Design of Industrial Robot Based on IWOA-PID Control

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Abstract. Aiming at the nonlinear strong coupling system composed of the joints of 6-axis industrial robot, the traditional PID control is difficult to achieve the accuracy and convergence speed requirements of robot trajectory tracking, an intelligent control method based on IWOA-PID (Improved Whale Optimization Algorithm-PID) is proposed. IWOA is an improved intelligent heuristic algorithm based on the Whale Optimization Algorithm (WOA). Using IWOA to dynamically adjust PID control parameters, so as to improve the accuracy and convergence speed of robot trajectory tracking. Using MATLAB toolbox and Simulink to build simulation model. In the simulation experiment and field test, IWOA-PID control is compared with WOA-PID control and traditional PID control. The experimental results show that the trajectory tracking accuracy of each joint is high and the convergence speed is fast based on IWOA-PID control, and it has high engineering practical value.

1. Introduction

Robotic Industries Association defines the industrial robot as an automatic control, reprogrammable, multi-purpose, fixed installation or mobile programmable mechanical operating mechanism with more than three joint axes [1]. With the development of intelligent manufacturing technology, industrial robots are more and more widely used in manufacturing industry [2].

As one of the core of industrial robots, the motion control algorithm will directly affect the accuracy of robot trajectory tracking [3]. At present, the traditional PID control is mostly used in the motion control algorithm of 6-axis industrial robot. Traditional PID control can effectively control the linear constant system, but for the nonlinear system with high uncertainty, it is difficult to achieve accuracy requirements of trajectory tracking. In the reference [4], fuzzy PID control is used in the
system which is not easy to establish accurate mathematical model, but the improvement of control effect is not obvious [5]. Some scholars have proposed many heuristic intelligent optimization algorithms to improve the motion control accuracy of 6-axis robot, such as Particle Swarm Optimization (PSO) [6], Curved Space Optimization (CSO) [7], Seeker Optimization Algorithm (SOA) [8], etc., but the PSO-PID control has poor timeliness [9]; CSO-PID and COS-PID control have defects in structure and response speed [10]. The Whale Optimization Algorithm (WOA) proposed by Mirjalili has the advantages of less adjustment parameters and less computation [11]. In reference [12], WOA is used for PID parameter adjustment. Compared with other intelligent PID controls such as ABC-PID and GA-PID, it improves the tracking accuracy of 6-axis robot, but its robustness is poor. In order to improve the convergence speed and global search ability of WOA, the inertia weight of WOA is adjusted dynamically [13], the improved WOA is used for PID parameter adjustment, and the advantages of IWOA-PID control are proved by simulation experiments.

2. Improved Whale Optimization Algorithm

Whale optimization algorithm is a heuristic intelligent algorithm proposed by Mirjalili, which is inspired by the behavior of humpback whales. This algorithm imitates humpback whale's strategy of using "spiral bubble net" to search for food by reducing the encirclement, updating the position of spiral and random hunting mechanism. WOA adopts constant inertia weight, which will not change during algorithm iteration, so the convergence speed and global search ability of the algorithm cannot change with the change of population search position. In order to improve the convergence speed and global search ability of WOA, and to improve the tracking accuracy and robustness of 6-axis robot's motion track after using WOA to dynamically adjust PID parameters, the constant inertia weight is changed into dynamic adjustable weight in this paper.

The IWOA mathematical model includes: dynamic adjustable weight, encircling and predation, updating the position of spiral and search predator.

2.1. Dynamic adjustable weight

Dynamic adjustable weight is a control factor to balance the global search ability and local development ability of the algorithm. Larger inertia weight can enhance the global search ability of the algorithm, and smaller inertia weight can improve the local development ability and convergence speed of the algorithm. Therefore, most intelligent optimization algorithms will adopt the improvement strategy of dynamic adjustment of inertia weight [14], as shown in formula (1):

$$\omega(t) = \omega_{\text{min}} + (\omega_{\text{max}} - \omega_{\text{min}})r_1 \frac{d}{T_{\text{max}}}$$

Where $\omega(t)$ is dynamic adjustable weight, $\omega_{\text{min}}$ is minimum weight, $\omega_{\text{max}}$ is maximum weight, $r_1$ is internal random number in [0, 1]. The improved WOA weight is generated by the combination of nonlinear decreasing method and random generation method. In this way, the weight is large in the early stage of the algorithm, and the global search ability is strong. After introducing random factors, the convergence speed can be enhanced; in the later stage of the algorithm, the local optimization can also be jumped out through random factors [15, 16].

