Adaptive Force Control for Robotic Grinding of Complex Blades

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Abstract. Aiming at solving the robotic grinding problem of aircraft engine blades with complex surface, this paper proposed an adaptive force control method using fuzzy PID algorithm, which can ensure that blade surface is completely polished to eliminate residual texture and harmful stress concentration. First, an intelligent digital compliant grinder with active and passive compliance was developed. Second, a fuzzy PID adaptive algorithm was proposed, which can stabilize the contact force between the grinder and the blade. Third, a protection scheme was proposed to prevent excessive grinding. In the polishing process, the robot arm was fitted with the blade. According to the surface profile of the blade, the robot arm moved in a specific trajectory, keeping the blade in contact with the grinder. During grinding, some parameters, such as the abrasive belt velocity, the abrasive belt type and contact force, could affect the quality of the grinding process. Therefore, appropriate parameters were selected. The experimental results showed that the actual force fluctuates within 0.5N. In addition, the original surface roughness was 1.672 μm, which was reduced to 0.054 μm by adaptive force control method, comparing to 0.589 μm with the non-force control. Not only is the contact force more precisely controlled, but the grinding accuracy is greatly improved.

1. Introduction
Robots have been widely applied in machining parts with complex surfaces. For the complex curved plane's engine blades, it is one of the key components, besides its quality and machining accuracy greatly affect the performance of the engine. Because of the intricacy of the aero-engine blades structure, when the engine works and blades are under enormous pressure, so it is easy for the blades to deform. In addition, a not quality surface and remaining texture lines on blades, which do not meet the requirements, may make wicked effect to the movement of air inside the engine. In addition, it leads to large fluctuations in machining accuracy of intake and exhaust edges of the blades [1-2].

There are several methods of blades grinding, such as manual grinding, abrasive flow grinding, and multi-axis Computerized Numerical Control machine grinding [3]. Abrasive flow machining (AFM) is a new type of finishing method using extruding abrasive media through parts’ surfaces [4]. But AFM has a disadvantage is that the shape error cannot be corrected. The effects of manual grinding depend on the worker's experience and the tiny particles during grinding are harmful to health when inhaled by workers. To enhance both the processing efficiency and the quality, recently, industrial robots are diffusely applied in the blades grinding field [5]. For polishing blades, the advantages of robotic grinding are less costing, better agility and multiformity than a multiaxial machine tool. In the robots polishing intricate curved blade process, one of the difficulties to ensure the quality of blade surface is
the fluctuation of contact force, which has a tremendous negative impact. For the better processing quality, some researchers put forward that the active compliance control and the passive compliance control should both be applied [6]. In addition, some researchers propose that limiting the fluctuation of contact force can effectively improve the blade processing quality [7]. The researchers proposed disparate methods of force control to precisely control the contact force. Dai et al. [8] put forward a parametric modelling controller to adjust the normal grinding force precisely. Liu et al. [9] propose a neoteric scheme for robot grinding, which uses passive force control to substantially reduce the drastic mechanical shock and applies active force control to acquire expectable force accuracy. All these methods have a common point, that is, the industrial robot whose instinct is low positioning accuracy is used in the active force control, therefore, it is difficult to guarantee the precision of force control. The researchers used a new approach to estimate and compensate industrial robot positioning errors. Specifically, the control method used an intelligent digital flexor grinder to directly control the contact force, instead of applying the active force of the robot.

As for the adaptive force control method, the conventional proportional–integral–derivative (PID) controllers stay to be the most prevalently used in the industrial processes [10]. In practice, lots of physical systems have inbred uncertainty traits such as non-linearities and high order. [11]. Hence, the famous method was proposed. Ziegler–Nichols method, supplies a systematic tuning method for the PID parameters which has good load disturbance reduction, but has unsatisfying weaknesses, such as, a long settling time and large overshoot [12]. For improving systems’ overshoot, rise time, and integral of the absolute error. Theoretically, some researchers come up with it is suitable to utilize of fuzzy logic, combining features on the basis of the experiences of specialists with regard to PID gain scheduling. Practically, it has been used with great successful in industry applications. Fuzzy PID controllers have been displayed and inspected, and their adequate performance in several plants has been exhibited. Fuzzy PID controller is often deemed as a succedaneum to classical PID controllers in high non linearity and intricate situations. Fuzzy logic has a superiority of simplicity as well as precision with its simulation results.

