



# Research on Motion Stability Control Algorithm of Multi-axis Industrial Robot Based on Deep Reinforcement Learning

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**Abstract.** When the multi-axis industrial robot is disturbed by the outside, there will be some problems, such as large deviation of heading angle, time-consuming motion control and long one-way adjustment distance. Therefore, a motion stability control algorithm of multi-axis industrial robot based on deep reinforcement learning is proposed. Design the structural characteristics of multi-axis industrial robot, consider that the foot position can reach the expected motion range, and optimize the motion trajectory planning mode of multi-axis industrial robot. According to the expected movement speed and angular velocity of the center of mass specified artificially in advance, the position vector of the nominal foothold of the foot end of the multi-axis industrial robot is calculated. Based on deep reinforcement learning, the dynamic equation is constructed, and the motion stability control algorithm is designed by describing the change rate of the momentum of the center of mass. Experimental results show that the average deviation of heading angle of the proposed algorithm is 5.92, the average time of motion control is 2.57 s, and the average distance of one-way adjustment is 31.78 mm, which shows that the proposed method has good fault tolerance of motion stability control and can effectively improve the accuracy and efficiency of motion stability control.

**Keywords:** Deep Reinforcement Learning · Multi-Axis Industrial Robot · Motion Stability Control · Structural Features · Motion Trajectory

## 1 Introduction

In the face of industrial transformation and upgrading, especially the manufacturing industry directly promotes the more and more extensive application of multi-axis systems such as CNC machining centers and industrial robots. For multi-axis industrial robots, stability refers to the ability to maintain stability during motion, such as the anti-overturning ability of a footed robot. The more the number of spindles in the multi-axis system, the higher the complexity of the control, and the more difficult it is to coordinate and control each axis. The stable motion of the multi-axis robot is the basis for the robot to complete its tasks. Due to the special structure of the footed mobile robot, maintaining

a continuous and stable walking is an important challenge that must be overcome for robot research tasks. As a typical multi-axis system, industrial robots usually require multiple axes to coordinate movement at the same time, which can reduce errors, ensure processing quality, and improve processing speed, which is an objective production need. The motion stability control of multi-axis industrial robots can effectively ensure the safe and reliable operation of robots. Therefore, it is of great significance to study the motion stability control of robots.

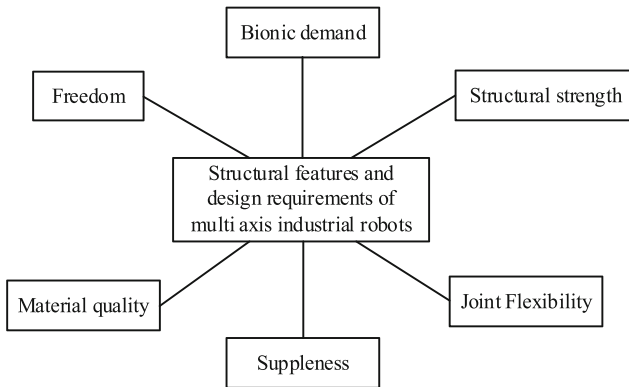
At present, scholars in related fields have carried out research on robot motion stability control, and have achieved certain research results. Reference [1] conducts kinematic analysis on the three-dimensional modeling of industrial robots, establishes DH parameter table, and calculates the inverse solution of industrial robots. The 3D model plug-in is imported into Simulink, and the motion control of the industrial robot is realized by building the mechanical control model and improving the motor drive physical model. This method has certain validity and feasibility, but its heading angle deviation is relatively large. Reference [2] uses the embedded ARM industrial computer as the host computer, selects C++ as the programming language for development, and realizes the motion stability control of the industrial robot through the NURBS real-time interpolation algorithm. This method has certain practicability and generality, but its motion control takes a long time. Reference [3] proposed a multi-layer neural network trajectory tracking control method for industrial robots based on iterative learning control. A multilayer neural network is trained to model the dynamical inverse of the nonlinear inner-loop dynamics using the desired trajectory and the corresponding refined input trajectory. Tracking performance still improved when applying the trained neural network to a physical robot, but not as well as in the simulator.

