



NEURAL NETWORK BASED MULTISENSOR FUSION IN A NOVEL PERMANENT MAGNET MULTI-DOF ACTUATOR ORIENTATION DETECTION SYSTEM

Zheng LI

School of Electrical Engineering

Hebei University of Science and Technology

Shijiazhuang 050018, China

Email: Lzhfgd@163.com

Submitted: Aug. 10, 2012

Accepted: Sep. 17, 2012

Published: Dec.1,2012

Abstract- The methods of multi-DOF actuator orientation detection based on machine vision and magnetic field sensor and neural network based multisensor fusion are presented in this paper. Special grid pattern is printed on the surface of rotor according to the pseudo-random encoder for the camera capturing the image of the rotor. The magnetic field sensors are adopted and properly placed circling the shaft of rotor for detection the orientation information. By analyzing the image of the rotor, the coordinates of characteristic points in the coordinate system fixed on the rotor are derived. Combined with the magnetic sensor scheme to reduce the measurement error and enhance the fault tolerant ability, a multisensor data fusion scheme using BP neural network is developed and validated by experiment. The results show that multisensor data fusion based on NN is superior to single

measurement method with more accuracy and high reliability, which is more effective and practical for applications.

Index terms: Permanent magnet, multi-DOF, orientation detection, machine vision, magnetic sensor.

I. INTRODUCTION

With the development of the industry and technology, robot and manipulators which can achieve three-degree-of-freedom (3-DOF) motion are used more and more widely. This kind of devices are usually built with several convention driver motor, each having single degree-of-freedom (DOF), which reduces the position accuracy, efficient, dynamic performance of the system. In this condition, the multi-DOF actuators or motors have attracted many attentions. To realize precision control, the feedback control system is necessary. However, the measurement systems used for single-DOF feedback control system is not suitable for the multi-DOF feedback control system. So the orientation detection becomes a crucial problem and should be paid more attentions. There are mainly five methodologies to measure multi-DOF orientations recently. These measurement methods are classified into two kinds contact and noncontact methods. Because of the flaws of contract measurement method, using non-contract method is the development trends of the orientation measurement.

K.M. Lee et al developed a contact measurement system that used three single-axis encoders for measuring 3-DOF motions [1]. It required a mechanism which introduced friction and inertia to constrain the device. D. Stein used 96 point sensors to measure the orientation of the rotor based on the color detected by the sensors [2-4]. The rotor was painted in two colors. It was difficulty to transfer the pattern to the rotor and used too many sensors. K.M. Lee and D. Zhou presented a non-contract optical sensor for real-time orientation measurement [5]. The optical sensors detected the microscopic changes of surface feature. The surface property of the rotor influenced the resolution of the measurement system. W. Wang et al used six hall devices to detect the orientation of the rotor according to the magnetic field due to the rotor permanent magnets [6,7]. The measurement accuracy was affected by the magnetic field generated by the stator winding current, so the sensor outputs should be compensated according to the current. Using vision based sensor to detect the orientation was firstly proposed by H. Garner et al. [8]. Different from the

linear and the circular strings designed by H. Garner, Z. Qian et al. presented a new grid pattern design and construction method using pseudo-random-sequence (PRS) [9]. The size of the windows limited the measurement accuracy of these vision based method, because spherical curved plane is equivalent to flat plane in image processing procedure for extracting information of the characteristic points.

In this paper, an effective pattern design method and image matching algorithm to avoid the equivalence for improving the detection accuracy are presented combined with the 3-DOF magnetic field sensor based detection method. The two modes both have the reliability and outer disturbance problems, so neural network based multisensor fusion methods are adopted. The camera based machine vision measurement calibrated data are used as training samples for the magnetic sensors modeling and complete data fusion and the error analysis in fault cases is carried out by experiments.

II. OPERATION PRINCIPLE OF THE PM MULTI-DOF ACTUATOR

The motor prototype consists of a ball-shaped rotor with four layers of 40 poles and two layers of 24 poles. There are 10 poles with equally spaced position of alternative N-S distribution for the rotor. There are 12 poles in each layer and controlled separately for the stator. Figure 1 shows the basic structure of the actuator. The actuator is designed to implement maximum 67 degrees tilt motion and 360 degrees rotation. The illustration of the torque produced by one pair of poles can be shown in figure 2.

