An improved Rational Bezier model for pneumatic constant force control device of robotic polishing with hysteretic nonlinearity

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Research Article

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An improved Rational Bezier model for pneumatic constant force control device of robotic polishing with hysteretic nonlinearity
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ABSTRACT: The pneumatic constant force control device has been widely used in robot deburring, sanding, polishing, and other fields due to its good flexibility, simple control, and low cost. The force control accuracy of the pneumatic constant force system could be greatly affected by its nonlinear hysteresis characteristics in the process from the cylinder input to the force output at the end of the device. A Rational Bezier based state fitting method (BSFM) has been presented for calibrating the inherent nonlinearity of the low-cost pneumatic constant force system. Compared with the most widely used PSFM, which is a Polynomial based state fitting method, the BSFM could calibrate the strong inherent nonlinearity of the system more smoothly with the lower ordered model and in a continuous form rather than the piecewise form of the PSFM. The BSFM could maintain a balance between simplicity and precision. Through a series of comparative experiments with different contact forces and feed rates, the proposed method has smaller force overshoot and when active force control is turned on the force variation is greatly reduced to less than 2 N. The average roughness of the workpiece reached 0.4 µm after polishing.

Keywords: Robotic polishing, Force control, Constant force control devices, Pneumatic constant force system

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1. Introduction

The pneumatic constant force control device has been widely used in robot deburring, sanding, polishing, and other fields due to its good flexibility, simple control, and low cost \cite{1,2}. The pneumatic constant force control device can ensure that the tool and the workpiece always maintain a constant force contact state, and it is used as an additional end constant force control actuator to realize the constant force control indirectly. Compared with the direct constant force control method that drives the joint torque of the robot, this method has the following advantages: it requires less precision for the robot, only the robot needs to complete the position control, and the device is responsible for the constant force control to realize the solution of force-position hybrid control coupling \cite{3}; control is easy to implement, and there is no need to re-develop the underlying program of the robot \cite{4,5}; it can effectively avoid the inertial impact of the robotic arm \cite{6}. Benefiting from the above advantages, a series of pneumatic constant force control device products have been used in the fields of robot deburring, sanding, polishing, etc \cite{7,8}. However, the compliant structure of the pneumatic constant force control device improves the flexibility of the system, but also increases the difficulty of its precise control, making it difficult to apply it to high-precision and fast-response occasions.

Aiming at the problems of poor precision and slow response of constant force control of pneumatic constant force control devices, many researchers have proposed many effective methods \cite{9-12}. The pneumatic constant force control device developed by Liao et al. \cite{9} is made of three pneumatic cylinders to extend the tool spindle for the polishing force control. A recursive least-squares estimator is developed to estimate the pneumatic model, and then a minimum-degree pole-placement method is applied to design a self-tuning controller. Jin et al. \cite{10} established a multi-variable coupled contact force model of the airbag polishing tool and obtained the predicted air pressure for inflating the airbag under the condition that both the airbag downward pressure and the polishing contact force were determined. Using the BP neural network PID control strategy to realize the polishing contact force online is controllable. The steady-state error of the control system is no more than 2 N. Huang et al. \cite{11} and Ma et al. \cite{12} both adopted cylinder, guide element, and electric proportional valve as the main components of the constant force control device. This device quickly adjusts the output pressure through the internal adjustment algorithm of the electric proportional valve, thereby ensuring the constant output force of the device.
Since it is difficult to obtain the grinding and polishing force directly and accurately in the grinding and polishing process, the pneumatic constant force control device mainly formulates the indirect closed-loop control strategy of the grinding and polishing force based on the feedback of the cylinder pressure. The design of the controller of this indirect closed-loop control strategy is usually more complicated and the amount of calculation is slightly larger. In addition, most of the existing studies have ignored the nonlinear hysteresis characteristics in the process from the cylinder input to the force output at the end of the device [13]. This nonlinear characteristic will not only reduce the force control accuracy of the pneumatic constant force control device but also increase the design difficulty and calculation amount of the controller.