Aiming at the above problems, a motion stability control algorithm for multi-axis industrial robots based on deep reinforcement learning is proposed. By designing the structural features of the multi-axis industrial robot, the motion trajectory planning mode of the multi-axis industrial robot is optimized, and the position vector of the nominal foot end of the multi-axis industrial robot is calculated. The dynamic equation is constructed based on deep reinforcement learning, and the motion stability control algorithm is designed. The motion stability control of this method has better fault tolerance, higher accuracy and higher efficiency.

## 2 Design the Structural Features of Multi-axis Industrial Robots

The motion of multi-axis industrial robots depends on the design of the overall structure of the robot. The overall structure of the robot affects its motion mode, motion speed, kinematics and dynamic equations, workspace and load conditions and other motion properties. Its motion stability mainly refers to the performance of the multi-axis industrial robot always maintaining a stable posture when moving under a pre-specified motion gait. If a multi-axis industrial robot wants to go out of the laboratory and complete work tasks in various complex natural environments, it not only needs to walk stably on the flat ground, but also needs to have the ability to avoid obstacles autonomously in various environments. Therefore, the overall structure of the robot is particularly important. The gait of a multi-axis industrial robot refers to the motion form of stepping during the

process of walking. According to the different duty ratios, the gait of the robot can be divided into different gaits by imitating the motion gait of animals. The duty cycle refers to the ratio of the time that a single leg is supported on the ground when the robot moves to the total time of one cycle movement. The overall structure of a multi-axis industrial robot is generally composed of a fuselage and legs. The fuselage contains the installation of the legs, the layout and fixation of lidar and depth cameras and other hardware accessories, and the single leg contains the transmission of the mechanical structure of the legs and the drive. When the robot is in static motion, it needs to satisfy at least three legs in a supporting state at any time. Its stability is usually judged by the supporting triangle. The supporting triangle stability criterion indicates that the projection of the center of mass on the plane of the supporting point must be located within the supporting triangle, so that the system can maintain balance and static stability. The design of the single-leg structure of the robot and the transmission mode of the drive directly affect the difficulty of the robot control algorithm. Therefore, the most important part of the design of the robot is the leg structure and the transmission mode of the drive. Due to its simplicity, it is still in use today, especially in scenarios with high security and stability requirements that require static motion. The robot will encounter various complex working environments during the movement process. The reasonable structure design of the whole machine can directly reduce the friction between the parts, reduce the energy loss of the system, and improve the movement speed and movement efficiency. And it will also greatly affect the robot power components, the size of the actuator, the force state and the overall layout [3, 4]. When the projected point of the center of gravity on the support area is inside the support triangle, the stability margin value is positive, and when it is outside the support triangle, the value is negative. The larger the stability margin value, the more stable the robot is. From this, the structural feature design requirements of the multi-axis industrial robot are obtained, as shown in Fig. 1.



**Fig. 1.** Schematic diagram of structural feature design requirements for multi-axis industrial robots

Therefore, it is very important to carry out a reasonable mechanical structure design of the whole robot on the basis of meeting the structural characteristics design requirements of the multi-axis industrial robot. On the one hand, it is necessary to ensure that

