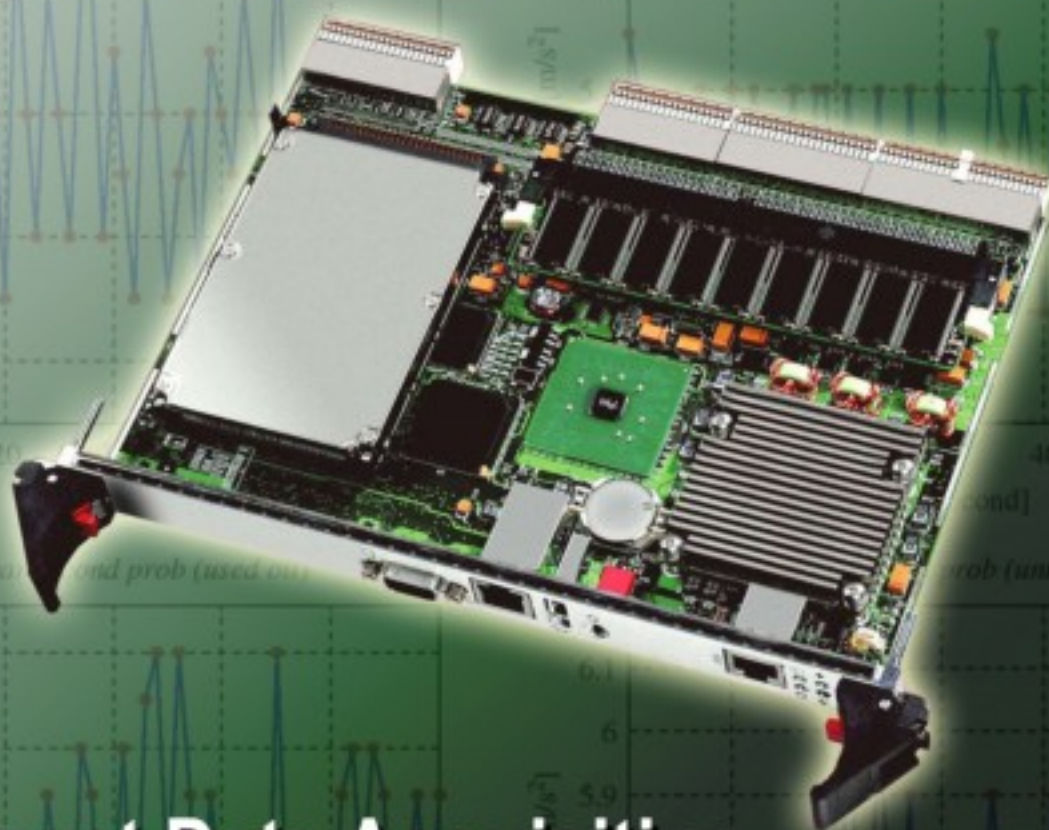


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International Frequency Sensor Association Publishing



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Accuracy of Experimental Platform of Controlled Five-bar Linkages

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Abstract: Controlled mechanism is a new powerful subject. It is engendered with the developing of modern science and combined modern computer technique, control technique, sensor technique and other modern science and technology with old mechanisms. It is also engendered with the demand of high accuracy and high flexibility for modern machine. Controlled five-bar is an important area of contemporary mechanism. On account of the current gap in experimental platform and its accuracy about five-bar, a controlled five-bar experimental platform (CFEP) has been designed and its accuracy was studied. Mathematical expression of the accuracy of experimental platform of controlled plate five-bar linkages was achieved by differential method. The accuracy quantitative of CFEP was analyzed using C++ programming. It is the theoretical design foundation of controlled five-bar linkages. Copyright © 2012 IFSA.

Keywords: Accuracy, Differential method, Five-bar linkages, C++, controlled five-bar experimental platform (CFEP).

