Identification of Friction Parameters of Robot Joints Based on Energy Consumption Model

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Abstract. In order to solve the problem that the joint friction torque value of industrial robots is difficult to be measured in practice, the joint friction identification method based on the energy model is used to indirectly obtain the friction model parameters by measuring the energy consumption value. According to the energy model and the measured robot energy value, the genetic algorithm is used to realize the parameter identification of the Stribeck friction model of joint friction. The results of the two identification methods based on friction torque identification and energy model identification are compared. The simulation results show that the error ratio of all the friction model parameters obtained by the two identification methods is less than 8%, and the error target value of the two identification results is less than 0.1%, which can effectively identify the relevant friction parameters. By designing an experimental scheme, the different speeds and corresponding energy consumption data of the IRB140 robot when joint 1 operates at a constant speed in a specified time are measured, and the Stribeck friction model parameters of the IRB140 robot’s joint 1 are identified by the proposed method.

1. Introduction
With the development of modern industry and the rapid development of science and technology, China's industrial system is constantly improving. Industrial robots have gradually become an important equipment of industrial production and the core link of the development of intelligent industry. When the robot is working, the limited energy is used reasonably and effectively, thereby reducing the energy consumption in the robot cycle, which is in line with the national energy conservation and emission reduction policy. It is estimated that the energy loss due to friction in industry accounts for about 1/3~1/2 of the total energy consumption[1]. Therefore, in the analysis of energy consumption, the influence of joint friction must be considered, and the selection and parameter identification of the joint friction model should be carried out.

In view of the above problems of joint friction model and parameter identification, scholars at home and abroad have done a lot of research. In terms of friction models, based on friction phenomena, the friction models proposed by the researchers can be roughly divided into two categories: static friction models and dynamic friction models. Static friction models mainly include Coulomb model, Coulomb-viscosity model, static friction-Coulomb-viscosity model, exponential model, karnopp model, etc[2]. Dynamic friction models have been proposed successively, including Dahl model[3], LuGre model[4], Leuven model[5], GMS model[6], etc. In terms of friction model parameter identification, intelligent algorithms can be used to achieve high-precision parameter identification. Liu Peng[7] et al. from the Robotics Institute of Shanghai Jiaotong University identified the parameters of the Stribeck friction model. The identification error is less than 5%, which effectively avoids the problem of local optimal solution, and the adaptive genetic algorithm is applied to fit the
experimental data. Liu Boxi[8] et al. from Xiangtan University identified LuGre model by combining least square method and interval analysis. The identification process was divided into two steps to identify 4 static parameters and 2 dynamic parameters, and the static parameters were identified by dynamic method. Z.ingul, O.Karahan[9] et al. designed a method to identify the physical parameters of the nonlinear system by using particle swarm optimization algorithm, and effectively realized the identification of 16 physical parameters in the RX-60 manipulator.

But in actual work, the joint friction value for industrial robots cannot be easily obtained. Therefore, this paper proposes an identification method of joint friction parameters based on the energy model. According to the analysis of the Strubeck friction model, the friction model is replaced by the corresponding energy model. Finally, the genetic algorithm is used to identify the friction parameters of the joint by measuring the energy value.

2. Friction Characteristic Analysis

For a typical electromechanical servo system friction in lubrication, the two mutual contact surfaces of the system from static to sliding friction will change in four stages, each stage is static friction, boundary lubrication stage, the mixed lubrication stage and the hydrodynamic lubrication stage. The lubrication phase is shown in Figure 1.