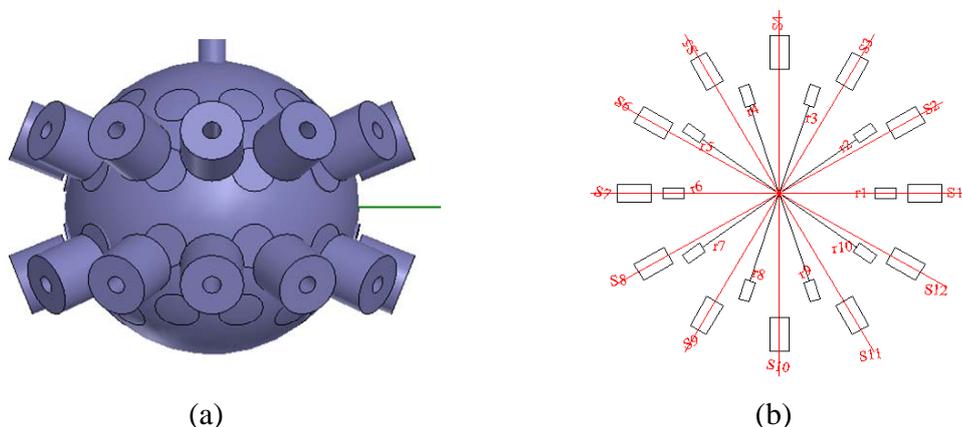
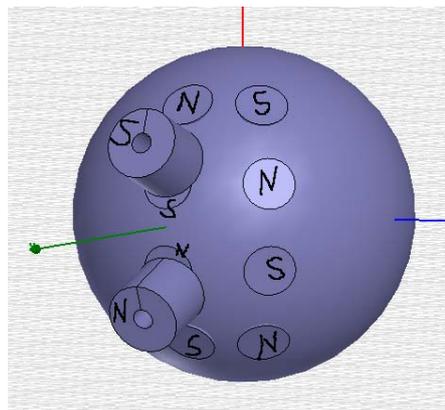


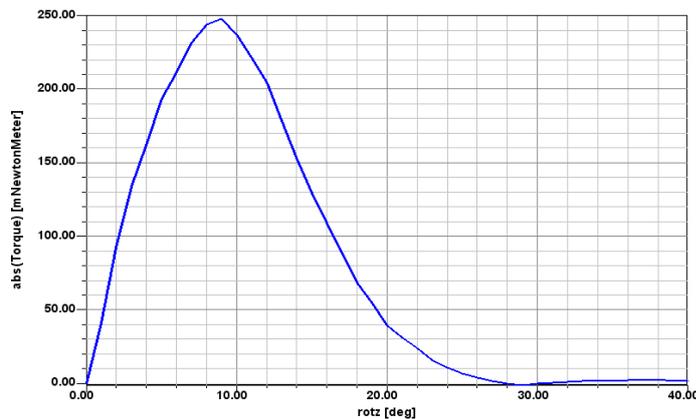
Figure 1. Basic structure of the actuator

(a) Side view of the stator and rotor, (b) Matching arrangement of the stator and rotor poles

Using the Lagrange energy method, the dynamic equations of multi-DOF actuator are obtained. Each equation represents an axis of Cardian Angle. It can be seen that there are many one-order and two-order coupling terms in the equation, which indicates serious inter-axes nonlinear coupling of the spherical actuator.



(a)



(b)

Figure 2. The illustration of the torque produced by one pair of poles

(a) The stator/rotor pole pairs' positions, (b) The interaction torque between one pole pair

III. ORIENTATION DETECTION METHODOLOGY AND MULTISENSOR FUSION SCHEME

a. Machine vision based image orientation method

To obtain the rotor position signal by image analysis, the first step is coating the rotor surface with a characteristic pattern. Stevenson and Jordan firstly introduced the flat grid to the position measuring system for the measurement of automatic navigation vehicle position offset [15], but this method can only measure the offset of the two directions and can not measure the amount of rotation. In this work, with the unequal spacing of grid lines on the part of rotor surface with the spraying method, the position features of the rotor can be loaded into the image. Grid spacing to be ranked is in accordance with the principle of pseudo-random coding. Figure 3 shows the plane and spherical surface grid to generate pseudo-random graphs. Diagram of the grid does not use the Earth's latitude and longitude interval distribution, which is to guarantee the uniqueness of the rotor in an arbitrary rotation angle and direction of image features.

The vision sensor selects a region of image for the rotor surface to eliminate the effects of spherical curvature deformation, and only part of the extraction of the central region image is analyzed and calculated. The selected area is smaller and can be approximated to a plane processing, thus avoiding the image deformation. The straight-line distance available for matching feature points can take instead of the spherical distance.

Like the vessel tracking method, the feature points are obtained from the vision sensor rotor image (intersection center point of grid lines). Extract two-phase vertical grid lines in the grid obtained within the central region as the search direction. After matching, according to the location of these points in the original sequence, the latitude and longitude in the rotating coordinate system can be determined and also the coordinates in this coordinate system.