the robot output unit can meet the requirements of the work. And its key components must have sufficient strength and rigidity, and on the basis of meeting the working requirements of the system, the weight of each component unit of the robot should be reduced as much as possible to facilitate the control of the robot's motion state. The triangular stability criterion based on the projected point of the centroid is only applicable when the robot is free from external forces and walks statically at a constant speed in a horizontal, flat terrain in a constant direction. On the other hand, reasonable use of the limited space on the whole machine ensures that the various unit components of the robot are connected effectively and reliably and transmit motion accurately. And in the design of the whole machine, the compact and stable internal structure of the robot should also be considered, and the appearance and structure are beautiful and delicate. During the movement of the robot, considering that the position of the foot end can reach the expected range of motion, and to avoid friction and collision with other links during movement, each leg of the robot needs to be set with three degrees of freedom. When the robot is subjected to interference force, there is acceleration, or the contact point of the foot end is not in the same plane, the resultant point of the robot is often not at the center of mass of the robot body. Therefore, it is necessary to judge the stability of the robot through motion analysis of the robot. And starting from the project requirements, the leg structure not only needs to have sufficient strength and stiffness, but also needs to have a large load-bearing capacity so that heavier materials can be transported during work. When the robot needs to accelerate the movement, the robot can complete the acceleration movement by applying a torque at the joints to generate a reaction force at the foot end. Therefore, the zero-moment point can be defined as the resultant point of the foot force on the support plane of the hypothetical robot, and the zero-moment point can be obtained by solving the robot motion equation. Considering that the robot may face a variety of complex terrain environments, the robot needs to have good motion stability, and the single-leg structure also needs to have a certain buffering capacity. In addition, the single leg of the robot should also meet the requirements of simple structure, flexible movement, and easy control.

### **3 Optimizing the Motion Trajectory Planning Mode of Multi-axis Industrial Robots**

The motion mode of multi-axis industrial robots is usually to first plan the motion trajectory of the foot end, then use inverse kinematics to calculate the angle of each joint, and finally use the servo controller to realize the joint position servo. The swing phase refers to the period from when the multi-axis industrial robot lifts its legs so that the foot ends are lifted off the ground until the legs are vacated to the ground. The purpose of the swing phase trajectory planning is to make the swing legs have enough height from the ground to avoid obstacles. To plan the motion trajectory of the foot end, it is first necessary to calculate the desired motion landing point of the robot [5, 6]. And reduce the energy loss in the movement process, considering that the legs are not affected by environmental forces at this time, so higher speed and acceleration can be pursued. In the process of triangular gait, the position vector of the nominal landing point of the robot foot can be calculated according to the expected movement velocity and angular

velocity of the center of mass manually specified in advance:

$$d_\varepsilon = \phi + \frac{1}{\varepsilon} \quad (1)$$

In formula (1),  $\phi$  represents the position of the foothold, and  $\varepsilon$  represents the projected position of the hip joint on the support surface. The parameters that need to be paid attention to in the trajectory planning of the swing phase are the starting point, the foothold point, the swing amplitude and the function equation. Among them, the position difference between the landing point and the starting point determines the gait length and affects the movement speed of the robot. When the robot is in a diagonal gait, the two diagonally moving legs can be seen as a virtual leg, which simplifies the walking process into an elastically loaded inverted pendulum model. The midpoint of the movement process is called the support center point. It can be seen that when the foothold is just at the support center point, the robot can maintain a certain speed. When the landing point is in front of the center point, the robot will accelerate. The function equation determines the smoothness and real-time adjustment ability of the motion trajectory of the swing phase. In order to adjust the gait length with the speed of the robot, the calculation formula of the gait length is:

$$R = \frac{\gamma W}{2} - \varpi(h - \eta) + \frac{|h - 1|^2}{2} \quad (2)$$

In formula (2),  $\gamma$  represents the swing phase gait duty cycle,  $W$  represents the gait cycle,  $\varpi$  represents the control gain,  $h$  represents the desired motion speed of the robot, and  $\eta$  represents the starting position of the foot in a cycle. When the landing point is behind the center point, the robot will decelerate. The position of the center point can be obtained from the body movement speed, so during the normal walking process of the robot, the foothold should satisfy the following relationship:

$$Y = \frac{1}{\mu} \times \sqrt{\|\varphi - \lambda\|^2} \quad (3)$$

In formula (3),  $\mu$  represents the support center point,  $\varphi$  represents the standing time of the support leg, and  $\lambda$  represents the desired motion speed of the robot. When moving on the ground, the swing amplitude can be slightly smaller than the maximum leg height of the robot. After the starting point, gait length and swing amplitude are known, the function equation can use the cycloid function, and the motion trajectory of the foot end is obtained as:

$$Q = \sigma \times \frac{\sin\left(R - \frac{\gamma W}{2}\right)^2}{2\pi} \quad (4)$$

