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Attitude Detection for the Permanent-Magnet Spherical Motor Using two Optical Sensors

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Abstract. A rotor attitude-detection method for the permanent-magnet spherical motor (PMSM), using two optical sensors is proposed. A hemispherical shell is fixed on the PMSM rotor output shaft. The sensors are fixed on the stator shell, at a clearance of 90 degrees. When the spherical rotor moves, the sensors detect the displacement of the hemispherical shell surface. Using this information, the yaw and pitch angle of the hemispherical shell are obtained by calculating the displacement. Accordingly, the position coordinates of any point on the hemispherical shell can be determined. Since the rotor is concentric with the hemispherical shell, the coordinates of any point on the spherical rotor can be obtained.

Keywords： Permanent-magnet spherical motor, optical sensor, attitude detection, yaw and pitch angle, hemispherical shell.

Določanje položaja rotorja električnega motorja s trajnimi magneti z optičnima senzorjema

V članku predstavljamo metodo za določanje položaja rotorja električnega motorja s trajnimi magneti z optičnima senzorjema. Na gred motorja je pričvrščeno ohišje v obliki poloble. Dva optična senzorja, med seboj oddaljena pod kotom 90º, se nahajata na gredi statorja. Premik rotorja je zaznan z optičnima senzorjema. Na podlagi te informacije lahko z izračunom določimo kot zasuka in naklona ohišja. Posledično lahko določimo koordinate poljubnega premika rotorja.

1. INTRODUCTION

With the progress of science and technology, robots, manipulators and other precision devices for a multi-dimensional motion have been widely used in industrial control and other fields. Some special structural devices for complex motion require multiple motors to achieve multi-degree of freedom motion [2], which not only makes the whole system huge, but also makes the drive efficiency low, The accumulative error of the mechanical transmission system will lead to the accuracy decline of the whole control system [3].PMSM has a simple structure and small size, and can complete a multiple-degree of freedom motion independently. As soon as it was put forward, it received a high attention from academic circles worldwide.

The rotor-position detection is one of the key methods to achieve a high-performance motion control of spherical motors. The spherical-motor position-detection methods can be roughly divided into four categories: 1) The measurement method of the encoder and sliding-rail module [4-6]. 2) Visual measurement method to identify spherical features [7-9]. 3) Hall-element measurement method based on the variation the rotor spherical magnetic field [10-11]. 4) Photoelectric encoded detection method [12-16]. This kind of the method involves to a non-contact measurement. It effectively avoids the impect of friction caused by a contact measurement on the rotor dynamic response .In this paper,a PMSM attitude-detection method using two optical sensors is proposed.

2 PMSM STRUCTURE

2.1 The basic PMSM structure

Relecting to [17], a new PMSM is proposed. 40 PMs with a uniform and symmetrical polarity distribution are embedded in the rotor in four layers. The rotor is embedded in the stator shell. The spherical rotor is concentric with the stator shell. The magnetic gap is about 1mm. 24 symmetrical and evenly distributed coils are embedded in the stator shell in two layers. The rotor output shaft is fixed on the spherical rotor. The spherical motor structure is shown in Figure 1. Limited by the structure of the stator shell, the maximum inclination angle of the output shaft is 75 degrees.

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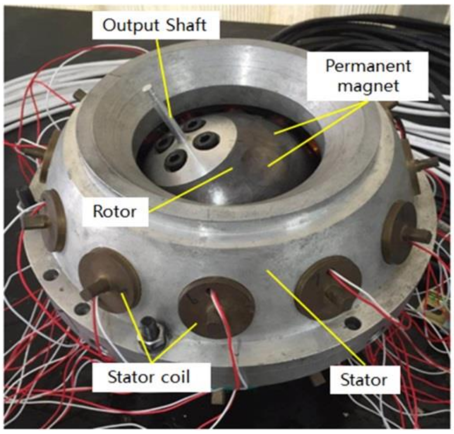


Figure 1.Structure PMSM

3 THE PRINCIPLE OF THE ROTOR ATTITUDE DETECTION

3.1 The attitude-detection scheme

As shown in Figure 2, the hemispherical shell is fixed on the output shaft of the spherical rotor. The hemispherical shell is concentric with the spherical rotor. Two optical sensors are fixed on the stator shell. They are 90 degrees apart. The projection of the two optical sensors in the XOY plane falls on the X and Y axes, O is the spherical rotor center. The two optical sensors are named optical sensor 1 and optical sensor 2. There is a 45 degree angle between the XOY plane and the connection which is between the central point of the two optical sensors and the sphere center of the spherical rotor. The two optical sensors are fixed at the upper position, to ensure that the output shaft of the spherical rotor spins and inclines within the maximum inclination angle of 37.5 degrees, and avoids the existence of a non-detection zone.