This paper uses an unconventional blade grinding method, and applies a combination of intelligent digital compliant grinder including the flexible grinder and the robot arm. To be more specific, the robot arm loading fixture is used to hold the clamping parts, and artificially planning the unique and corresponding movement path of the robot arm according to the contour of the external surface of the grinding part. The flexible grinder has the active compliance control at the control strategy level and the passive compliance control is the spring as a compliant mechanical component, and the grinder with force sensor is carried by a motor to move with one degree of freedom, which is controlled with a closed loop of current. Moreover, the novel intelligent algorithms precisely control the contact force between the polishing tool and the workpiece during the grinding process, and a protection in the control program reduce the risk of excessive grinding during the beginning of the actual grinding process. All of those ensure better surface quality of the blades.

The paper is organized as follows. In Section II, the original position-based impedance control, an optimization method for the controller parameters and fuzzy-PID algorithm are detailed introduced. Section III discusses the intelligent digital compliant grinder, experiment procedures, the experimental program design, and an innovative method to prevent excessive grinding. Experiment results and analysis are provided in Section IV. Section V gives the conclusion.

2. Fuzzy - proportional integral differential (PID) controller design and preventing excessive grinding

2.1 Force control analysis

Due to the complex shape of aero-engine blade and the high quality of requirement for its machining surface, the contact force of grinding blade must be strictly controlled during mechanical grinding and polishing. Based on this, this paper combines the fuzzy theory with the PID control algorithm, a self-tuning fuzzy-PID controller formed out. Through the fuzzy-PID control, the reference position
trajectory that adjusts the movement of the grinding machine is designed to generate the required contact force, in the absence of environmental stiffness and location information. In this scheme, adaptation allows automatic acquire modulation to provide a unitive property despite changes in environment parameters. The holistic structure of the robot grinding controller is revealed in figure 1, where e is the deviation, ec is the deviation change rate, \( F'_a \) is the actual grinding force measured by the force sensor, as well as \( F_d \) is the required grinding force.

![Figure 1. Holistic structure of the fuzzy-PID controller.](image)

The PID control algorithm realized by computer is adopted, and its discrete PID control law is as follows:

\[
F(n) = K_p e(n) + K_i \sum_{i=0}^{n-1} e(i) + K_d [e(n) - e(n-1)]
\]

(1)

At the Nth sampling time, \( F(n) \) is the output of the controller; \( e(n) \) is the deviation signal as input of the controller; \( K_p, K_i \), and \( K_d \) are the proportional, integral, and differential coefficients, respectively.

Taking deviation e and deviation rate ec as inputs, which is able to keep self-tuning of the PID parameters of deviation e and deviation rate ec at reasonable values under different circumstances. By using fuzzy theory to correct PID parameters online, a self-tuning fuzzy-PID controller is constructed.

2.2 Fuzzy-PID parameter control algorithm

In the fuzzy structure, there are two inputs, more precisely, the deviation e and the deviation rate ec of the force signal. Equations (2) and (3) are used to periodically update the values of the deviation e and the deviation rate ec, where \( F_d \) represents the ideal contact force and \( F_a \) represents the actual measured force transmitted by tetrad force sensors.

\[
e = F_d - F_a
\]

(2)

\[
e c = e(i) - e(i-1)
\]

(3)

\( \Delta K_p, \Delta K_i \), and \( \Delta K_d \) are the three outputs of the fuzzy force controller, and automatically adjust the value of PID parameters in accordance with the state of the force deviations. The real-time value can be calculated by using equation (4). Where \( K_{p0}, K_{i0} \), and \( K_{d0} \) are the initial design values of the proportional integral differential parameters, which is 0.5, 0.2 and 0.01 respectively according to the experiment experience.

\[
\begin{align*}
K_p &= K_{p0} + \Delta K_p \\
K_i &= K_{i0} + \Delta K_i \\
K_D &= K_{d0} + \Delta K_D
\end{align*}
\]

(4)