1. Introduction

Multi-degree controlled mechanism is an important branch of contemporary mechanism. As the simplest multi-degree mechanism, controlled five-bar mechanism is becoming the hot spot of mechanism. Controlled five-bar mechanism has two initiative parts with one part motioning constantly and the other controlled by computer to give compensating motion, so the required track will be generated by one or more links on the mechanism. Professor Kong of Wuhan University of Science and Technology [1], professor Zhang Ce of Tianjin University [2] and professor Zou Huijun of Shanghai Jiaotong University

[3], etc. have made a lot of representative researches. Their researches are focused on realizing the track "accurately" for the starting point, and then are extended continuously. But documents [4, 5] break away from accurately realizing track and only study characteristic of five-bar mechanism, organization of itself only, put forward existence condition of double crank, type and singularity etc. The research results of these documents are undeniable, but the following subject matter exists: 1) Realize track of a few points position (about ten or twenty points), and can't reflect the inherent characteristic of realizing; 2) Initial purpose of five-bar mechanism is ignored, and it's very difficult to exist single crank of "accurately" realizing continuous track of five-bar mechanism; 3) There is a lack of design methods model universe and number value universe optimization "accurately" realizing the continuous track" of five-bar mechanism.

To make the experimental platform of controlled plate five-bar linkages work well, the geometrical parameters of five-bar linkages must be rationally ascertained. And the paper introduces how to determine the geometrical parameters of platform of controlled plate five-bar linkages [6]. Design of experimental platform of controlled plate five-bar linkages was introduced, but the accuracy of experimental platform is not discussed [7]. It is well known that the positioning precision and resolution of manipulators, including micro/nano manipulation systems, mainly depend on their topology and mechanical structures, actuators and transducers, sensing and measurement techniques, and control methodologies [8-11] and. Due to the backlash and stiction of the revolute joints and the geometric and dimensional errors of the components of the conventional manipulation systems, the conventional mechanisms cannot fulfill the requirements of the micro/nano manipulation tasks. Therefore, different mechanisms must be developed to overcome these problems. One of the best approaches to overcome the above problems is to utilize flexure-based mechanisms, where the conventional kinematic pairs are replaced by the flexure hinges. These types of joints have a number of advantages including no backlash, zero friction, and negligible hysteresis [12, 13]. In addition, such flexure-based mechanisms can be monolithically manufactured and thus reducing assembly errors and guaranteeing the machining accuracy [14].

The differential method is used to achieve the mathematical expression of the accuracy of experimental platform of controlled plate five-bar linkages, and C++ programming is used to analyze the accuracy in quantity. The result provides a theoretical foundation of the design and application of controlled five-bar linkages.

2. Differential Method

Mechanism error is calculated by the follower movement principle. Obviously, position error of mechanism follower is shown as equation (1). Where Y is defined as actual position of mechanism follower, Y_0 is defined as ideal position of mechanism follower, X_i is defined as independent position parameters of ideal driving part and middle fittings, ΔX_i is defined as infinitely small number of total differential.

$F(X_i) - F_0(X_i)$ in equation (1) represents the method error in mechanism. If the design of actual institution is accurate, and there isn't the approximate design principle, then the method error is zero, namely, $F(X_i) = F_0(X_i)$ and position error ΔP of mechanism follower is expressed as equation (2).

Position error of mechanism follower is equal to the sum of local position errors caused by each original error, which is called independent action principle or superposition principle. Partial derivative in equation (2) is the scaling of each mechanism original errors transferred to the follower, which is called error transfer coefficient or error transfer ratio, and called error influence coefficient generally. Error influence coefficient varies, influence on follower position error ranges too. Mechanism accuracy,

namely the relationship between mechanism position error and each original error, can be expressed by total differential of mechanism transmission equation actually. Infinitely small number of total differential ΔX_i can be replaced by $\Delta_i X_i$, for size parameter error of each mechanism is much smaller than its size. Hence, each partial derivative value of total differential is calculated and multiplied by responsive original error, and then error action principle is used to add each local error, the sum of follower position error is obtained. This is the differential method of calculation mechanism accuracy.

Some relevant factors are ignored in equation (2), for example there isn't design error and the effect of higher-order derivative is ignored. An approximation solution is got by differential method, but its accuracy is enough. So this method is often used to calculate mechanism accuracy.

$$\Delta P = \Delta Y = Y - Y_0 = F(X_i) - F_0(X_i) + \sum_{i=1}^n \left(\frac{\partial Y}{\partial X_i} \right)_1 \Delta X_i, \quad (1)$$

$$\Delta P = \sum_{i=1}^n \left(\frac{\partial Y}{\partial X_i} \right)_1 \Delta X_i = \left(\frac{\partial Y}{\partial X_1} \right)_1 \Delta X_1 + \left(\frac{\partial Y}{\partial X_2} \right)_1 \Delta X_2 + \cdots + \left(\frac{\partial Y}{\partial X_n} \right)_1 \Delta X_n \quad (2)$$