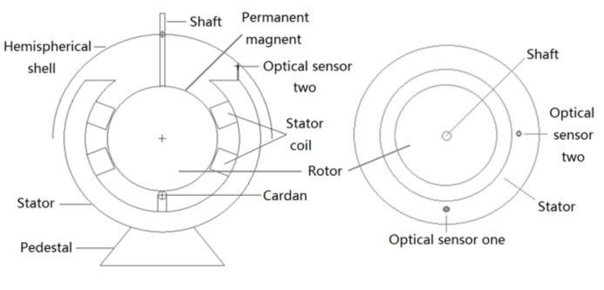


Figure 2.Structure of the detection scheme

As shown in Figure 3, C is the hemispherical shell, U is the spherical rotor, P is the pending point on the hemispherical shell. S is the pending point on the spherical rotor. The initial static position of the spherical-rotor output shaft coincides with the Z axis of the geodetic coordinate system. When the spherical rotor is in a steady-state, the optical sensors 1 and 2 are placed in points S_1 and S_2, respectively. The yaw angle of point S_1 is $\angle$MOX and the pitch angle is $\angle S_1$OP. The yaw angle of point S_2 is $\angle$QOX and the pitch angle is $\angle S_1$OP. The initial values of the yaw and pitch angle for points S_1 and S_2 correspond to the position of the optical sensor when it is in its initial stationary state.

3.2 Coordinate calculation of the spherical-rotor points:

(1) When the spherical rotor spins an angle from the initial position, the pitch angle of the spherical rotor is constant and the yaw angle varies with the motor rotation. The variation of the yaw angle for point S can be detected by optical sensor 1, thus, the position of the spherical rotor is determined.

(2) When the spherical rotor inclines an angle from its initial position, optical sensor 1 is moving from point S_1 to point A. The tracking of optical sensor 1 on the hemispherical shell is arc $\mathrm{S_1}$A. During this motion, the data detected by optical sensor 1 is the projection of $\mathrm{d_{x1}}$, $\mathrm{d_{y1}}$ on the hemispherical shell which is the arc length. $\mathrm{L_{x1}}$, $\mathrm{L_{y1}}$, d_{x1}, d_{y1} are the tangents along the horizontal and vertical direction of point S_1. The arc length component $\mathrm{L_{x1}}$ takes T as a center of a circle and a section of a circular arc with a radius of ST. This component changes the yaw angle of the spherical rotor. Arc length component L_{y1} takes O as a center of a circle and a section of the circular arc with radius R. This component changes the pitch angle of the spherical rotor. R is the radius of the spherical rotor. The variation of the yaw and pitch angle of the hemispherical shell is calculated by using $L_{x1}$and L_{y1}.

After the variation of the yaw and pitch angle of the hemispherical shell is determined, the coordinate calculation method for point P is as usual: when the spherical rotor rotates an angle in the initial position, all parts of the hemispherical shell will rotate the same angle around the axis of the rotation apart from the axis of rotation. The variation of the yaw and pitch angle of point P is the same as the point S_1. The initial position of point P and its variation of the yaw and pitch angle are known. According to the relationship between their radius, position coordinates of point P can be obtained through position calculation, then the position coordinates of point S on the spherical rotor are obtained.

(3) When the spherical rotor rotates around the S_1O axis, optical sensor 1 cannot detect the displacement data of the hemispherical shell on the surface. The data detected by optical sensor 2 is a projection of $\mathrm{d_{x2}}$, $\mathrm{d_{y2}}$ on the hemispherical shell which are arc lengths $\mathrm{L_{x2}}$, $\mathrm{L_{y2}}$. d_{x2}, d_{y2} are the tangents along the horizontal and vertical directions of point S_2. In this case, the displacement data detected by optical sensor 2 are used to calculate the yaw and pitch angle of the spherical rotor. The calculation method for the position coordinates of the P and S points is similar to the method described in 2.2.1 and 2.2.2.

