sensor near the end effector of the robot arm to detect the force and torque applied during operation in real time. The force feedback system has collision detection and avoidance functions, monitors contact force in real time, and immediately stops or adjusts the movement of the robot arm when abnormal force is detected to avoid collision and damage.[18]At the same time, the system has a fault diagnosis function that can detect sensor or actuator failures and switch to safe mode or issue an alarm in time to ensure the safe operation of the system.

Through the above design, the dual-arm collaborative robot systemWellsiteIt can efficiently and accurately perform diverse tasks in complex environments to meet the needs of industrial automation and intelligent manufacturing.The final product is named S30 robot arm. Its DH parameters and 3D model are shown in the following chart.

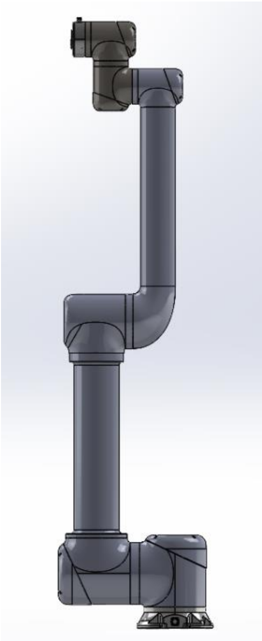


Figure 4.5 S30 robotic arm model

ClassicDHParanetersofTheS30				
#	θ	d	a	α
Joint1	0	0.1857	0	π/2
Joint2	0	0.264	-0.85	0°
Joint3	0	0.2065	-0.7915	0°
Joint4	0	0.1585	0	π/2
Joint5	0	0.1585	0	-π/2
Joint6	0	0.1345	0	0°

Table 4.1S30 robot arm DH parameters

4.2 Mission Planning

We divide the derrick disassembly and assembly tasks into four main tasks and four secondary tasks to better plan and execute the entire process. The four main tasks are the ejection and pressing of the pin, the disassembly and assembly of the shackle, the removal and hanging of the wire rope sleeve, and the rapid replacement of the end actuator. Each main task involves specific operating steps and action sequences to ensure the efficient and safe completion of the task.

First of all, the ejection and pressing of the pin is a key step in the entire disassembly and assembly process. The robot arm needs to accurately align the position of the pin and then apply appropriate force to eject or press it in. This process requires the robot arm to have high-precision positioning capabilities and sufficient strength, and also needs to cooperate with sensors for real-time monitoring to prevent damage to the pin or derrick structure.

Figure 4.6 Working position of pins at the derrick disassembly and assembly site

Secondly, the assembly and disassembly of the shackle is also an important task. The shackle connects various important parts and requires reliable assembly and disassembly operations. The robot arm must be able to operate the shackle flexibly and maintain stability during the assembly and disassembly process to prevent the shackle and its connected parts from accidentally falling off or being damaged.

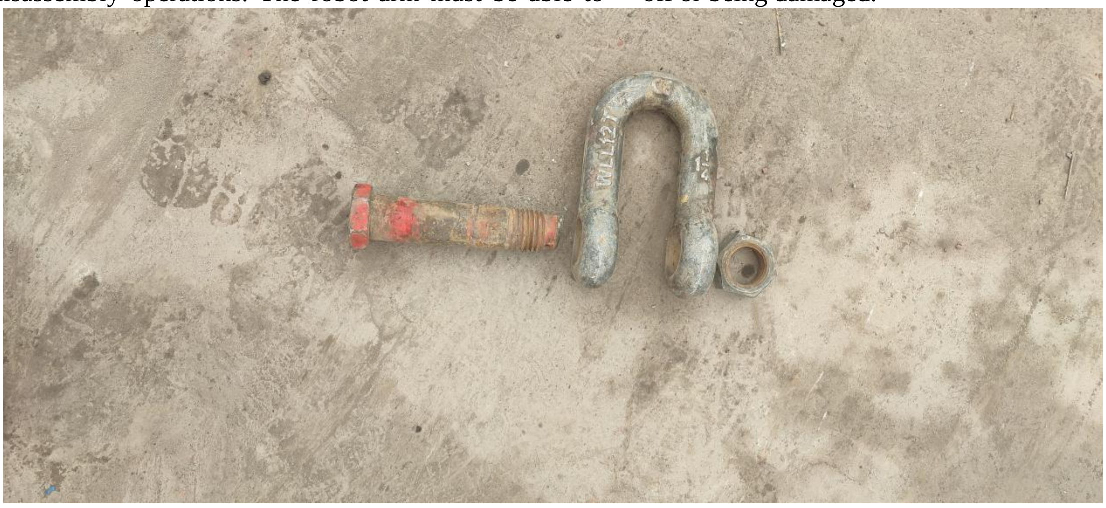


Figure 4.7 Schematic diagram of shackle structure

Third, the removal and hanging of the wire rope sleeve involves high-altitude operations, which are difficult to operate. The robot arm needs to accurately remove or hang the wire rope sleeve at the height of the derrick. This requires not only good motion control capabilities, but also excellent grasping and fixing functions to ensure that the wire rope sleeve is always in a safe state during the entire removal and hanging process.