![Friction Characteristic under Lubrication](image)

\[ F_f = \begin{cases} f_c + (f_s - f_c)e^{-|v/v_s|}f \cdot sgn(v) + \sigma v, & v \neq 0 \\ F_e & v = 0 \text{ and } |F_e| < F_s \\ f_s \cdot sgn(F_e) & \text{Other} \end{cases} \] (1)

Where \( F_f \) is the friction. \( f_c \) is Coulomb friction. \( f_s \) is the maximum static friction. \( v \) is the relative velocity of the two contact surfaces. \( v_s \) is the Strubeck speed. \( \xi \) is the empirical parameter. \( \sigma \) is the coefficient of viscous friction. \( F_e \) is the applied external force. \( sgn(\cdot) \) is a symbolic function.
3. Simulation of Friction Parameter Identification for Single-degree-of-freedom Systems

For a mechanical arm of a six-degree-of-freedom system, it is composed of a set of rigid body links and joints, where each link is connected by a joint. The entire system is a series mechanism that is structurally independent of each other and interacts in motion. In order to identify the friction parameters of the six joints, the specific method can refer to the holistic method in the analysis of physical problems, using step-by-step identification to complete the identification of the friction parameters of each joint in turn[10]. In the step-by-step identification process, a joint is selected separately for identification, and the manipulator is divided into two parts from the joint to be identified. Among them, the two separated parts are regarded as a whole without considering the internal friction. Finally, the friction model parameter identification of the six-degree-of-freedom system is realized.

3.1. Single-degree-of-freedom System Analysis

For the analysis of single-degree-of-freedom systems, taking the shaft body rotating around a fixed axis as an example, the process of parameter identification of the Strubeck friction model in a single-degree-of-freedom system based on friction torque and energy model is introduced. For a single-degree-of-freedom system rotating around a fixed axis, according to Newtonian mechanical analysis, the motion of the system can be described by an equation, and the dynamic equation is expressed as

\[ J\ddot{\theta} = \tau - M_f \]  \hspace{1cm} (2)

Where \( J \) represents the rotational inertia of the shaft, \( \theta \) is the rotation angle of the shaft, and \( \tau \) is the input torque.

The energy equation derived from the dynamic equation is expressed as

\[ W_c = \int_0^t (\tau \dot{\theta}) dt = \int_0^t (J\ddot{\theta} + M_f) \dot{\theta} dt \]  \hspace{1cm} (3)

For the friction model, according to the stribeck friction model expression (1), when the servo motor rotates in different directions, the parameters in the friction model are different. In order to facilitate the analysis, set the same friction parameters in the forward and reverse directions to identify the friction parameters, and take the empirical parameter \( \xi = 2. \) At this time, the corresponding relationship between the specific static friction torque and the rotation speed in the rotating system is expressed as:

\[ M_f = M_c^+ + (M_c^+ - M_c^-)e^{-|\dot{\theta}/\nu_s|^2} + \sigma^+ \dot{\theta} \]  \hspace{1cm} (4)

According to the energy equation, the corresponding relationship between the energy consumption and speed of the system can be obtained as the following formula (5).

\[ W_c = \int_0^t (\tau \dot{\theta} + M_f) \dot{\theta} dt = \int_0^t (J\ddot{\theta} + M_c^+ + (M_c^+ - M_c^-)e^{-|\dot{\theta}/\nu_s|^2} + \sigma^+ \dot{\theta}) \dot{\theta} dt \]  \hspace{1cm} (5)

According to the above speed-friction torque and speed-energy consumption correspondence, two identification methods are designed, which are based on friction torque and energy consumption to identify the friction model parameters in a single-degree-of-freedom system. And the identification errors of the two methods are compared. The specific steps to achieve are as follows: the friction parameter identification process shown in Figure 2.
Figure 2. Process diagram of friction parameter identification.

3.2. Obtaining Strubeck Curve and Energy Consumption Curve of Friction Model

For the acquisition of friction torque and energy consumption, we can know from the equation of motion (2) and the equation of energy (3) that when $\dot{\theta} = 0$, the running speed is constant. At this time, according to the speed-friction force correspondence, it is equivalent to constant friction, so the following equation (6) holds.

$$\tau = F_r, W_r = \int_0^\epsilon |(M_f)| |\dot{\theta}| dt = \left| \left(M_c^+ + (M_c^+ - M_c^+)e^{-|\dot{\theta}/v_\alpha|^2} + \sigma^+ \dot{\theta} \right) \right| |\dot{\theta}| dt \quad (6)$$