Existing studies have shown that using a model to characterize the nonlinearity of a system with hysteresis and establish a hysteresis compensation controller is an effective way to improve the performance of the control system [14]. The models can be mainly divided into three types of hysteresis models: operators, differential equations, and intelligent computing [15]. In recent years, intelligent computing models have also been widely used in nonlinear system identification and controller design. Among them, the polynomial fitting model is relatively low cost and high efficiency [16,17]. Therefore, it is essential to work for the pneumatic constant force device to guarantee its control accuracy by establishing an effective model for the hysteresis nonlinearity of the pneumatic constant force control device to achieve high-precision compensation control.

The rest of this paper is organized as follows. In Section 2, the typical pneumatic constant force system is introduced briefly. The hardware of the experimental setup, the calibration method, and the parameter optimization model are presented in Section 3. Discussion of the experimental results and verification for the proposed system is presented in Section 4. Finally, the conclusions and future works are given in Section 5.

2. The pneumatic constant force system

To achieve a predefined contact force between the tool and workpiece, the pneumatic constant force system generally includes a pneumatic constant force device, and a pneumatic constant force control unit. Pneumatic control components and pneumatic actuators are important components of a pneumatic constant force device. Electro-pneumatic regulators and double-acting pneumatic cylinders are often used as pneumatic control and executive components of pneumatic constant force devices. The Electro-pneumatic regulator can continuously convert the input electric signal
into a pressure output element. Its built-in pressure sensor can detect the output pressure value in real-time and convert it into an analog signal for feedback. It adopts closed-loop control technology to achieve continuous and precise control of the output pressure. However, its steady-state characteristics have obvious hysteresis. The double-acting pneumatic cylinder can output pressure or tension, however, the friction between its mechanical parts is difficult to ignore.

The key to the design of the pneumatic constant force control unit is the establishment of the force control model. When the PC sets the output force target value that needs to be kept constant, based on the force control model of the pneumatic constant force system, the controller outputs the corresponding electrical signal to the electro-pneumatic regulator. The electro-pneumatic regulator can convert the input electric signal into gas pressure. In the working state of the electromagnetic directional valve as shown in Fig.1, the cylinder will output thrust under the action of the corresponding gas pressure. When the contact force of the device on the workpiece changes, the electro-pneumatic regulator will quickly adjust the output pressure through the internal adjustment algorithm, to ensure the constant output force of the device. In the case that the cylinder is required to output the pulling force, the electromagnetic reversing valve can change the gas flow direction in time to realize the reversal.

3. Modeling

3.1 Experimental setup

A robot pneumatic constant force polishing platform was established to verify the proposed modeling method, as shown in Fig. 2. The experimental system in this study consists of a robot arm,
a pneumatic constant force device, and a contact/polishing force measurement system. The robot arm is ABB IRB120 six-axis industrial robot arm, it has a handling capacity of 3 kg and 0.58 m reach and is controlled by ABB IRC5 M2004 industrial controller. A pneumatic constant force device includes an electro-pneumatic regulator (model No. SMC ITV2050-312L) as the pneumatic control component, which can step-less control air pressure (peak air pressure up to 0.9 MPa) in proportion to the DC voltage. This air pressure is almost constant in the specified voltage input range of the electro-pneumatic regulator (0 to 10 V input range). An air slide table (model No. JEND MXS) of 8 mm cylinder diameter and a 30 mm stroke was employed as the pneumatic actuator. The air slide table consists of a cross roller guide that is designed for the slide table to achieve a reliable linear motion relative to the cylinder piston rod. Hence, it carries the linear motion of the L-type connector to the polishing head. The polishing head of the end-effector consists of a polishing pad of 25 mm diameter and it is driven by a DC motor with a torque up to 0.8 Nm and a rated rotational speed up to 12000 rpm. The weight of the end-effector is 0.6 Kg, which is within the payload limits of the ABB IRB120.

