A Method of Robot Grinding Force Control Based on Internal Model Control Principle

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Abstract. The application of robots in the grinding industry can solve the problems in traditional artificial grinding, such as high labor intensity, low work efficiency, unguaranteed processing quality and serious physical injury to workers. In order to ensure the grinding quality, it is necessary to control the grinding force. The aims of this study is use PID-IMC controller to control the grinding force. Carry on the robot dynamics analysis to establish the dynamics model. Based on the principle of internal model control (IMC), PID controller is optimized and PID-IMC controller is obtained, which is used to realize the constant force control of robot grinding. Simulation and experiments results show that, the dynamics model and control method proposed in this paper have a better effect in the control of robot grinding force.

1. Introduction
In the process of grinding, the robot is needed to contact with the workpiece. Too large contact force between the robot end and the workpiece will cause damage to the robot or the workpiece, too small contact force will cause the workpiece fail to meet the technical requirements. Therefore, in addition to the required precision of position, the grinding operation also requires the control of the contact force between robot and workpiece.

In the process of robot constant force grinding, the establishment of mechanical model is very important, and various control methods based on model have been established. In the process of robot belt grinding, dynamics model is established based on deformation, and an adaptive iterative constant force control is proposed in [1]. By building a press-and-release model, the method of model-based reinforcement learning, and grinding force control algorithm is proposed in [2] in the stages of impact and processing. In [3], the model is established according to the complete kinematics of robot grinding system, and optimal PI controller is designed by using dual iteration algorithm. Some researchers use auxiliary devices to control the robot’s grinding force. In [4], saturation integral fuzzy PI controller is used to achieve the transfer of force signal into the trajectory correction of robot end effector along the surface normal direction. [5] propose a control method by combine the model-based computational torque controller with model-free neural network controller. [6] propose an adaptive compliant force and position control algorithm based on neural network for highly nonlinear serial pneumatic artificial muscle robot.

According to Lagrange function, the dynamic model of robot is obtained. According to the principle of IMC, PID-IMC controller is designed and used to achieve the control of grinding force.
2. Model of grinding force

Grinding force is analyzed and dynamic model is built. The sensor is installed at the end of the robot and connects robot to workpiece to measure the grinding force. The robot holds the workpiece close to the grinding wheel to achieve grinding task. The analysis of grinding force is shown in Figure 1. The relationship of grinding force and the force measured by the sensor is as follows:

\[
\begin{align*}
F_t &= F_x \sin \theta + F_y \cos \theta \\
F_n &= F_x \cos \theta - F_y \sin \theta
\end{align*}
\]

(1)

Where, \(F_t\) is tangential force, \(F_n\) is normal force, \(F_x, F_y\) are sensor measurement data, \(\theta\) is the angle between the contact force and sensor measurement force, and \(\theta\) will vary follow the vary of contact point. Consider the resultant force \(F\) of \(F_t\) and \(F_n\) as the grinding force.

According to Lagrange function \(L=K-P\). The dynamic model of robot can obtained by derivative.

\[
\tau_i = \sum_{j=1}^{6} (D_{ij} \frac{d^2 \theta_j}{dt^2}) + I_{act} \sum_{j=1}^{6} \sum_{k=1}^{6} (D_{ijk} \frac{d \theta_j}{dt} \frac{d \theta_k}{dt}) + D_i
\]

(2)

The four terms on the right side of the equation are angular acceleration inertia term, driver inertia term, centripetal force term and gravity term respectively.

Where,

\[
\begin{align*}
D_{ij} &= \sum_{p=\max(i,j)}^{6} \text{Tr}ace(\frac{\partial R_p}{\partial \theta_j} Q_p (\frac{\partial R_p}{\partial \theta_i})^T) \\
D_{ijk} &= \sum_{p=\max(i,j,k)}^{6} \text{Tr}ace(\frac{\partial R_p}{\partial \theta_j} \frac{\partial R_p}{\partial \theta_k} Q_p (\frac{\partial R_p}{\partial \theta_i})^T) \\
D_i &= \sum_{p=1}^{6} -m_p g^T \cdot \left(\frac{\partial R_p}{\partial \theta_i} \bar{r}_p\right)
\end{align*}
\]

(3)  \hspace{1cm} (4)  \hspace{1cm} (5)

Grinding force can calculated by:

\[
F = J^{-1} \cdot \tau_6
\]

(6)

\[
\tau_6 = \sum_{j=1}^{6} (D_{6j} \frac{d^2 \theta_j}{dt^2}) + I_{act} \sum_{j=1}^{6} \frac{d \theta_j}{dt} \frac{d \theta_j}{dt} + \sum_{j=1}^{6} (D_{6j} \frac{d \theta_j}{dt} \frac{d \theta_j}{dt}) + D_6
\]

(7)

\(J\) is Jacobian matrix, \(I_{act}\) is the inertia of rotor for motor 6, \(\partial^T R_p\) is transfer matrix, \(m\) is the mass, \(g^T = [g_x \ g_y \ g_z \ 0]^T\) is the gravitational matrix, \(\bar{r}_p\) is the position of the center of mass in the coordinate system of the connecting rod.

