Development of a Posture Sensor for the Spherical Motor

Tomoaki YANO*1, Nagayoshi KASASHIMA*2 and Kiwamu ASHIDA*2

When a spherical motor with multi degrees of freedom like a human shoulder joint is in practical use, a lot of systems with multi degrees of freedom will be compact, lightweight, and high performance. However, the motors are controlled by open-loop, as there are no good rotor posture sensors. This paper reports the basic experimental results of a developed posture sensor with two mouse sensing devices. The basis transformation matrix is used to represent the rotor posture. At first, researches of the posture sensors for the spherical motor are reviewed. Among the previous work, select a posture sensor with two mouse sensing devices. Show the advantages of using the basis transformation matrix to represent the rotor posture. The basic ideas for getting the posture from the data of two mouse sensing devices are presented. A posture sensor with two mouse sensors is developed and tested.

Keywords: posture sensor, spherical motor, image sensor, basis transformation matrix.

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NOMENCLATURE

basis of the stator coordinate system

\[ S = \{s_1, s_2, s_3\} \]

sequence of bases of the rotor coordinate system

\[ R^{(i)} = \{r_{1}^{(i)}, r_{2}^{(i)}, r_{3}^{(i)}\} \]

basis of the sensor coordinate system

\[ M = \{m_1, m_2, m_3\} \]

basis transformation matrix from \( R^{(i)} \) to \( R^{(i+1)} = K R_i \)

rotor angular velocity vector on \( S = \omega_S \)

unit vector of the rotational axis on \( S = n_S \)

angle of rotation around \( n_S = \theta \)

position vector of the mouse sensor \( j \) on \( S = (p_j)_S \)

unit vectors of sensing direction of mouse sensor \( j \) on \( S \)

\[ u_{1j}, u_{2j} \]

reading data of mouse sensor \( j = (v_{1j}, v_{2j}) \)

a set of reading data of mouse sensors = \( v \)

sequence of sensing time interval = \( \{\Delta T_k\} \)

1. Introduction

From humanoid robots to automobiles, the number of degrees of freedom of mechanical systems continues to grow. There has also been a proportional increase in the number of motors used in the mechanical systems. On the other hand, the human joints like the shoulder joints have at least three degrees of freedom (lateral direction, anteroposterior direction, and arm rotation). When a spherical motor with multi degrees of freedom like a human shoulder joint is in practical use, a lot of systems with multi degrees of freedom will be compact, lightweight, and high performance.

Therefore, various kinds of spherical motors have been developed and tested [1-7]. The authors also proposed the structures of the spherical motors based on the polyhedrons [8,9]. The performances of the proposed spherical motors are expected to be the same in any rotational direction by their spherical symmetric structures. The experimental results of developed spherical motors are shown in the previous papers [10,11]. However, the motors are controlled by open-loop, as there are no good rotor posture sensors. The performances of the developed motors are limited without posture sensor.

There are several reports for the posture sensors of the sphere. The most popular sensing system uses gimbal mechanism fixed on the rotor output shaft [12]. Three rotational angle sensors are put on the pivots of the gimbal. The rotary encoders are usually used to measure the rotational angles. The absolute posture is calculated from the measured three angles, which are roll, pitch, and yaw. However, the gimbal mechanism has several problems. It will make the motor large and heavy and limit the working area of the rotor.

Y. Wada and A. Gofuku developed an absolute rotor posture sensor with 64 Hall devices [13]. The sensor can measure the absolute posture of the 100mm diameter rotor with 32 permanent magnets. However, the posture measurement error is around 5deg. As the radius of a Hall device’s sensing area is around 8mm, a lot of Hall devices should be needed for the precise posture sensing.

M. Aoyagi et al. developed an absolute rotor posture sensor with CCD camera [14]. Two luminescence devices are fixed on the rotor surface. The rotor posture is calculated from the two luminescence device coordinates on the graphic image of the CCD camera. The sensor resolution is 0.57 deg and the measurement area is 70 x 70 x 360 deg. This sensor system needs a wide opening in the stator for taking the graphic image.

