

The Immune Self-adjusting Contour Error Coupled Control in Machining Based on Grating Ruler Sensors

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Abstract: The actual dynamic performance of each feed axis can't match well usually, which will destroy machine tool contour accuracy seriously. The immune self-adjusting contour error coupled control method based on grating ruler sensors is developed to improve machine tool contour accuracy in the paper. Firstly, measure and convert the feed axis actual displacement into pulse signals with grating ruler sensors on each sampling period; then calculate the contour error and contour error compensation control quantity. The method combines the advantages of immune mechanism and classical Proportion Integration Differentiation (PID) control algorithm. The introduced method is testified on the three-axis computer numerical control (CNC) milling machine with three high precision grating ruler sensors. And the experimental results show that the proposed immune self-adjusting contour error coupled control method can improve machine tool contour accuracy remarkably. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Grating ruler sensor, Displacement measurement, Contour error, Immune mechanism, Contour precision.

1. Introduction

In manufacturing fields, many parts have complex profile [1]. For these complex parts machining, one way is to approximate parts profile with linear segments and adopt linear interpolation. Another approach is to directly use curve interpolation method. Compared with the linear segments approximation and linear interpolation, the curve direct interpolation method can improve machining accuracy and processing speed synchronously in theory [2].

For multi-axis CNC machine tool, the contour precision is the most important factor to determine the machining accuracy. In CNC machining, the

contour error is defined as the shortest distance between the current cutter position and the command tool path curve [3]. The contour precision relates to the dynamic characteristics matching degree of each feed axis, and depends on the multi-axis linked precision [4]. The CNC machine tool servo drive system is much complex, and the transmission parts friction and electrical components parameters may change in machining. So the actual dynamic performance of each axis can't match well usually, which will destroy the machine tool contour accuracy seriously. Compared with advanced single axis servo controller, the contour error coupled control is more effective to improve contour accuracy [5-6]. Many researchers conduct in-depth study on the contour

error calculation and compensation approach in CNC machining. For plane and space curves, Geng et al. defined the distance as contour error, from the actual cutter location to the line through the two interpolation points on the current sampling period and the last sampling period [7]. Yeh et al. put forward a contour error tangent approximation algorithm, which defined the distance from the actual cutter position to the tangent through the current ideal interpolation point on the command tool path [8]. LEE et al. developed a contour error vector control method for the parameter curve, which calculated the contour error through solving nonlinear equations with bisection algorithm and Newton iterative algorithm on each sampling period [9].

In the contour error coupled control, the most important thing is to calculate the contour error compensation control quantity, which is a voltage signal. Then compute the sum of contour error compensation control quantity and following error position control quantity, and output to each axis servo system [10]. The PID controller is adopted to compute CNC machine tool following error position control quantity usually. And many researchers use intelligent methods such as neural networks to calculate contour error compensation control quantity. But the neural network algorithm is slow sometimes, which will destroy the CNC system real-time performance [11, 12]. Furthermore, the tracking curve curvature changes and disturbances reduce the contour error compensation effect. So it is urgent to put forward a method with predictive function and adaptive ability to achieve contour error compensation control quantity.

Consequently, the immune self-adjusting contour error coupled control method in machining is developed in the paper.

Firstly, the CNC machine tool contour error coupled control principle and the commonly used contour error computing models are discussed in details; Secondly, the immune self-adjusting contour error coupled control method based on grating ruler sensors is introduced to improve machine tool contour accuracy; Finally, the introduced method is testified on the three-axis CNC milling machine. And the experimental results show that the proposed method can improve efficiently the machine tool contour accuracy

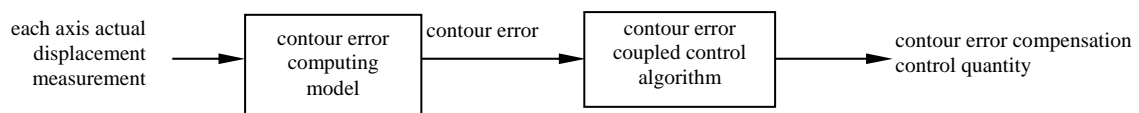


Fig. 1. The contour error coupled control steps.

