Research on Nonlinear Decoupling Method of Piezoelectric Six-Dimensional Force Sensor Based on BP Neural Network

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Abstract: The six-dimensional force sensor has become one of the major bottlenecks restricting the development of robots in China. In this paper, the problem of the decoupling of the piezoelectric six-dimensional force sensor with four-point support structure is studied, and the static decoupling method is studied. Firstly, the principle of nonlinear decoupling algorithm for six-dimensional force sensor is analyzed, and experimental data obtained by decoupling are acquired through calibration experiments, and sample selection and normalization processing are performed. After that, the BP forward feedback neural network was used to optimize the multi-dimensional nonlinear characteristics of the sensor output system, and the input and output mapping relationship of the sensor was determined, and the decoupled sensor output data was obtained. The determinant sensor's measurement accuracy evaluation index is compared with linearity error and coupling rate error.

1. Introduction

The development characteristics and trends of robotics technology are intelligence and the interaction between humans and robots. Intelligence is the third stage of robot development. Robots with sensing and autonomous behavior control functions have become a trend [1-2]. The six-dimensional force sensor can sense all information of the space six-dimensional external forces and moments of the joints of the robot wrist, etc., and is an important part of the intelligent robot. The piezoelectric sensor is a non-elastic body type power sensor, which is one of the most promising sensors in the development of smart structures and robotics [3-4].

The accuracy and reliability of the six-dimensional force sensor's technical parameters are directly related to the quality of the robot, and thus relate to the accuracy, safety, and reliability of the robot's work. In the signal output process, coupling between the dimensions of the signal will reduce the sensor's measurement accuracy, restricting the application of the sensor in the high, fine, and sharp areas [5]. Although the linear decoupling algorithm can reduce the influence of inter-dimensional coupling to a certain extent, the decoupling principle model is established under the assumption that the sensor system is linear. So the decoupling effect is not ideal. In order to further improve the measurement accuracy, research on nonlinear decoupling algorithms must be carried out. Many scholars have proposed various decoupling algorithms for strained six-dimensional force sensors with different configurations [6-7]. For piezoelectric six-dimensional force sensors, there are relatively few reports on nonlinear decoupling algorithms [8-10], and the coupling error is large.

At present, neural networks play an extremely important role in the fields of computer science,
artificial intelligence, engineering, and robotics, and their application scope is also expanding. It is an important branch of intelligent development. The neural network can be subjected to a simple non-linear mapping and further stronger non-linear processing capabilities. It can build a coupling relationship between multidimensional data based on experimental data and achieve nonlinear decoupling [11]. In this paper, the decoupling algorithm of BP neural network is mainly used to study the nonlinear decoupling of piezoelectric six-dimensional force sensor.

2. Nonlinear decoupling principle
The principle of the nonlinear decoupling algorithm for piezoelectric six-dimensional force sensor based on neural network is shown in Figure 1.

![Figure 1. Nonlinear decoupling principle of six-dimensional force sensor based on neural network](image)

The experimental object of this experiment is the four-point support structure piezoelectric six-dimensional force sensor developed by the research group [9]. Through the reasonable arrangement of the four quartz crystal groups, the generalized six-dimensional force is detected. The piezoelectric six-dimensional force sensor was calibrated to obtain the calibration experimental sample data, and then the nonlinear decoupling algorithm model for the piezoelectric six-dimensional force sensor based on BP neural network was designed.

3. Static Decoupling of Piezoelectric Six-Dimensional Force Sensor Based on BP Neural Network

![Figure 2. Flowchart of nonlinear decoupling algorithm based on BP neural network](image)

In this paper, a three-layer BP neural network is used to construct the model of decoupling algorithm for six-dimensional force sensor. Each neuron in the next layer is connected to each neuron in the previous layer with a certain weight, and the connection weight between the neurons in the same layer is zero. Connection weight determines the connection strength between neurons. Changing the weight and threshold can change the mapping relationship between input and output of neural network. The
BP neural network model of piezoelectric six-dimensional force sensor is shown in Figure 2.

The S-type (Tansig) function can be used as an activation function for hidden layer cell nodes, and the Purelin function can be used as an activation function for the output layer cell nodes. The six-dimensional output signal sample collected in the loading experiment is used as the input data of the input layer unit node. The actual loading force vector in the loading experiment is used as the output data of the output layer unit node.

When decoupling the forces/torques of each dimension, five sets of experimental data are selected to be normalized and treated as network training samples. A group of data that has not participated in training is normalized and used as a network test sample. The structural model is trained to obtain the right corresponding layer weights and thresholds, so that the mean square error between the predicted value and the expected value meets the set conditions, and the corresponding parameters of the sensor decoupling network model are obtained.