Simplify the formula (6):

$$W_r = \left| \left(M_c^+ + (M_c^+ - M_c^+)e^{-|\dot{\theta}/v_\alpha|^2} + \sigma^+ \dot{\theta} \right) \right| |\dot{\theta}| t \quad \text{for } \dot{\theta} > 0 \quad (7)$$

Therefore, the constant speed-friction torque numerical sequence can be obtained by designing a constant speed tracking experiment. At the same time, when the constant speed running time $t$ is set, the energy loss of friction in this time period can be obtained through the energy equation of the system, so as to obtain the speed-energy consumption sequence within the specified time. Among them, the specific method of obtaining friction torque and energy consumption is that a set constant speed closed-loop system takes the sequence $\{\dot{\theta}_i\}$ as the speed command signal, by using the PD control law, to achieve accurate speed controlled object tracking, the corresponding sequence of control moment $\{u_i\}$ , thereby obtaining a corresponding set of static friction torque sequence $\{M_i\}$ and energy consumption sequence $\{W_i\}$. The PD control law is

$$u_i = K_p e_i + K_d \dot{e}_i \quad (8)$$
The Stribeck curve and the energy consumption curve are obtained through constant-speed tracking simulation. During constant-speed track, the constant speed run time is set to 10s, \( t = 10s \), the controlled object is set to formula (2), \( J \) is taken as 0.20. And the friction model represented by formula (4) is taken as the static friction of the actual system. At the same time, the corresponding speed sequence \( \{\dot{\theta}_i\} \) is set as the command signal, which is used to obtain the friction torque value and the energy consumption value corresponding to the speed. Among them, set the speed sequence as \( \{\dot{\theta}_i\} = [-1:0.05:1] \), a total of 41 sets of data. For ease of analysis, the relevant parameters in the friction model are set to \( M_c^x = 0.4, M_s^x = 1.2, V_s^x = 0.1, \sigma^x = 0.25 \). The PD control law is used to accurately track each speed signal, and the parameters in the control law are \( K_p = 200 \) and \( K_d = 100 \). Using Matlab software for simulation, the fitted Stribeck curve is shown in Figure 3 and the speed-energy consumption curve is shown in Figure 4.

\[ \text{Figure 3. Fitting graph of Stribeck curve.} \]

\[ \text{Figure 4. Fitting graph of energy consumption curve.} \]

Figures 3 and Figures 4 are the Stribeck curve and energy consumption curve obtained by setting friction parameters, where "○" represents the friction torque sequence and energy consumption sequence corresponding to the speed sequence. Comparing the analysis of friction characteristics, in the Stribeck friction model curve of Figures 3, when the speed interval is \([0, 0.05]\), it corresponds to the static friction stage. When the speed interval is \([0.05, 0.2]\), it corresponds to the mixed lubrication stage. When the speed interval is \([0.2, 1]\), it corresponds to the hydrodynamic lubrication stage. After the simulation is completed, the obtained 41 sets of speed-static friction torque sequence and speed-energy consumption sequence are saved. This data is used as the actual value of friction torque and energy consumption of the actual system, and is used as identification error comparison data in the identification process.

3.3. Genetic Algorithm Design of Friction Model Parameter Identification

On the basis of the obtained 41 sets of speed-static friction torque sequence and speed-energy consumption sequence, genetic algorithm was used to identify the parameters of the model. One is based on the speed-static friction torque sequence, and the other is based on the speed-energy consumption sequence. And the identification errors of the two are compared.

According to the established friction model, there are 4 parameters \((M_c, M_s, \nu_s, \sigma)\) to be identified. Set these four friction parameter vectors to be identified as individuals, and each iteration of the genetic algorithm will have corresponding parameter identification values. Set the parameter identification value as

\[
\hat{x}_m = [\hat{M}_c^+, \hat{M}_s^+, \nu_s^+, \sigma^+]^T \quad m = 1, 2, \cdots, M
\]

(9)

Where \( M \) is the population size.