2.2. Encircling and predation

Assuming that the current optimal individual position of whale group (the best candidate solution) is
at the target prey position or the closest to the target position, the mathematical expression of its position update is shown in formula (2):

\[ X_{d+1} = \omega_{(t)} \cdot X^*_{d} - A \cdot D \]  (2)

Where \( X^*_{d} \) is the best spatial position of the whale group, \( D \) is the distance between the current best position of the ith whale group and its prey, \( A \) is the coefficient, and \( A \cdot D \) is the surrounding step length. The calculation method of \( D \) and \( A \) is shown in formula (3) and (4):

\[ D = \left| C \cdot X^*_{d} - X_d \right| \]  (3)

\[ A = 2a \cdot r_2 - a \]  (4)

Where \( C \) is coefficient, \( X_d \) is the position of the ith whale in space, \( r_2 \) is random number in [0, 1], \( a \) is convergence factor, whose value decreases linearly from 2 to 0, expressed as: \( a = 2 \cdot \frac{2d}{T_{max}} \), \( d \) is the current number of iterations, \( T_{max} \) is the maximum number of iterations. The calculation method of coefficient \( C \) is shown in formula (5):

\[ C = 2r_3 \]  (5)

Where \( r_3 \) is random number in [0, 1].

2.3. Updating the position of spiral

First calculate the distance between the whale group position and prey, and then create a spiral mathematical model between the whale group position and prey position, as shown in formula (6):

\[ X_{d+1} = D \cdot e^{b_l} \cdot \cos(2\pi l) + \omega_{(t)} \cdot X^*_{d} \]  (6)

Where \( b \) is logarithmic spiral shape constant, \( l \) is random number in [-1, 1], \( D \) is the distance between the current best position of the ith whale and its prey, and the calculation method is shown in formula (7):

\[ D = \left| X^*_{d} - X_d \right| \]  (7)

Whale prey moves along spiral path while contracting and encircling its prey, the probability of choosing the location renewal of the shrinkable surrounds or the spiral position renewal is the same, both of which are 50%. The mathematical model is shown in formula (8):

\[ X_{d+1} = \begin{cases} \omega_{(t)} \cdot X^*_{d} - A \cdot D, & \rho \leq 0.5 \\ D \cdot e^{b_l} \cdot \cos(2\pi l) + \omega_{(t)} \cdot X^*_{d}, & \rho > 0.5 \end{cases} \]  (8)

Where \( \rho \) is random number in [0, 1].

2.4. Search predation

In addition to the "bubble net method" search strategy, whale groups can also search prey randomly according to each other's positions. The mathematical model for updating their positions is shown in formula (9):

\[ X_{d+1} = \omega_{(t)} X_{rand} - A \cdot D \]  (9)
\[ D' = |C \cdot X_{\text{rand}} - X_d| \]  

Where \( X_{\text{rand}} \) is the randomly selected individual position of whales in the whale group, \( D' \) is the distance between the current best position of the ith whale in the whale group and its prey. When \(|d| > 1\), a random search is used to update the position; when \(|d| \leq 1\), a spiral contraction encirclement is used to update the position.

3. IWOA-PID Model

The control algorithm of the robot directly affects the tracking accuracy, convergence speed and robustness of the robot. PID control is a real-time control method which adjusts the difference between input and feedback through proportion, integral and differential operation, in which the proportion \( (K_p) \) can improve the regulating speed; the integral \( (K_i) \) can reduce the system steady state error; the differential \( (K_d) \) can improve the system stability and dynamic performance. Considering the influence of the gravity of industrial robot, the Lagrange dynamic equation is shown in formula (11):

\[ D(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau \]  

Where \( D(q) \) is the \( n \times n \) inertia matrix of the robot, \( C(q,\dot{q}) \) is the centrifugal force and Coriolis force vector, \( G(q) \) is the \( n \times 1 \) gravity vector, \( n \) is the joint number of the robot, \( q, \dot{q}, \ddot{q} \) are joints position, joints speed and joints acceleration respectively, \( \tau \) is the motor torque \([17,18]\). The PID control law of the robot multi axis control system is shown in formula (12):

\[ u(t) = (K_p + K_i)e + K_i \int_0^t e(\delta)d\delta + K_d\dot{e} \]  

Where \( e = q_d - q \) is trajectory tracking error, \( \dot{e} = \ddot{q} - \dot{q} \) is track error derivative, \( q_d \) is ideal trajectory position, \( \dot{q}_d \) is ideal speed, \( e(\delta) \) is joint error varying with time.

IWOA-PID control is to dynamically adjust parameters \( K_p, K_i \) and \( K_d \) in PID through IWOA, its structure is shown in Figure 1. Its fitness function and objective function are shown in formula (13) and (14), find the optimal solution of fitness function through IWOA to adjust \( e(t) \) and \( u(t) \) in the function, and realize the adjustment of \( K_p, K_i \) and \( K_d \) through the adjusted \( u(t) \). Let the three parameters \( K_p, K_i \) and \( K_d \) in PID regulation be respectively the three position components of whale.

Where \( r(t) \) is system input, \( y(t) \) is system output, \( e(t) \) is system error. The formula of fitness function is:

\[ f = \frac{1}{1 + J} \]  

Where \( J \) is objective function, the formula is:

\[ J = \int_0^t |e(t)(e(t) + u^2(t))|dt \]  

(14)
4. Experimental analysis

4.1. Experiment platform and modelling

Take SYJI-0035 6-axis robot of Henan Senyuan electric robot research center as the experimental platform, and its substance is shown in Figure 2; the robot simulation model is established by using MATLAB robotics toolbox and Simulink, as shown in Figure 3.