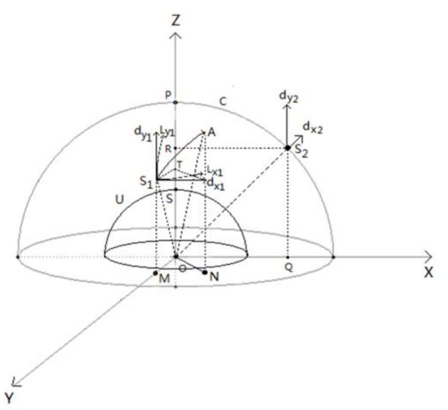


Figure 3. Diagram of the detection scheme

3.3 Algorithm realization of the rotor attitude detection for PMSM

(1) As shown in Figure 3, when the spherical rotor spins an angle from the initial position, the arc length component of L_{x1} is set to positive, the arc length to zero and the pitch angle of the rotor does not change. Point S_1 can be characterized. The pitch and the yaw angle of point S_1 are expressed as follows:

Pitch angle:

$$S_1OP\_S_1 = S_1OP\_0 \tag{1}$$

Yaw angle:

$$MOX\_S_1 = MOX\_0 - \frac{L_{x1}}{R/\sqrt{2}} * \frac{180^\circ}{\pi} \tag{2}$$

Therefore, the coordinates of point S_1 in the three-dimensional space are as follows:

$$\begin{cases} S_1\_X = R * sin(S_1OP\_S_1) * cos(MOX\_S_1) \\ S_1\_Y = R * sin(S_1OP\_S_1) * sin(MOX\_S_1) \\ S_1\_Z = R * cos(S_1OP\_S_1) \end{cases} \tag{3}$$

(2) When the spherical rotor inclines an angle from the initial position, the calculation method of the yaw and pitch angle of point S on the spherical rotor is as follows:

The initial pitch angle of point S_1 is S_1OP_0 and the initial yaw angle is MOX_0 in the process of the rotor motion. The variation of the yaw and pitch angle of point S is:

$$S_1OP\_S_1 = \frac{L_{y1}}{R} * \frac{180^\circ}{\pi} \tag{4}$$

$$MOX\_S_1 = \frac{L_{x1}}{R/\sqrt{2}} * \frac{180^\circ}{\pi} \tag{5}$$

Where:

① Pitch angle of point S_1: the angle between the Z axis and the OS_1 segment; yaw angle: MO is a projection of OS_1 on the XOY plane, the yaw angle is between MO and positive direction of the X axis.

② Taking S_1 as the reference point, the displacement of the optical sensor detected in direction of d_{x1} and d_{y1} is positive. Otherwise it is negative.

③ The range of the pitch angle is 0. 90°, and that of the yaw angle is 0.360°.

The rotor position in characterized by point S in the process of an inclining motion:

The variation of the pitch angle of point S is:

$$S_1OP\_P = \frac{L_{y1}}{R} * \frac{180^\circ}{\pi} \tag{6}$$

The variation of the yaw angle of point S is:

$$MOX\_P = \frac{L_{x1}}{R/\sqrt{2}} * \frac{180^\circ}{\pi} \tag{7}$$

Where:

① The pitch angle of point P: the angle between the Z axis and OP; the yaw angle: the angle between the positive direction of the X axis and the projection of OP on the XOY plane.

② The variation range of the pitch and yaw angle for point P is the same as the S_1.

Therefore, after the rotation of the spherical rotor, the coordinates of point P in the three-dimensional space are calculated:

① When the arc-length component of L_{x1} and L_{y1} is positive, projection of point P on the XOY plane is in the area which belongs to the negative part of the X-axis and positive part of the Y-axis. The pitch angle of point P is S_1 OP_P. The yaw angle is 90° +MOX_P. The coordinates of point P in the three-dimensional space are as follows:

$$\begin{cases} S_1\_X = -R * sin(S_1OP\_P) * \sin(MOX\_P) \\ S_1\_Y = R * sin(S_1OP\_P) * \cos(MOX\_P) \\ S_1\_Z = R * cos(S_1OP\_P) \end{cases} \tag{8}$$