According to the following formula (10,11), the corresponding friction torque identification value and energy consumption identification value are obtained respectively.
\[ \hat{M}_i = \hat{M}^i_c + (\hat{M}^i_c + \hat{M}^i_s) e^{-|\theta_i|^2} + \sigma^i \theta \hat{\theta} \quad (10) \]

\[ \hat{W}^i_f = \hat{W}^i_f = (\hat{M}^i_c + (\hat{M}^i_c + \hat{M}^i_s) e^{-|\hat{\theta}/\hat{\theta}|^2}) \cdot \theta t \quad (11) \]

The identification error is obtained by the difference between the friction torque and energy consumption sequence obtained before and the corresponding identification value, respectively set as

\[ e_i = M_i^j - \hat{M}^i_j \quad i = 1, 2, \ldots, N \quad (12) \]

\[ e_i = W_f^i - \hat{W}_f^i \quad i = 1, 2, \ldots, N \quad (13) \]

There are 41 sets of data in total, and the sum of the squares of the identification errors corresponding to each speed is taken as the objective function, which is expressed by the following formula (14).

\[ J_m = \sum_{i=1}^{N} e_i^2 \quad m = 1, 2, \ldots, M \quad (14) \]

The function of selecting individual fitness is expressed by the following formula (15).

\[ \begin{cases} C_{\text{max}} = \max(J_m) \\ f_m = C_{\text{max}} - J_m \end{cases} \quad (15) \]

Using decimal floating point encoding format, the steps of genetic algorithm design are as follows:

Step 1: The evolutionary algebra \( G \) is set to 0, and the initial population is randomly generated within the set search range;

Step 2: Calculated for each individual fitness value \( f(X_i) \);

Step 3: Determine whether the maximum evolutionary generation is reached. If the maximum evolutionary algebra is reached, the algorithm is terminated; otherwise, it is transferred to step 4;

Step 4: Perform the selection operation. Select and generate a new generation of population according to the fitness value.

Step 5: Crossover operations are performed between individuals with a set crossover probability. Random mutation crossover operations are performed in each individual with a set the mutation probability.

Step 6: Perform \( G+1=G \) and go to step 2.

3.4. Results Analysis Of Friction Model Parameter Identification

According to the genetic algorithm designed above, set the following parameters: the population size is set to \( M=200 \), the maximum genetic number is set to \( G=1000 \), the crossover probability is set to \( P_c=0.9 \). The mutation probability is set to \( P_m=0.1 \times (1:1:1:1) \times 0.01/\text{Size} \). Because the larger the individual adaptation value, the smaller the mutation probability, and the dynamic mutation probability can improve the algorithm convergence speed. Set the corresponding search range of the four friction parameters to be identified as \( M_c \in [0, 1], M_s \in [0, 2], v_s \in [0, 5], \sigma \in [0, 0.5] \). The genetic algorithm is used for identification based on the speed-static friction torque sequence and the speed-energy consumption sequence. The identification Strubeck curve results of the two identification schemes are shown in figure 5 and figure 6, respectively. Figure 7 is a graph of energy consumption identified by energy consumption sequence. The results of friction model parameters identified by the two identification methods are shown in Table 1.
Figure 5. Striebeck curve identified by friction torque sequence.

Figure 6. Striebeck curve identified by energy consumption sequence.

Figure 7. Energy consumption graph identified by energy consumption sequence

Table 1. Comparison of two friction parameter identification results.

| Identification parameters of friction model                                      | $M_c$ | $M_z$ | $\nu_5$ | $\sigma$ |
|---------------------------------------------------------------------------------|-------|-------|---------|---------|
| The true value of the parameter                                                 | 0.4   | 1.2   | 0.1     | 0.25    |
| Identification value obtained by friction torque                                | 0.3998| 1.2428| 0.101   | 0.2506  |
| Corresponding error ratio                                                       | 0.05% | 3.57% | 1.00%   | 0.24%   |
| Identification value obtained by energy consumption                            | 0.3974| 1.108 | 0.104   | 0.2518  |
| Corresponding error ratio                                                       | 0.65% | 7.67% | 4.00%   | 0.72%   |