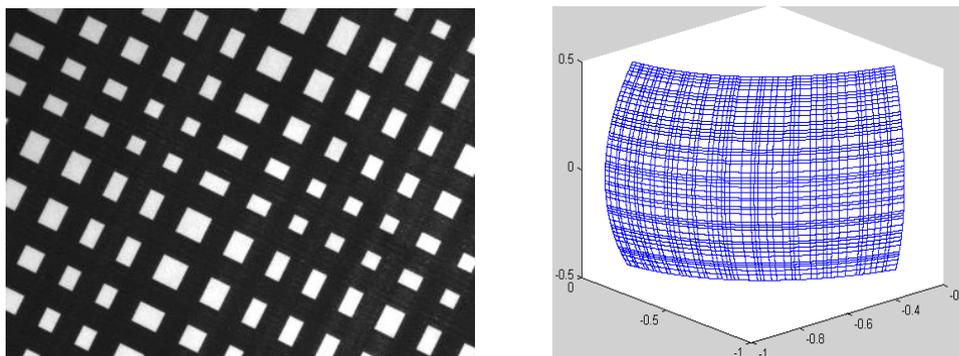


Figure 3. Schematic Grid pattern on the plane and rotor surface

The vision sensor calibration is to establish the relationship between the sensor pixel location and scene locations. The sensor model parameters can be solved according to the known feature

points' image coordinates and world coordinates. The initial position of the world coordinate system fixed at the center of the sphere of spherical rotor, even with the solid overlap in center of the rotor rotating reference frame. In this paper, the linear model of the sensor is used to simplify the computation to estimate the sensor parameters.

$$s_i \begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \end{bmatrix} \begin{bmatrix} X_i \\ Y_i \\ Z_i \\ 1 \end{bmatrix} \quad (1)$$

where u_i, v_i are the pixel points in the image, X_i, Y_i, Z_i are the coordinates of the world coordinate system.

Eliminating the parameter s_i of (1), simplified into

$$u_i = \frac{m_4 X_i + m_5 Y_i + m_6 Z_i + m_7}{m_1 X_i + m_2 Y_i + m_3 Z_i + 1} \quad (2)$$

$$v_i = \frac{m_8 X_i + m_9 Y_i + m_{10} Z_i + m_{11}}{m_1 X_i + m_2 Y_i + m_3 Z_i + 1} \quad (3)$$

It is needed as least 6 feature points to construct an over determined equations. 11 parameters are solved using the least squares fitting method.

The visual sensor's optical axis is perpendicular to the surface of the rotor, and intersects with the centre of the sphere. Firstly, accurately positioning the location of the rotor and stator, using the known coordinates of the spherical feature points in the world coordinate system to calibrate the sensor. Ideally rotor only rotates around the centre of the sphere and the sensor location is fixed after calibration, so the sensor calibration needs only once.

Let the coordinates of feature points in the world coordinate system and the rotation coordinate system can be expressed as $(X_i, Y_i, Z_i), (x_i, y_i, z_i)$ ($i = 1, 2, \dots, n$) respectively. The corresponding vectors are set as $\dot{r}_{r,i}, \dot{r}_{l,i}$. The feature points distribute on the rotor surface and the constraint equation $X_i^2 + Y_i^2 + Z_i^2 = r^2$ (r denotes the spherical radius), combined with (2) and (3), the feature points on the image can be converted to coordinates in the world coordinates

In photogrammetry, using the known coordinates of the points in two different coordinate systems, calculate the positional relationship between the coordinate system is a classic problem.

Reference [16] presented the closed solution to achieve absolute orientation quaternion. Set the coordinate system rotation matrix R , the coordinate inter-relationship can be expressed as:

$$\dot{r}_r = sR(\dot{r}_l) + \dot{r}_0 \quad (4)$$

where s is the proportional factor, r_0 is the origin point offset scale.

The principle of calculation matrix is to make $\sum_{i=1}^n \|\dot{r}_{r,i} - sR(\dot{r}_{l,i}) - \dot{r}_0\|^2$ reach its minimal value, i.e. to

make $\sum_{i=1}^n \dot{r}'_{r,i} \cdot R(\dot{r}_{l,i})$ to its maximal value.

Let $\dot{r}_l = \frac{1}{n} \sum_{i=1}^n \dot{r}_{l,i}$, $\dot{r}_r = \frac{1}{n} \sum_{i=1}^n \dot{r}_{r,i}$, $r'_{l,i} = \dot{r}_{l,i} - \bar{r}_l$, $r'_{r,i} = \dot{r}_{r,i} - \bar{r}_r$. Using the quaternion to represent the rotation $\dot{r}' = \dot{q}\dot{r}\dot{q}^*$, \dot{q} is the quaternion.

$$\sum_{i=1}^n \dot{r}'_{r,i} \cdot R(\dot{r}_{l,i}) = \dot{q}^T N \dot{q} \quad (5)$$

$$N = \begin{bmatrix} S_{xx} + S_{yy} + S_{zz} & S_{yz} - S_{zy} & S_{zx} - S_{xz} & S_{xy} - S_{yx} \\ S_{yx} - S_{zy} & S_{xx} - S_{yy} - S_{zz} & S_{xy} + S_{yx} & S_{zx} + S_{xz} \\ S_{zx} - S_{xz} & S_{xy} + S_{yx} & -S_{xx} + S_{yy} - S_{zz} & S_{yz} + S_{zy} \\ S_{xy} - S_{yx} & S_{xy} + S_{yx} & S_{yz} + S_{zy} & -S_{xx} - S_{yy} + S_{zz} \end{bmatrix}$$

where $S_{xy} = \sum_{i=1}^n x'_{l,i} \cdot x'_{r,i}$, \dot{q} is the eigenvector of the largest positive eigenvalue, \dot{q}^* is the conjugate of \dot{q} .