In formula (4),  $\sigma$  represents the height of the raised leg, and  $R$  represents the forward length. Considering that the robot can resume normal motion when it is disturbed by external, the position of the capture point is introduced into the calculation formula of the nominal landing point in the robot. Therefore, considering the given movement speed

and the detected movement disturbance, the appropriate foothold can be calculated. The disturbed foothold position is shown in the formula:

$$U = \sqrt{\frac{1}{g} \times (g - \psi)^2 - \frac{1}{\psi}} \quad (5)$$

In formula (5),  $g$  represents the height of the robot's hip joint, and  $\psi$  represents the swing time of a single leg. The starting point of the foothold position is calculated from the projected position of the hip joint on the support surface instead of the actual position in world coordinates, which can avoid leg drift caused by calculation errors. The support phase refers to the period of time during which the legs of the multi-axis industrial robot support the ground. If the trajectory planning of the support phase is directly carried out and converted into joint angles for position control, it is easy to cause rigid impact to the multi-axis industrial robot, damage the internal structure, and is not conducive to stable motion control. When the robot is moving forward, the legs need to move to a desired position in the moving forward direction within a certain period of time, and the desired position is calculated according to the method described above [7, 8]. Therefore, using impedance control to ensure flexible contact between the leg and the ground when the leg touches the ground can effectively reduce the impact. For the use of traditional position control, high stiffness can improve control accuracy, but high stiffness may cause damage to the airframe. To move the robot to the desired position, the trajectory of the swing leg needs to be planned. In order to make the robot have higher stability, the swing trajectory of the foot end needs to ensure that the speed at the initial moment of raising the leg and the moment of landing is zero, and it also needs to have a certain height to overcome obstacles on the road. To avoid this problem, the control needs to be compliant. There are two main types of compliance control: passive and active. Passive compliance is mainly achieved by springs, which requires high mechanical design of the robot. Active compliance is mainly achieved through control algorithms, using a virtual spring structure to connect the internal action points of the robot to generate corresponding virtual forces to drive the robot to move.

## 4 Constructing Dynamic Equations Based on Deep Reinforcement Learning

Because the deep reinforcement learning algorithm itself requires the agent to obtain information independently by interacting with the environment without external supervision. Therefore, the stronger the exploration ability of the algorithm, the more fully understand the environmental information, the higher the reward, the better the learning strategy. In the deep reinforcement learning algorithm, the action network is responsible for generating actions, and the evaluation network is responsible for evaluating the generated actions. The goal of learning is that under the more effective guidance of the evaluation network, the action network can learn the optimal motion strategy. Although some control methods can adjust the trajectory of the foot according to the speed of the robot, the entire modeling control process still requires complicated and tedious manual tuning, cannot find the optimal control strategy for the terrain environment, and has poor

real-time adjustment ability. The strategies in policy gradient reinforcement learning can generally be divided into two types: stochastic strategies and deterministic strategies. The random strategy is that in a certain state, there are multiple actions with different probabilities to choose from, and the random strategy uses a normal distribution to generate an action. Theoretical mathematical models can be used to design effective leg motion planning or control algorithms. If the established model equations are always true during the motion time, it is considered that the motion planning or control algorithm designed according to the given model is physically correct and feasible. These models quantify the relationship between the input parameter  $\alpha$  and the current state  $\beta$  of the system, and the resulting change in state  $\alpha$ . This can be expressed in ordinary differential equations, as shown in formula (6):

$$\beta_z = F \times \frac{\alpha}{z} - \sqrt{\|\alpha - z\|^2} \quad (6)$$

In formula (6),  $F$  represents the joint control amount,  $z$  represents the mechanical parameter of the leg member. Deep reinforcement learning can continuously learn in the interaction with the environment. In the multi-axis industrial robot motion control problem, without the need to accurately model the robot, the robot can actively adapt to the new environment and avoid designing control algorithms for each scene. The deterministic strategy is to only select the action with the highest probability as the only choice, and no longer consider other actions, which can speed up the learning speed, but it may also lead to the failure to find the global optimal solution. Then according to the actual situation of motion, reasonable assumptions are made to deduce the state space dynamics model that can be used for controller design [9]. According to the Lagrangian dynamic calculation method, the complete dynamic equation of the multi-axis industrial robot is established as shown in formula (7):