The rapid replacement of the end effector is designed to improve work efficiency. Different tasks may require different end tools, so the robot arm must be able to quickly and accurately replace the end effector. This task requires the interface design of the robot arm to be universal and easy to operate, and it needs to be equipped with an automated replacement system to reduce human intervention and replacement time.

In addition to the above four main tasks, we also planned four secondary tasks to assist the smooth progress of the main tasks. These secondary tasks include rope hook hanging point protection, traction rope hooking, aerial guidance and docking of the derrick, and fixed-point storage of completed parts.

The purpose of the rope hook's lifting point protection is to protect the rope hook from damage during operation and ensure that it does not accidentally wear or break during the lifting process. The traction rope hook means that during the operation, the manipulator needs to reasonably manage and operate the traction rope to ensure that it does not get tangled or knotted, thereby ensuring the smooth progress of the traction work.

The aerial guidance and docking tasks of the derrick require the robot arm to accurately guide and dock the various parts of the derrick at high altitudes. This process requires a high degree of coordination and precise operation to ensure the correct docking of the various parts of the derrick, thereby ensuring the stability and safety of the entire structure.

Finally, the fixed-point storage of the finished parts is to ensure the cleanliness and orderliness of the work site. After completing the task, the robot arm needs to store the used parts and tools in the predetermined location. This not only helps to quickly find and use them during the next operation, but also reduces the chaos and safety hazards on site.

By decomposing and planning the derrick disassembly and assembly tasks in detail, we can more effectively utilize the advantages of the robotic arm, improve operational efficiency, and ensure the safe and smooth completion of the task. Each subtask corresponds to a specific operation step and action sequence, which helps to clarify the operational requirements and goals of the robotic arm, thereby achieving efficient automated operations.

4.3 Simulation Verification

4.3.1 Forward kinematics analysis

The forward kinematics problem of a robotic arm refers to solving the pose (position and attitude) of the end effector when the variables of each joint (i.e., joint angle) are known. Using the Denavit-Hartenberg parameter method, we can establish the homogeneous transformation matrix of each joint and multiply these matrices to obtain the homogeneous transformation matrix of the end effector relative to the base. The homogeneous transformation matrix of each joint isAiIt can be expressed as:

$$\begin{pmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Substitute the above matrices into the parameters in Table 2.1 one by one to obtain the transformation matrix of each joint:

$$A_1 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0.1857 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A_2 = \begin{pmatrix} 1 & 0 & 0 & -0.85 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0.264 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A_3 = \begin{pmatrix} 1 & 0 & 0 & -0.7915 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0.2065 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A_4 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0.1585 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A_5 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0.1585 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$A_6 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0.1345 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

These matrices are multiplied to obtain the total homogeneous transformation matrix for matrix multiplication operation, and finally the homogeneous transformation matrix of the end effector is obtained, which contains the position and posture information of the end effector in space.

$$\mathrm{T} = \mathrm{A_1A_2A_3A_4A_5A_6T} = \begin{pmatrix} 1 & 0 & 0 & -1.6415 \\ 0 & 0 & -1 & -0.7635 \\ 0 & 1 & 0 & 0.0272 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

4.3.2 Inverse kinematics analysis

The inverse kinematics problem of a robot arm refers to solving the joint variables (i.e., joint angles) when the position and posture of the end effector are known. Inverse kinematics problems are usually more complex than forward kinematics problems because there may be multiple solutions or even no solution. Common methods for solving the inverse kinematics of the S30 robot arm are algebraic, geometric, or numerical iteration methods. In this section, we will use the geometric method for solving the problem. The geometric method usually analyzes the geometric structure of the robot arm.[19], and gradually solve each joint angle. Since the S30 robot has 6 degrees of freedom, we can determine the angle of each joint by step-by-step reverse deduction.