The contact force measurement system in this study consists of a contact force measurement device and a data acquisition unit. The contact force measurement device is designed to ensure the contact force which was generated between the polishing pad and the workpiece only in the normal direction was measured by a force sensor during operation. The vise, which is used for clamping the workpiece, is bolted to a force transmission plate which is attached to the slider of the linear guide. Hence, the vise moves linearly along the guideway. Once the robot arm rotates 90 degrees around the 5th axis (as shown in Fig. 2), realizing telescopic motion along the polishing spindle to transmit the only normal contact force to the force sensor of the data acquisition unit. Fig. 3 shows schematically the hardware used to control the contact/polishing force in the proposed end-effector. The contact force in the normal direction was measured by a force sensor (model No. KH-L6N) with a maximum range of 10kg and 1mV/V sensitivity, which is connected to the NI 9237 module with a 24-bit resolution.
3.2. An improved Rational Bezier model

Based on the experimental platform, the electro-pneumatic regulator is connected to the analog output of the NI 9263 module, as displayed in Fig. 3. During the tests, continuously output the voltage signal to the electro-pneumatic regulator. The voltage signal is set at 0.1 V intervals,
increasing from 0 to 5 V and then decreasing from 5 to 0 V as a group. And the output data of the force sensor is collected in real-time, 10 groups are collected in total. Through the linear relationship between voltage and air pressure for interval dimensionalization, the hysteresis loop between input air pressure and output force of a pneumatic constant force system can be observed in Fig. 4. The non-linear behavior of the hysteretic loop of the pneumatic constant force system is probably caused by the fact that the rolling friction behavior of the cross-roller linear guide in the sliding table cylinder, the friction behavior between the cylinder wall and the piston rod in the sliding table cylinder, etc.

### 3.2.1. Polynomial and Rational Bezier fitting method

The Polynomial Fitting Method (PFM) is applicable in most cases of modeling of nonlinear hysteresis. Consider as the input pressure $x$ and $f$ as the output force. Based on the polynomial fitting method, the relationship between the two can be described by Eq. (1)\cite{17}. The optimization problem of the PFM, that is Eq. (1) is solved by MATLAB polynomial fitting function based on the $x$ and $f$ with different fitting order from $n=1$ to $n=15$. As the polynomial fitting model order $n$ increases from 1 to 15, the optimal objective function $o_p$ decreases from 0.1004N to 0.0971N gradually, as shown in Fig. 6(a). What can be seen in Fig. 6(a) is the steady decline of the optimal objective function after the polynomial fitting model order $n=3$. Therefore, some comparisons between the experimental value and experimental polynomial fitting model are displayed in Fig. 4(a) with fitting order of $n=2$ and $n=3$, respectively.

$$f_p(x) = \sum_{i=1}^{n+1} p_i x^{n-i+1}$$

(1)

Where $n$ denote the fitting order and $p_i$ denote the unknown fitting parameters. The unknown parameters $p_i$ could be determined by parameter optimization method based on the measured sampling sequences of $x$ and $f$ by minimizing the objective function

$$o_p = \min \left( \| e_p \|_2 \right)$$

(2)

Where $e_p = f - f_p(x)$ denote the residual error of the PFM.

The rational Bezier Fitting Method (BFM) is based on the Bezier curve theory, which could
calibrate the strong inherent nonlinearity of the system more smoothly with the lower ordered model. The lower ordered model could benefit from the real-time calibration stability and reduce the computing cost. According to the rational Bezier curve theory [18], a standard n-ordered rational Bezier curve could be described by Eq. (3). The objective of the optimization is to minimize the Euclidian 2-norm of residual error $e_b = f - f_b(x)$ . Where, $f_b$ and $f$ denote the experimental sampling sequences of $f_b(x)$ and $f$. The optimization problem of the BFM, that is Eq. (3) is solved by MATLAB programming with different model order from $n=1$ to $n=15$. A comparison between optimal objective function $o_b$ and $o_p$ with respect to different model order is displayed in Fig. 6(a). As the order $n$ of the BCM increases from 1 to 15, the optimal objective function $o_b$ decreases from 0.1014N to 0.0971N gradually. What can be seen in Fig.6(a) is the steady decline of the optimal objective function after the rational Bezier fitting model order $n=2$. Therefore, some comparisons between the experimental value and experimental rational Bezier fitting model are displayed in Fig. 4(b) with fitting order of $n=1$ and $n=2$, respectively.