Firstly, Fuzzification converts the input and output variables into corresponding fuzzy quantities. Input and output variables were divided into seven language labels: NB(negative big), NM(negative medium), NS(negative small), ZO(zero), PS(positive small), PM(positive middle), PB(positive big).
Meanwhile, in the discrete domain, their variation ranges were divided into seven levels: -3, -2, -1, 0, 1, 2, 3. Their actual variables are shown in Table 1. The relationship between variables in different fields is established by using the scaling factor, and the scaling factor is defined by using equation (5).

\[
\begin{align*}
    K &= \frac{W_h - W_l}{Z_h - Z_l} \\
    K' &= \frac{Z_h - Z_l}{W_h - W_l}
\end{align*}
\]

where \( K \) and \( K' \) represent the scale factors of the input and output, respectively. \([w_i, w_f]\) represents the range of variables in the discrete domain, and \([z_i, z_f]\) represents the range of the actual variables. Fuzzy reasoning is a process of establishing fuzzy rules. Firstly, it is necessary to convert all variables into membership functions of fuzzy sets. The membership function is a curve that defines how each variable is mapped to a membership value between 0 and 1 [13]. It is reasonable to choose the common triangle membership function, which has the characteristics of simple calculation and good performance [14]. As shown in Figure 2, it is a membership function of the reference fuzzy set.

| Table 1. The actual parameter variables. | e | ec | \( \Delta K_m \) (\( m = P, I, D \)) |
| Change block | [-10, 10] | [-10, 10] | [-0.7, 0.7] |
| The scaling factor | 0.35 | 0.35 | 0.23 |

![Figure 2. Fuzzy-PID-Membership function for e, ec, \( K_p \), \( K_i \), and \( K_o \).](image)

The fuzzy rules are constructed by using the if-then statement, and the 49 rules are refined to form a fuzzy rule base of \( K_p \), \( K_i \) and \( K_o \). In the PID controller, the \( K_i \) value determines the response speed of the system, the \( K_p \) value is used to eliminate the steady-state error of the system, and the \( K_o \) value improves the dynamic characteristics of the system, eliminates oscillations, and reduces the influence of system inertia. In the early stage of regulation, a large \( K_p \) value ensures the system response speed, a small \( K_i \) value or even zero value to avoid system integration saturation, and a large \( K_o \) value to avoid overshoot; In the middle stage of regulation, small \( K_p \), \( K_o \) and large \( K_i \) values are selected to ensure the response speed and stability of the system. In the later stage of regulation, in order to reduce the static error and improve the control accuracy of the system, the values of \( K_p \) and \( K_i \) should increase. At the same time, in order to compensate for the extended regulation time caused by the large \( K_o \) value in the early stage of regulation, the \( K_o \) value was supposed to be large. According to the above description, this section formulated the fuzzy rule base of \( K_p \), \( K_i \) and \( K_o \), as shown in sequence in Table 2.
Table 2. The $K_p$, $K_i$ and $K_o$ rule base for the fuzzy combiner.

| $e$ | PB | PB | PB | PM | PM | PM | ZO | PS | PS | ZO | PS | ZO | NB | NB | NB | NB | NB | NM | NM | NS | NS | NS | ZO | ZO | NM | NM | NM | NM | NM | NM | NM | NB | PB | ZO | ZO | ZO | ZO | ZO | ZO | ZO | PM | PB | PB | PB | PB | PB | PB | PS | PS | PS | PS | PS | PS | PS | PB | PB | PB |
|-----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

Finally, the center of gravity method is selected to defuzzify and get the values of $\Delta K_p$, $\Delta K_i$ and $\Delta K_o$, as shown in equation (6), where $\mu(e)$ and $\mu(ec)$ respectively represent the degree of membership corresponding to the deviation $e$ and $ec$, and $\mu(K_p)$, $\mu(K_i)$ and $\mu(K_o)$ respectively represent the membership degree corresponding to $K_p$, $K_i$ and $K_o$.