$$G = T_v + Y_{t-1} + \sum \sum \left| \frac{T_v}{Y_{t-1}} \right|^2 \quad (7)$$

In formula (7),  $T$  represents the inertia matrix of the joint space,  $Y$  represents the generalized coordinate of the robot,  $v$  represents the Coriolis force, centrifugal force and gravity term, and  $t$  represents the external force on the robot. The robot can be divided into a joint-driven part and an under-actuated floating base part, and the two parts have a cross-dependency relationship, that is, there is a dynamic coupling between the base and the legs, and also contains a large number of nonlinear constraints. The full dynamics model is extremely complex due to the highly coupled and dynamic nature of the model. At the same time, the goal of reinforcement learning is to find an optimal policy that computes the mathematical expectation of the return values of all segments downsampled by each policy, and this optimal policy has the largest expectation [10]. The return value is calculated as the accumulation of a fragment, and there is a large sample deviation. First, it is assumed that the robot is only affected by the ground force, and the robot can also be regarded as a part of its own gravity when it is loaded. The robot's floating base and four legs are then modeled as a whole and the mass of the legs is ignored. By describing that the rate of change of the centroid momentum is equal to the sum of the external torques, the centroid dynamics model can be established, as

shown in formula (8):

$$\frac{l}{\partial} = [(b - 1) - k]^2 \quad (8)$$

In formula (8),  $\partial$  represents the mass of the robot,  $l$  represents the gravitational acceleration,  $b$  represents the position of the center of mass in the world coordinate system, and  $k$  represents the position of the foot end in the world coordinate system. At the same time, in order to solve the problem of deterministic strategy, the DDPG algorithm draws on the idea of experience replay in DQN. The current state, action, reward feedback and next state are stored in the experience replay pool as a tuple, and the action network and evaluation network are trained by continuously extracting data randomly from the experience replay pool, which effectively increases the amount of training data. Therefore, the value function is used to predict the return value, that is, to calculate the expectation of the return value, which is mainly used to evaluate the quality of different states, and can be used to guide the selection of actions. In order to be able to apply the model predictive control algorithm, it is necessary to do some combination of multi-axis industrial robots to build a convex model that can be used for linear optimization. The DDPG algorithm also draws on the idea of the dual network in DQN, and promotes the learning effect and improves the learning performance by using the current network and the target network with different update frequencies.

## 5 Design Motion Stability Control Algorithm

The motion stability of the robot mainly refers to the performance that the robot always maintains a stable posture when moving under a pre-specified motion gait. When the robot is walking, the friction force of the ground is a problem that needs to be considered in the stability analysis process. The gait of a multi-axis industrial robot refers to the movement of stepping during the process of walking. According to the different duty ratios, the gait of the robot can be divided into different gaits by imitating the motion gait of animals. Since the foot end of the robot studied in this paper and the ground can be regarded as point contact, the ground provides support force and horizontal friction force to the support legs during the movement. The duty cycle refers to the ratio of the time that a single leg is supported on the ground when the robot moves to the total time of one cycle movement. Next, the geometric and mechanical stability of multi-axis industrial robots and the stability of diagonal gait motion under disturbance are discussed. If a footed robot needs to move forward, there must be an external force, and this external force is the friction and support provided by the ground. In a steady state of equilibrium, the rate of change of the centroids is zero and there is no movement in the horizontal direction. In order to make the multi-axis industrial robot support stably on the ground without relative sliding between the support foot and the ground, it is necessary to ensure that the resultant force of the support leg and the ground in the support phase is within the friction cone. When the robot does not have accelerated motion, the zero-moment point is the projection point of the center of mass on the support surface. Therefore, the dynamic stability criterion based on the zero moment point can still adopt the static triangle stability criterion to define the stability of the robot. When the robot is subjected