2.2. The Commonly Used Contour Error Computing Models

The contour error tangent approximation computing model is shown in Fig. 2 [12]. For the

2. The Contour Error Coupled Control Principle and Commonly Used Contour Error Computing Models

2.1. The Contour Error Coupled Control Principle

With the two-axis linked machining arc profile as example, discuss the contour error when the actual servo gains of two feed axis are inconsistent. Suppose the center of arc profile at origin, and the ideal position loop gain of both X axis and Y axis servo system is k_s . However, the actual position loop gain of each axis can't match well usually in CNC machining, because of mechanical transmission parts friction and various disturbances. Suppose the servo gains of X axis and Y axis is k_{sx} and k_{sy} respectively, the feed speed be v , and the radius of arc profile be R . Then the radial error between the actual circle profile and the ideal circle profile caused by the inconsistent X axis and Y axis servo gain is as follows:

$$\Delta R = \pm \frac{v}{2} \left(\frac{k_{sx} - k_{sy}}{k_{sx} \times k_{sy}} \right) \sin 2\theta, \quad (1)$$

where θ is the angle between the actual cutter position vector and X axis vector. The radial error ΔR is negative when machining arc profile clockwise; And the radial error ΔR is positive when machining arc profile anticlockwise.

The actual tool path is an ellipse curve. As shown in Equation (1), the radial error ΔR has connection with feed speed and the actual feed axis servo gains. The long axis of the ellipse in the 45° line through origin when machining arc profile counterclockwise in XY plane; While the long axis of the ellipse in the 135° line through origin when machining arc profile clockwise in XY plane. This may destroy the machining quality and precision. Consequently, it is necessary to study the multi-axis coordinated control approach to improve the system contour precision.

Compared with the advanced single axis servo controller, the contour error coupled control is a more effective way to improve machine tool contour accuracy. The contour error coupled control steps are shown in Fig. 1.

general two-dimensional curve, suppose point P be the actual cutter position on some sampling period, point P^* be the ideal cutter position on the moment, line L be the tangent through point P^* on the ideal tool path, the angle between line L and X axis be θ ,

and the following error which expresses the distance between the actual and the ideal cutter position be E , then it can be obtained:

$$E = P^* - P, \quad (2)$$

Suppose the projection of following error E along X axis and Y axis be E_x and E_y respectively, and the closest point from point P to the target contour be P_1 . Then the contour error can be obtained:

$$\varepsilon = P_1 - P, \quad (3)$$

The calculation of point P_1 coordinates is very complicated for the complex curve. So many researchers use the contour error tangent approximation computing model. Let PP_1^* perpendicular to tangent L . When the following error is smaller, the contour error can be calculated approximately with Equation (4):

$$\varepsilon^* = P_1^* - P, \quad (4)$$

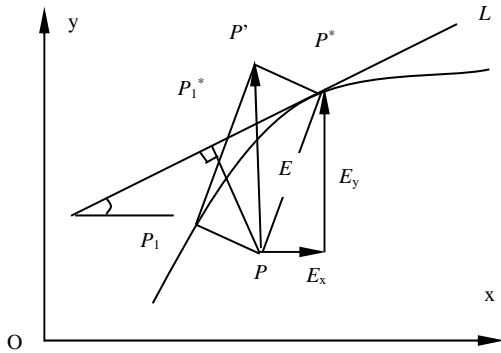


Fig. 2. The contour error tangent approximation calculation.

For the general curve, the curvature radius of certain point can be obtained:

$$\rho_k = \frac{[1 + (\frac{dy}{dx})^2]^{3/2}}{|\frac{d^2y}{dx^2}|}, \quad (5)$$

where $\frac{dy}{dx}$ and $\frac{d^2y}{dx^2}$ are the first derivative and second derivative respectively.

Consequently, the contour error can be obtained with Equation (6) for general profile curve:

$$\varepsilon \approx \varepsilon^* = -E_x c_x + E_y c_y, \quad (6)$$

$$c_x = \sin \theta - E_x / (2\rho_k), \quad (7)$$

$$c_y = \cos \theta + E_y / (2\rho_k), \quad (8)$$

$$\sin \theta = \frac{dy/dx}{\sqrt{1 + (dy/dx)^2}}, \quad (9)$$

$$\cos \theta = \frac{\text{sgn}(dy/dx)}{\sqrt{1 + (dy/dx)^2}}, \quad (10)$$

3. The Immune Self-adjusting Contour Error Coupled Control Method

As shown in Fig. 1, the contour error which calculated according to interpolation instruction and actual tool position on each sampling period, should be converted into contour error compensation control quantity. The commonly used contour error compensation control method is shown in Fig. 3. On each sampling period, adopt following error PID position controller to calculate contour error compensation control quantity. This method is simple, but the compensation effect is unsatisfactory in machining.