$$
\Delta K_p = \frac{\sum_{i=0}^{1} \mu_i(e) \times \sum_{j=0}^{1} \mu_j(ec) \times \mu_j(K_p)}{\sum_{i=0}^{1} \mu_i(e) \times \sum_{j=0}^{1} \mu_j(ec)}
$$

$$
\Delta K_i = \frac{\sum_{i=0}^{1} \mu_i(e) \times \sum_{j=0}^{1} \mu_j(ec) \times \mu_j(K_i)}{\sum_{i=0}^{1} \mu_i(e) \times \sum_{j=0}^{1} \mu_j(ec)}
$$

$$
\Delta K_o = \frac{\sum_{i=0}^{1} \mu_i(e) \times \sum_{j=0}^{1} \mu_j(ec) \times \mu_j(K_o)}{\sum_{i=0}^{1} \mu_i(e) \times \sum_{j=0}^{1} \mu_j(ec)}
$$

The $\Delta K_p$, $\Delta K_i$, and $\Delta K_o$ values obtained are sent to the PID controller. Equations (1), (4) and (5) are used to establish a robot control model to polish the blades.

2.3 Excessive grinding preventing
In the experiment of polishing the flat plate, there would be too much grinding at the position where the flat plate and the grinding belt just contacted, for the following reasons. According to the principle of fuzzy PID algorithm, when the blade and belt are not in contact at the beginning of grinding, grinding force is set and the force error is maximized, and the proportional coefficient calculated by fuzzy-PID algorithm is also relatively large, which further makes the motor speed very high. This condition can cause the initial contact position to be excessive ground. Excessive grinding is abominable and must be avoided, so a novelty means was proposed. According to the classification standard of contact force, the polishing process can be divided into three parts: Firstly, before polishing, the loading part of the robot arm moves towards the polishing machine, and the contact force is 0N, which may lead to excessive grinding. Secondly, during the polishing process, the contact force fluctuates between 3N and 7N.
Thirdly, after grinding, the blade will return to its original position with a contact force of 0, so it is impossible for the blade to contact the belt, and excessive grinding does not occur. According to the difference between the actual force $F_a$ and the setting force $F_d$, which is used as the judgment basis. And the limiting motor voltage module is increased. This paper designed a protection module in the program. The logic is as shown in Figure 3:

![Figure 3. Excessive grinding preventing](image)

### 3. Experimental validation

This section is not only going to introduce the laboratory equipment, such as an industrial robot and a sand belt grinding mechanism, but also puts forward the experimental process. On the basis of the correlative experience of the belt grinding of Computerized Numerical Control machine, advisable the polishing parameters was chosen, for instance, the abrasive belt type, the polishing contact force and the abrasive belt velocity. All these contribute to the grinding of blades that meet quality requirements.

#### 3.1 The experimental platform

To carry out experimental analysis of the grinding blade processes, a setup for the robotic grinding was designed and applied as shown in Figure 4.

![Figure 4. Robotic grinding setup](image)

1 - robot; 2 - fixture; 3 - blade; 4 - tension wheel; 5 - force sensor; 6 - sand belt grinding mechanism

The robotic arm is equipped with a clamp attached to the engine blades. The robot arm moves in a set path that conforms to the blade surface profile during grinding. Abrasive belt grinding machine with flexible mechanism, for example, tensioning wheel with spring. A powerful sensor on the grinding device feeds back the contact force.

#### 3.2 Plate grinding and overgrinding preventing

First of all, it is reasonable to perform experiments on a simple flat plate. Refer to previous experiments of the belt grinding of CNC machine, the material of engine blade is superalloy material, and we choose advisable the polishing parameters, for instance, the abrasive belt type, using alumina stacked abrasive belt (KK718X), the polishing contact force as 4.8N and the abrasive belt velocity as 2800 rpm. Experiments verified the procedures for preventing excessive grinding. In Figure 5, a superalloy plate
with excessive grinding was shown. In the next subsection, the pictures of the blades without excessive grinding were shown.

![Excessive grinding](image)

**Figure 5.** The plate with excessive grinding

### 3.3 Blade grinding and experimental results

After finishing the grinding test of the above flat plate, the experience was summarized and the grinding experiment of the blade was carried out. Set the trajectory of the robot arm, in addition, used the same belt type, polishing contact force, and belt speed as the plant experiment did. Made sure that other influencing factors remain the same, two control groups were done. One group did not exert force control, the other group exerted force control fuzzy PID algorithm. Experimental results were obtained, as shown in the Figure 6.