② When the arc-length component of L_{x1} and L_{y1} is negative, the projection of point P on the XOY plane is in the area which belongs to the positive part of the X-axis and the negative part of the Y-axis. The pitch angle of point P is - S_1 OP_P. The yaw angle is 270°+ (-MOX_P). The coordinates of point P in the three-dimensional space are as follows:

$$\begin{cases} S_1\_X = R * sin(S_1OP\_P) * \sin(MOX\_P) \\ S_1\_Y = R * sin(S_1OP\_P) * \cos(MOX\_P) \\ S_1\_Z = R * cos(S_1OP\_P) \end{cases} \tag{9}$$

③ When the arc length component of L_{x1} is negative and of L_{y1} is positive, the projection of point P on the XOY plane is in the area which belongs to the positive part of the X and Y-axis. The pitch angle of point P is S_1 OP_P. The yaw angle is 90° - (-MOX_P). The coordinates of point P in the three-dimensional space are as follows:

$$\begin{cases} S_1\_X = -R * sin(S_1OP\_P) * \sin(MOX\_P) \\ S_1\_Y = R * sin(S_1OP\_P) * \cos(MOX\_P) \\ S_1\_Z = R * cos(S_1OP\_P) \end{cases} \quad (10)$$

④ When the arc length component of L_{x1} is positive and of L_{y1} is negative, the projection of point P on the XOY plane is in the area which belongs to the negative part of the X and Y-axis. The pitch angle of point P is -S_1 OP_P. The yaw angle is 270° -MOX_P. The coordinates of point P in the three-dimensional space are as follows:

$$\begin{cases} S_1\_X = R * sin(S_1OP\_P) * \sin(MOX\_P) \\ S_1\_Y = R * sin(S_1OP\_P) * \cos(MOX\_P) \\ S_1\_Z = R * cos(S_1OP\_P) \end{cases} \quad (11)$$

(3) Special movement 1: when the rotor output shaft moves on the XOZ plane, the track of the detected optical sensor 1 is a circle using the Y-axis as the rotating shaft, R as the radius, and the arc length component of L_{y1}, L_{x2} is zero. There is an arc-length component only in the L_{x1} , L_{y2} direction. The calculation method of the rotor position is as follows:

① When the arc length component of L_{y2} is positive, the rotor output shaft moves to the positive axis of X. The variable quantity of the pitch angle is $\frac{L_{y2}}{R} * \frac{180^{\circ}}{\pi}$. Therefore, the coordinates of point P in the three-dimensional space are as follows:

$$\begin{cases} S_1\_X = R * sin(\frac{L_{y2}}{R} * \frac{180^{\circ}}{\pi}) \\ S_1\_Y = 0 \\ S_1\_Z = R * cos(\frac{L_{y2}}{R} * \frac{180^{\circ}}{\pi}) \end{cases} \quad (12)$$

② When the arc length component of L_{y2} is negative, the rotor output shaft moves to the negative axis of X. The variable quantity of the pitch angle is $\frac{-L_{y2}}{R} * \frac{180^{\circ}}{\pi}$. Therefore, the coordinates of point P in the three-dimensional space are as follows:

$$\begin{cases} S_1\_X = -R * sin(\frac{-L_{y2}}{R} * \frac{180^{\circ}}{\pi}) \\ S_1\_Y = 0 \\ S_1\_Z = R * cos(\frac{-L_{y2}}{R} * \frac{180^{\circ}}{\pi}) \end{cases} \quad (13)$$

(4) Special movement 2: when the rotor output shaft moves on the YOZ plane, the track of the detected optical sensor 2 is a circle using the X-axis as a rotating shaft, R as the radius, and the arc-length component of L_{x1}, L_{y2} is zero. There is an arc-length component only in the L_{y1}, L_{x2} direction. The calculation method of the rotor position is as follows:

① When the arc length component of L_{y1} is positive, the rotor output shaft moves to the positive axis of Y. The variable quantity of the pitch angle is $\frac{L_{y1}}{R} * \frac{180^{\circ}}{\pi}$. Therefore, the coordinates of point P in the three-dimensional space are as follows:

$$\begin{cases} S_1\_X = 0 \\ S_1\_Y = R * sin(\frac{L_{y1}}{R} * \frac{180^{\circ}}{\pi}) \\ S_1\_Z = R * cos(\frac{L_{y1}}{R} * \frac{180^{\circ}}{\pi}) \end{cases} \quad (14)$$

