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Adaptive variable impedance constant force control of robot grinding for casting surface defects

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Abstract

To solve the problem of insufficient adjustment ability of traditional impedance control due to uncertainty of environmental parameters when the robot grinds castings, an adaptive variable impedance constant force control method for robot grinding with unknown environmental parameters is proposed. In the proposed method, first, self-impedance impedance control is used as inner loop control to realize fast tracking response of actual trajectory to reference trajectory and reduce overshoot of grinding force; secondly, fuzzy adaptive variable impedance control is used as outer loop control to realize real-time prediction of unknown environmental parameters and real-time adjustment of impedance parameters; finally, the constant force control of robot grinding in unknown environment is realized by combining inner and outer loop control. In order to verify the effectiveness of the proposed method, the simulation model of the algorithm is constructed based on the MATLAB-SIMULINK simulation platform for simulation analysis, and experimental verification is carried out on the casting surface defects robot grinding platform. The simulation and experimental results show that the algorithm can control the grinding force well when grinding unknown environmental parameters, the force control accuracy is within $\pm 1\text{N}$, the average grinding force error of casting fin grinding is about 7.59%, the average grinding force error of casting riser grinding is about 5.31%, and the contour accuracy of casting surface defects is good after grinding by force control, and the surface quality after grinding is improved.

Keywords Robot assisted grinding Casting surface defect Self-impedance impedance control
Fuzzy adaptive variable impedance control Unknown environment

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1 Introduction

Casting is one of the common molding methods in equipment manufacturing, which has the advantages of low cost and good adaptability[1]. Complex castings are an important part of high-end equipment, and their quality determines the function and performance of the equipment. Most parts are obtained by casting, and the casting residual features of the blank must be cleaned before entering the subsequent finishing or assembly process. At present, more than 95% of enterprises use manual operation to clean casting surface defects, manual operation is generally through angle grinder and other equipment to remove casting riser and fin, there are problems of low efficiency and poor consistency, so it is imperative to use automatic equipment to grind casting surface defects. Because of its good flexibility, large workspace and high efficiency, industrial robots[2-4] can better adapt to complex and diverse processing paths and improve production efficiency. At present, it is generally believed that robot processing complex parts has become the mainstream processing mode of robot intelligent manufacturing[5,6], especially for the grinding of casting surface defects. Robot grinding is a typical constrained operation mode[7]. The force change cannot be ignored when robot interacts with environment[8]. In order to better complete the grinding task and improve the contour accuracy of casting surface defects, robot grinding force control is the key[9]. Due to the weak rigidity, complex force and strong coupling of industrial robots, it is difficult to control the grinding force, so the robot grinding force control technology has always been a difficult and hot spot in this field.

The grinding force control method of robot end is mainly divided into passive force control[10-11] and active force control[12-13]. Passive force control is realized through energy absorption or storage of auxiliary flexible mechanism, which requires complex actuator to be installed at robot end. Under the condition of limited load on robot end, higher requirements are put forward for the design of end mechanism[14-15]. At the same time, passive force control can not adjust the control force in real time, and its universality is poor, and it is only suitable for the working conditions with low control accuracy, so active grinding force control with force feedback becomes the main research direction of robot constant force control. Scholars at home and abroad have carried out a lot of research on robot grinding constant force control methods. Hogan[16] first proposed the concept of impedance control, which greatly promoted the development of robot grinding force control technology. The basic idea of impedance control is to couple force and position, and indirectly control grinding force by correcting the position of robot end. Bu[17] proposes an adaptive system that enables impedance controllers to adjust parameters automatically without much force overshoot. Guo et al[18] introduced Q-learning learning algorithm to change the parameters of impedance controller in the case of unknown system dynamics. Duan et al[19] set the expected stiffness to zero and proposed an adaptive impedance control method with uncertain variable damping parameters under the condition of known environmental position and unknown environmental stiffness. However, the feasibility of this method highly depends on the value and range setting of controller parameters. Shen et al[20] uses recursive least squares iterative method to estimate environmental parameters, which can track the required force without knowing environmental information. Kakinuma et al[21] constructed a robot grinding control system based on macro and micro mechanism to realize dynamic grinding force control. Lakshminarayanan et

al[22] proposed an iterative learning controller based on impedance control for tracking workpiece contour and adjusting position and force in robot grinding operation. Kana et al[23] proposed a collaborative curve-following control method based on impedance control to achieve human-machine collaborative edge chamfering and grinding tasks. Zhu et al[24] proposed a hybrid robot attitude/force control structure with contact point variation compensation to achieve force tracking control in uncertain environments. Zhang et al[25] proposed a force coordination method based on impedance control to reduce the impact caused by critical contact between robot working tool and workpiece. Domroes et al[26] studied the difference between position control and force control in robot grinding process by constructing robot grinding experimental system with six-dimensional force sensor. Although the influence of grinding force fluctuation on material removal rate was analyzed, this grinding method was not suitable for complex parts.

Roveda et al[27-28] overcome the force overshoot problem by using impedance control and iterative learning in fine interaction tasks, and have been applied to industrial interaction tasks. Zhai et al[29] improved the impedance control model through RBF neural network, compensated the position error and stiffness error in unknown environment, and improved the stability of grinding force. Portillo-Velez et al[30] proposed an impedance control method based on modified reference trajectory to solve the force limitation problem in robot cooperative motion. Zhang et al[31] proposed a PPO constant force grinding control algorithm based on reinforcement learning, which solved the problem of unstable actual grinding force caused by low robot stiffness and positioning error. Xu et al[32] designed a grinding robot composed of manipulator and 2-DOF parallel structure, and proposed to overcome the limitations of impedance control through model-based predictive optimization (MPO), which improved the force tracking ability of the system. Zhao et al[33] developed a normal search algorithm for unknown workpiece contour on the basis of adaptive control to control force and position in normal and tangential directions, which can realize direct grinding. Cheng et al[34] studied the grinding force during microgroove grinding (MSG) of single crystal sapphire. The grinding tool and measuring equipment were installed on the robot and fixed side respectively, but only the grinding force could be monitored. They did not use force control technology. Zhang et al[35] designed a controller based on radial basis function neural network for robot tracking control, reducing robot vibration and improving system stability. Kana et al[36] proposed a collaborative curve-following control method based on impedance control to achieve man-machine collaborative edge chamfering and grinding tasks.

In fact, the robot grinding casting is carried out in an unknown environment, the environmental parameters have the characteristics of real-time change, and the grinding operation belongs to the process of reducing materials, and the corresponding grinding force cannot exceed the threshold value. Overgrinding will reduce the contour accuracy of the workpiece, and in serious cases, the workpiece will be scrapped. Although the above-mentioned grinding force control method has certain control effect in impedance parameter tuning and parameter prediction, it requires high accuracy of the model, the calculation amount of the control method and controller is large, and it is difficult to determine the stability of control boundary conditions. Continuous contact grinding operation of industrial robot requires good interaction between robot and workpiece [37-38]. In order to ensure grinding quality and contour accuracy, grinding force control method with fast response speed and good stability is particularly important[39-40].

In order to solve the problem that the robot has insufficient adaptive adjustment ability of grinding force due to lack of environmental information or inaccurate environmental information

when grinding castings, the adaptive variable impedance constant force control of robot grinding castings with surface defects is studied in this paper, and a grinding force control method combining unknown environmental parameter prediction and variable impedance parameter is proposed. In the control process of the method, firstly, self-impedance impedance control is used as the inner loop control to realize the fast tracking response of the actual trajectory of the robot terminal to the reference trajectory and reduce the overshoot of the grinding force; secondly, the fuzzy adaptive control is used as the outer loop control to realize the prediction of unknown environmental parameters and the adjustment of impedance parameters; and finally, the constant force control of the grinding process is realized by combining the two. Before the force control, the sensor parameters are calibrated to eliminate the sensor error and the influence of the end load gravity on the sensor perception, so that the external actual grinding force can be accurately obtained during the force control process.

The rest of this paper is organized as follows: in the second section, the filtering process of the information collected by the six-dimensional force sensor at the end of the robot and the solution method of the load and zero point of the sensor at the end of the robot are introduced; in the third section, the contact model of the grinding system and the mathematical model of the grinding force control algorithm are introduced; in the fourth section, the MATLAB-SIMULINK simulation results of the algorithm are analyzed; in the fifth section, the casting grinding experiment is carried out, and the experimental results are analyzed and discussed in the sixth section.