Figure 1. IWOA-PID algorithm structure diagram

Figure 2. SYJI-0035 robot

Figure 3. Model of the 6-axis robot
4.2. Simulation results and analysis

In MATLAB, the functions of assignin ('base', 'Kp', x(1)), assignin ('base', 'Ki', x(2)) and assignin ('base', 'Kd', x(3)) are used to transfer the $K_p$, $K_i$ and $K_d$ values adjusted by IWOA in real time and input them to PID controller to realize the motion control of 6-axis robot.

The IWOA-PID control model in Simulink is shown in Figure 4, in which (1) is the setting module of starting point and ending point position, (2) is the IWOA-PID control module, (3) is the inverse kinematics solution module of robot, and (4) is the dynamics module of robot. In (1), set the robot's initial point position $q=[0,0,0,0,0,0]$ and end point position $q_f=\begin{bmatrix}\frac{\pi}{2} & -\frac{\pi}{2} & \frac{\pi}{3} & \frac{\pi}{3}
\end{bmatrix}$. In IWOA, the number of iterations is 100, the whale group size is 100, the maximum weight is 1.2, and the minimum weight is 0.8; in WOA, the number of iterations is 100, the population size is 100, and the weight is 1. As shown in Figure 5, 6, 7, 8, 9 and 10, it is the trajectory tracking error curve of traditional PID, WOA-PID and IWOA-PID in each joint of 6-axis industrial robot.

Figure 4. IWOA-PID model

According to the traditional PID, WOA-PID and IWOA-PID trajectory tracking error curves shown in Figure 5, 6, 7, 8, 9 and 10, the trajectory position prediction error of the three algorithms decreases in turn, and the convergence time of the trajectory position error reducing to 0 decreases in turn. When the robot is controlled by IWOA-PID, the trajectory of 6 joints is closest to the ideal trajectory, with the shortest convergence time and the smallest fluctuation, which greatly improves the robustness of the robot. Through the field test of 6-axis robot, the maximum synchronization error of 50 times average trajectory position is shown in Table 1. Among the maximum synchronization errors of each joint, the synchronization error of IWOA-PID control is the smallest. Compared with the traditional PID control, the maximum synchronization error of each joint is reduced by 28.3%, 15.4%, 24%, 56.3%, 25%, 80%; compared with the WOA-PID control, the maximum synchronization error of each joint is reduced by 14%, 15.4%, 22.2%, 36.4%, 16.7%, 72.2%; the synchronization error is obviously reduced, so the trajectory prediction accuracy of 6-axis robot based on IWOA-PID control is significantly high. Table 2 shows the convergence time of 50 times average trajectory position error to 0 in field test. It can be seen that the synchronization error of IWOA-PID control is the smallest in the convergence time of trajectory position error to 0 of each joint in 6-axis robot. Compared with the traditional PID control, the convergence time of each joint is reduced by 23%, 16%, 27%, 40%, 31.2%,
20%; compared with the WOA-PID control, the convergence time of each joint is reduced by 14%, 11%, 20%, 20%, 15%, 14%. Therefore, based on IWOA-PID control, the overshoot of 6-axis robot system is reduced and the convergence speed is significantly improved.

**Figure 5.** Trajectory tracking error of joint 1

**Figure 6.** Trajectory tracking error of joint 2

**Figure 7.** Trajectory tracking error of joint 3
Figure 8. Trajectory tracking error of joint 4

Figure 9. Trajectory tracking error of joint 5

Figure 10. Trajectory tracking error of joint 6
Table 1. Trajectory position maximum synchronization error

| Joint | Joint PID | WOA-PID | IWOA-PID |
|-------|-----------|---------|----------|
| 1     | 0.00120   | 0.00100 | 0.00086  |
| 2     | 0.00039   | 0.00039 | 0.00033  |
| 3     | -0.00046  | -0.00045| -0.00035 |
| 4     | 0.00016   | 0.00011 | 0.00007  |
| 5     | 0.00020   | 0.00018 | 0.00015  |
| 6     | 0.0005    | 0.00036 | 0.0001   |

Table 2. Convergence time of Trajectory position error to 0

| Joint | Joint PID | WOA-PID | IWOA-PID |
|-------|-----------|---------|----------|
| 1     | 4.8       | 4.3     | 3.7      |
| 2     | 5.0       | 4.7     | 4.2      |
| 3     | 4.3       | 4.0     | 3.2      |
| 4     | 2.0       | 1.5     | 1.2      |
| 5     | 1.6       | 1.3     | 1.1      |
| 6     | 1.5       | 1.4     | 1.2      |

5. Conclusion
Based on IWOA, paper studies the IWOA-PID motion control algorithm to realize the motion control of 6-axis industrial robot. Through the simulation and field test of traditional PID control, WOA-PID control and IWOA-PID control, the experimental results verify the effectiveness of IWOA-PID for the control of 6-axis industrial robot. Through comparison of three algorithms, it can be seen that the IWOA-PID control algorithm based on IWOA-PID control algorithm has high trajectory tracking accuracy, fast convergence speed and small moving fluctuation in the moving stage of robot.

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