② When the arc length component of L_{y1} is negative, the rotor output shaft moves to the negative axis of Y. The variable quantity of the pitch angle is $\frac{-L_{y1}}{R} * \frac{180^{\circ}}{\pi}$. Therefore, the coordinates of point P in the three-dimensional space are as follows:

$$\begin{cases} S_1\_X = 0 \\ S_1\_Y = -R * sin(\frac{-L_{y1}}{R} * \frac{180^{\circ}}{\pi}) \\ S_1\_Z = R * cos(\frac{-L_{y1}}{R} * \frac{180^{\circ}}{\pi}) \end{cases} \quad (15)$$

So, the position coordinates of point S on the spherical rotor are as follows:

The radius of the hemispherical shell is R, the radius of the spherical rotor is r, and the set is r=t*R, where t is the proportional coefficient. The position coordinates of point S are as follows:

$$\begin{cases} S\_X = t * P\_X \\ S\_Y = t * P\_Y \\ S\_Z = t * P\_Z \end{cases} \quad (16)$$

4 SIMULATION STUDY

Using a physical model of the PMSM rotor in the ADAMS software, the coordinate system is established in the center of the spherical rotor which is called the geodetic coordinate system, By determining points S_1 and S_2 , which are 90 degrees apart, the system establishes the coordinate system at points S_1 and S_2 which are termed the moving coordinate system. There is an angle of 45 degrees between the XOY plane and the connection between S_1, S_2 and the center of the spherical rotor. The projection of S_1 and S_2 falls on the X and Y axes, respectively.

As shown in Figure 4, the arc lengths l_{x1}、l_{x2} are a projection of x_1、y_2 on the spherical rotor, respectively.

It changes the yaw angle of the spherical rotor. The arc lengths l_{y1}, l_{y2} are a projection of z_1, z_2 on the spherical rotor, respectively. It changes the pitch angle of the spherical rotor. The Cartesian coordinates of the S_1, S_2 points are S_1 (0, $0.0325\sqrt{2}$, $0.0325\sqrt{2}$), S_2 ($0.0325\sqrt{2}$,0, $0.0325\sqrt{2}$). The spherical coordinates of points S_1 and S_2 are S_1 (R， θ_{10} ， ψ_{10}), S_2(R， θ_{20}， ψ_{20}).

The translational displacement of points S_1, S_2 in the geodetic coordinate system are obtained by using the ADAMS post-processing module. According to the translational displacement, the rectangular coordinates of points S_1 and S_2 are obtained after the motion of the spherical rotor. Then the spherical coordinates of points S_1 and S_2 are obtained after the motion of the spherical rotor , expressed as S_1(R， θ_1， ψ_1)、S_2(R， θ_2， ψ_2). Therefore, the variation of the yaw angle of point S_1 is θ_1-θ_{10}, the variation of the pitch angle of point S_1 is ψ_1-ψ_{10}. Then the arc lengths l_{x1} and l_{y2} are obtained. The variation of the yaw angle of point S_2 is θ_2-θ_{20}, the variation of the pitch angle of point S_2 is ψ_2-ψ_{20}.Then the arc lengths l_{x2} and l_{y2} are obtained.

According to the arc-length components l_{x1}, l_{y1} and l_{x2}, l_{y2}, the yaw and pitch angle of points S_1 or S_2 on the spherical rotor are calculated using methods described in 2.1, 2.2, and 2.3. then obtained position coordinates of point P.

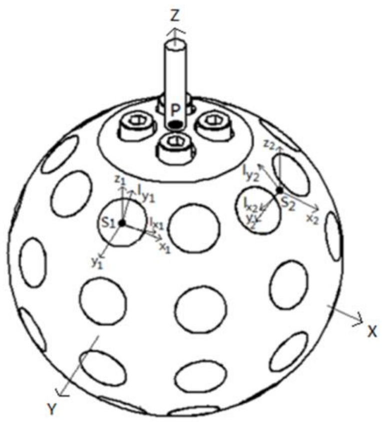


Figure 4. Physical model of the PMSM rotor

Based on the above theoretical analysis and adding a torque to the spherical rotor model in ADAMS, the spherical rotor can spin and incline according to the added torque. The trajectory of point P on the spherical rotor is obtained by processing the simulated data.