2 Industrial robot grinding force sensing system

As a key part of force control to obtain the grinding force signal between tool and workpiece, the real-time performance and accuracy of industrial robot grinding force sensing system are particularly important. As shown in Fig.1, the robot grinding force sensing system consists of a six-dimensional force sensor, a switching power supply, a communication device and a force information processing system. The six-dimensional force sensor is installed between the flange of the robot and the grinding tool to monitor the change of grinding force. The force information processing system includes signal filtering and gravity compensation.

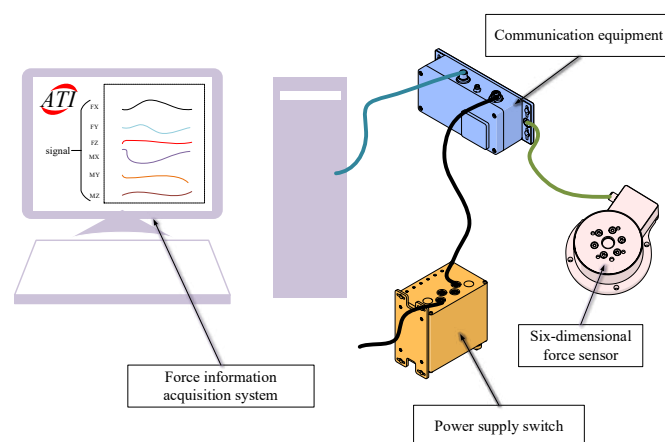


Fig.1 Grinding force sensing system for industrial robots

There is a certain deviations between the measured position trajectory and the reference position trajectory of the blade surface, as shown in Figure 3. The trajectory deviations of any point on the blade concave surface is 0.5329mm, and the blade convex surface is -0.5455mm.

2.1 Signal filtering

Due to the influence of grinding environment, the signal collected by force sensor contains gaussian noise signal, which seriously interferes with the acquisition of actual grinding force signal and can not be used as force feedback information directly. Therefore, it is necessary to denoise the collected signal. First, analyze the amplitude-frequency characteristics of the signal through Fast Fourier Transformation (FFT), and then filter the signal through low-pass filter to eliminate the interference of noise signal. Set the cut-off frequency as 5Hz, the signal characteristics before and after filtering and their spectrum diagram are shown in Fig.2.

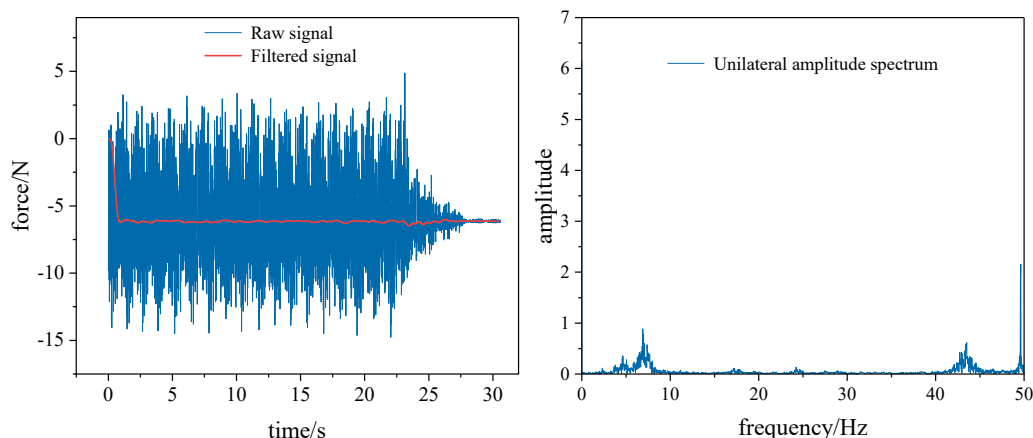


Fig.2 Grinding force signal before and after filtering and its amplitude-frequency diagram

2.2 Gravity compensation

The schematic diagram of the coordinate system of the robot grinding system is shown in Fig.3(a), and $O_B-X_B Y_B Z_B$ represents the base coordinate system, $O_F-X_F Y_F Z_F$ represents the robot end flange coordinate system, $O_S-X_S Y_S Z_S$ represents the sensor coordinate system, and $O_T-X_T Y_T Z_T$ represents the tool coordinate system. The force signal measured by the force sensor consists of four parts: (1) sensor zero drift, (2) load gravity, (3) inertial force, and (4) external grinding force. The attitude of the robot constantly changes during the grinding process. When the load gravity direction is inconsistent with the three coordinate axes of the sensor coordinate system, gravity compensation is required to balance the gravity effect. The relative relationship between the load gravity direction and the sensor coordinate system is shown in Fig.3(b) show.

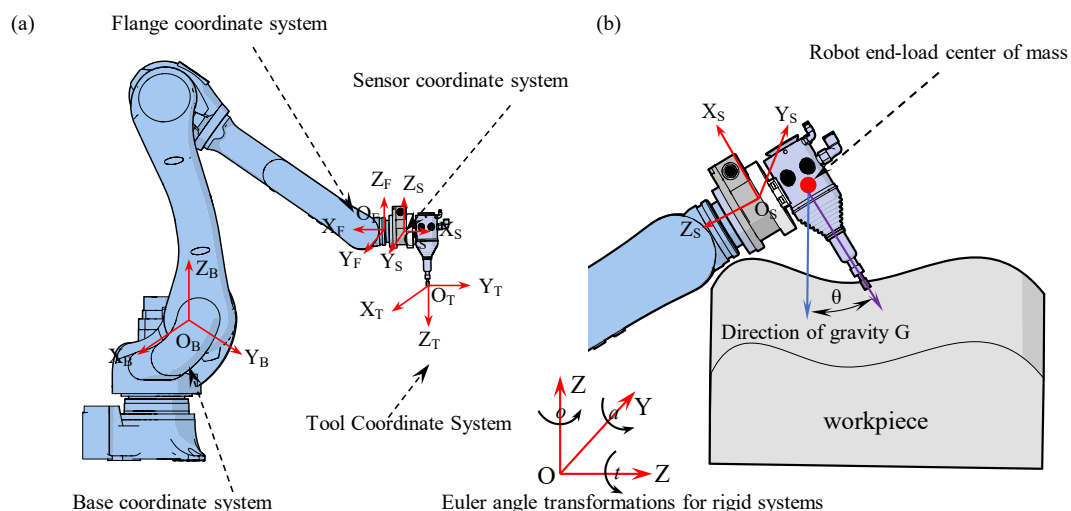


Fig.3 Robot grinding system: (a) coordinate system schematic diagram; (b) load gravity and sensor coordinate system relative relationship schematic diagram

Euler angles of Kawasaki robot system are expressed as o , a , t , namely roll angle o , yaw angle a and pitch angle t . According to Euler angles and attitude transformation relations, a transformation matrix between sensor coordinate system and base coordinate system is obtained as:

$${}^B_T R^T = \begin{pmatrix} co \cdot ca \cdot ct - so \cdot st & so \cdot ca \cdot ct + co \cdot st & -sa \cdot ct \\ -co \cdot ca \cdot st - so \cdot ct & -so \cdot ca \cdot st + co \cdot ct & sa \cdot st \\ co \cdot sa & so \cdot sa & ca \end{pmatrix} \quad (1)$$

where s represents $\sin()$ and c represents $\cos()$.

The normal vector of the load gravity is expressed in the base coordinate system as:

$$g_0 = \begin{pmatrix} 0 \\ 0 \\ -1 \end{pmatrix} \quad (2)$$

Combining equations (1) and (2), three components of gravity in the sensor coordinate system can be calculated as:

$$\begin{cases} g_x = \sin a \cdot \cos t \cdot G \\ g_y = -\sin a \cdot \sin t \cdot G \\ g_z = -\cos a \cdot G \end{cases} \quad (3)$$

where G represents the magnitude of the end-load gravity.

Therefore, the external actual grinding force can be calculated as:

$$\begin{cases} F_{ex} = F_x - F_{x0} - g_x \\ F_{ey} = F_y - F_{y0} - g_y \\ F_{ez} = F_z - F_{z0} - g_z \end{cases} \quad (4)$$

where $F_{(ex, ey, ez)}$ represents the actual grinding force, $F_{(x, y, z)}$ represents the sensor measurement force, and $F_{(x0, y0, z0)}$ represents the sensor zero drift.