3. Accuracy Calculation of Controlled Plate Five-bar Linkages

Track point P in Fig. 1 can be expressed as following.

$$\rho = \rho_0 + l_1 e^{i\phi} + r e^{i(\phi_2 + \alpha)} \quad (3)$$

$$x = x_0 + l_1 \cos \varphi + r \cos(\phi_2 + \alpha) \quad (4)$$

$$y = y_0 + l_1 \sin \varphi + r \sin(\phi_2 + \alpha), \quad (5)$$

where x_0, y_0 are coordinates of hinge point A; l_1 is the crank length; φ is the crank angle; r is the track rod length; α is the angle between track rod and connecting rod; ϕ_2 is the angle between rocker and X axis; ϕ_3 is the angle between support rod and X axis; l_2 is the connecting rod length; l_3' is the rocker length, namely the sum of initial four-bar rocker length and slide compensation distance; l_4 is the frame length.

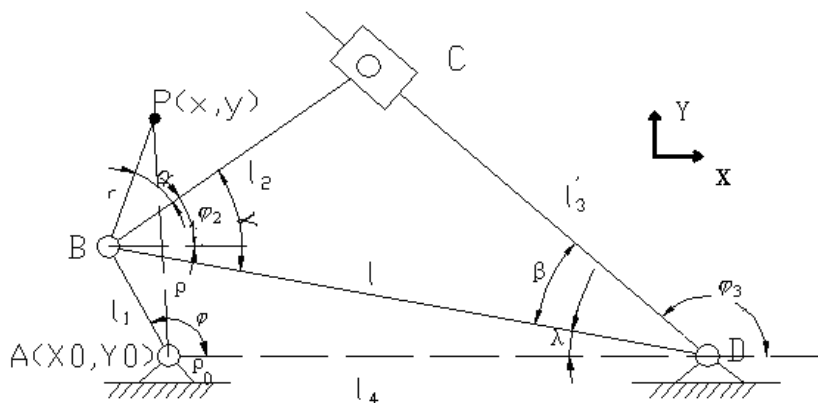


Fig. 1. Five-bar linkages track figure.

According to equation (2), derivation of $x_0, l_1, l_2, l_3', l_4, \phi, r, \alpha$ by x are did respectively, error influence coefficient of above several parameters influence on track accuracy are got. Derivation should be paid attention as following. ϕ_2 is the implicit function of $l_1, l_2, l_3', l_4, \phi$. Because compensation movement is sure, controlled five-bar linkages can be seen as four bar linkages. There are five independent variables in four bar linkages, namely $Z=4+1=5$.

$$\Delta x = \Delta x_0 + [\cos \phi - r \sin(\phi_2 + \alpha) \frac{\cos(\phi - \phi_3)}{l_2 \cos(\phi_2 - \phi_3)}] \Delta l_1 - r \sin(\phi_2 + \alpha) \frac{\cos(\phi_2 - \phi_3)}{l_2 \sin(\phi_2 - \phi_3)} \Delta l_2 + r \sin(\phi_2 + \alpha) \frac{1}{l_2 \sin(\phi_2 - \phi_3)} \Delta l_3' + r \sin(\phi_2 + \alpha) \frac{\cos \phi_3}{l_2 \sin(\phi_2 - \phi_3)} \Delta l_4 + [-l_1 \sin \phi + r \sin(\phi_2 + \alpha) \frac{\frac{\partial [S(\phi)]}{\partial \phi} + l_1 \sin(\phi - \phi_3)}{l_2 \sin(\phi_2 - \phi_3)}] \Delta \phi + \cos(\phi_2 + \alpha) \Delta r - r \sin(\phi_2 + \alpha) \Delta \alpha \quad (6)$$

$$\Delta y = \Delta y_0 + [\sin \phi + r \cos(\phi_2 + \alpha) \frac{\cos(\phi - \phi_3)}{l_2 \cos(\phi_2 - \phi_3)}] \Delta l_1 + r \cos(\phi_2 + \alpha) \frac{\cos(\phi_2 - \phi_3)}{l_2 \sin(\phi_2 - \phi_3)} \Delta l_2 - r \cos(\phi_2 + \alpha) \frac{1}{l_2 \sin(\phi_2 - \phi_3)} \Delta l_3' - r \cos(\phi_2 + \alpha) \frac{\cos \phi_3}{l_2 \sin(\phi_2 - \phi_3)} \Delta l_4 + [l_1 \cos \phi - r \cos(\phi_2 + \alpha) \frac{\frac{\partial [S(\phi)]}{\partial \phi} + l_1 \sin(\phi - \phi_3)}{l_2 \sin(\phi_2 - \phi_3)}] \Delta \phi + \sin(\phi_2 + \alpha) \Delta r + r \cos(\phi_2 + \alpha) \Delta \alpha \quad (7)$$