4.1 Center-point spin motion

When the spherical rotor spins, point P spins in the place of origin. So the motion state of the spherical rotor can't be characterized by point P. In this case, we can use point S_1 to characterize the spin angle of the spherical rotor. The spin trajectory for point S_1 on the spherical rotor is obtained by processing the simulation data with Matlab, as shown in Figure 5.

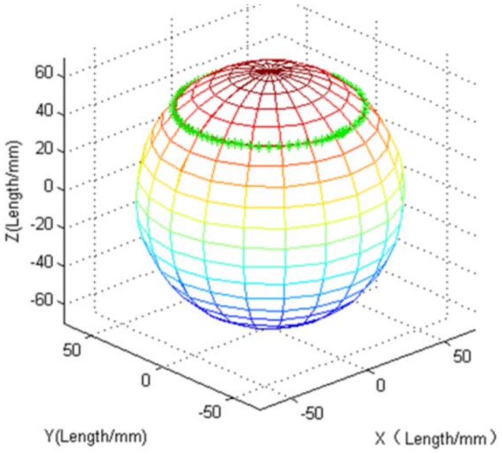


Figure 5.Trajectory of point S_1 for the rotor spin motion

4.2 Axial incline motion

When the spherical rotor inclines, point P is used to characterize the position of the spherical rotor. The trajectory of the incline for point P on the spherical rotor is obtained by processing the simulation data with Matlab, as shown in Figure 6.

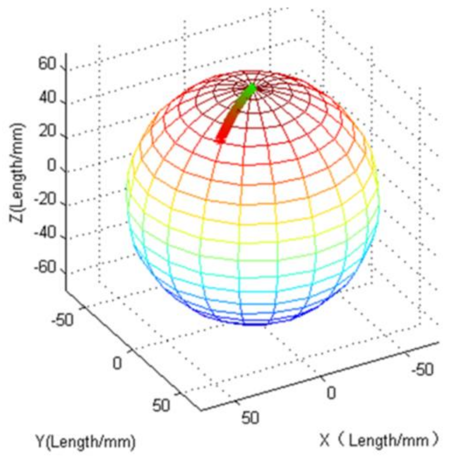


Figure 6. Point P trajectory for the rotor incline motion

5 COMPARITIVE EXPERIMENT

5.1 Hardware setup for comparitive experiments

The experimental setup consists of PMSM, hemispherical shell, control circuit, power supply, drive circuit, hardware detection circuit using two optical sensors, position detection device using one MEMS sensor MPU6050, ARM and PC, as shown in Figure 7. The optical sensor detects the displacement data of the hemispherical shell. ARM receives the optical sensor data and sends it to PC, to process them.

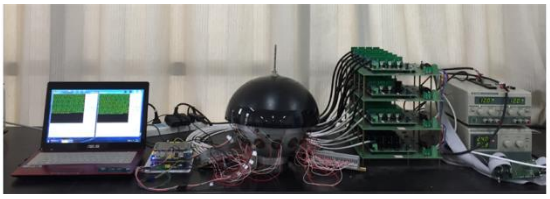


Figure 7. Comparitive experiment setup

In the experiment, two methods are used to detect the rotor position in the same motion process, as shown in Figure 8. The detected data of the optical sensor is processed by PC. The trajectory curve of point P on the spherical rotor is obtained by comparing the motion trajectories of point P detected by the two methods and calculating their error. The reliability of the detection method described in this paper is verified. Due to limitations of the experimental conditions, the experiments can be performed only on center point spin and at axial incline motion.

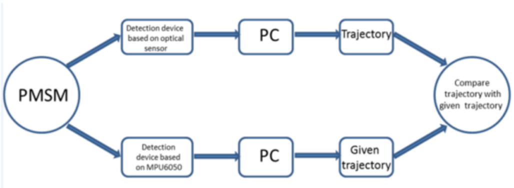


Figure 8. Flow chart of the comparitive experiment

5.2 *Center-point spin motion*

In the comparitive experiment of the center-point spin motion, the experiment takes four seconds. The rotor spins at 360 degrees, and is affected by gravity and other factors. The movement of point P deviates from the Z axis about 10mm. The data detected by using the optical and MEMS sensor is processed by PC. The trajectory curve of point P is then obtained, as shown in Figure 9.