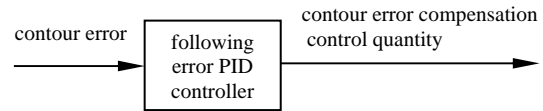


Fig. 3. The commonly used contour error compensation control method.

There are T cells and B cells in the immune system of organisms. And B cells can secrete antibody to eliminate external invasion antigen [13]. In immune response process, T cells can promote or inhibit the proliferation and differentiation of B cells, which plays an important role in immune regulation. Adopting the biological systems immune mechanism, the immune self-adjusting contour error coupled control method is developed in the paper, which combining the advantages of the immune mechanism and classical PID control algorithm. The introduced method can obtain satisfactory system accuracy and system robustness even curve curvature change and external disturbances. The structure of the immune self-adjusting contour error coupled control is shown in Fig. 4.

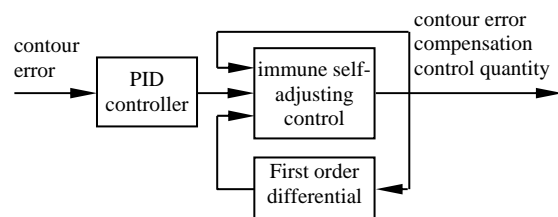


Fig. 4. The immune self-adjusting contour error coupled control structure.

The corresponding relationship between immune system and the contour error compensation control system is shown in Table 1.

Table 1. The corresponding relationship.

Immune system	Contour error compensation control system
The K generation of antigen and antibody breeding	The K sampling period of CNC system
Antigen concentration	Contour error
Antibody concentration	Contour error compensation control quantity

The introduced immune self-adjusting contour error control method is a nonlinear PID controller essentially. Suppose the variable gain in the k sampling period be $k_{p1}(k)$, then

$$k_{p1}(k) = \frac{\varepsilon(k)}{\sum_{i=1}^N \varepsilon(k-i)/N}, \quad (11)$$

where N is the constant. Suppose the control coefficients of X axis following error PID controller be k_{px} , k_{ix} , and k_{dx} respectively; Suppose the control coefficients of Y axis following error PID controller be k_{py} , k_{iy} , and k_{dy} respectively; Suppose the control coefficients of Z axis following error PID controller be k_{pz} , k_{iz} , and k_{dz} respectively. Suppose the projection of contour error $\varepsilon(k)$ along X axis, Y axis and Z axis be $\varepsilon_x(k)$, $\varepsilon_y(k)$ and $\varepsilon_z(k)$ respectively. Then the outputs of the immune self-adjusting contour error coupled control in the k sampling period along X axis, Y axis and Z axis can be obtained:

$$\begin{aligned} u_{cx}(k) &= u_{cx}(k-1) + k_{p1}(k) \cdot k_{px} \\ & \left((\varepsilon_x(k) - \varepsilon_x(k-1)) + \frac{k_{ix}}{k_{px}} \right. \\ & \left. \varepsilon_x(k) + \frac{k_{dx}}{k_{px}} (\varepsilon_x(k) - 2\varepsilon_x(k-1) + \varepsilon_x(k-2)) \right) \end{aligned}, \quad (12)$$

$$\begin{aligned} u_{cy}(k) &= u_{cy}(k-1) + k_{p1}(k) \cdot k_{py} \\ & \left((\varepsilon_y(k) - \varepsilon_y(k-1)) + \frac{k_{iy}}{k_{py}} \right. \\ & \left. \varepsilon_y(k) + \frac{k_{dy}}{k_{py}} (\varepsilon_y(k) - 2\varepsilon_y(k-1) + \varepsilon_y(k-2)) \right) \end{aligned}, \quad (13)$$

$$\begin{aligned} u_{cz}(k) &= u_{cz}(k-1) + k_{p1}(k) \cdot k_{pz} \\ & \left((\varepsilon_z(k) - \varepsilon_z(k-1)) + \frac{k_{iz}}{k_{pz}} \right. \\ & \left. \varepsilon_z(k) + \frac{k_{dz}}{k_{pz}} (\varepsilon_z(k) - 2\varepsilon_z(k-1) + \varepsilon_z(k-2)) \right) \end{aligned}, \quad (14)$$

Then the sum of contour error compensation control quantity and the following error position control quantity is output to each axis servo system to achieve position control.