After gravity compensation, the influence of end load gravity and sensor zero drift is eliminated. When the robot is not in contact with the environment, the external contact force is zero, as shown in Fig.4. After compensation, the force in three directions of the sensor fluctuates within $\pm 1\text{N}$.

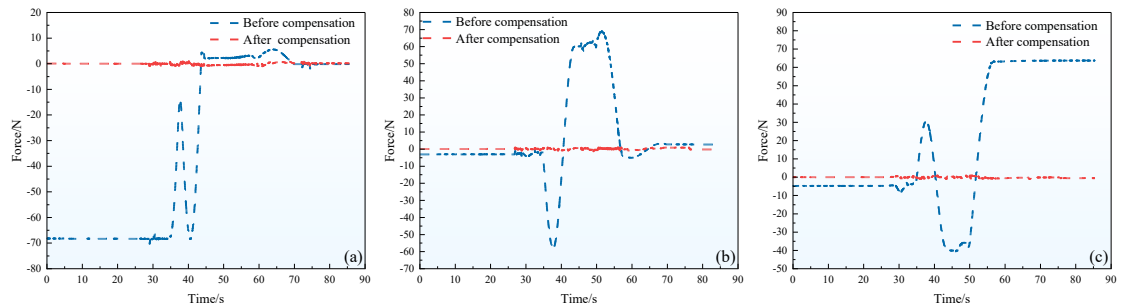


Fig. 4 Comparison of forces before and after gravity compensation: (a) x direction; (b) y direction; (c) z direction

3. Control strategy of grinding force of industrial robot for casting surface defects

3.1 Position-based impedance control strategy

The contact process between the end of the industrial robot and the environment is generally divided into three stages, as shown in Fig.5, which can be described as the constrained space from the free motion space to the collision contact with the environment, and its dynamic characteristics

present different situations at each stage.

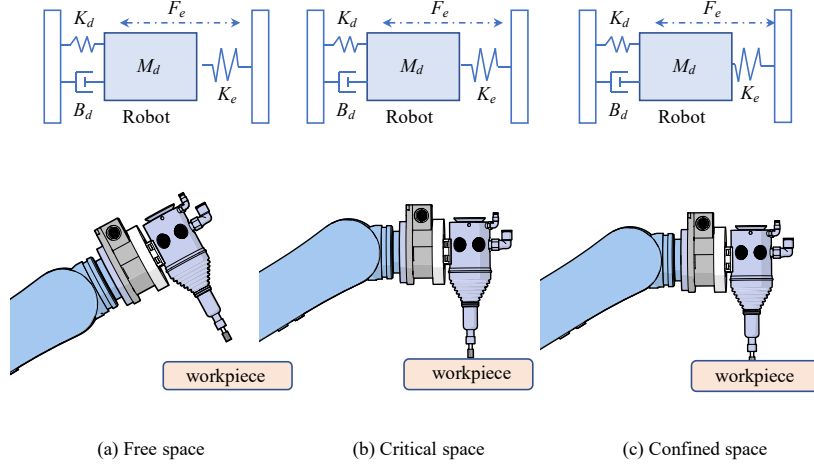


Fig.5 There are three phases of robot contact with environment: (a) free space; (b) critical space; (c) constrained space

In the position-based impedance control model, the robot end is equivalent to a second-order spring-mass-damping system, and the environment is equivalent to a spring contact model, the mathematical model is shown in equation 5.

$$\begin{cases} M_d(\ddot{X}_d - \ddot{X}_r) + B_d(\dot{X}_d - \dot{X}_r) + K_d(X_d - X_r) = F_d - F_e \\ F_e = k_e(x - x_e) \end{cases} \quad (5)$$

where, M_d , B_d , K_d respectively represent the mass, damping and stiffness coefficient matrix of the system, X_d , $\dot{X}_d$, $\ddot{X}_d$ respectively represent the desired position, velocity and acceleration of the robot, X_r , $\dot{X}_r$, $\ddot{X}_r$ respectively represent the reference position, velocity and acceleration of the robot, F_d respectively represent the desired contact force and F_e represent the actual contact force, x represents the actual position of the robot, and x_e represents the environmental position.

Based on the above model, a position-based impedance control strategy framework is built as shown in Fig.6.

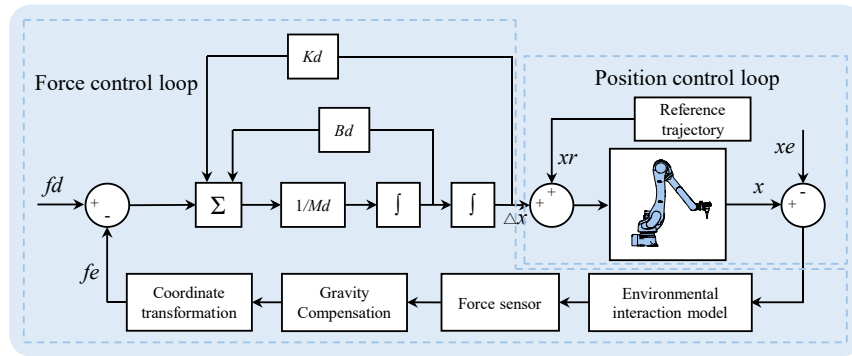


Fig.6 Framework diagram of impedance control strategy based on position

In the robot grinding process, only the force in a single direction is considered, and the model is simplified to a single-degree-of-freedom system, as shown in equation 6:

$$m_d(\ddot{x}_d - \ddot{x}_r) + b_d(\dot{x}_d - \dot{x}_r) + k_d(x_d - x_r) = f_d - f_e = \Delta f \quad (6)$$

Applying the laplace transform to equation 6 yields:

$$\frac{\Delta x}{\Delta f} = \frac{1}{m_d s^2 + b_d s + k_d} \quad (7)$$

Assuming that there is no position control error in the internal position control ring of the industrial robot, the actual position of the robot end can be replaced by the reference position, i.e. $x_r = x$, and the force control error of the robot grinding workpiece can be expressed as:

$$\Delta f = f_d(s) - f_e(s) = f_d(s) - k_e(x(s) - x_e(s)) \quad (8)$$

From equations (7) and (8):

$$\Delta f(s) = f_d(s) - k_e(x(s) - x_e(s)) + \frac{1}{ms^2 + bs + k} \Delta f(s) - x_e(s) \quad (9)$$

$$\Delta f(s) = \frac{ms^2 + bs + k}{ms^2 + bs + k + k_e} (f_d(s) - k_e(x(s) - x_e(s))) \quad (10)$$

The force error calculated from formula (10) when the robot grinds stably is:

$$\begin{aligned} \Delta f_{ss} &= \lim_{s \rightarrow 0} \left(\frac{ms^2 + bs + k}{ms^2 + bs + k + k_e} (f_d(s) - k_e(x(s) - x_e(s))) \right) \frac{1}{s} \\ &= \lim_{s \rightarrow 0} \frac{k}{k + k_e} (f_d - k_e(x - x_e)) \end{aligned} \quad (11)$$

3.2 Design of self-immunity controller

In order to realize the smooth transition of step signal of closed-loop system, an self-immunity controller is constructed based on the nonlinear model of robot grinding system. The self-immunity controller can make the contact force not overshoot under the premise of ensuring fast tracking force signal, improve the robustness of the system, and then ensure that the robot grinding operation does not produce overwear. The controller consists of the following three parts:

1) Tracking differentiator (TD):

$$\begin{cases} x_1(k+1) = x_1(k) + h \cdot x_2(k) \\ x_2(k+1) = x_2(k) + h \cdot f_{st}(x_1(k) - v(k), x_2(k), r, h_0) \end{cases} \quad (12)$$