And $\rho^2 = x^2 + y^2$ derivate ρ by $l_1, l_2, l_3', l_4, \phi, r, \alpha$, there is:

$$\left| \frac{\partial \rho}{\partial l_1} \right| = \frac{x[\cos \phi - \frac{r \sin(\phi_2 + \alpha) \sin(\phi - \phi_3)}{l_2 \cos(\phi_2 - \phi_3)}] + y[\sin \phi + \frac{r \cos(\phi_2 + \alpha) \sin(\phi - \phi_3)}{l_2 \sin(\phi_2 - \phi_3)}]}{\sqrt{x^2 + y^2}} \quad (8)$$

$$\left| \frac{\partial \rho}{\partial l_2} \right| = \frac{x[-r \sin(\phi_2 + \alpha) \frac{\cos(\phi_2 - \phi_3)}{l_2 \sin(\phi_2 - \phi_3)}] + y[r \cos(\phi_2 + \alpha) \frac{\cos(\phi_2 - \phi_3)}{l_2 \sin(\phi_2 - \phi_3)}]}{\sqrt{x^2 + y^2}} \quad (9)$$

$$\left| \frac{\partial \rho}{\partial l_3'} \right| = \frac{x \frac{r \sin(\phi_2 + \alpha)}{l_2 \sin(\phi_2 - \phi_3)} + y \frac{r \cos(\phi_2 + \alpha)}{l_2 \sin(\phi_2 - \phi_3)}}{\sqrt{x^2 + y^2}} \quad (10)$$

$$\left| \frac{\partial \rho}{\partial l_4} \right| = \frac{x \frac{r \sin(\phi_2 + \alpha) \cos \phi_3}{l_2 \sin(\phi_2 - \phi_3)} + y \frac{-r \cos(\phi_2 + \alpha) \cos \phi_3}{l_2 \sin(\phi_2 - \phi_3)}}{\sqrt{x^2 + y^2}} \quad (11)$$

$$\left| \frac{\partial \rho}{\partial \phi} \right| = \frac{x[-l_1 \sin \phi + \frac{r \sin(\phi_2 + \alpha) [\frac{\partial [S(\phi)]}{\partial \phi} + l_1 \sin(\phi - \phi_3)]}{l_2 \sin(\phi_2 - \phi_3)}] + y[l_1 \cos \phi - \frac{r \cos(\phi_2 + \alpha) [\frac{\partial [S(\phi)]}{\partial \phi} + l_1 \sin(\phi - \phi_3)]}{l_2 \sin(\phi_2 - \phi_3)}]}{\sqrt{x^2 + y^2}} \quad (12)$$

There is the following geometric relationship in Fig. 1.

$$l = \sqrt{l_1^2 + l_4^2 - 2l_1 l_4 \cos \phi} \quad (13)$$

$$\lambda = \arccos \frac{l_4^2 + l^2 - l_1^2}{2l_4 l} \quad (14)$$

$$\beta = \arccos \frac{l_3'^2 + l^2 - l_2^2}{2l_3'l} \quad (15)$$

$$\gamma = \arccos \frac{l_2^2 + l^2 - l_3'^2}{2l_2l} \quad (16)$$

$$\varphi_2 = \gamma - \lambda \quad (17)$$

$$\varphi_3 = \pi - \lambda - \beta \quad (18)$$

From the above equations, error influence coefficients of each parameter are all functions along with the change of φ , and φ is the crank angle changing between the cycles of $0-2\pi$, so error influence coefficient is the cycle function of φ . Length size of controlled plate five-bar linkages is put into equation (6) ~ equation (18), error influence coefficients of l_1 , l_2 , l_3' , l_4 , φ , r , α can be got. In order to simplify the problem, assuming that there is no installation error of linear motor, that is to say, the parallel degree error between linear motor and slider is zero in Fig. 1. And the Installation position deviation of linear motor is zero, so the length of l_3' consists of connecting rod length l_3 and slider compensation distance $S(\varphi)$. In experimental platform of controlled plate five-bar linkages, slider compensation distance $S(\varphi)$ is achieved by controlling linear motor motivation, the motion accuracy of which is 0.001 mm. Hence, its motivation error can be ignored, and the error of l_3' is only the error of connecting rod length l_3 .