to a lateral impact from the outside world, it must quickly judge the motion state and trend of the fuselage, and determine whether the impact is large enough to cause the fuselage to overturn, and then measures to stabilize the lateral impact must be taken. That is, during the triangular gait motion of the multi-axis industrial robot, when the zero moment point is located inside the support triangle, the stability margin value is positive, and when it is outside the support triangle, the value is negative. The larger the stability margin value, the more stable the robot is. Based on the lateral stability conditions and the rolling motion of the body under lateral impact, the lateral speed and roll angle are monitored by the body sensing device as the conditions for dynamic stability determination. Let the upper limit of the lateral speed and roll angle of the fuselage be  $m$ ,  $n$ , respectively, when the fuselage moves stably in place or in the forward direction. It can be considered that when the airframe sensor detects that the lateral speed of the body or the roll angle exceeds the upper limit, the body is subjected to a lateral impact, and the lateral impact stability control needs to be completed. The dynamic stability judgment of whether the state of the body has a tendency to overturn can be expressed as for:

$$P = \begin{cases} 1 & |m_0| > |m_1| \cup |n_0| > |n_1| \\ 0 & \end{cases} \quad (9)$$

In formula (9),  $m_0$ ,  $m_1$  represents the upper limit of the lateral speed during stable motion in the original and forward directions, respectively, and  $n_0$ ,  $n_1$  represents the upper limit of the roll angle during stable movement in the original and forward directions, respectively. However, if only the influence of the center of mass of the robot base and the position of the resultant force point on the stability is discussed, the influence of the motor torque and power consumption limitation of the system is actually ignored, which is very inconvenient for the application of the robot in actual work. According to the necessary conditions of the lateral impact control strategy, lateral stride is the key to keep the robot body stable and counteract the lateral speed. When the robot has too much weight or has a large load, the torque required by the joint may be greater than the maximum torque that the joint can provide. The legs of the robot cannot reliably support the weight of the entire body, and the phenomenon of falling and overturning will occur. Therefore, it is also necessary to consider the joint torque limit of all joints of the real robot to avoid any joint torque in the leg being higher than the maximum allowable torque. In addition, since the synchronous control of multiple axes of an industrial robot requires the controller to ensure that the trajectory tracking error of each axis converges to zero, on the other hand, it also handles and adjusts the synchronization error between each axis, and the burden of control computing tasks is relatively large. From this, the expression formula of the constant velocity approach rate of the stability control algorithm is obtained as:

$$H = -t \times \frac{q^2}{\text{sgn}(f)} \quad (10)$$

In formula (10),  $t$  represents the exponential approach term,  $q$  represents the jitter amplitude, and  $f$  represents the jitter coefficient. In Trot gait, the two legs on the diagonal line are grouped in pairs, each group of legs moves in the same form, and the force of the hip joints on the torso is also similar. Therefore, the movement of the two legs on

the diagonal can be equivalent to a virtual leg. In the physical system, the point-to-face contact model is constrained by a friction cone. When the ratio of the tangential friction force of the contact surface to the normal contact force is greater than a certain value, the foot end will slide. In order to avoid this phenomenon, the tangential force of the contact surface should be limited within the friction cone range. If the number of axes is large, the control amount will increase geometrically, and the hardware requirements such as the main frequency of the controller will be very high, so it is necessary to select an appropriate synchronization function relationship. In the support phase, the support leg controls the robot body to follow the lateral impact direction and move toward the landing point of the laterally straddling swing leg. If can achieve balance in one step, you can return to the original Trot gait in the next gait cycle by controlling the movement of the body to the middle position between the swing leg and the support leg. If the synchronization error is defined as a specific functional relationship between each axis and all other axes of the system, the calculation of the error becomes complicated, which challenges the calculation performance and real-time performance of the controller. If the airframe speed or roll angle cannot be controlled within the threshold value of dynamic stability judgment by one step, it is necessary to realize the stability of the motion state through continuous strides. Therefore, choosing the cross-coupling control strategy of the minimum relevant axis can not only establish indirect connection between each axis, meet the requirements of multi-axis synchronous control, but also limit the calculation amount of each axis.