The function $f_{st}(\cdot)$ is defined as follows:

$$\begin{cases} f_{st}(x_1(k) - v(k), x_2(k), r, h_0) = -r \cdot \text{sat}(a, d) \\ \text{sat}(a, d) = \begin{cases} a / d, |a| \leq d \\ \text{sgn}(a), |a| > d \end{cases} \\ d = rh_0 \\ a = \begin{cases} x_2(k) + \frac{1}{2} rh_0 (\sqrt{1 + \frac{8|y|}{rh_0^2}} - 1), |y| > d \\ x_2(k) + y / h_0, |y| \leq d \end{cases} \\ y = x_1(k) + h_0 x_2(k) \end{cases} \quad (13)$$

where $v(k)$ is the expected force input signal at the k th time, r is the velocity factor, h is the sampling period, h_0 is the filter factor, $x_1(k)$ is the expected force output at the k th time, $x_2(k)$ is the derivative of the expected force output at the k th time, $x_1(k+1)$ is the expected force output at the $k+1$ th time, $x_2(k+1)$ is the derivative of the expected force output at the $k+1$ th time, and $\text{sgn}()$ is the sign function;

2) Nonlinear state error feedback (NLSEF):

$$\begin{cases} u = k_p \text{fal}(e_1, \alpha_1, \delta_1) + k_i \text{fal}(e_2, \alpha_2, \delta_2) + \frac{hk_d \text{fal}(f_e - z_1, \alpha_3, \delta_3)}{b} \\ \text{fal}(e, \alpha, \delta) = \begin{cases} \frac{e}{\delta^{\alpha-1}}, |e| \leq \delta \\ |e|^\alpha \text{sgn}(e), |e| > \delta \end{cases} \end{cases} \quad (14)$$

where u is the control system input, e_1 is the desired force error signal, e_2 is the desired force error differential signal, $k_p, k_i, k_d, \alpha_1, \alpha_2, \alpha_3, \delta_1, \delta_2, \delta_3$ is the gain factor.

3) Extended state observer (ESO):

$$\begin{cases} z_1(k+1) = z_1(k) + h \cdot (z_2(k) - \beta_{01} \cdot (z_1(k) - f_e)) \\ z_2(k+1) = z_2(k) + h \cdot (z_3(k) - \beta_{02} \cdot \text{fal}(z_1(k) - f_e, 0.5, \delta)) + bu \\ z_3(k+1) = z_3(k) - h \cdot \beta_{03} \cdot \text{fal}(z_1(k) - f_e, 0.25, \delta) \\ \text{fal}(e, \alpha, \delta) = \begin{cases} \frac{e}{\delta^{\alpha-1}}, |e| \leq \delta \\ |e|^\alpha \text{sgn}(e), |e| > \delta \end{cases} \end{cases} \quad (15)$$

where $z_1(k)$ is the observed value of the output of the system at the k th time, $z_1(k+1)$ is the observed value of the output of the system at the $k+1$ th time, $z_2(k)$ is the observed value of the output of the system at the k th time, $z_2(k+1)$ is the observed value of the output of the system at the $k+1$ th time, $z_3(k)$ is the observed value of the output of the system at the k th time, $z_3(k+1)$ is the observed value of the output of the system at the $k+1$ th time is the actual contact force, f_e is the actual contact force, $\beta_{01}, \beta_{02}, \beta_{03}$ is the gain coefficient, α, δ is constant, α takes values between 0 and 1, b is the disturbance compensation coefficient.

According to equations (11)~(14), an self-immunity controller is constructed (The control strategy frame diagram is shown in Fig.7) to realize the overshoot suppression of the grinding force signal and the estimation and compensation of the position error. The specific process is as follows: 1) introducing the fastest synthesis function, smoothing the input expected force signal f_d through the tracking differentiator, and obtaining x_1 and its derivative x_2 ; 2) nonlinear combining the force error and its derivative through the nonlinear error feedback control rate, and obtaining the control quantity; 3) state observation is carried out on the sum of internal and external disturbances of the system in the grinding process through an extended state observer to obtain compensation quantities z_1 and z_2 of the input signal and compensation quantity z_3 of the control quantity.

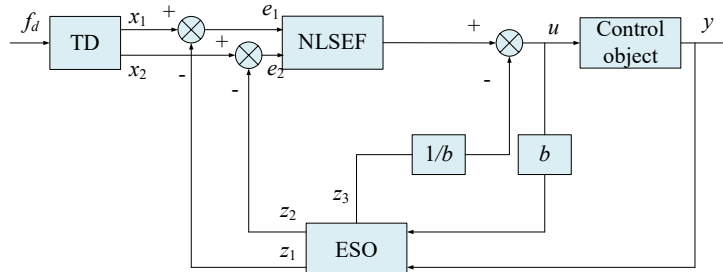


Fig.7 Frame diagram of self-immunity controller

3.3 Design of adaptive variable impedance controller

For the robot grinding working condition with complex and changeable contact environment, the fuzzy control with strong adaptability and robustness, which is not affected by the control object

model, can be used to optimize the impedance parameters in real time, so as to solve the problems such as failure of fixed parameter impedance control when grinding some surfaces. At the same time, the adaptive controller is combined to predict the unknown environmental parameters. The combination of the two improves the adaptive adjustment ability of the system. The control principle diagram is shown in Fig.8.

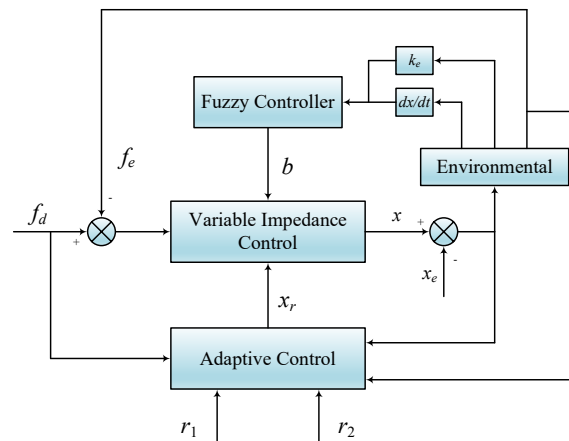


Fig.8 Frame diagram of adaptive variable impedance control

In order to reduce the oscillation of the system, the mass coefficient is not modified in general, so the change of damping coefficient is used as an adaptive parameter to modify the impedance model. Through normalization processing of quantization factor and scaling factor, the robot terminal feed speed and environmental stiffness are taken as inputs of the fuzzy controller, and the variation of damping parameters is taken as the output of the fuzzy controller. The two inputs and one output are divided into four levels, as shown in Table 1, and Gaussian membership function curves are adopted. The input variable domain of the fuzzy controller is set to $[0,3]$, as shown in Fig 9. According to fuzzy control rules, fuzzy inference is carried out to obtain fuzzy control output, and then the output is processed clearly to obtain the change of damping coefficient Δb .

Tab.1 Fuzzy control rule table

ke	v			
	ZE	PS	PS	PB
ZE	ZE	PS	PS	PM
PS	PS	PS	PM	PM
PM	PS	PM	PB	PB
PB	PM	PM	PB	PB

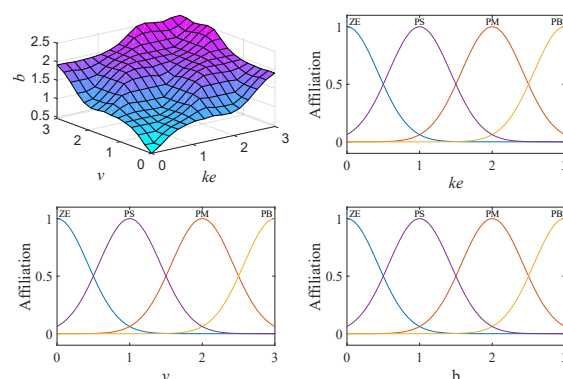


Fig. 9 Fuzzy control rule and membership function curve

The impedance control model modified by fuzzy control is shown as follows:

$$m_d(\ddot{x}_d - \ddot{x}_r) + (b_d + \Delta b)(\dot{x}_d - \dot{x}_r) + k_d(x_d - x_r) = \Delta f \quad (16)$$

In the actual grinding process, due to the uncertainty of the environment interaction model, it is very difficult to obtain accurate environment position and environment stiffness information. Therefore, setting the estimated values of environment stiffness and environment position as $\hat{k}_e$ and $\hat{x}_e$, the estimated value of grinding force can be expressed as:

$$\begin{cases} x_r = \hat{x}_e + \frac{f_d}{\hat{k}_e} \\ \hat{f}_e = \hat{k}_e(x - \hat{x}_e) \end{cases} \quad (17)$$

Putting $k_x = k_e x_e$ into the above equation gives:

$$\hat{f}_e - f_e = [x_e - 1] \begin{bmatrix} \hat{k}_e - k_e \\ \hat{k}_x - k_x \end{bmatrix} \quad (18)$$