4. The Contour Error Coupled Control Experiments

4.1. The Developed Three-axis CNC Milling Machine

The three-axis high precision CNC milling machine is built up with personal computer (PC) and digital signal processing (DSP) motion card. The X axis, Y axis and Z axis adopt Yaskawa alternating current (AC) servo motors and drivers. The Z axis servo motor has brake function. All of the feed axis adopts grating ruler sensors for displacement measurement and feedback, and the pulse equivalent is 0.001 mm. As shown in Fig. 5, the grating ruler sensors are composed of instruction grating and grating reading head. The instruction gratings are fixed in the milling machine moving parts, and the grating reading head are arranged in the milling machine fixed component. The three-axis high precision CNC milling machine hardware structure is shown in Fig. 6.

In the three axis CNC milling machine, the PC acts as upper computer and man-machine interface, which performs the command control, code editing, state detection and display function; And the DSP motion control card acts as lower machine which performs interpolation, position control, contour error coupled control functions. The PC adopts the Windows XP as development platform, and the data communication between PC and DSP is achieved through USB2.0. The software function structure of the CNC milling machine is shown in Fig. 7.

4.2. The Contour Error Coupled Control Experiments

As shown in Fig. 8, the tool path is expressed with NURBS curve:

The control points be $A_1(55,0,55)$, $A_2(55,55,55)$, $A_3(0, 55,0)$, $A_4(-55, 55,-55)$, $A_5(-55, 0,-55)$, $A_6(-55, -55,-55)$, $A_7(0,-55,0)$, $A_8(55, -55,55)$, $A_9(55,0,55)$;

The corresponding weights are (1, 0.6, 1, 0.2, 1, 0.5, 1, 0.3, 1);

The knot vector be (0, 0, 0, 0, 0.25, 0.375, 0.5, 0.625, 0.75, 1, 1, 1, 1).
The feed speed is 700 mm/min.



Fig. 5. The grating ruler sensors structure.

When adopting the existing contour error compensation control method shown in Fig. 3, the interpolation feed contour error curve is shown in Fig. 9. Under the same working conditions, when adopting the developed immune self-adjusting contour error control method, the interpolation feed contour error curve is shown in Fig. 10. The contour error curve between Fig. 9 and Fig. 10 is compared in Table 2. The experiment results show that the proposed immune self-adjusting contour error control method can improve machine tool contour accuracy remarkably.

Table 2. The contour error curve comparison.

Figure	Contour error max / (mm)	Contour error mean / (mm)	Contour error std / (mm)
Fig. 9	0.081	0.034	0.027
Fig. 10	0.052	0.026	0.012

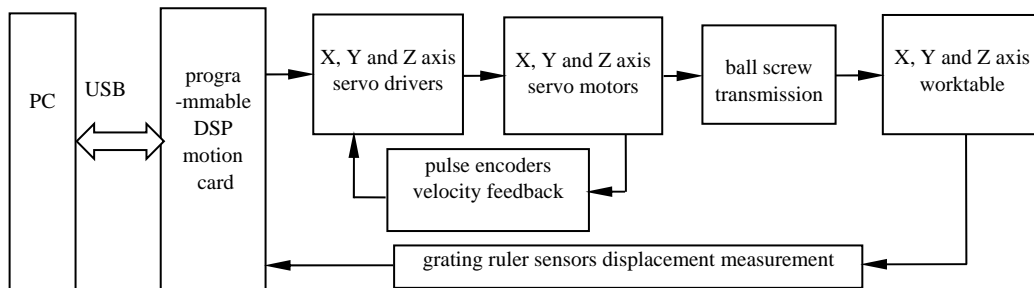


Fig. 6. The three-axis high precision CNC milling machine hardware structure.