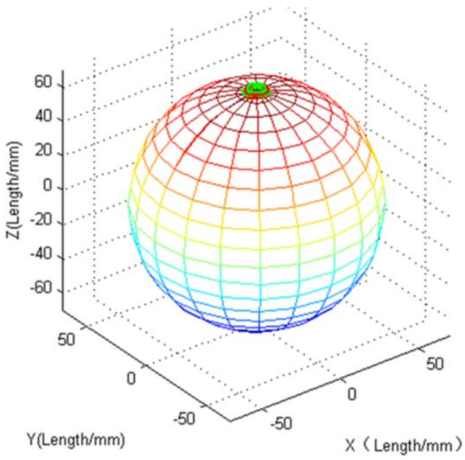


Figure 9. Trajectory of point P for the rotor spin motion and center-point spin motion

5.3 *Axial incline motion*

The comparitive experiment of the spherical rotor axial incline motion takes one second. The rotor inclines at 37.5 degrees. The data detected by using the optical and MEMS sensor is processed by PC. The trajectory curve of point P is then obtained, as shown in Figure 10.

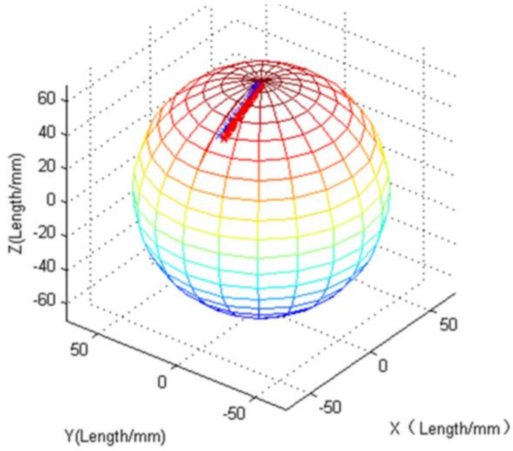
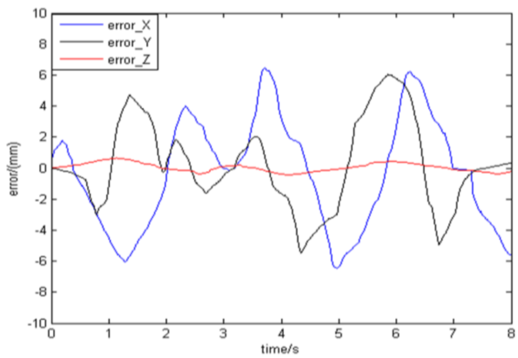


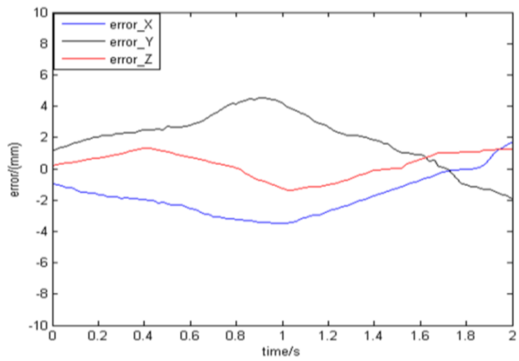
Figure 10. Trajectory of point P for the rotor axial incline motion

5.4 *Error comparison*

From the trajectory of rotor point P calculated by the detection method using the MEMS sensor and the trajectory of the rotor point P calculated by the proposed detection method ,the error curves are obtained for the directions of the X,Y and Z axes for the center-point spin motion and axial-inclin motion experiment, as shown in Figure 11



(a) Error curve of the rotor center-point spin motion



(b) Error curve of the rotor axial incline motion

Figure 11. Error curve of the comparative experiment

6 CONCLUSION

A PMSM rotor attitude detection method is proposed. A hemispherical shell is fixed on the rotor output shaft. An optical sensor detects a displacement change in the hemispherical shell. The attitude information of the spherical rotor is obtained by calculating its yaw and pitch angle. The simulation results show that the feasibility of the rotor attitude can be calculated by crawing the change in surface displacement. The experimental results verify the simulation results. A comparitive experiment shows the effectiveness and feasibility of the proposed method. The detection error is relatively small, providing a valuable reference for the research and application of the spherical motor position-detection method.

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