Let be $\begin{bmatrix} \hat{k}_e - k_e & \hat{k}_x - k_x \end{bmatrix}^T$, define Lyapunov equation as:

$$\dot{V} = \dot{Q}^T P Q \quad (19)$$

Define matrix P as positive definite matrix $\begin{bmatrix} r_1 & \\ & r_2 \end{bmatrix}$, where q_1 、 q_2 are positive numbers, when $\hat{f}_e$ tending to f_e , when the system tends to stability, the derivative of Lyapunov equation should be less than 0, therefore, constructed $\dot{Q}$ as:

$$\dot{V} = 2\dot{Q}^T P Q = -2\dot{Q}^T \begin{bmatrix} x_e \\ -1 \end{bmatrix} (\hat{f}_e - f_e) = -2(\hat{f}_e - f_e)^2 \quad (20)$$

Therefore, we can obtain $\hat{x}_e$ 、 $\hat{k}_e$, respectively:

$$\begin{cases} \dot{\hat{k}}_e = -r_1 x (\hat{f} - f) \\ \dot{\hat{x}}_e = \frac{\hat{f} - f}{\hat{k}_e} (r_1 x \hat{x}_e + r_2) \end{cases} \quad (21)$$

From this, we can see that $\dot{V}$ negative definite, V positive definite, Lyapunov stability is satisfied, nonlinear function is introduced to improve convergence rate, and then combined with the self-immunity controller model in section 3.2, the adaptive control model can be calculated as:

$$\begin{cases} \hat{f} = \hat{k}_e(x - x_e) \\ f_{ext} = \hat{f}_e - f_e \\ x_r = \hat{x}_e + \frac{k_p b fal(e_1, \alpha_1, \delta_1) + k_i b fal(e_2, \alpha_2, \delta_2) + k_d h fal(e, \alpha_3, \delta_3)}{b \hat{k}_e} \\ \hat{x}_e = \hat{x}_e(0) + r_1 \int_0^t \frac{\mu fal(f_{ext}, \alpha, \delta)}{k_e} (x \hat{x}_e + \frac{r_2}{r_1}) dt \\ \hat{k}_e = \hat{k}_e(0) - r_1 \int_0^t x \lambda fal(f_{ext}, \alpha, \delta) dt \end{cases} \quad (22)$$

where $\hat{f}_e$ is the estimated value of the contact force, f_{ext} is the deviation value between the estimated value of the contact force and the actual value of the contact force, $\hat{k}_e$ is the estimated value of the environmental stiffness, x is the robot terminal position, x_r is the compensation displacement of the robot, $\hat{x}_e$ is the estimated value of the environmental position, $\hat{x}_e(0)$ is the initial value of the environmental position, $\hat{k}_e(0)$ is the initial value of the environmental stiffness, r_1 、 r_2 is a constant, and λ 、 μ is a compensation coefficient.

Combined with the above analysis, the principle diagram of adaptive variable impedance control strategy based on self-immunity control is established as shown in Fig.10. The main components of the proposed method are as follows: 1) self-immunity control is used as feedforward control of impedance control to process the input expected force signal and improve the force overshoot phenomenon; According to the feedback information of the end effector, the adaptive variable impedance control is designed to optimize the impedance parameters online, realize the dynamic adjustment of the grinding force correction, and solve the problem that the adaptive adjustment ability of the fixed parameter impedance is insufficient when grinding some surfaces. 2) establish the impedance control model of end-effector contact with environment, which calculates the compensation amount of end-position according to the difference between actual grinding force and expected grinding force. 3) combining the position compensation value with the reference position calculated by adaptive control, input it to the robot controller to control the robot movement, and realize the adaptive active grinding force control of robot grinding operation.

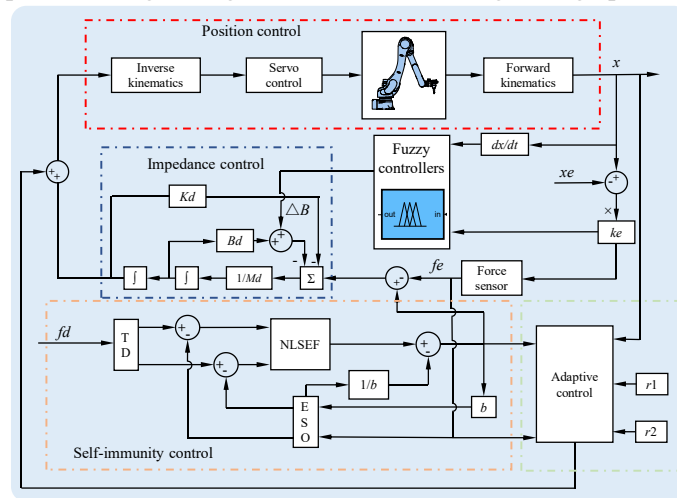


Fig.10 Schematic diagram of adaptive variable impedance control based on self-immunity control

4 Simulation analysis

In order to verify the feasibility of the proposed control strategy, simulation models as shown in Fig.11 and Fig.12 are built in Matlab-Simulink, and simulation analysis is carried out under

different conditions. The impedance parameters M_d , B_d and K_d of the two control strategies are 200kg, 1000N/(m/s) and 1500N/m respectively, and the expected grinding force is 5N. Based on the above parameters, the simulation analysis is carried out for the following working conditions.

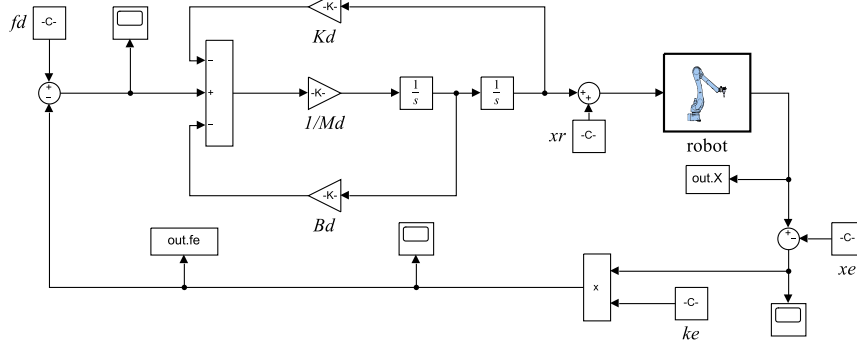


Fig.11 Simulation model of traditional position-based impedance control

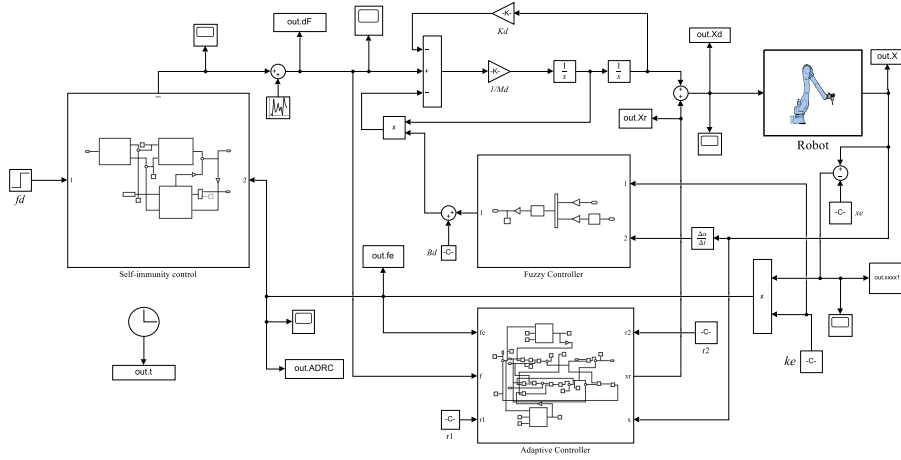


Fig.12 Simulation model of adaptive variable impedance control based on self-immunity control

4.1 Simulation results of planar environment surface with different environmental stiffness

In order to verify the regulation effect of the algorithm under different environmental stiffnesses in planar environment, set the environmental position $x_e=0\text{mm}$, set the environmental stiffnesses $k_e=10000$, 15000 and 20000N/m, and the simulation results of traditional impedance control are shown in Fig.13, and the simulation results of adaptive variable impedance control based on automatic disturbance rejection are shown in Fig.14. It can be seen from Fig.13 that force overshoot phenomenon will occur under three different environmental stiffnesses, and there are steady-state errors. The greater the environmental stiffness, the greater the force overshoot, but the steady-state error will decrease. It can also be seen from the output displacement of the robot end that in the initial contact period, the fluctuation of the output displacement of the end is large, resulting in the overshoot of the contact force. As can be seen from Fig.14, compared with traditional impedance control, the adaptive variable impedance control based on auto-disturbance rejection has smaller force overshoot and contact force steady-state error, which benefits from its excellent ability to regulate the output displacement of the end. In contrast, this method has more advantages in regulating contact force.