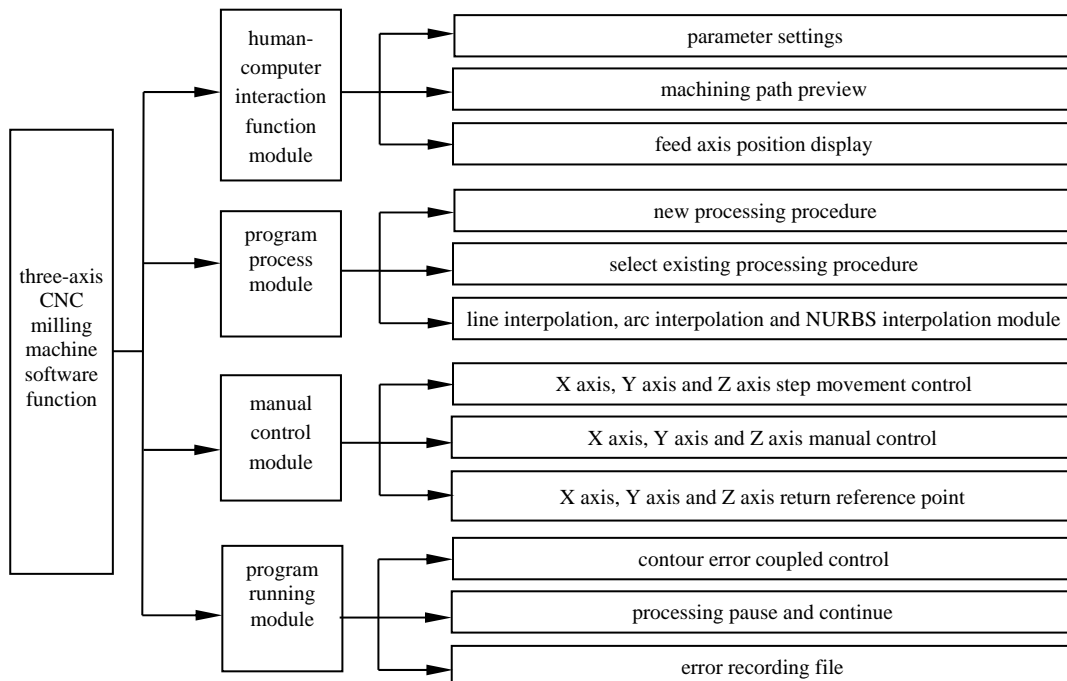


Fig. 7. The software function structure of the three-axis CNC milling machine.

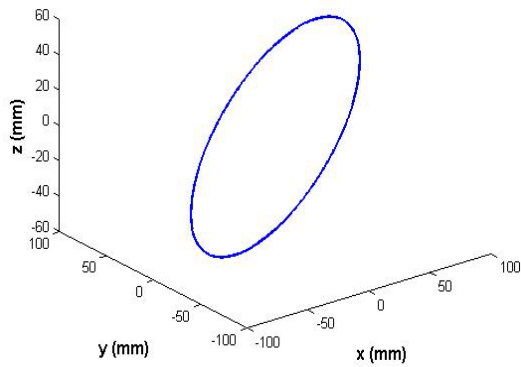


Fig. 8. The tool path curve.

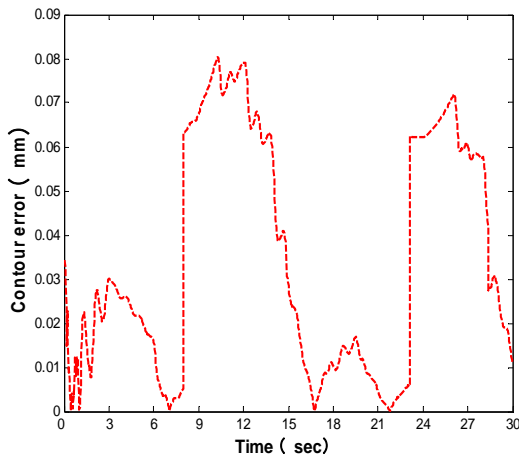


Fig. 9. The contour error curve when adopting the existing contour error compensation method shown in Fig. 3.

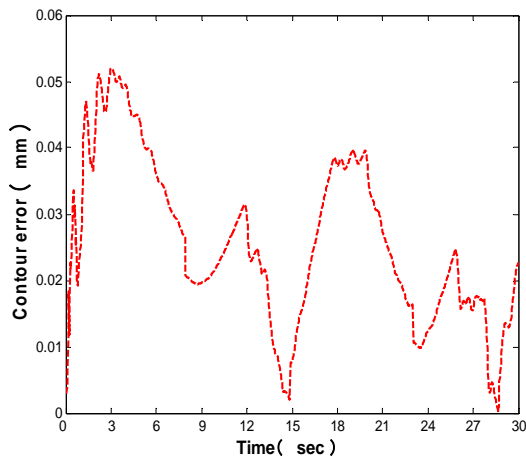


Fig. 10. Contour error curve when adopting the developed immune self-adjusting contour error control method.