## 6 Simulation Analysis

### 6.1 Experiment Preparation

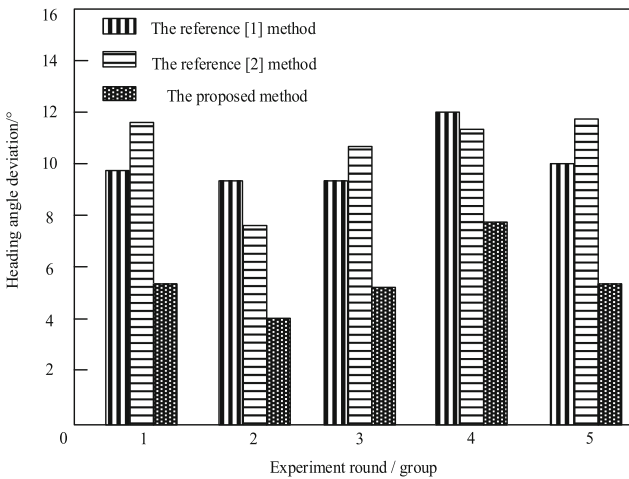
The robot in this experiment is driven by 12 torque motors, that is, it is composed of 4 legs with joints with 3 degrees of freedom each, which can perform various gaits and adapt to different terrains for movement. Before using an industrial robot, it is necessary to understand the important parameters of the robot, such as D-H parameters, maximum motion range and dynamic parameters, so as to establish a realistic robot model within the specified mechanical performance parameters and maximize the use of and protect robots. The single leg has three degrees of freedom, and its joints are arranged as hip flexion and extension, knee flexion and extension, and hip adduction and abduction. With larger offset settings, each joint can achieve a larger range of motion, demonstrating high mobility. The master station writes its messages into standard Ethernet data frames and encapsulates them into EtherCAT data frames. Devices are identified by frame type Ox88A4. The motion range of the first joint of the robot leg ( $\pm 90^\circ$ ), the second joint ( $\pm 180^\circ$ ), and the motion of the third joint are infinite. The setting of the workspace makes the robot leg configuration variable and the movement very flexible. The EtherCAT protocol was adapted for cyclic process data in the industrial sector, eliminating the need for a large protocol stack. The EtherCAT data frame sequentially includes an Ethernet frame header, an EtherCAT header, an EtherCAT data segment, and an FCS frame check sequence. The robot hardware system is mainly composed of Intel NUC control computer, sensor, driver, robot joint, battery and remote operation terminal. The robot has 12 drive joints, each joint has a rated working torque of 60 Nm and a peak

torque of 120 Nm. It needs to communicate synchronously, so the EtherCAT bus is used for communication. The EtherCAT data segment contains an indefinite number of sub-messages, and the headers of the sub-messages indicate the access mode of the master device. The data segment of the sub-packet can be embedded in the data format of other protocols such as CoE or SoE as required. Sensors used include binocular cameras, inertial measurement units and lidars, and the IMU provides measurements of the azimuth and angular velocity of the robot base.

## 6.2 Experimental Results

In this simulation experiment, the method of reference [1], the method of reference [2] and the proposed method are selected for comparative analysis. In order to ensure the higher reliability of the experimental results, 5 groups of experiments were set up, each group of experiments was carried out 20 times, and the average value was taken as the final result. The heading angle deviation, motion control time-consuming and one-way adjustment distance of the three methods were respectively tested under the condition of 50 kg load pressure.

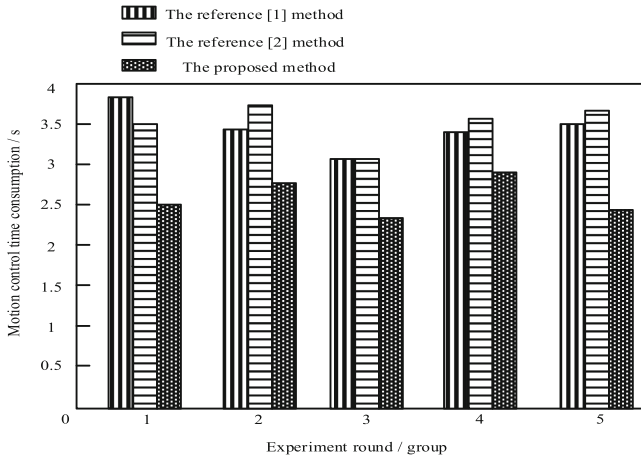
The heading angle deviation is used as an evaluation index for the accuracy of the robot motion stability control. The smaller the heading angle deviation is, the higher the accuracy of the robot motion stability control method is. The comparison results of the heading angle deviation of the three methods are shown in Fig. 2.