4. Accuracy of Experimental Platform

There are following parameters in the experimental platform of controlled plate five-bar linkages. $l_1 = 100\text{mm}$, $l_2 = 390\text{mm}$, $l_3' = 655\text{mm} + S(\phi)\text{mm}$, $l_4 = 576\text{mm}$, $\alpha = 15^\circ$, $S(\phi) = 5\sin\phi$, using C++ to program, error influence coefficient curve of such l_1 , l_2 , l_3' , l_4 , φ , r , α by x , y , ρ and maximum error influence coefficient of each parameter can be got (note: X, Y and ρ in the figure respectively represents partial derivative the above parameter by x , y , ρ , namely error influence coefficient).

5. Results Analysis

From Figs. 2-8, maximum error influence coefficient of each parameter occurs in different phase. Hence, it is impossible that each original error maximum (namely maximum tolerance) occurs at the same time, and it's much impossible that errors add in the same direction. In addition, length error has a little effect on track accuracy in the instance, but the angle error has large effect on track accuracy. Error influence coefficients of l_2 , l_3 , l_4 and r are all smaller than 1. In other words, they reduce length error, which has a little effect on track accuracy. But l_1 is opposite rightly, it has a bigger effect on track accuracy. And error influence coefficient of both two angles φ and α is bigger, for example, when $\Delta\varphi = 1^\circ$, $\Delta\rho_{\max} = 4.096 \times 1 = 4.096\text{ mm}$. From the above analysis, angle has a bigger effect on track accuracy, so manufacturing accuracy in actual manufacture must be controlled strictly.

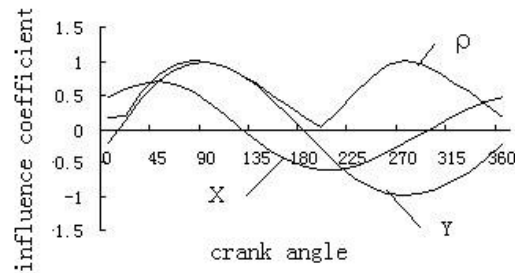


Fig. 2. Error influence coefficient of l_1 .

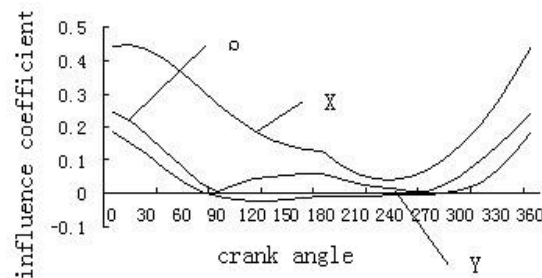


Fig. 3. Error influence coefficient of l_2 .

6. Conclusion

Controlled five-bar has become the hot spot of contemporary mechanism as the simplest multi-degree mechanism. So far, some theory outcomes of controlled five-bar have been achieved. However, as the practical achievement of theory, accuracy of experimental platform about five-bar linkages is seldom encountered. Ordinary expression of controlled plate five-bar linkages realizing tract is concluded by differential approach. The error effect factors of each parameter are calculated by C++ programs and analysis and synthesis of accuracy are studied by statistics means. It provided a reliable and practical work platform for researching and applying controlled mechanism.

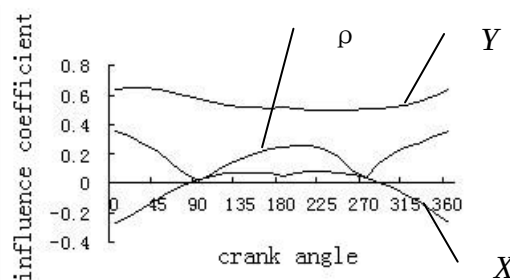


Fig. 4. Error influence coefficient of l_3' .