5. Conclusions

The CNC machine tool servo drive system is much complex, and the transmission parts friction and electrical components parameters may change in machining, which will destroy the contour accuracy. The CNC machine tool contour error coupled control

principle is analyzed in details with the arc profile machining as example, and the commonly used contour error computing models are discussed. Adopting the biological systems immune mechanism, the immune self-adjusting contour error coupled control method based on grating ruler sensors is developed in the paper, combining the advantages of the immune mechanism and classical PID control algorithm. The introduced method is testified on the three-axis CNC milling machine. And the results show that the proposed immune self-adjusting contour error control method can improve machine tool contour accuracy remarkably.

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References

- [1]. Byung-Sub Kim, Seung-Kook Ro, Jong-Kweon Park, Development of a 3-axis desktop milling machine and a CNC system using advanced modern control algorithms, *International Journal of Precision Engineering and Manufacturing*, Issue 11, 2010, pp. 39-47.
- [2]. Xu Zhixiang, Zhao Guoyong, Zhao Fuling, A multi-axis cross-coupling control approach based on NURBS curve interpolation, *Mechanical Science and Technology*, Vol. 25, Issue 12, 2006, pp. 1451-1453.
- [3]. Peng Chao-Chung, Chen Chieh-Li, Biaxial contouring control with friction dynamics using a contour index approach, *International Journal of Machine Tools and Manufacture*, Vol. 47, Issue 10, 2007, pp. 1542-1555.
- [4]. Ming-Yang Cheng, Ke-Han Su, Shu-Feng Wang, Contour error reduction for free-form contour following tasks of biaxial motion control systems, *Robotics and Computer-Integrated Manufacturing*, Vol. 25, Issue 2, 2009, pp. 323-333.
- [5]. Zhao Ximei, Guo Qingding, Zero phase adaptive robust cross coupling control for NC machine multiple linked servo motor, *Proceedings of the China Electrical Engineering*, Vol. 28, Issue 12, 2008, pp. 129-133.
- [6]. Liu Yi, Cong Shuang, Optimal contouring control based on task coordinate frame and its simulation, *Journal of System Simulation*, Vol. 21, Issue 11, 2009, pp. 3381-3386.
- [7]. Geng Lirong, Zhou Kai, Research on real time compensation method based on time series predictive technology for contour error of CNC machine tool, *Manufacturing Technology & Machine Tool*, Issue 6, 2004, pp. 22-25.
- [8]. Syh-Shiuh Yeh, Pau-Lo Hsu, Analysis and design of integrated control for multi-axis motion systems, *IEEE Transactions on Control Systems Technology*, Vol. 11, Issue 3, 2003, pp. 375-382.
- [9]. Myung-Hoon Lee, Seung-Han Yang, Young-Suk Kim, A multi-axis contour error controller for free form Curves, *JSME International Journal*, Vol. 47, Issue 1, 2004, pp. 144-149.

- [10]. Song Bao, Zhou Yunfei, Research of the multi-axis integrated control, *Machine Tool & Hydraulics*, Issue 10, 2004, pp. 141-143.
- [11]. Ke-Han Su, Ming-Yang Cheng, Contouring accuracy improvement using cross-coupled control and position error Compensator, *International Journal of Machine Tools and Manufacture*, Vol. 48, Issue 12, 2008, pp. 1444-1453.
- [12]. Syh-Shiuh Yeh, Pau-Lo Hsu, Estimation of the contouring error vector for the cross-coupled control design, *IEEE/ASME Transactions on Mechatronics*, Vol. 7, Issue 1, 2002, pp. 44-50.
- [13]. Wang Bin, Li Aiping, Optimal design of fuzzy immune nonlinear PID control, *Control Engineering of China*, Issue 14, 2007, pp. 81-83.

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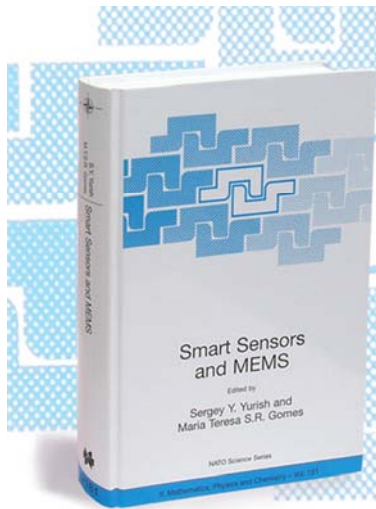
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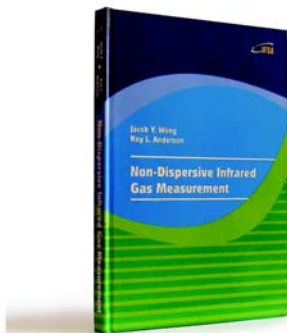
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