$$f_b(x) = \sum_{i=1}^{n+1} C_{n+1}^{-i+1} w_{i-1} b_{i} x^{i-1}(1-x)^{n-i+1}$$

(3)

Where $b_i$ denote the displacement coefficients of the handle points. Where $w_{i-1}$ denote the weight coefficients of the handle points, the turning radius of the curve could be adjusted by weight coefficients to achieve a better local description.
Fig. 4. The PFM and BFM fitting. (a) Comparisons between the experimental conventional true value $f$ and PFM $f_p$ with model $n=2, n=3$ respectively. (b) Comparisons between the experimental conventional true value $f$ and BFM $f_b$ with model $n=1, n=2$ respectively.

3.2.2. Rational Bezier based state fitting method

From Fig. 4, it can be seen that for a certain calibration efficiency, the BFM has the advantage to reduce the calibration model order, which is beneficial for accelerating the computing process and guaranteeing fitting stability. But it could be also observed that the BFM cannot describe the hysteretic loop of the pneumatic constant force system. To improve the fitting performance of the nonlinearity with hysteretic loops, a feasible way is to divide the BFM fitting model into some segments and become a piecewise form.

The input pressure $x$ and the measured output of the force sensor $f$ have been divided into two sets of $\{x_i, f\}$ and $\{x_d, f\}$, where $x_i = x \cap (\& 0)$ and $x_d = x \cap (\& < 0)$. Based on the above design sets, the optimization problem of the BSFM, that is Eq. (4) is solved by MATLAB programming with different model orders from $n=1$ to $n=15$. To make a distinction from the BFM, the objective function $\min_{bs} o_{bs} = \min(\|e_{bs}\|_2)$ is adopted for the BSFM, where $e_{bs} = f - f_m(x)$. To analyze the effectiveness of this method, PSFM also be obtained based on the above method and equation (1), as shown in Fig. 5(a). A comparison between optimal objective functions $o_{ps}$ and $o_{bs}$ with respect to different model orders is displayed in Fig. 6(b). As the order $n$ increases from 1 to 15, the optimal objective function $o_{ps}$ and $o_{bs}$ decreases from 0.1400N to 0.0279N and from 0.1100N to 0.0237N, respectively. It should be noted that the PSFM needs at least a third-order model to achieve a fitting, whereas the BSFM needs only a second order to achieve a fitting is displayed in Fig. 5(c).

Comparing Fig. 5(b) and Fig. 5(d), it could be observed that BSFM could calibrate the system’s inherent nonlinearity in a continuous form rather than piecewise form of the PSFM. The continuous form BSCM could be generated into C language code in one go.

$$f_{bs}(x) = \begin{cases} f_{bs}(x_i) & x_i = x \cap (\& 0) \\ f_{bs}(x_d) & x_d = x \cap (\& < 0) \end{cases}$$ (4)

where input pressure state variables $x_i$ and $x_d$ denote the increasing and decreasing velocity state of the electro-pneumatic regulator, respectively.
Fig. 5. The PSFM and BSFM calibration. (a) Comparisons between the experimental conventional true value $f$ and PSFM $f_{ps}$ with model $n=2$, $n=3$ respectively. (b) Enlarged view of the figure a. (c) Comparisons between the experimental conventional true value $f$ and BSFM $f_{bs}$ with model $n=2$, $n=3$ respectively. (d) Enlarged view of the figure c.
3.3. Experimental validation of BSFM

To verify the accuracy of the proposed improved polynomial model, based on the experimental platform (Fig.2), the obtained optimal BSFM and PSFM are compiled into the MCU. During the validation tests, the electro-pneumatic regulator is forced to produce reciprocating air pressure that drives the air slide table. And the desired force $f_d$, the measured force of the BSFM $f_{bs}$ and PSFM $f_{ps}$ is sampled into experimental ones in real-time, is compared in Fig.7a.