By solving above equation, it can be derived as

$$s = \frac{\sum_{i=1}^n (\dot{q}\dot{r}'_{l,i}\dot{q}^*) \cdot \dot{r}'_{r,i}}{\sum_{i=1}^n \dot{r}'_{r,i} \cdot \dot{r}'_{r,i}} \quad (6)$$

Substituting s into (4), based on the known feature points, the two sets of coordinate values under two coordinate systems, the over determined equations can be set to solve the rotation matrix R and the offset value \dot{r}_0 .

The transformation matrix between the world coordinate and the rotation coordinate system can be written as

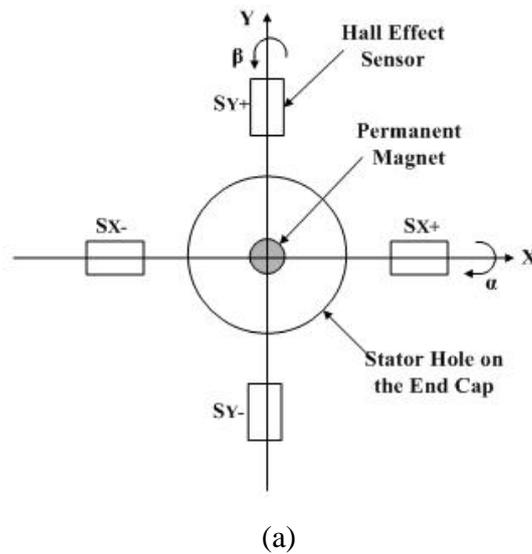
$$C = \begin{pmatrix} c\beta c\gamma & -c\beta s\gamma & s\beta \\ c\alpha s\gamma + s\alpha s\beta c\gamma & c\alpha c\gamma - s\alpha s\beta s\gamma & -s\alpha c\beta \\ s\alpha s\gamma - c\alpha s\beta c\gamma & c\alpha s\beta s\gamma + s\alpha c\gamma & c\alpha c\beta \end{pmatrix} \quad (7)$$

where α, β, γ are the Euler angles, \cos and \sin denote the cosine and sine functions.

So $\dot{r}_r = C \cdot \dot{r}_l$. When the centre of sphere is fixed, $C = sR$. Three general Euler angles α, β, γ can be solved. The space positions of permanent magnets after rotor rotation are determined from the rotation matrix, so as to provide position feedback control signal.

b. Magnetic orientation sensor measurement of M-DOF motions

Magnetic sensors are widely available at low cost due to the rapid advancement of semiconductor fabrication technology. The Hall-effect sensors which can measure either a constant or a varying flux possess both small size and electronics elements compatibility. The distributed multi-pole (DMP) method can be effectively used for the multi-DOF actuator or motor torque modeling and other related magnetic field problems [17-20]. Unlike other field calculation methods (such as FEM), the DMP models can be computed in real-time for motion estimation. Once the magnetic fields are obtained, the forces and torques on the PM assembly can also be computed from the surface integration in terms of a Maxwell stress tensor. The Schematic illustration of the magnetic field sensors for orientation detection can be shown in figure 4.



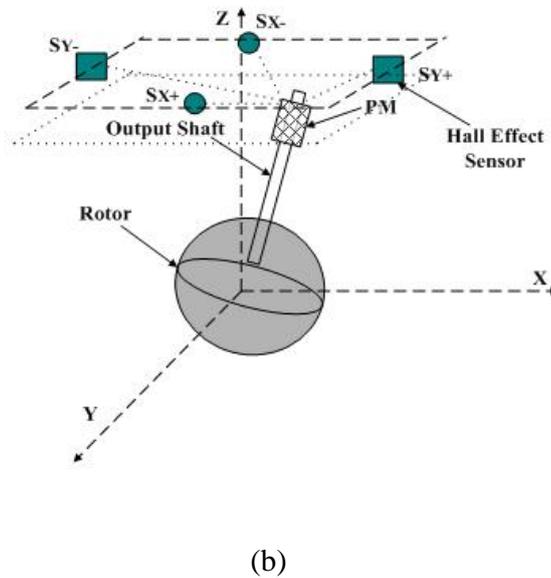


Figure 4. Schematic illustration of the magnetic field sensors for orientation detection
 (a) Top view with the shaft vertical position, (b) Perspective view of a special position