4. Training, Testing and Experimental Data Analysis of BP Neural Network

Using the BP algorithm toolbox that comes with MATLAB software, the network structure model of the BP algorithm that meets the decoupling requirements can be easily constructed, and the weight threshold initialization, data training, and test output work can be quickly completed [11]. In the decoupling model training process, because there is no uniform method to select the number of hidden layer element nodes, it needs to be preset based on experience. The number of hidden layers is initially set to 4-13, and then the network is trained separately. The number of hidden layers is determined by the results of multiple experiments. In the BP neural network model parameter setting, set the number of termination iterations epochs=10000, the momentum term coefficient to $mc=0.9$, the training speed set to $lr=0.05$, and the mean square error set to $10^{-5}$. Other parameters are default. When the number of hidden layer cell nodes is different, the results of the decoupling effects are listed in Table 1. It can be seen from Table 1 that when the number of nodes in the hidden layer is 9, it is appropriate to analyze from the perspective of mean square error, convergence speed, or network complexity. And the training effect is optimal. Figure 3 shows the minimum square root error performance drop curve and error gradient drop curve for the BP feedforward neural network when the hidden layer is 9. At this point, the number of network training steps is only 41 steps, and the mean square error can meet the target requirement of less than $10^{-5}$, and the network training ends.

| Hidden node | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Training step length | 10000 | 949 | 10000 | 55  | 70  | 41  | 41  | 74  |
| Training time    | 124.9 | 32.8 | 37.0 | 37.8 | 32.1 | 33.4 | 37.4 | 21.5 |
| Detection error  | 0.0556 | 0.0139 | 1.1e-5 | 9.9e-6 | 9.8e-6 | 9.9e-6 | 9.8e-6 | 9.9e-6 |

**Table 1. Comparison of decoupling performance with different number of hidden layer cell nodes**

![Minimum square root error drop curve](image.png)

(a) Minimum square root error drop curve
5. Decoupling effect analysis of BP neural network decoupling algorithm

Using the neural network structure obtained by training, the test sample is input into the network structure, and partial data of the decoupled input force value $F_{BP}$ is obtained. According to the data of the applied load value $F$ and the input force value $F_{BP}$, the performance curve of the six-dimensional force measurement force is shown in Figure 4. It reflects the correspondence between the decoupled applied load value and the input force value $F_{BP}$.

When the various force/moment loadings are applied, it can be seen from the figure 4 that the decoupled input force value and the actual expected value curve are nearly completely coincident, and the linearity is good. When a three-dimensional force load is applied, the influence on the coupling output of the three-dimensional torque is small; when three-dimensional torque is applied, the three-dimensional force is coupled and output, but the influence on the three-dimensional force full-scale value is small.

The percentage static coupling rate matrix algorithm is used to verify the decoupling effect of the BP neural network decoupling algorithm. The decoupled input force value $F_{BP}$ and the percentage static coupling rate matrix $E_{BP}$ are as shown in Equation 1 and 2.
From the static coupling rate matrix, after the decoupling of the BP forward feedback neural network, the I-type errors of the six-dimensional force sensor are: \(F_x\) is 0.08\%, \(F_y\) is 0.50\%, \(F_z\) is 0.14\%, and \(M_x\) is 0.20\%. \(M_y\) is 0.04\% \(M_z\) is 0.43\%. That is, the maximum Class I error is 0.50\%. When force \(M_z\) is loaded, \(F_y\) is strongly coupled by \(M_z\), and the inter-dimensional coupling strength is maximum. That is, the maximum class II error is 2.93\%. After decoupling by the BP decoupling algorithm, the linearity error and the coupling rate error of the sensor are reduced, and the measurement accuracy of the sensor can be more effectively improved.

6. Conclusion
In this paper, a static calibration experiment was conducted for a four-point support structure piezoelectric six-dimensional force/torque sensor prototype developed by the laboratory, and the reasons for the coupling of the sensors were briefly analysed. A mathematical model based on BP neural network decoupling algorithm was established and decoupled calculations were performed. After compensating the experimental data obtained by the calibration experiment of the sensor, it is verified that the decoupling algorithm based on BP neural network is adopted. Can more accurately reflect the nonlinearity of the sensor system, and to a greater extent improve the measurement accuracy of the sensor. Effectively solve the problem of sensor decoupling difficulties, and provide a basis for the engineering application research of the decoupling method of piezoelectric six-dimensional force sensor.

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