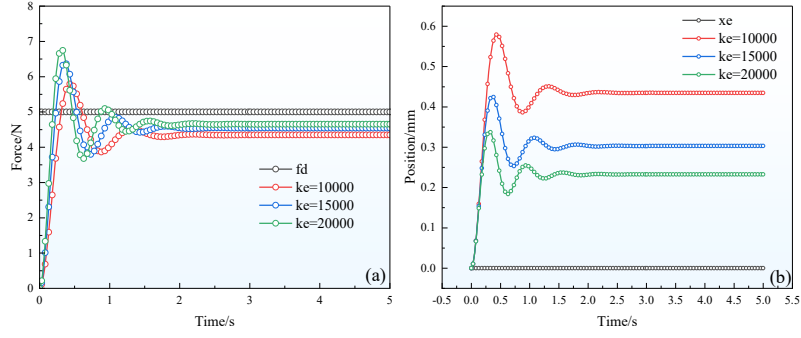


Fig.13 Simulation results of traditional impedance control under different environmental stiffnesses: (a) change of contact force; (b) change of terminal position

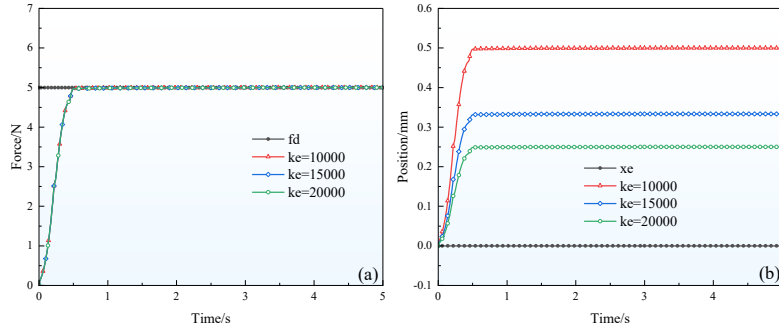


Fig.14 Simulation results of adaptive variable impedance control based on self-immunity control under different environmental stiffnesses: (a) variation of contact force; (b) variation of terminal position

4.2 Simulation results of curved environment surface with different environmental stiffness

Fig.15 and Fig.16 show the simulation results of the two methods under curved surface environment and different stiffnesses. The environmental position changes with sinusoidal curve with amplitude of 0.25mm and frequency of 1rad/s. It can be seen from Fig.15 that the force overshoot phenomenon still occurs in the traditional impedance control under curved surface environment, and the contact force fluctuates greatly and is unstable. From the perspective of terminal displacement change, the output displacement of the traditional impedance control deviates from the environmental position to a certain extent. The adaptive variable impedance control based on self-immunity control can adapt to the change of environmental parameters better, and its terminal output displacement is basically consistent with the change trend of environmental position, so the overshoot and steady-state error of contact force are very small. The simulation results show that the force control method proposed in this paper has better adaptive ability than traditional methods in the face of complex environmental parameters.

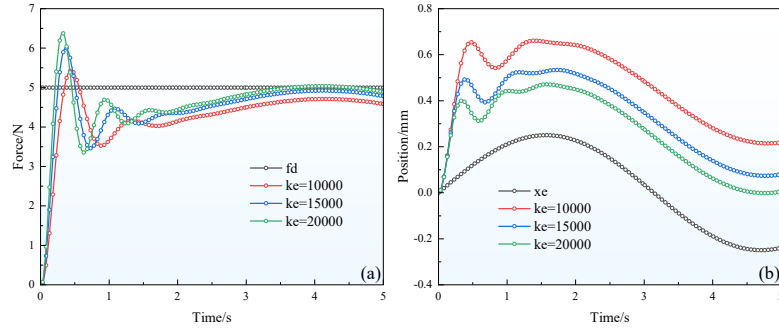


Fig.15 Simulation results of conventional impedance control under different environmental stiffnesses: (a) change of contact force; (b) change of terminal position

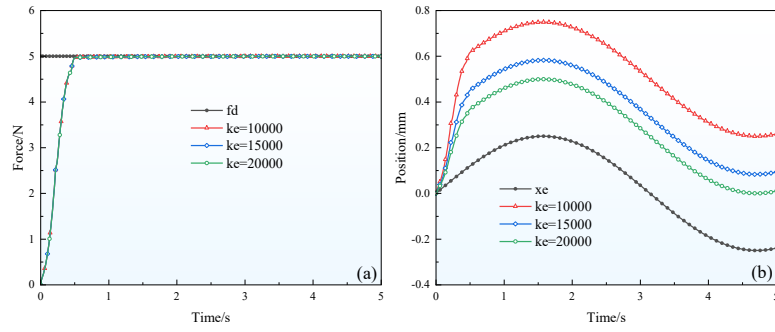


Fig.16 Simulation results of adaptive variable impedance control based on self-immunity control under different environmental stiffnesses: (a) variation of contact force; (b) variation of terminal position

5 Experimental studies

5.1 experimental facility

In order to verify the feasibility of the proposed grinding force control method in practical application, an experimental platform as shown in Fig.17 is built, including a computer, a robot, a robot controller, a six-dimensional force sensor and grinding equipment. The robot, the six-dimensional force sensor and the robot controller are connected through Ethernet. The robot adopts TCP/IP communication protocol, and the six-dimensional force sensor adopts UDP communication protocol. The grinding system is an integrated system integrating force signal filtering, end load gravity compensation and grinding force control strategy.

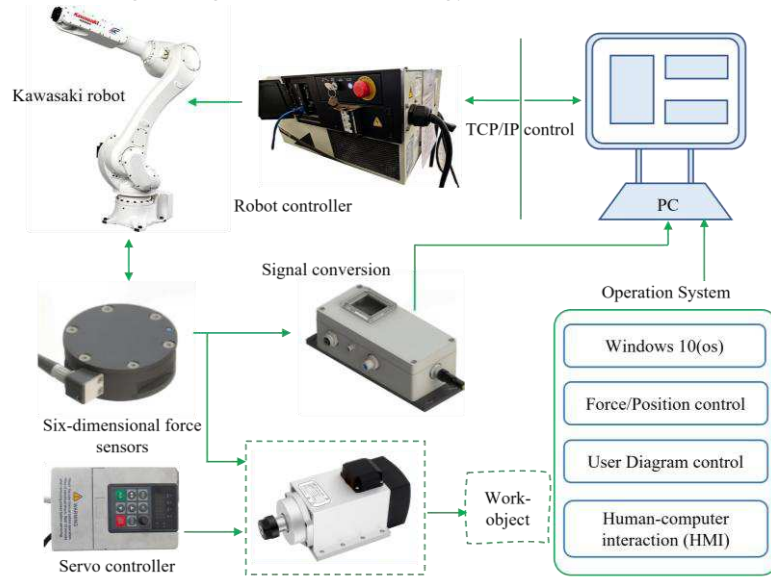


Fig.17 Robot grinding experimental platform

5.2 Algorithm feasibility verification

In this paper, aluminum alloy plate specimen as the grinding object, respectively compared the position control, traditional impedance control and adaptive variable impedance control based on automatic interference rejection of the three methods of grinding effect, and through the hualang handheld three-dimensional laser scanner measurement grinding effect, equipment model holon 751, experimental control flow chart as shown in Fig.18, the specific process is: 1) planning the initial grinding track, and the track will be transmitted to the robot controller, control robot movement; 2) The six-dimensional force sensor collects the grinding force in real time and transmits the force signal to the computer; 3) The force signal is filtered and gravity compensated by the written internal program, and the processed signal is input to the force control program, and then the terminal

position compensation value is calculated and output;4) The compensation value is input to the robot controller for regulation.