Using the DMP modeling method, in the x-y-z coordinate system the closed-form solution characterizing the magnetic flux density B of the single PM on the shaft is given by [18]

$$B = \frac{\mu_0}{4\pi} \sum_{j=0}^k m_j \sum_{i=1}^n \left(\frac{a_{R_{ji+}}}{R_{ji+}^2} - \frac{a_{R_{ji-}}}{R_{ji-}^2} \right) \quad (8)$$

where $\frac{a_{R_{ji\pm}}}{R_{ji\pm}^2} = -\frac{P - P_{ji\pm}}{|P - P_{ji\pm}|^3}$, μ_0 is the permeability of free space, m_j is the dipole moment in the j th loop; $P - P_{ji\pm}$ is the position vector from the i th dipole in the j th loop to arbitrary position $P(x, y, z)$ of interest; and $R_{ji\pm} = |P - P_{ji\pm}|$.

The general flux density B can be approximated as an n th order polynomial with the form:

$$\hat{B}_k = (\alpha, \beta) = \sum_{i=0}^n \sum_{j=0}^n c_{ij} C_k^j S_k^i \quad (9)$$

where the subscript k denotes the k th sensor; and n is the orders of the approximation.

After deriving \hat{B} , the orientation angle (α, β) can be solved as the inverse problem, which is related with the order of approximation. The following two equations can be used for each pair of sensors opposite on the axis:

$$\bar{B}_A = \frac{\hat{B}_{A+} + \hat{B}_{A-}}{2} = \sum_{i=0}^n \left(\sum_{j=0}^n c_{ij} C_{\alpha}^j \right) S_{\beta}^i, \text{ when } i \text{ is even}$$

$$\tilde{B}_A = \frac{\hat{B}_{A+} - \hat{B}_{A-}}{2} = \sum_{i=1}^n \left(\sum_{j=0}^n c_{ij} C_{\alpha}^j \right) S_{\beta}^i, \text{ when } i \text{ is odd}$$

where C and S denote the cosine and sine function of subscript angles respectively.

Then two sets of (α, β) estimating values can be solved from the pair of equations, one from each sensor pair.

c. Neural network based multisensor integration and fusion

The multisensory information fusion technology mainly aims to solve the information processing problems, which focuses on the using the information derived by multiple sensors to construct complete and proper description on the special object or environment features [21, 22]. Multisensor fusion and integration is a rapidly evolving research area and requires interdisciplinary knowledge in control theory, signal processing, artificial intelligence, probability and statistics, etc. There has been much research on the subject of multisensor and fusion in recent years. A number of researchers have reviewed the multisensor fusion algorithms, architectures, and applications.

During current neural networks' development, the back propagation theory based feed-forward neural network (BP) is more mature and widely used as shown in figure 5 and parameters in table 1. Neural network is with the essence of the nonlinear system that can approximate any nonlinear relationship, which is very appropriate for the data fusion applications as in this work. From the above, it can be known that the orientation detection data by machine vision and magnetic field sensors methods can be integrated and fused. The work can be divided into two parts: firstly, the data derived from the machine vision measurement can be taken as training samples for the magnetic field sensors mapping relations constructing; secondly, in the case of single measurement method in effect. It is known that the PM actuator has x, y, z rotation angles in three different degrees-of-freedom, so it needs 4 inputs and 3 outputs, this paper uses a neural network to realize the presented fusion and calibration method.

Table 1: Parameters of the neural network for applications

Parameter	Parameter Value	Parameter	Parameter Value
Number of Input Neural Nodes	4	Minimum Mean Squared Error	1e-1
Number of output Neural Nodes	3		
Number of Hidden Layer Neural Nodes	6	Minimum Gradient	1e-20
Hidden Layer Neural Nodes' Transfer Function	Logsig		
Output Neural Nodes' Transfer Function	purelin	Maximum Training Times	500