According to the pose matrix of the end effector $T = \begin{pmatrix} 1 & 0 & 0 & -1.6415 \\ 0 & 0 & -1 & -0.7635 \\ 0 & 1 & 0 & 0.0272 \\ 0 & 0 & 0 & 1 \end{pmatrix}$

We can decompose the rotation matrix and position vector: by analyzing the position and orientation of the end effector, we can gradually solve for the angle of each joint.$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{pmatrix}$ $p = \begin{pmatrix} -1.6415 \\ -0.7635 \\ 0.0272 \end{pmatrix}$ $T = \begin{pmatrix} R & p \\ 0 & 1 \end{pmatrix}$

4.3.2.1 Geometric method to solve joint angle

By analyzing the geometric structure of the robot arm, the angle of each joint is gradually solved. For each joint, the following geometric relationships can be used:i

Construct each transformation matrixT_{i-1}^{i}:

$$T_{i-1}^{i} = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i)\cos(\alpha_i) & \sin(\theta_i)\sin(\alpha_i) & a_i\cos(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i)\cos(\alpha_i) & -\cos(\theta_i)\sin(\alpha_i) & a_i\sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\theta_1 = \arctan\left(\frac{y}{x}\right)$$

There are two solutions: and , corresponding to the forward and reverse directions respectively.$\theta_1 \theta_1 + \pi$

$$L = \sqrt{x^2 + y^2}$$

$$D = \frac{L^2 + (z - d_1)^2 - a_2^2 - a_3^2}{2 \cdot a_2 \cdot a_3}$$

The value must be in the range $[-1,1]$[-1, 1]$[-1,1]$, otherwise there is no solution.D

$$\theta_3 = \arctan\left(\pm\sqrt{1 - D^2}, D\right)$$

Each solution has two possibilities (stretching and bending).θ_3

$$\theta_2 = \arctan\left(\frac{z - d_1}{L}\right) - \arctan\left(\frac{a_3\sin(\theta_3)}{a_2 + a_3\cos(\theta_3)}\right)$$

Each solution also has two possibilities (stretching and bending)θ_2.

Calculate the transformation matrix of the end of the arm relative to the base:T_0^3

$$T_0^3 = T_0^1 \cdot T_1^2 \cdot T_2^3$$

The transformation matrix from the end effector to the third joint can be expressed as follows:T_3^6 T_0^6

$$T_3^6 = T_0^6 \cdot (T_0^3)^{-1}$$

Among them, is the transformation matrix of the target end effector, and is the inverse transformation matrix of the forward kinematics part obtained previously.$T_0^6 (T_0^3)^{-1}$

$$\theta_4 = \arctan2\left(T_{3,2}^6, T_{3,1}^6\right)$$

Solution: The rotation matrix is the rotation part of:$R_3^6 R_3^6 T_3^6$

$$R_3^6 = [T_{3,1}^6 \quad T_{3,2}^6 \quad T_{3,3}^6]$$

$$\theta_5 = \arctan2\left(\sqrt{\left(R_{3,3}^6\right)^2 + \left(R_{2,3}^6\right)^2}, R_{1,3}^6\right)$$

Make sure the pose of the end effector is perfectly aligned.

$$\theta_6 = \arctan2\left(-R_{2,3}^6, R_{1,3}^6\right)$$

According to the above steps, for each group (,,) of solutions:$\theta_1 \theta_2 \theta_3$

θ_4: Each group of (,,) has at most 2 solutions (different posture directions).$\theta_1 \theta_2 \theta_3$

θ_5: Each group of (,,) has at most 2 solutions (different posture directions).$\theta_1 \theta_2 \theta_3$

θ_6: Each group (,,) has at most 2 solutions (with different rotation directions).$\theta_1 \theta_2 \theta_3$

Combining these calculations, we get:

Each solution has 2 solutions.$\theta_1 \theta_4$

Each (,) solution group has 2 solutions.$\theta_1 \theta_4 \theta_5$

Each (,,) solution group has 2 solutions.$\theta_1 \theta_4 \theta_5 \theta_6$

The final number of solutions is: $2(\text{for } \theta_1) \times 2(\text{for } \theta_4) \times 2(\text{for } \theta_5) \times 2(\text{for } \theta_6) = 16$solutions

Since the joint angle results of the robot arm inverse kinematics solution are not unique, when actually selecting the robot arm inverse kinematics solution, the rationality of the angle selection should be judged by the walking trajectory of the robot arm's end actuator.

4.3.3 Robotic arm workspace analysis

The workspace refers to the area of all positions that the end effector of the manipulator can reach during the derrick disassembly and assembly process. Evaluating the workspace is crucial to determining whether the manipulator can perform the derrick disassembly and assembly task efficiently and comprehensively. Therefore, in-depth analysis of the manipulator's workspace is of great significance in practical applications [20]. In this paper, the Monte Carlo method is used to simulate and analyze the workspace of the manipulator.