According to the analysis in Table 1, the result error ratio of all friction model parameter identification of the two identification methods is less than 8%, and the target value of the error of the two identification results is less than 0.1%, which can effectively identify the relevant friction parameters. Comprehensively comparing the curves drawn by the two different methods to the Striebeck model parameter identification results, the Striebeck curves fitted by the two identification methods can better reflect the true curves. By comparing the difference between the fitted curve and the real curve, the speed stage can be divided into a low speed area and a high speed area. Among them, the speed interval [0,0.2] is divided into a low-speed zone, corresponding to the first three stages of friction; the speed interval [0.2,1] is divided into a high-speed zone, corresponding to the hydrodynamic lubrication stage of friction. The analysis is based on the identification curve of the
energy law, comparing the fitting errors of the low-speed zone and the high-speed zone, it can be seen that there are large errors in the low-speed zone, and the high-speed zone is basically completely fitted. The main reason for this result is that there is too little sampled data in the low speed area, which makes the error of the maximum static friction torque \( M_s \) in the friction parameter identification result too large, up to 7.67\%, but the accuracy can still be used in situations where accuracy is not required.

4. Acquisition of IRB140’s Energy Consumption Value

In a two-degree-of-freedom system, the equation of motion[11] can be simplified as follows:

\[
\begin{bmatrix}
T_i \\
T_j
\end{bmatrix} =
\begin{bmatrix}
D_{ii} & D_{ij} \\
D_{ji} & D_{jj}
\end{bmatrix}
\begin{bmatrix}
\dot{\theta}_i \\
\dot{\theta}_j
\end{bmatrix} +
\begin{bmatrix}
D_{iii} & D_{iij} \\
D_{jii} & D_{jjj}
\end{bmatrix}
\begin{bmatrix}
\dot{\theta}_i^2 \\
\dot{\theta}_j^2
\end{bmatrix} +
\begin{bmatrix}
D_{iij} & D_{ijj} \\
D_{jii} & D_{jjj}
\end{bmatrix}
\begin{bmatrix}
\dot{\theta}_i \dot{\theta}_j \\
\dot{\theta}_j \dot{\theta}_i
\end{bmatrix} +
\begin{bmatrix}
D_1 \\
D_2
\end{bmatrix}
\]

(16)

In the formula (16), the coefficient \( D_{ii} \) represents the effective inertia at the joint i. At joint i, the torque generated by the acceleration is equal to \( D_{ii} \dot{\theta}_i \). The coefficient \( D_{ij} \) represents the coupling inertia between joint i and joint j. When the joint i or the joint j has acceleration, the moment \( D_{ij} \dot{\theta}_j \) or \( D_{ji} \dot{\theta}_i \) is generated at the joint j or the joint i. For the two-link system \( D_{ii}, D_{jj} \) is zero. The term \( D_{ij} \dot{\theta}_j^2 \) represents the centripetal force generated on the joint i due to the velocity at the joint j, and its value is zero when only one joint moves. All \( \dot{\theta}_i \dot{\theta}_j \) terms represent the Coriolis acceleration, and the Coriolis force is multiplied by the corresponding inertia. The remaining \( D_1 \) represents the gravity at joint i.

For a six-joint robot, when one joint moves and the remaining joints are locked, according to the above analysis, the inertial force is zero, the Coriolis force term is zero, and the centripetal force term is also zero. Therefore, for any robot joint i, if the axis of the joint i is parallel to the direction of gravity, when the joint i moves at a constant speed and the other joints are locked, the input torque is equal to the friction torque. At this time, the energy consumption of joint friction can be obtained by ensuring the uniform movement of the joint. Set the motion path of joint 1 as shown in Figure 8. When the parallel condition of the axis of the joint i and the direction of gravity is not satisfied, the joint i will also be affected by the effect of gravity during its movement, and its constant speed movement needs to overcome both the friction torque and the gravity moment. In this case, the motion path of the joint 2 is set in Figure 9. And the energy consumption corresponding to different speeds is measured under the condition of uniform speed. Two sets of experiments were designed. Experiment 1: Joint i moves from joint angle \( \theta_1 \) to \( \theta_2 \) at a constant speed, and the recording time is \( t_1 \sim t_2 \). Experiment 2: Joint i moves from joint angle \( \theta_2 \) to \( \theta_1 \) at a constant speed, and the recording time is \( t_2 \sim t_3 \).