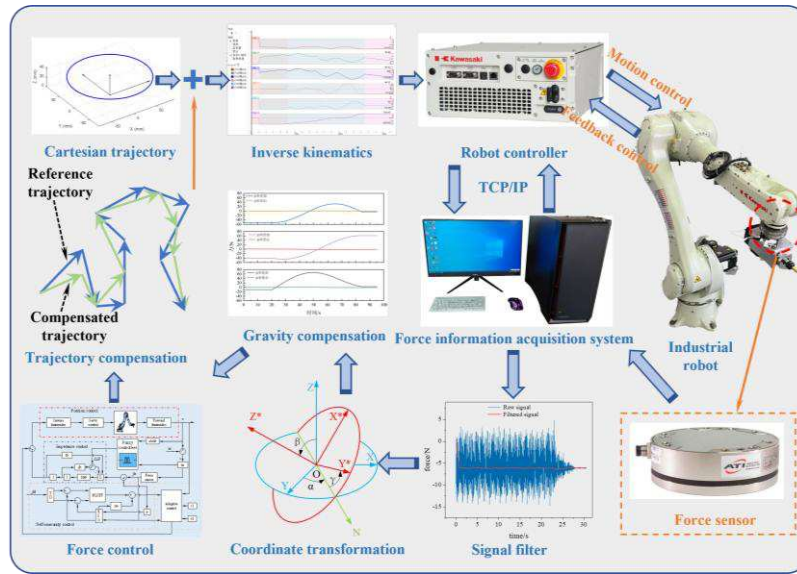


Fig.18 Control flow chart of robot grinding experiment

The change of contact force in the grinding process of the three control methods is shown in Fig.19. It can be seen from Fig.19(a) that when grinding is only controlled by position, the fluctuation of contact force is large due to the existence of grinding track error, and the contact force fluctuates between -2N and -20N in the whole grinding process, which is not conducive to the stability of the system; On this basis, the expected contact force is set to -8N, and the impedance control is superimposed to carry out the experiment. As shown in Fig.19(b), the contact force fluctuates between -6N and -12N, and the average contact force error is 21.33%. Compared with the position control, the fluctuation of grinding force is obviously reduced. However, due to the limitation of traditional impedance control, its internal impedance parameters cannot match the actual environmental parameters optimally, and there is still room for further improvement in the actual regulation effect. The adaptive variable impedance control based on auto-disturbance rejection is optimized and improved on the basis of the traditional impedance control. The contact force variation curve in the grinding process is shown in Fig.19(c). The contact force fluctuates between -7N and -9N, and the average contact force error is 5.72%. Compared with the traditional impedance control, the average contact force fluctuation is reduced by about 15.61%. The results show that the adaptive adjustment ability of this method is better.

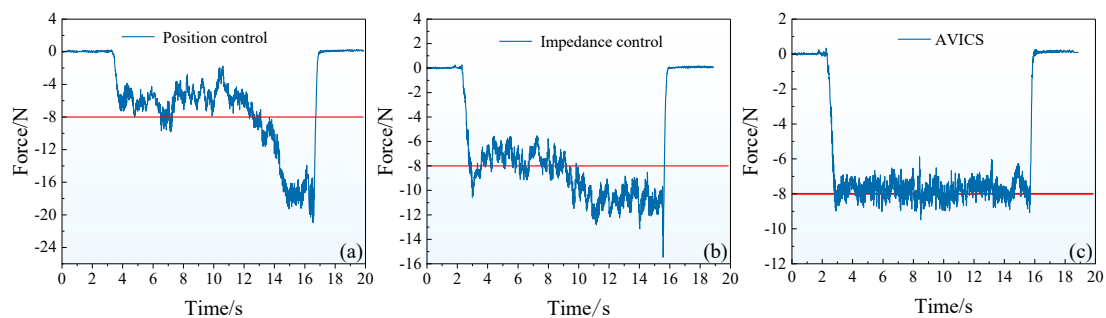


Fig.19. Contact force variation of three control methods: (a) position control; (b) traditional impedance control; (c) adaptive variable impedance control based on auto-disturbance rejection

The surface profile of the test piece before and after processing is obtained by a three-

dimensional laser scanner, and three-dimensional profile comparison is carried out. The result is shown (1) in Fig.20(a) is the position control grinding effect, (2) is the traditional impedance control grinding effect, and (3) is the adaptive variable impedance control grinding effect based on auto-disturbance rejection. Fig.20(b) corresponds to Fig.20(a). It can be seen from Fig.20(b) that the existence of track error leads to the phenomenon of overgrinding and undergrinding after grinding of the test piece, and the contour accuracy is poor; After grinding with traditional impedance control, underwear phenomenon is eliminated by compensating displacement, overwear phenomenon is improved to some extent, but the overall profile is still uneven and inconsistent. After grinding with adaptive variable impedance control based on auto-disturbance rejection, the overall profile accuracy is further improved, which proves that the adaptive variable impedance control method based on auto-disturbance rejection proposed in this paper has more advantages than traditional impedance control in contact force regulation.

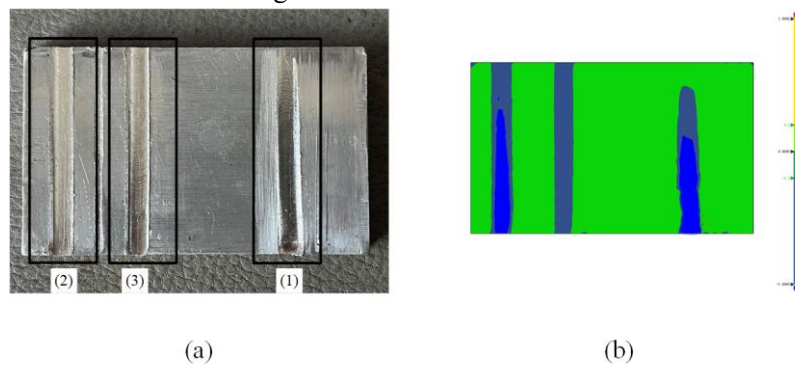


Fig.20 Experimental results: (a) Comparison of specimens before and after machining; (b) Comparison of three-dimensional profiles

5.3 Grinding experiment of casting surface defects

On the basis of verifying the feasibility of the algorithm proposed in this paper, the grinding experiments of casting surface defects (casting riser, casting fin) are carried out, and the grinding track is planned by offline programming, as shown in Fig.21. As shown in Fig.22, the change curve of contact force during position control and force control grinding is shown in Fig.22(a). It can be seen that during position control grinding, the contact force fluctuates between 3N and 12N, and the fluctuation of contact force is relatively large. Based on this, superimposed force control is used for grinding, and the expected contact force is set to 4N. As shown in Fig.22(b), the contact force fluctuates between 3N and 5N during grinding, and the fluctuation of contact force is obviously reduced. The average error of contact force is 7.59%.

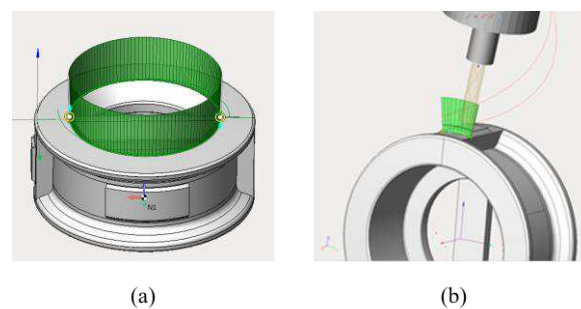


Fig.21 Robot grinding track: (a) casting fin grinding track; (b) casting riser grinding track

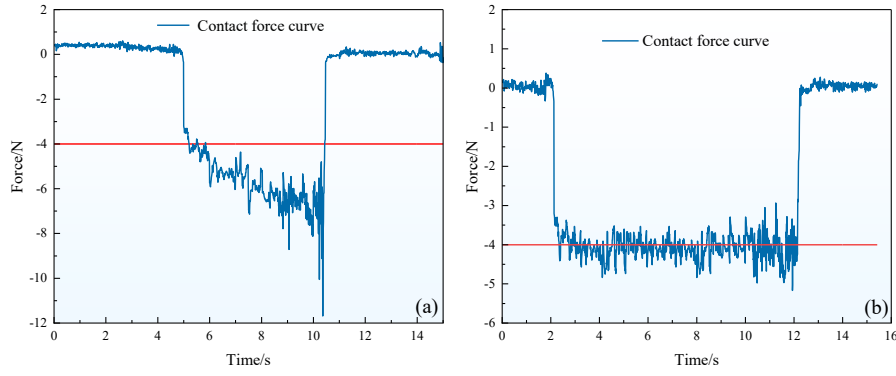


Fig.22 Contact force for casting fin grinding: (a) position control; (b) force control

The effect before and after casting fin grinding is shown in Fig.23. After grinding by position control, overgrinding phenomenon occurs, and the contour accuracy is poor. Measure the casting fin height before and after grinding. Take 15 measurement points, and the measurement results are shown in Fig.24(a). From the measurement results, it can be seen that overgrinding occurs in many places from 0mm to 1.5mm after grinding by position control. After the force-controlled grinding, the overall contour accuracy is improved, the contour of the casting fin area after the force-controlled grinding is basically consistent with the surface of the casting substrate, and the residual height of the casting fin is distributed between -0.5mm and 0.5mm. The result is shown in Fig 24(b), and the contour accuracy is good.