A quantitative comparison between the BSFM and PSFM is given in Fig.7b by $e_{bs} = f_{bs}(x) - f_d$ and $e_{ps} = f_{ps}(x) - f_d$. Where $e_{bs}$ and $e_{ps}$ represent the experimental fitting error of the BSFM and PSFM, respectively. And after the fitting, the maximum fitting error of the BSFM and PSFM is about 1.32N and 2.65N, respectively. It can be seen that the significant differences among the error distribution by two methods. The errors distribution of the PSCM is relatively consistent, mainly negative. However, during the force rising phase, the error distribution of BSFM is mainly negative. In the force drop phase, the error distribution of BSFM is mainly positive. The changes in the direction of system friction can be the plausible reason for this difficulty. It reveals that for the hysteresis loops fitting problem, the BSFM exhibits better-fitting ability than PSFM.
4. Discussion

4.1. The step response characteristic

Based on the experimental platform shown in Fig. 2, the step force control response of the pneumatic constant force system is studied. In the test, the desired driving force $f_d$ is sequentially set to 5~40N with an increment of 5 N. After the force control reaches the steady-state for a certain period, unload to the no-load state, and then the next step force loading control is performed according to the desired driving force. Fig. 8 shows the step force control response of the system under different desired driving forces.

As shown in Fig. 8, when the desired driving force is 5N, both BSFM and PSFM exhibit poor fit ability. When the desired driving force is 10N, both BSFM and PSFM can fit well. However, when the desired driving force is greater than 10N, the BSFM exhibits better-fitting ability than PSFM. For BSFM: When the steady-state error is 2 N, the minimum force control stabilization time is 0.27s ($f_d = 20N$), the longest force control stabilization time is 0.43s ($f_d = 40N$), and the average force control stabilization time is 0.38s. When the steady-state error is 1 N, the minimum force control stabilization time is 0.33s ($f_d = 10N$), the longest force control stabilization time is 0.49s ($f_d = 40N$), and the average force control stabilization time is 0.38s. It should be noted that when the force is 5N, only 2N steady-state error force control can be achieved. The stabilization time of the proposed system is not fast, due to the hysteresis behavior of the system and is limited by the
low response frequency of the electro-pneumatic regulator, however, it is within an acceptable range.

![Fig.8. Step response characteristics of the actuating force.](image)

**4.2. Force tracking under different feed rates**

To verify the performance of the proposed system to track the desired contact force on the surface of the workpiece, this paper designed force tracking experiments under different contact forces (i.e., 10 and 15 N) and feed rates (i.e., 5 and 15 mm/s). In these experiments, the robot carried the pneumatic constant force system to contact a flat stainless-steel workpiece (150 × 62 × 22 mm) as shown in Fig. 2(a), and horizontally polished along the long side of the workpiece through a polishing pad (50 mm diameter) with 240-grit size sandpaper as shown in Fig. 2.

The force tracking results with the rotational movement included or excluded are shown in Fig. 9. It can be seen that the maximum steady-state error of the proposed pneumatic constant force system tracks the desired force is within 2N. As seen in Fig. 9(a) and Fig. 9(c), the force is much smoother and more stable without the rotational movement because this motion does most of the work in material removal during polishing processing, generating mechanical vibrations and increasing control difficulty. As seen in Fig. 9(c) and Fig. 9(d), with a feed rate of 15 mm/s, the proposed system tracks the desired force more accurately with a smaller overshoot and a shorter settling time.