The steps of the Monte Carlo simulation analysis workspace are as follows:

1.Forward kinematics calculation

The position vector of the end effector is calculated using the forward kinematics model of the robot. The forward kinematics calculation is based on the DH parameters of the robot. The global position and posture of the end effector are obtained by calculating the transformation matrix of each joint and multiplying and accumulating them.θ_i= 0, the simplified matrix is:

$$T_{i-1}^{i} = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i)\cos(\alpha_i) & \sin(\theta_i)\sin(\alpha_i) & a_i\cos(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i)\cos(\alpha_i) & -\cos(\theta_i)\sin(\alpha_i) & a_i\sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Substituting θ_i=0:

$$T_{i-1}^{i} = \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & \cos(\alpha_i) & -\sin(\alpha_i) & 0 \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_0^6 = T_0^1 \cdot T_1^2 \cdot T_2^3 \cdot T_3^4 \cdot T_4^5 \cdot T_5^6$$

Calculate the matrix product and get: To simplify the operation definition:T_0^6

$$c_{23} = \cos(\theta_2 + \theta_3)$$
$$c_{234} = \cos(\theta_2 + \theta_3 + \theta_4)$$
$$c_{2345} = \cos(\theta_2 + \theta_3 + \theta_4 + \theta_5)$$
$$c_{23456} = \cos(\theta_2 + \theta_3 + \theta_4 + \theta_5 + \theta_6)$$

So on and so forth.

The positions are extracted from the elements in the last column of the first three rows:$(x, y, z)T_0^6$

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} c_1 \cdot c_{2345} \cdot c_6 \cdot c_5 - s_1 \cdot s_{2345} \cdot s_{56} \\ c_{2345} \cdot c_5 \cdot s_6 + s_{23} \cdot c_5 \cdot c_6 \\ s_{23} \cdot c_{45} + c_{23} \cdot s_{45} \end{bmatrix}$$

The pose is extracted from the first three rows and first three columns:

$$R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix}$$

2. Random Angle Generation

The Monte Carlo method requires generating a large number of random angle combinations within the range of joint angles. MATLAB The function generates uniformly distributed random numbers and scales them to a range. By using the random numbers generated by the function, we can calculate the random angle of each joint. Specifically, we first use rand() to generate a random number between 0 and 1, then multiply it by the range of the joint angle (that is, the difference between the maximum and minimum values), and finally add the minimum value of the angle. In this way, we can get the random angle of each joint. The mathematical expression is:rand$[-\pi, \pi]$rand( )

$$\theta_i = \theta_{min,i} + \left(\theta_{max,i} - \theta_{min,i}\right) \times \text{rand}(\,)$$

Among them, and represent the minimum and maximum values of the joint angle, respectively, and$\theta_{min,i}\theta_{max,i}$irand( )

is a generated random number. This formula applies to all joint angles$i \in [1,5]$。

Calculate the end effector position

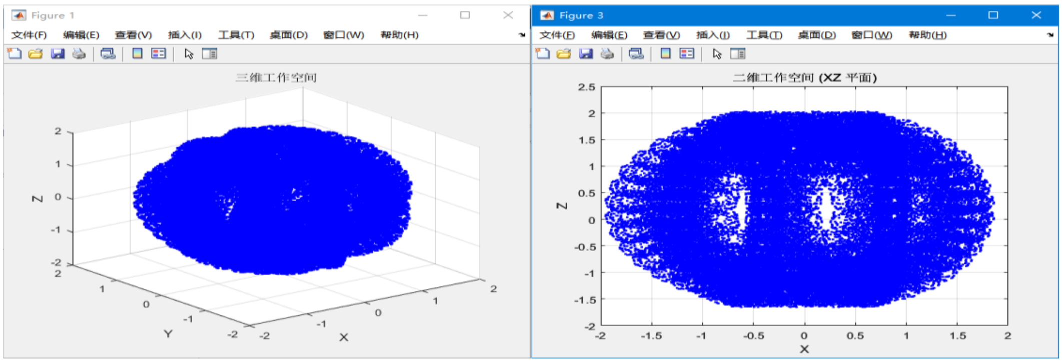
For each set of randomly generated angles, substitute

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} c_1 \cdot c_{2345} \cdot c_6 \cdot c_5 - s_1 \cdot s_{2345} \cdot s_{56} \\ c_{2345} \cdot c_5 \cdot s_6 + s_{23} \cdot c_5 \cdot c_6 \\ s_{23} \cdot c_{45} + c_{23} \cdot s_{45} \end{bmatrix}$$

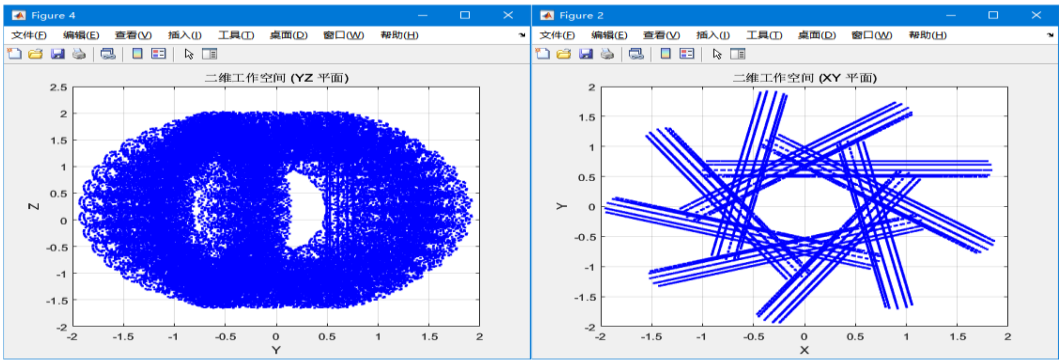
Through the above calculations, we can obtain the spatial point set of all working positions that the end effector of the derrick assembly and disassembly robot can reach.MATLABThe software calculates the position of the end effector and draws a 3D workspace cloud map and a 2D workspace cloud map. These graphics can intuitively show the robot's working range during the derrick disassembly and assembly process.