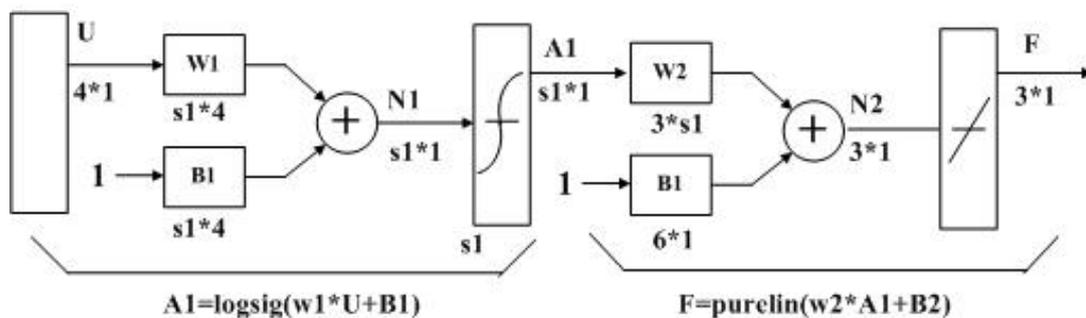


Figure 5. The structure of BP neural network

After calibration, certain sets of motion measurement data can be collected and used as the input of neural network with 120 sets as the training samples and 60 sets as the test samples. The number of hidden nodes is determined by the empirical formula $m = \sqrt{n+l} + \alpha$, where m denotes the number of hidden nodes, n denotes the number of input layer nodes, l denotes the number of output layer nodes, and α is constant number of 1~10. According to the input and output nodes, the nodes' numbers of hidden layer are set with 6, 7, 8, 9, 10, 11, and 12 to train and test. The training process can be shown in figure 6.

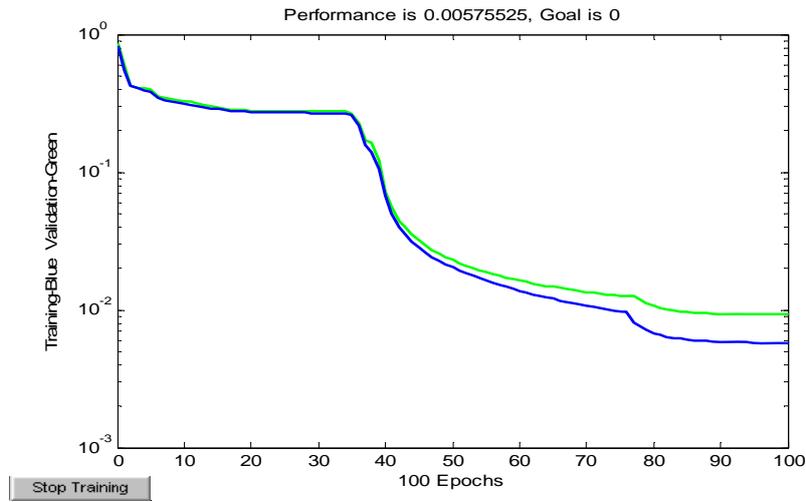


Figure 6. The training process of neural network

IV. RESULTS AND DISCUSSION

In order to verify the reliability of the presented orientation detection methodology of combined two modes, an experiment platform was built and applied for this work. The spherical rotor and grid painting parameters: the width of the grid lines along the spherical angle is 0.4 degree. The sensor optical axis is directed through the center of the sphere. In the initial rotor position, the world coordinate system is fixed and coincided with the rotor moving coordinate system. Due to the limits of experimental conditions, in the experiment, only the upper hemisphere of rotor is used and the feature points are directly marked on the rotor sphere surface. The experiment device can be shown in figure 7. The machine vision system contains the NI CVS vision disposal system and the main vision sensor uses the SONY XCD-X710 CCD camera. The manufactured experiment actuator prototype can be shown in figure 8. Four Hall Effect sensors are taken as the magnetic field detection element. Detailed Hall sensor is shown in figure 9.

Calibrate the vision sensor at the initial position and the vision sensor matrix can be derived as

$$M = \begin{bmatrix} -536.47 & -2763.7 & 3090.1 & 351.43 \\ -3806.6 & -1131 & -1104.3 & 396.11 \\ -0.036092 & -3.2893 & -1.3373 & 1 \end{bmatrix}$$

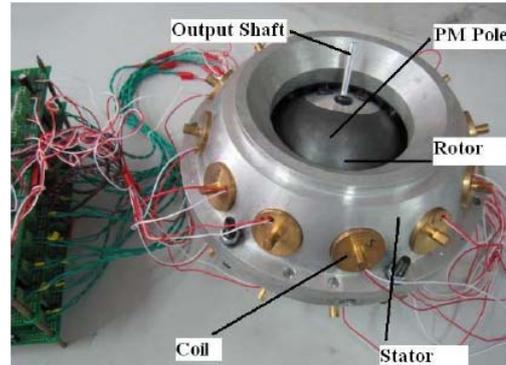


Figure 7. The photograph of experimental platform Figure 8. Experiment prototype of multi-DOF actuator



Figure 9. Experiment built Hall Effect sensor

The experiment motion is set with three tilt rotations in sequence, with single rotation with respect to X axis, Y axis and both combined rotation. The measurement data by the two modes are collected and compared. The real standard motion data was firstly implemented by high precision optical encoder for reference with repeated processes. The measured trajectory data can be shown in figure 10. Figure 11 gives the errors of different measurement modes for comparison. To test the reliability and practicability, the fusion effects in the case of magnetic sensor fault are evaluated. The magnetic sensor is exerted with an outer disturbance at the interface of the first and second segment as shown in figure 10 and 11 of sudden change on the trajectory and error data. It can be seen from the results, compared with single machine vision and magnetic sensor method, the neural network based data fusion application can improve the tracking accuracy with lower errors and anti-interference ability.