When the rotational movement was included in the tests, the polishing motor of the proposed design was turned on with a rotational speed of 3900 rpm. As seen in Fig. 9(b) and Fig. 9(d), there is a larger overshoot and vibration, regardless of the feed rate.

To ensure that the results of the force control experiments were not affected by the workpiece surface’s topography, the steel plate used in this paper was pre-processed via milling. Due to the
characteristics of milling, the milled surface contains a directional line from the milling tool as shown in Fig.10(a), which were obtained with the Olympus DSX510 under 20 times magnification. To avoid the influence of the motor starting and stopping moments on the surface roughness, the roughness at three different surface areas as shown in Fig.2 was measured with Mahr MarSurf-PS1. The measurement results are in a range of around 0.815 ~ 1.285 µm. The 2D topographies of the workpiece surface after five times repeated polishing experiments are shown in Fig.10(b)- (e). It can be seen that the proposed system can decrease the machining marks from the milling processing shown in Fig.10(a). It can also be seen that the surface of the workpiece obtained by the proposed system controlling the contact force at 10N with a slow feed rate of 5 mm/s is smoother and more consistent (Fig. 10(b)). The surface roughness of the workpiece after five times repeated polishing experiments is shown in Fig.10(b)-(e). The roughness value used for comparison is the roughness of each experiment is the average value of four measurements using three different surface areas as shown in Fig.2. The experimental results shows that the average roughness of the workpiece reached 0.4 µm after polishing. And under the same force, the surface roughness value of the lower moving speed of the robot arm is smaller. And with the same robot arm moving speed, the surface roughness value is smaller when the force is large.
Fig. 9. Force tracking results under different levels of desired contact/polishing forces and feed rates. (a) with a feed rate of 5 mm/s and without rotational movement. (b) with a feed rate of 5 mm/s and rotational movement. (c) with a feed rate of 15 mm/s and without rotational movement. (d) with a feed rate of 15 mm/s and rotational movement.

Fig. 10. Workpiece surface of the workpiece surface. (a) 2D topography of the workpiece surface after milling
(before polishing). (b) Workpiece surface after polishing with a feed rate of 5 mm/s and a desired force 10N. (c) with a feed rate of 15 mm/s and a desired force 10N. (d) with a feed rate of 5 mm/s and a desired force 15N. (e) with a feed rate of 15 mm/s and a desired force 15N.

5. Conclusions

In this study, a Rational Bezier based state fitting method (BSFM) has been presented for calibrating the inherent nonlinearity of the low-cost pneumatic constant force system. Compared with the most widely used PSFM, which is a Polynomial based state fitting method, the BSFM could calibrate the strong inherent nonlinearity of the system more smoothly with the lower ordered model and in a continuous form rather than the piecewise form of the PSFM. The lower ordered model could benefit from the real-time calibration stability and reduce the computing cost. The continuous form BSFM could be generated into C language code in one go. The BSFM could maintain a balance between simplicity and precision.

Several experiments are conducted including force tracking during contact and real polishing with different levels of desired contact/polishing forces and feed rates. The experimental results show that the proposed method has smaller force overshoot and when active force control is turned on the force variation is greatly reduced to less than 2 N. From the 2D topographies of the polished workpiece surface, the experimental results shows that the average roughness of the workpiece reached 0.4 µm after polishing.

Declarations

a. Funding (information that explains whether and by whom the research was supported)

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b. Conflicts of interest/Competing interests (include appropriate disclosures)

Not applicable.

c. Availability of data and material (data transparency)

All data generated or analyzed during this study are included in this published article and its supplementary information files.

d. Code availability (software application or custom code)

Not applicable.

e. Ethics approval (include appropriate approvals or waivers)

Not applicable.
The force control accuracy of the pneumatic constant force system could be greatly affected by its nonlinear hysteresis characteristics in the process from the cylinder input to the force output at the end of the device. A Rational Bezier based state fitting method (BSFM) has been presented for calibrating the inherent nonlinearity of the low-cost pneumatic constant force system. The BSFM could maintain a balance between simplicity and precision.

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