4.3.4 Robotic Arm Workspace Simulation

useMATLABIn the softwareRobotics Toolbox, the workspace of the derrick disassembly and assembly robot was simulated and analyzed, and 80,000 random points were generated to simulate the three-dimensional workspace of the robot[21]. By calling and drawing commands, the three-dimensional workspace cloud map of the five-degree-of-freedom robot and the two-dimensional workspace cloud map in the and planes were obtained.plotplot3xoy,yoz,xoz



(a) 3D image of the robot’s workspace (b) Xoz surface projection



(c) yoz surface projection (d) xoy surface projection

Figure 4.8 Cloud diagram of the three-dimensional and two-dimensional workspace of the robot

It can be seen from the three-dimensional workspace cloud map (Figure 4.8(a)) that the workspace that the end-effector of the robot arm can reach is approximately ellipsoidal in shape. The two-dimensional workspace cloud map (Figure 4.8(d)) shows that the farthest distance that the end-effector of the robot arm can reach is about 1751.2 mm. The simulated workspace cloud map is consistent with the actual working conditions of each joint, and the space size is consistent with the design parameters of the robot arm. On the two-dimensional cloud map, the area that the end-effector can reach is evenly distributed. The simulation results are consistent with the actual workspace, providing a theoretical basis for the practical application of the derrick disassembly and assembly robot arm.

4.3.5 Robotic Arm Trajectory Planning

The Robotics Toolbox in MATLAB can perform tasks such as robot modeling, workspace simulation analysis, and trajectory planning, and display the simulation results in the form of images to facilitate observation of the robot's motion status. In order to ensure that the end effector of the derrick disassembly and assembly robot can reach the target position smoothly, it is necessary to plan the trajectory of the robot. During the derrick disassembly and assembly process, the robot adjusts its posture through 5 rotating joints to ensure that the end effector can accurately reach the specified position.

4.3.6 MATLAB 3D modeling of robotic arm

existMATLABIn the , Link() function and SerialLink() function are used to assist in the establishment of the robot model. First, the link model of the robot is created through the Link() function. Its calling format is L = Link([a, theta, d, offset], modified);, where a, theta, d and offset represent the link length, joint angle, link offset and joint angle offset in the DH parameters respectively. The parameter modified specifies whether to use the modified DH parameters. Depending on the type of joint, jointtype can be set to 'P' to indicate a mobile joint.

Subsequently, the SerialLink(L) function is used to connect the links generated by the Link() function to build the entire robot model. By calling the teach() function, the three-dimensional mathematical simulation model of the robot can be drawn, as shown in Figure 4(a). In addition, the plot() function can be used to draw the model driver, as shown in Figure 4(b). By dragging the slider in the model driver, the user can control the movement of each joint of the robot. These functions provide effective support for the modeling and simulation of the robot, and can intuitively display the movement status of the robot.