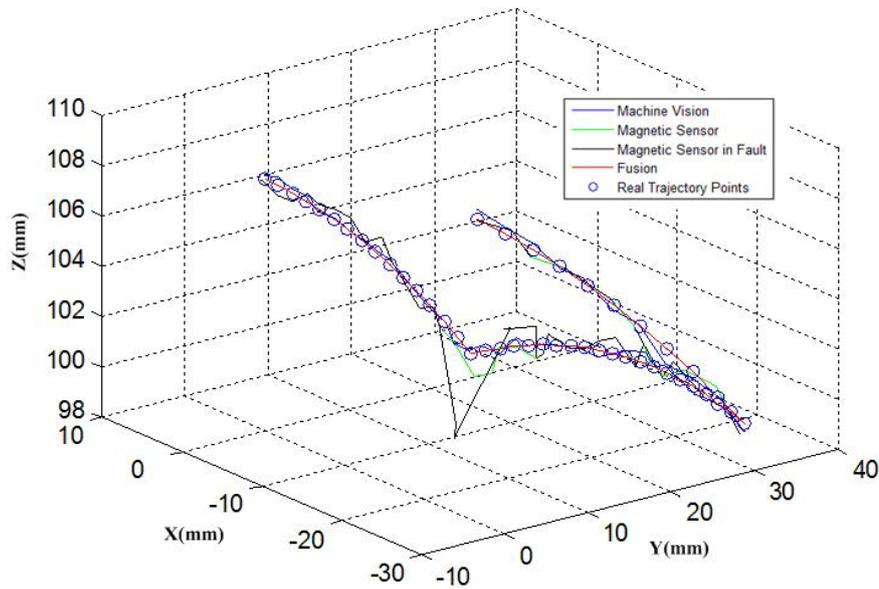


Fig. 10. The trajectory data plots in 3D space for comparison by experiment

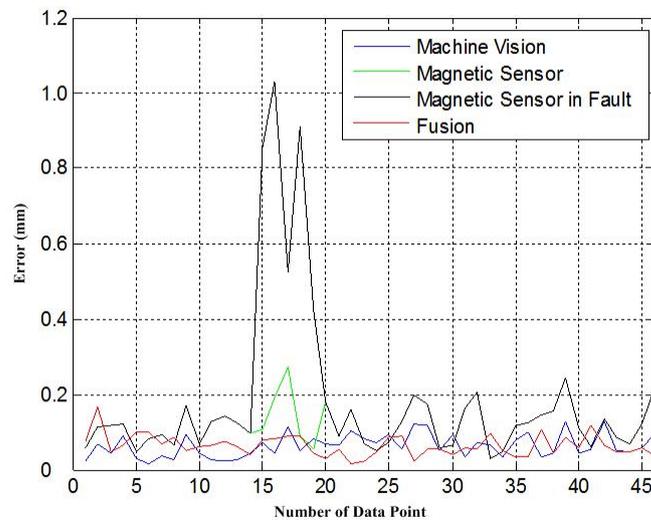


Fig. 11. The errors of two modes and the fusion method by experiment

V. CONCLUSIONS

This paper presents the multisensor fusion based orientation detection methodology for multi-DOF actuator or motor applications. The two modes as machine vision and magnetic field sensor are all applied in related industrial areas with their special features of advantages. In this work,

the calibrated machine vision mode is used for neural network training and magnetic field sensor modeling. Experiment is carried out to validate the effectiveness of presented methodology by setting three tilt motion segments in sequence. The results prove the methodology is available and effective. It is expected that the presented scheme is able to provide a reference for further research and investigation for similar measurement problems of multi-DOF actuators or motors.

ACKNOWLEDGEMENT

This work is supported by the National Natural Science Foundation of China (No.51107031, 50677013), the Natural Science Foundation of Hebei Province of China (No.E2009000703), the Foundation of Hebei Educational Committee (No.Z2010135), the Scientific Research Start Foundation of Doctoral Scholars of Hebei University of Science and Technology (QD200909) and the Funds for Distinguished Young Scholar of Hebei University of Science and Technology.

REFERENCES

- [1] Lee K M, Kwan C K., "Design concept development of a spherical stepper for robotic applications", *IEEE Transactions on Robotics and Automation*, vol. 7, no. 1, 1991, pp.175-181.
- [2] Gregory S Chirikjian, David Stein, "Kinematic design and commutation of a spherical stepper motor", *IEEE Transactions on Mechatronics*, vol. 4, no. 4, 1999, pp. 342-353.
- [3] David Stein, Gregory S Chirikjian, "Experiments in the Commutation and Motion Planning of a Spherical Stepper Motor", *Proc. ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Baltimore, Maryland, 2000, pp. 1-7.
- [4] David Stein, Edward R. Scheinerman, Gregory S Chirikjian, "Mathematical Models of Binary Spherical-Motion Encoders", *IEEE/ASME Transactions on Mechatronics*, vol. 8, no. 2, 2003, pp. 234-244.
- [5] Kok-Meng Lee, Debao Zhou, "A real-time optical sensor for simultaneous measurement of three-DOF motions", *IEEE/ASME Transactions on Mechatronics*, vol. 9, no. 3, 2004, pp. 499-507.