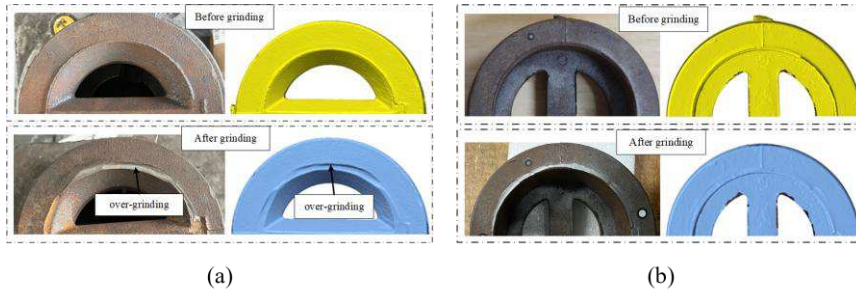


Fig.23 Comparison of casting fin grinding effects:(a) position control; (b) force control

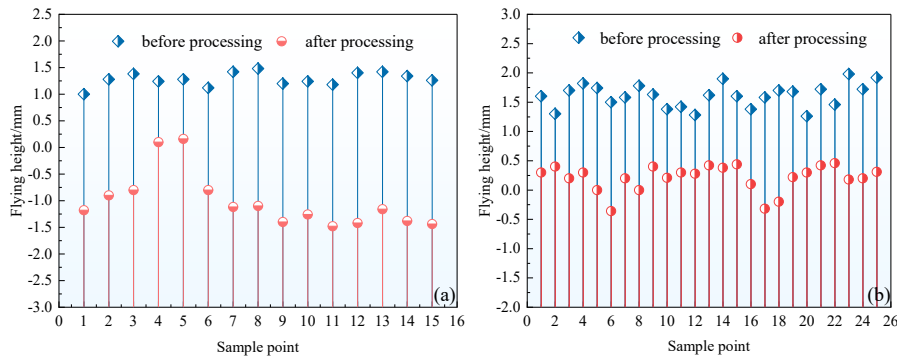


Fig.24 Casting fin height variation: (a) position control; (b) force control

The curve of contact force variation during riser grinding of castings is shown in Fig.25. When position control grinding is adopted, the contact force fluctuates between 0N~-18N, and the fluctuation of grinding force is large, resulting in obvious robot shaking and poor stability during the whole grinding process. According to the experimental results, the expected contact force is -10N, and the contact force fluctuates between -9N and -11N. The average contact force error is 5.31%, which effectively improves the stability of grinding process.

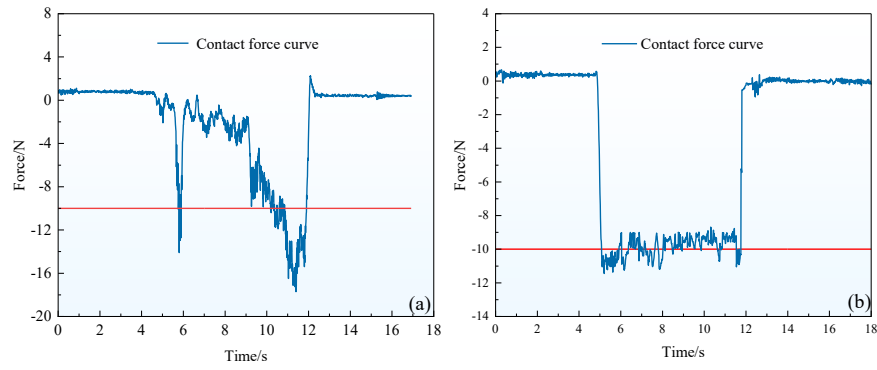


Fig.25 Riser grinding contact force: (a) position control; (b) force control

After force control grinding, the point cloud model before and after grinding is obtained by a handheld 3D laser scanner. Three sections are taken respectively, the section positions are shown in Fig.26. The contour changes before and after processing are compared, the results are shown in Fig.27. The black contour line in the figure is the riser contour before grinding, the blue is the riser contour curve after grinding, and the green is the casting matrix contour. The contour after grinding in the riser area is basically consistent with the casting matrix contour. It shows that the contour accuracy after force-controlled grinding can meet the processing requirements of the casting. The physical comparison before and after grinding is shown in Fig.28.



Fig.26 Riser profile comparison cross section position

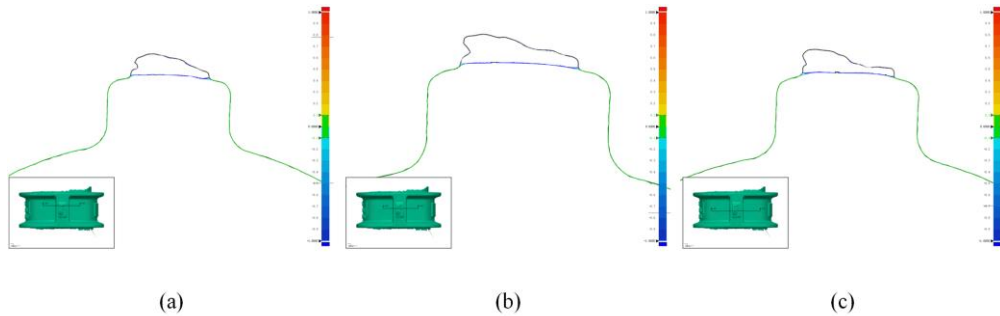


Fig.27 Comparison of profiles before and after riser grinding:(a) section 1; (b) section 2 ;(c) section 3



Fig.28 Comparison of physical model before and after grinding: (a) before grinding;(b) after grinding

6 Conclusions

In order to solve the problems of low flexibility in the process of robot grinding casting surface defects and insufficient adaptive adjustment ability of robot grinding constant force when facing unknown environment or inaccurate environmental information, an adaptive variable impedance control method for robot grinding constant force with real-time prediction of unknown environmental parameters is proposed:

(1) The proposed control method uses auto-disturbance rejection impedance control as inner loop control, then fuzzy adaptive control as outer loop control, and the combination of inner loop and outer loop control forms a closed loop control to realize adaptive constant force control of robot grinding operation.

(2) Matlab-Simulink simulation model is used to build the algorithm. Simulation results show that compared with traditional impedance control, the proposed method has better control effect on contact force in complex environment, and the steady-state error and overshoot are smaller. The impact of grinding tool on workpiece surface is effectively reduced, which verifies the feasibility and effectiveness of the proposed method.

(3) The results show that the average grinding force error of the proposed method is 5.72%, and the fluctuation of grinding force is reduced by 15.61% compared with the traditional impedance control. The results show that the average grinding force error of casting fin grinding is about 7.59%, the average grinding force error of casting riser grinding is about 5.31%, and the profile accuracy after grinding can meet the requirements, which verifies the feasibility of this method in the process of grinding casting surface defects.

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Declarations

Ethical approval: Not applicable.

Consent to Participate: Not applicable.

Consent to publication: Not applicable.

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Conflicts of interest/Competing interests:

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Non-financial interests: Authors Tianqi Wang and Jia Liu, Xiuhong Li, Fengyi Guo did not get paid from the funding.

Availability of data and material: All data generated or analyzed during this study are included in this published paper.

Code availability: Not applicable.

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