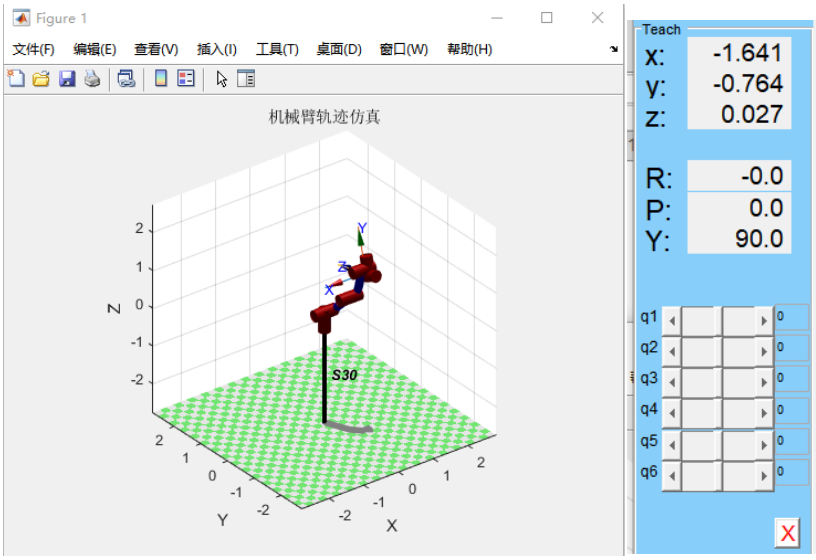


Figure 4.9 Robotic arm model and model driver

4.3.7 Robotic Arm Trajectory Planning Simulation

existMATLABIn Robotics Toolbox, you can use the jtraj function in Robotics Toolbox to plan the space trajectory of the robot. The calling format of this function is [q, qd, qdd] = jtraj(qini, qtar, t), where qini is the initial joint position of the robot, qtar is the target joint position of the robot, and t is the given simulation time. The function return value q represents the joint space trajectory from qini to qtar, and qd and qdd are the velocity and acceleration of each joint in the trajectory planning.

In practical applications, it is assumed that the initial joint position of the robot, qini, is set to [0 0 0 0 0], the terminal position, qtar, is [π/2 -π/4 -π/6 π/3 -π/2], the motion time is set to 10 seconds, and the unit step length is 0.2 seconds. The five joints of the robot are simulated and analyzed, and the jtraj function generates the trajectory data of the joints. By calling the plot3() command, the end effector trajectory from the initial position qini to the terminal position qtar can be plotted, as shown in Figure 7. At the same time, using the plot() command, the angular displacement, angular velocity, and angular acceleration curves of each joint can be plotted, as shown in Figure 8. These graphs show the motion state of the robot in trajectory planning, providing intuitive data support for further analysis and optimization.