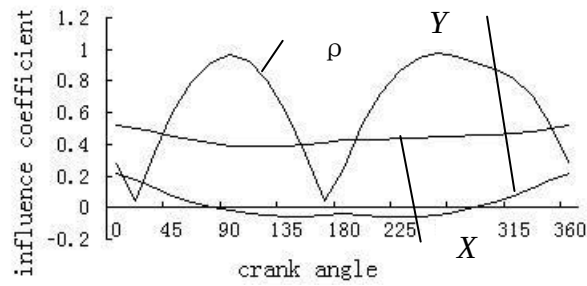


Fig. 5. Error influence coefficient of l_4 .

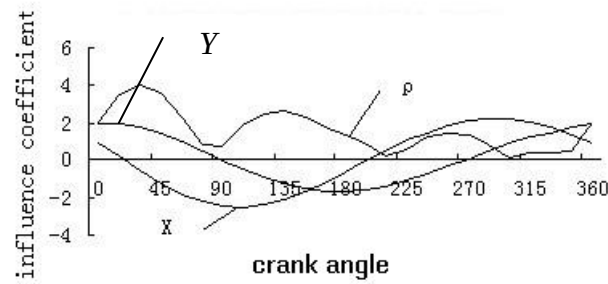


Fig. 6. Error influence coefficient of rank angle φ

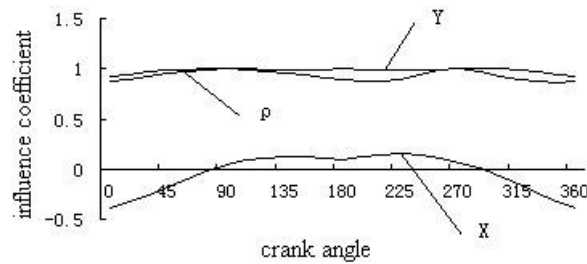


Fig. 7. Error influence coefficient of track stem r .

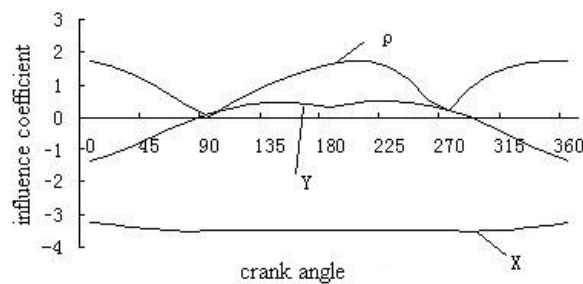


Fig. 8. Error influence coefficient of angle α between track stem and connecting rod.

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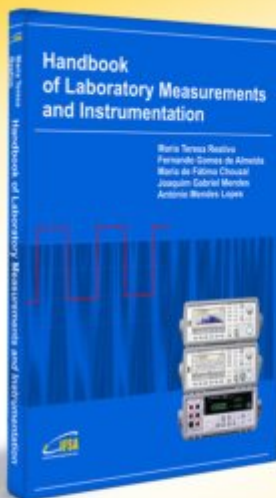


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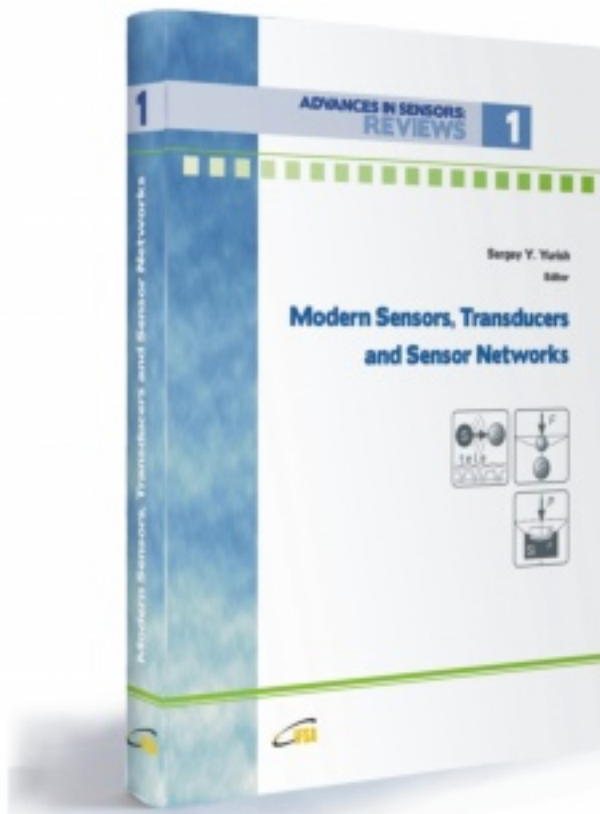
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