![Experimental results](image)

**Figure 6.** Comparison of experimental results

In the experimental group without force control, the surface roughness was improved, but it could not meet the requirements of blade surface roughness. In the experimental group with fuzzy PID algorithm, the roughness is greatly improved, specifically, the surface roughness is 0.054 μm, and the blade surface has benign consistency, meeting the requirements of grinding.
4. Conclusion
This paper introduces an innovative intelligent digital compliant grinder, which applies fuzzy-PID algorithm for active force control to ensure constant contact force during the polishing process in robotic polishing. Those works enormously lessen the milling mask of the blade and boost the surface quality. Firstly, this paper did experiments with the superalloy plate, employing optimal polishing parameters, and put forward a program method to prevent excessive grinding. Secondly, this study conducted robotic blade polishing experiment, and verified the availability of the proposed method. The original surface roughness of engine blade was 1.672μm, when the active contact force under fuzzy PID algorithm was applied, surface roughness was reduced to 0.054μm, comparing to the surface roughness 0.589μm by the non-force control, and the actual force fluctuates were within 0.5N. The results demonstrate that the machining consistency and surface roughness are remarkably improved with the proposed the robotic intricate blade polishing algorithm.

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Reference
[1] Gao H , Zhao Z , Sun Y W . Recent Development of the Aero-Engine Impeller and Blade Surface Polishing Technology[J]. Advanced Materials Research, 2010, 135:7-12.
[2] Tian F , Lv C , Li Z , et al. Modeling and control of robotic automatic polishing for curved surfaces[J]. CIRP Journal of Manufacturing Science and Technology, 2016, 14:55-64.
[3] Liao L , Xi F , Liu K. Adaptive Control of Pressure Tracking for Polishing Process. ASME. J. Manuf. Sci. Eng. 2010;132(1):011015-011015-12.
[4] Haibo W, Hang G, et al. Development of novel guar gum hydrogel based media for abrasive flow machining: Shear-thickening behavior and finishing performance. (Elsevier: International Journal of Mechanical Science), 2019, Vol 157-158, pp 758-772.
[5] Zhong Z W. Recent Advances in Polishing of Advanced Materials[J]. Advanced Manufacturing Processes, 2008, 23(5):8.
[6] Fengjie Tian , Chong Lv, et al. Modeling and control of robotic automatic polishing for curved Surfaces. Vol 14 (Elsevier: CIRP Journal of Manufacturing Science and Technology), 2016, pp 55-64.
[7] Duan Jihao,Shi Yaoqiao,Li Xiaobiao,et al. Adaptive polishing for blisk by flexible grinding head[J].Acta Aeronautica et Astronautica Sinica,2011,32(5):934-940.
[8] Antnio Lopes, Almeida F . A force-impedance controlled industrial robot using an active robotic auxiliary device[J]. Robotics and Computer Integrated Manufacturing, 2008, 24(3):299-309.
[9] Dai H , Yuen K M , Elbestawi M A . Parametric modelling and control of the robotic grinding process[J]. International Journal of Advanced Manufacturing Technology, 1993, 8(3):182-192.
[10] Zhang J , Liu G , Zang X , et al. A hybrid passive/active force control scheme for robotic belt grinding system[C]/ 2016 IEEE International Conference on Mechatronics and Automation. IEEE, 2016.
[11] D Puangdownreong, T Kulworawanchpong, S Sujitjorn. Input weighting optimization for PID controllers based on the adaptive tabu search. 2004 IEEE Region 10 Conference D. 2004: 451-454.
[12] Adnan Jabbar Attiya, Yang Wenyu, et al. Fuzzy-PID Controller of Robotic Grinding Force Servo System, Telekomnika Indonesion Journal of Electrical Engineering,2015;15:515-525.
[13] Ocampo-Duque, W, et al. “Assessing water quality in rivers with fuzzy inference systems: A case study”, Environment International, (Elsevier: Environment International)2006; Vol 32, pp 733-742.
[14] Hong-Liang Gao, Xi-Sheng Zhan, Yi-Ran Yuan, Zi-Jie Pan, Guo-Long Yuan. “Mitigation of low frequency oscillations in power systems based on Mamdani fuzzy inference”, Transactions of the Institute of Measurement and Control, 2019.