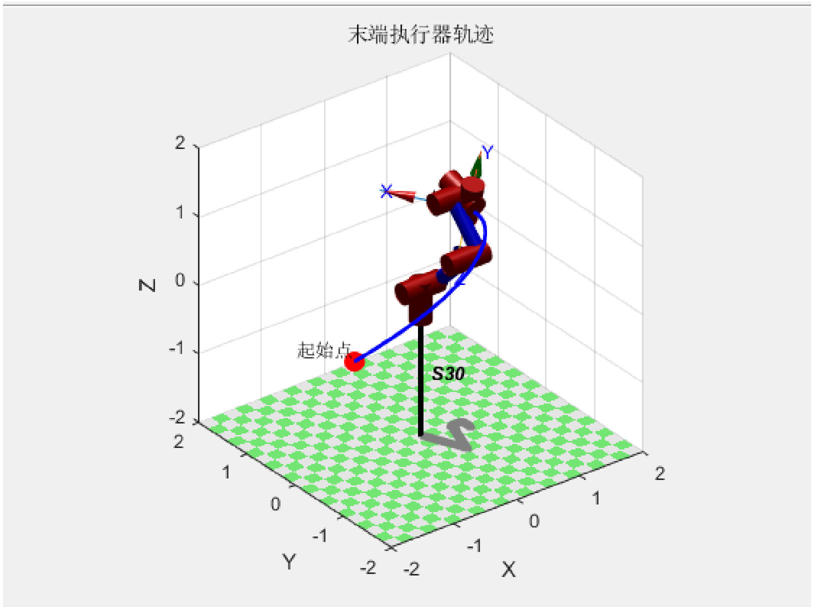


Figure 4.10 Robotic arm motion simulation

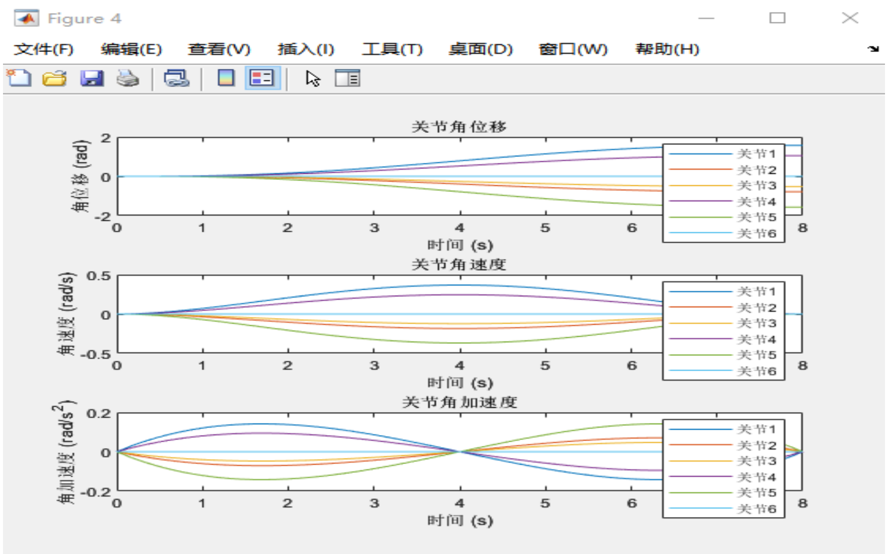


Figure 4.11 Movement curves of each joint

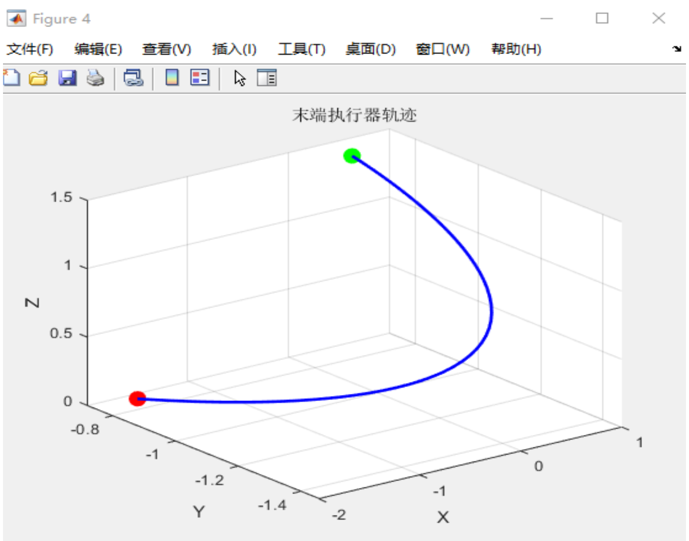


Figure 4.12 Trajectory of the end effector of the robotic arm

D4.11It can be observed that during the movement of the robot arm, the curves of angular displacement, angular velocity and angular acceleration of each joint show smooth and stable characteristics. As time goes by, the curve remains continuous without any mutation or discontinuity. This shows that the various links of the robot arm are properly designed and the joints will not be dislocated during the movement.[twenty two]The changing trend of the angular acceleration of each joint matches the change of its angular velocity, indicating that the planning of the joint space trajectory is reasonable.

V. **Experimental verification**

To verify the application potential of collaborative robots in derrick disassembly and assembly tasks, wePeopleAn experimental scene was built in an indoor environment. The construction of this experimental scene is intended to simulate actual disassembly and assembly conditions to evaluate the performance and applicability of the robot in a specific working environment. By testing in this experimental environment, I was able to systematically analyze and verify the operational capabilities of the collaborative robot and its adaptability to derrick disassembly and assembly tasks, thereby providing reliable data support for its promotion in practical applications.

(a) Rope hook removal simulation scene experiment

(b) Shackle used in simulation

(c) Derrick lug simulation scenario

Figure 5.1 Some scenes and props used in the simulation experiment

After systematic testing in indoor experimental scenarios, the results showed that the collaborative robot can complete the predetermined tasks efficiently and accurately. In the experiment, the robot successfully performed four main tasks and four secondary tasks, showing excellent operational capabilities and reliability. These experimental results verify the application potential of collaborative robots in the field of derrick disassembly and assembly, and show that its performance in handling actual disassembly and assembly tasks is in line with expectations. Therefore, this research result proves the practical application value of collaborative robots in derrick disassembly and assembly operations, and lays a solid foundation for its promotion and application in the industrial field.

VI.**in conclusionand Outlook**

This study systematically explores the application of dual-arm collaborative robots in derrick assembly and disassembly. After detailed modeling, simulation and field testing, its practical application potential in this field is verified. First, by constructing a mathematical model of the robot arm and performing forward kinematics and trajectory planning, the robot's accuracy and stability in task execution are ensured. Second, in the indoor experimental scene, the robot successfully completed four main tasks and four secondary tasks, showing excellent operational performance and reliability. These experimental results show that the dual-arm collaborative robot can not only efficiently complete complex assembly and disassembly tasks, but also has good adaptability and stability in practical applications. Although this study has verified the application effect of the dual-arm collaborative robot in derrick assembly and disassembly, there is still room for further optimization. Future research should focus on the following aspects: First, improve the robot's autonomous intelligence level, and realize dynamic adjustment and real-time optimization of the assembly and disassembly process by integrating advanced perception systems and artificial intelligence technologies. Second, expand the robot's working capabilities and develop multifunctional gripping tools and end effectors that adapt to different derrick structures and assembly and disassembly requirements. Third, explore the robot's remote operation and monitoring system to improve its safety and operational flexibility in dangerous environments. Fourth, we will conduct larger-scale field application tests to evaluate the long-term stability and economic benefits of the robot in an actual industrial environment. Through these measures, we hope to further enhance the application effect of the dual-arm collaborative robot in the field of derrick disassembly and assembly, and make greater contributions to the development of industrial automation.