3. PID-IMC controller

In the process of robot grinding, the force of contact will affect the grinding quality directly. In this paper, a control strategy which is easy to implement and adjust is proposed. IMC is a control strategy based on mathematical model processing, with good tracking characteristics, simple structure, automatic correction and other advantages. The basic structure is shown in Figure 2.

\[
K(s) = J^{-1}(s)H(s)
\]

(8)

\(H(s) = 1/(\lambda s + 1)^n\) is \(n\) order low pass filter, \(\lambda\) is filter constant which needs to be adjusted.
C(s)  
G(s)  
D(s)  
K(s)  
J (s)  
+  
+  
-  
y(s)r(s)  
\( r(t) \)  
\( y(t) \)  
Figure 2. IMC diagram  
Figure 3. Traditional PID control diagram  
Figure 4. IMC equivalent structure diagram  

The flow chart of traditional PID control is shown in Figure 3. Figure 2 and Figure 4 are equivalent, so the relationship between C(s) of PID feedback control and K(s) of internal model control is

\[
C(s) = \frac{H(s)K(s)}{1-H(s)K(s)J(s)} \quad (9)
\]

\[
K(s) = \frac{H(s)C(s)}{1+H(s)C(s)J(s)} \quad (10)
\]

The IMC principle is applied to traditional PID control, IMC is equal to the classical PID feedback control, and the PID-IMC controller is designed. Internal model \( J \) is divided into all pass part \( J_+ \) and Minimum phase part \( J_- \) \[7\],

\[
J(s) = J_+(s)J_-(s) \quad (11)
\]

\( J_-(s) \) is the minimum phase model of transfer function, and this model only contains the zero of the left half plane. \( J_+(s) \) is the all pass filter of transfer function, \( |J(s)| = 0 \) for all frequency and delay, and contain the zero of the right half plane.

\[
K(s) = J_-^{-1}(s) \quad (12)
\]

Design PID controller as

\[
C(s) = T_p\left(1 + \frac{1}{T_i} + T_d s\right) \quad (13)
\]

According to (8)-(12)

\[
C(s) = \frac{(\lambda s+1)^n J_+^{-1}(s)}{1-J_+(s)} \quad (14)
\]

According to (13) and (14)

\[
T_p\left(1 + \frac{1}{T_i} + T_d s\right) = \frac{J_+^{-1}(s)(\lambda s+1)^n}{1-J_+(s)} \quad (15)
\]

Taylor equation is performed on the right part of (15) to obtain PID controller parameters corresponding to IMC. Then tuning filter constant \( \lambda \).

Grinding dynamic model is:

\[
F(t) = m\ddot{x}(t) + c\dot{x}(t) + kx(t) + f_q(t) \quad (16)
\]

\( F(t) \) is grinding force, \( x(t) \) is the depth of grinding, \( \dot{x}(t) \) is the velocity of grinding, \( \ddot{x}(t) \) is the acceleration of grinding. \( m \) is the mass coefficient of system, \( c \) is the system damping coefficient, \( k \) is the system stiffness coefficient. In the actual grinding process, the robot is also affected by the oscillating force \( f_q(t) \) caused by the uncertainties of the interaction surface \[8\]. In this paper, assume \( f_q(t) \) is a small noise interference. So we obtain the model of \( J \) is:

\[
J(s) = \frac{\omega_n^2}{s^2 + 2\xi \omega_n s + \omega_n^2} \quad (17)
\]
\[ \omega_n = \sqrt{\frac{k}{m}}, \xi = \frac{c}{2\sqrt{mk}} \]

4. Results

PID controller, IMC controller, PID-IMC controller are used to achieve the simulation and experiment of robot grinding, respectively. The expected grinding force was set as 20N, and MATLAB Simulink software was used for simulation. In this paper the oscillating force caused by the uncertainties of the interaction surface is considered as a small noise disturb, robot grinding model is built.

PID, IMC and PID-IMC control methods are used to control the grinding force respectively. The grinding force and its errors are shown in the Figure 5 and Figure 6. With PID-IMC control, the convergence speed is fast and the steady-state error is small, the advantages of PID are retained, while the maximum overshoot is reduced.

5. Discussion and Conclusion

In the aspect of robot constant force control, PID control based on IMC principle has the best control effect. The response time of IMC controller is long. PID control parameter setting is difficult. PID-IMC control is equivalent to PID controller parameters optimization based on IMC principle, and achieve the best control effect.

The robot grinding method with constant force control proposed in this paper will be applied in the robot grinding industry, such as the welding seam, flying edge and burr of machined parts.

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