**Fig. 2.** Heading angle deviation of three methods

According to Fig. 2, the mean values of the heading angle deviations of the method of reference [1], the method of reference [2] and the proposed method are  $10.94^\circ$ ,  $11.81^\circ$  and  $5.92^\circ$ , respectively. It can be seen that the heading angle deviation of the proposed method is smaller than that of the method of reference [1] and the method of reference [2], which indicates that the proposed method has a higher accuracy of the robot motion stability control.

The motion control time is used as the evaluation index of the robot motion stability control efficiency. The shorter the motion control time, the higher the control efficiency of the robot motion stability of the method. The time-consuming comparison results of motion control of the three methods are shown in Fig. 2.



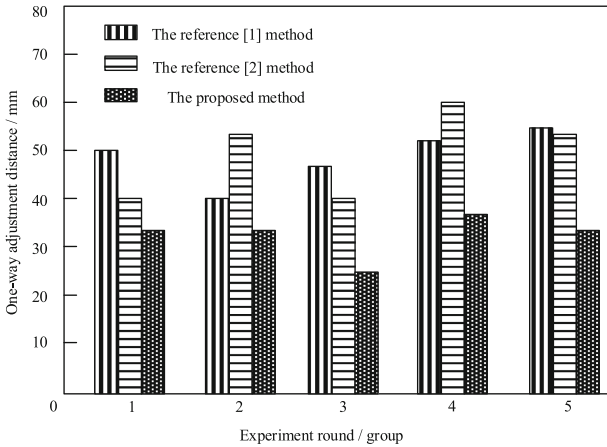
**Fig. 3.** Time-consuming motion control of the three methods

According to Fig. 3, it can be seen that the average time-consuming of motion control of the method of reference [1], the method of reference [2] and the proposed method are 3.74 s, 3.84 s and 2.57 s, respectively. It can be seen that the motion control time of the proposed method is relatively short, which indicates that the proposed method has high efficiency in controlling the motion stability of the robot.

The one-way adjustment distance is used as the evaluation index of the fault tolerance of the robot motion stability control. The shorter the one-way adjustment distance, the better the fault tolerance of the robot motion stability control of the method. The comparison results of the one-way adjustment distance of the three methods are shown in Fig. 3.

According to Fig. 4, the mean values of the one-way adjustment distances of the method of reference [1], the method of reference [2] and the proposed method are 47.70 mm, 49.51 mm and 31.78 mm, respectively. It can be seen that the one-way adjustment distance of the proposed method is short, which indicates that the proposed method has good error tolerance for robot motion stability control.

In summary, since this method is based on the prespecified desired motion speed and centroid mass angular velocity. The position vector of the nominal foothold of the robot foot is calculated. Using the deep reinforcement learning algorithm and design the motion stability control algorithm by describing the rate of change of the centroid momentum. Therefore, this method can effectively improve the accuracy and efficiency of motion stability control.



**Fig. 4.** One-way adjustment distance of three methods

## 7 Conclusion

This paper studies the motion stability control algorithm of multi-axis industrial robot based on deep reinforcement learning. By designing the structural features of the multi-axis industrial robot, the motion trajectory planning mode of the multi-axis industrial robot is optimized. Based on the deep reinforcement learning algorithm, the robot motion equation is established, and the motion stability control algorithm is designed by describing the change rate of the center of mass. The experimental verification results show that the motion stability control of the proposed method has good fault tolerance, high accuracy and efficiency. In the follow-up, we will continue to test the application effect of the multi-axis industrial robot motion stability control algorithm designed this time in complex environments.

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