References

1. Wang Yuechao, Tan Dalong. Research status and developm ent of collaborative robotics[J]. Robotics, 1998, (01): 70-7 6.
2. Wu Jun, Xu Xin, Lian Chuanqiang, et al. A review of res earch progress on collaborative multi-robot systems[J]. Jour nal of Intelligent Systems, 2011, 6(01): 13-27.
3. Chen Zhongze, Lin Liangming, Yan Guozheng. Multi-robot system based on MAS (Multi-Agent System): an importan t direction for the development of collaborative multi-robot ics[J]. Robotics, 2001, (04): 368-373. DOI: 10.13973/j.cnki. robot.2001.04.016.
4. I. EB ,S. AY ,I. VS , et al.Current state, pathways, and p rospects for the development of collaborative robotics from the perspective of a surgeon and engineer[J].Biomedical E ngineering, 2024,57(6): 434-438.
5. Li L ,Fu G ,Zishhuai Z , et al.Application, Development a nd Future Opportunities of Collaborative Robots (Cobots) i n Manufacturing: A Literature Review[J].International Journ al of Human–Computer Interaction,2024,40(4):915 -932.
6. Doyle B.COLLABORATIVE ROBOTS ARE A GROWING SOLUTION FOR SYSTEM INTEGRATORS[J].Plant engi neering,2016,70(10 App.1):12-13.
7. Chen Xiaoshan, Tong Menghan, Xiu Shichao. Application and development of human-machine collaborative robots in the automobile assembly industry[J]. Precision Manufactur ing & Automation, 2020, (03): 1-4. DOI: 10.16371/j.cnki.is sn1009-962x.2020.03.001.
8. Wen Xiao. Elephant: The new force of robots[J]. Automati on Expo, 2023, 40(08):14-15.
9. Zheng Changwan, Chen Yiguo, Kuang Shaolong, et al. An alysis of the development status of orthopedic surgical rob ots[J]. Chinese Journal of Bone and Joint Surgery, 2021, 1 4(10): 872-877.
10. Cao R ,Zhu H .Industry Status and Future Development T rend of Da Vinci Surgical Robot[J].Journal of Contemporar y Medical Practice,2024,6(6):102-106.
11. Shen C ,Yan W ,Chen S , et al.Robot-assisted Radical Pro statectomy with the KangDuo Surgical System Versus the da Vinci Si System: A Prospective, Double-center, Random ized Controlled Trial.[J].European urology focus,2024,
12. Anonymous .Machine Learning - Artificial Intelligence; Sci entists at University of Alberta publish new data on machi ne learning - artificial intelligence[J].Electronics Business J ournal, 2010,
13. Yamasaki Y ,Tokunaga M ,Sakai Y , et al.Effects of a for ce feedback function in a surgical robot on the suturing pr ocedure.[J].Surgical endoscopy,2024,38(3):1222-1229.
14. SY/T 6057-2012, Tower derrick disassembly and assembly and overall transportation operation procedures[S].
15. Du Bing, Wang Kun. Structural design optimization strateg y of industrial robot manipulator[J]. Mould Manufacturing, 2024, 24(07): 201-203+206. DOI: 10.13596/j.cnki.44-1542/ th.2024.07.065.
16. Qian Zhihong, Wang Yijun. A review of wireless sensor n etworks for the Internet of Things[J]. Journal of Electronic s & Information Technology, 2013, 35(01): 215-227.
17. Moon Y ,Trong VAT ,Ko YN , et al.Implementation of Et herCAT Master Middleware Component for Distributed Ro bot Control Architecture[J].IFAC Proceedings Volumes,2009, 42(3):139-143.
18. Hu T ,Wang T ,Li J , et al.Obstacle Avoidance for Redun dant Manipulators Utilizing a Backward Quadratic Search Algorithm[J].International Journal of Advanced Robotic Sys tems,2016,13(3):119-119.
19. Dong Hui, Li Chen, Yao Ligang, et al. An adaptive dyna mic differential evolution algorithm for solving the inverse kinematics of redundant manipulators[J]. Journal of Fuzho u University (Natural Science Edition), 2021, 49(04): 491- 499.
20. Jidai W ,Wenhao W ,Aiqin S , et al.Kinematics analysis a nd simulation of a cooperative manipulator[C]//Shandong U niv. of Science and Technology (China), 2021:
21. Cheng Yonglun, Zhu Shiqiang, Luo Lijia, et al. Kinematic analysis and simulation of QJ-6R welding robot based on Matlab[J]. Mechanical and Electrical Engineering, 2007, (11): 107-110.
22. He Jialai, Luo Jinliang, Huan Pengsong, et al. Workspace analysis of seven-DOF anthropomorphic robot based on M onte Carlo method[J]. Modular Machine Tool and Automat ed Processing Technology, 2015, (03): 48-51. DOI: 10.134 62/j.cnki.mmtamt.2015.03.013.