Figure 8. The motion path graph of joint 1
In experiment 1, the input torque of the joint is:

Figure 9. The motion path graph of joint 2
\[ \tau_{t1} = \tau_g(\theta) + M_f(\dot{\theta}) \]  
(17)

Because the movement direction of experiment 2 is opposite to experiment 1, the input torque meets the following formula (18):

\[ \tau_{t2} = \tau_g(\theta) + M_f(-\dot{\theta}) \]  
(18)

Where, \( \tau_g(\theta) \) is gravity moment and \( F_f(\dot{\theta}) \) is friction torque.

Because the robot platform uses high-precision reducer transmission. The difference between forward and reverse friction is small. Therefore, the following formula (19) holds.

\[ M_f(-\dot{\theta}) = -M_f(\dot{\theta}) \]  
(19)

Through experiment 1 and experiment 2, the whole motion finally returns the manipulator to its initial position, so the work of gravity torques is zero in the whole process. Therefore, the effective energy consumption of the manipulator in the period from \( t_1 \) to \( t_2 \) can be used as the friction torque energy consumption.

\[ \int_{t_1}^{t_3} M_f(\dot{\theta})\dot{\theta} dt = W_e \]  
(20)

In the formula (20), \( W_e \) represents the effective energy consumption of the manipulator.

For the experiment of the above design, \( \dot{\theta} \) is set to a constant operation, so the corresponding speed of the friction torque is also a fixed value. Therefore, formula (20) can be simplified as

\[ \dot{\theta}M_f(\dot{\theta})(t_3 - t_1) = W_e \]  
(21)

Energy consumption is measured using the following method. A resistor with high precision and small resistance is connected in series at the input end of the drive motor, and then an oscilloscope is used to connect the two ends of the resistor to measure the effective value of the voltage at both ends of the resistor during the operation of the motor. Then calculate the actual running current value according to Ohm's theorem, and the formula \( P=UI \) is used to calculate the motor driving power ignoring the small resistance voltage. Finally, the actual energy consumption value is calculated by \( W_M=Ut \). However, when measuring energy consumption, the measurement results include the heat loss of the motor. Therefore, the calculation formula of the total energy consumption includes the heat loss formula. And the calculation process is too complicated, so it is calculated according to the power factor of the motor. Here, the actual power consumed by the manipulator is multiplied by 0.8 as the effective power of the manipulator. That is to use \( W_e = 0.8Ut \) as the corresponding energy consumption test data.

5. Simulation of Friction Parameter Identification of IRB140’s Joint 1

According to the above experimental analysis, the energy consumption of joint friction is a function of joint angular velocity and time. Therefore, the corresponding friction energy consumption can be determined by measuring the different speeds and corresponding energy consumption data tables when the joint runs at a constant speed condition within a specified time. The genetic algorithm is used to identify the parameters of the friction model. According to the analysis, there are the following equations:

\[ \dot{\theta}M_f(\dot{\theta})(t_3 - t_1) = 0.8 \times W_M \]  
(22)

Taking the IRB140 industrial robot as the experimental object, and taking the movement of the joint 1 as an example, the MOVEJ instruction is used to set the joint 1 to run at different speeds. Then the corresponding data acquisition was completed. It should be noted that the speed set by MOVEJ is not expressed in degrees, so it needs to be converted. The average angular velocity of joint axis at different velocities was calculated from the experimental data. A total of 16 sets of data (V5, V10, V20, V30, V40, V50, V60, V80, V100, V150, V200, V300, V400, V500, V600 and V800) were set
respectively to make the movement run from the starting point P0 (such as 180°) to the intermediate point P1 (such as 0°), and then back to the initial point P0. If the Running time of The V800 is too short, the above-mentioned route points can be repeated during a single movement. Then all the sampling time points, the total energy value of the motor and the value of the rotation angle of the J1 axis are derived. The running time at V800 speed is taken as the total running time, and the time point of turning back at other speeds is found based on this. To make the difference between the before and after the point in time is equal to the total run time. Subsequently, the rotation angle and total energy of the corresponding start and end points are calculated. Finally, the average angular velocity at different rates and the total energy consumption of the manipulator in the same time are calculated. According to the experimental data, the total energy consumption of V800 in 0.336s~8.184s is 492.291J when the above routes P0~P1~P0 are run twice. Therefore, take the running time as 7.848s. The total energy consumption of the J1 axis at the same time is shown in Table 2 and Table 3.