- [6] J. Wang, G. W. Jewell, D. Howe, "Analysis, design and control of a novel spherical permanent-magnet actuator", IEE Proc. Electric Power Applications, vol. 145, no. 1, 1998, pp. 61-71.
- [7] W. Wang, J. Wang, G. W. Jewell and D. Howe, "Design and Control of a Novel Spherical Permanent Magnet Actuator With Three Degrees of Freedom", IEEE Transactions on Mechatronics, vol. 8, no. 4, 2003, pp. 457-468.
- [8] Harry Garner, Martin Klement, Kok-Meng Lee, "Design and analysis of an absolute non-contact orientation sensor for wrist motion control", Proc. IEEE/ASME International Conference on Advanced Intelligence Mechatronics, 2001, Italy, pp. 69-74.
- [9] Zhe Qian, Qunjing Wang, Lufeng Ju, Anbang Wang et al., "Studies on vision based absolute orientation detection method of spherical motor", Proc. the 2009 Int. Conf. on Electrical Machines and Systems, Tokyo, 2009, pp. 1-6.
- [10] Qunjing Wang, Zheng Li, Youyuan Ni, et al., "Magnetic Field Computation of a PM Spherical Stepper Motor Using Integral Equation Method", IEEE Trans. on Magnetics, vol. 42, no. 4, 2006, pp. 731-734.
- [11] Wang Qunjing, Li Zheng, Xia Kun, et al., "Calculation and Analysis on Configuration Parameters and Torque Characteristics of a Novel Spherical Stepper Motor", Proceedings of the CSEE, vol. 26, no. 10, 2006, pp. 158-165.
- [12] Wang Qunjing, Li Zheng, et al., "Kinematic Analysis and Simulation of Permanent Magnet Spherical Stepper Motor", Journal of System Simulation, vol. 17, no. 9, 2005, pp. 2260-2264.
- [13] Zheng Li, Yongtao Wang, "Finite Element Analysis and Structural Optimization of a Permanent Magnet Spherical Actuator. Electronics and Electrical Engineering", vol. 114, no. 8, 2011, pp. 67-72.
- [14] Zheng LI, "Robust control of PM spherical stepper motor based on neural networks", IEEE Transactions on Industrial Electronics. vol. 56, no. 8, 2009, pp. 2945-2954.
- [15] J. T. M. Stevenson, J. R. Jordan, "Absolute position measurement using optical detection of coded Patterns", Journal of Physics. vol. 21, no. 12, 1988, pp. 1140-1145.
- [16] Berthold K.P. Horn, "Closed-form solution of absolute orientation using unit quaternions", Journal of the Optical Society of American. vol. 4, no. 1, 1987, pp. 629-642.

- [17] Kok-Meng Lee, Kun Bai and Jungyoul Lim, “Dipole Models for Forward/Inverse Torque Computation of a Spherical Motor”, IEEE Transactions on Mechatronics, vol. 14, no. 1, 2009, pp. 46-54.
- [18] Wu Fang, Hungsun Son, “Optimization of Measuring Magnetic Fields for Position and Orientation tracking”, IEEE Transactions on Mechatronics, vol. 16, no. 3, 2011, pp. 440-448.
- [19] S. M. Sokolov, O.V. Trifonov, V. S. Yaroshevsky, “Control system design for spherical direct drive actuators with the Hall sensors”, Proc. the 1999 Int. Conf. on Advanced Intelligent Mechatronics, Atlanta, USA, 1999, pp. 916-921.
- [20] Shaohui Foong, Kok-Meng Lee, “Magnetic Field-Based Multi-DOF Orientation Sensor for PM-Based Spherical Actuators”, Proc. the 2009 Int. Conf. on Advanced Intelligent Mechatronics, Singapore, 2009, pp. 481-486.
- [21] S. Boukhenous, “A Low Cost Three-Directional Force Sensor”, International Journal on Smart Sensing and Intelligent Systems, vol. 4, no. 1, 2011, pp. 21-34.
- [22] M.F. Rahmat, N.H. Sunar, Sy Najib Sy Salim, Mastura Shafinaz Zainal Abidin, A.A Mohd Fauzi and Z.H. Ismail, “Review on Modeling and Controller Design in Pneumatic Actuator Control System”, International Journal on Smart Sensing and Intelligent Systems, vol. 4, no. 4, 2011, pp. 630-661.