| Table 2. The energy consumption of joint axis 1 at different speeds. |
|------------------|---|---|---|---|---|---|---|---|
| Set running speed | V5 | V10 | V20 | V30 | V40 | V50 | V60 | V80 |
| Average angular velocity (°/s) | 0.6 | 1.2 | 2.3 | 3.5 | 4.6 | 5.8 | 6.9 | 9.3 |
| Energy consumption at the same operating time (J) | 21.4 | 23.4 | 24.3 | 33.8 | 41.2 | 49.1 | 53.7 | 63.5 |

| Table 3. The energy consumption of joint axis 1 at different speeds. |
|------------------|---|---|---|---|---|---|---|---|
| Set running speed | V100 | V150 | V200 | V300 | V400 | V500 | V600 | V800 |
| Average angular velocity (°/s) | 11.6 | 17.4 | 23.1 | 34.7 | 46.2 | 57.5 | 69.2 | 92.1 |
| Energy consumption at the same operating time (J) | 73.5 | 97.7 | 124.1 | 178.3 | 235.8 | 297.8 | 359.3 | 492.3 |

According to the joint friction parameter identification method based on the energy consumption model proposed in this paper, the search range of the relevant parameters of the genetic algorithm is set to $M_c \in [0,1], M_s \in [0,5], v_s \in [0,100], \sigma \in [0,1]$. The results of the joint friction parameter identification of the joint axis 1 are shown in Table 4. The energy consumption figure 10 and the friction torque figure 11 drawn according to the identification results.

| Table 4. The identification result of the friction parameter of the joint axis 1. |
|------------------|---|---|---|---|
| Parameters identified by friction model | $M_c$ | $M_s$ | $v_s$ | $\sigma$ |
| Identification value obtained by energy consumption | 0.4367 | 0.8574 | 16.2675 | 0.0013 |

![Figure 10. Energy consumption result graph identified by energy consumption value.](image1)

![Figure 11. The friction torque curve obtained from the identification results.](image2)
According to the friction torque identification curve of Figure 11, it can be seen that the friction torque graph drawn using the joint friction parameters identified by the energy consumption model basically conforms to the friction torque characteristics of the foregoing analysis. According to the friction torque identification curve of Figure 11, it can be seen that the friction torque graph drawn using the joint friction parameters identified by the energy consumption model basically conforms to the friction torque characteristics of the foregoing analysis. According to the foregoing analysis results, the error of the joint friction identification result of the joint 1 is mainly at the low speed stage of the robot operation. The reason for this phenomenon is that there is too little data collection in the low-speed area and more data in the high-speed area in the experiment. Relatively speaking, the identification result of the hydrodynamic lubrication stage is more accurate.

6. Conclusions
In this paper, the parameter identification of the robot joint friction is studied. For the problem that the robot joint friction torque value is not easy to measure, a joint friction identification method based on the energy model is proposed. Compared with the identification method based on friction torque, the simulation results show that the error ratio of all friction model parameter identification results is less than 8%. In other words, both identification methods can effectively identify joint friction parameters. Among them, according to the results of joint friction parameter identification, it can be seen that the maximum error lies in the maximum static friction torque $M_s$, which can reach 7.67%. It reflects the low accuracy of the proposed method in the low-speed interval. But when the accuracy requirement is not high, the identification accuracy of this method can still be used. Moreover, this paper designs the actual energy consumption measurement scheme, and realizes the identification of the joint friction torque parameter of the IRB140 robot’s joint 1. In summary, when joint friction torque is required in some occasions and cannot be easily obtained by direct measurement, a practical method for indirectly identifying friction torque parameters can be obtained by measuring energy consumption.

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