Correspondence: T. YANO, Research Institute of Fundamental Technology for Next Generation, Kinki University, 1 Takaya Umenobe, Higashi-Hiroshima, Hiroshima 739-2116, Japan email: t.yano@hiro.kindai.ac.jp

*1 Kinki University *2 AIST Japan
D. Stain et al. developed an absolute spherical encoder [15]. The rotor surface is colored in black and white Voronoi diagram. 192 one bit black and white detect devices are put on a ring. The sensor can measure the posture of the rotor within 1 deg error by reference to the prepared posture map. This sensor needs a lot of black and white detect devices for the precise posture measurement.

K. M. Lee developed an incremental rotor orientation sensor with a vision sensing device [16]. A grid pattern and an origin marker are painted on the rotor. The orientation of the rotor is calculated from the vision.

N. Hama et al. developed an absolute rotor posture sensor with a full color sensing device [17]. The rotor surface is colored in Hue, Lightness, and Saturation changing around x axis, and Saturation changes around y axis. However, the sensing error is several deg.

M. Kumagai et al. developed an incremental ball rotating sensing system with three mouse sensors [18]. The diameter of the ball is 200 mm. The sensing error is less than 3.6 deg for each rotational axis after rotating the rotor 360 deg around the rotational axis at 100 deg/s.

This paper reports the basic experimental results of developed posturesensor with two mouse sensing devices.

At first, the representation of the rotor posture by the basis transformation matrix is proposed. Then, the basic ideas for getting the rotor posture from the data of two mouse sensing devices are presented. The basic experimental results of the developed posture sensor are shown.

2. Sensing Method

2.1 Representation of the Rotor Posture

The basis of the coordinate matrix system $R^{(0)} = \langle r^1_{(0)}, r^2_{(0)}, r^3_{(0)} \rangle$ is fixed on the rotor and the basis of the coordinate matrix system $S = \langle s_1, s_2, s_3 \rangle$ is fixed on the stator as shown in Fig. 1.

Matrix $K_{Ri}$ is referred to as the “basis transformation matrix from $S$ to $R^{(i)}$”, and can be used for transforming any vector $a$ from $S$ representation to $R^{(i)}$ representation, according to the following theorem:

$$a_{Ri} = K_{Ri} a_S$$

Therefore, when the basis vectors $(r^1_{(i)}, r^2_{(i)}, r^3_{(i)})$ are measured on the stator basis such as Eq. (2) (Fig.1), $K_{Ri}$ is simply represented by Eq. (3).

$$r^1_{(i)} = x^1_{(i)} s_1 + y^1_{(i)} s_2 + z^1_{(i)} s_3$$
$$r^2_{(i)} = x^2_{(i)} s_1 + y^2_{(i)} s_2 + z^2_{(i)} s_3$$
$$r^3_{(i)} = x^3_{(i)} s_1 + y^3_{(i)} s_2 + z^3_{(i)} s_3$$

$$K_{Ri} = \begin{bmatrix} x^1_{(i)} & x^2_{(i)} & x^3_{(i)} \\ y^1_{(i)} & y^2_{(i)} & y^3_{(i)} \\ z^1_{(i)} & z^2_{(i)} & z^3_{(i)} \end{bmatrix}$$

The rotor posture is represented by $K_{Ri}$. As $K_{Ri}$ is the orthogonal matrix, the inverse matrix $(K_{Ri})^{-1}$ is the transposed matrix $K^{T}_{Ri}$. Therefore, from the theorem of $K_{Ri}$, Eq. (4) are derived for any vector $a$.

$$a_S = K_{Ri} a_{Ri}$$

This is a very important transformation equation. For transforming any vector $a$ from $R^{(0)}$ representation to $S$ representation, only multiply $K_{Ri}$ to vector $a$

$K_{Ri}$ is also calculated from $n_S = ^{T}(n_1, n_2, n_3)$ and $\theta$ by Eq. (5), where $n_S$ is a unit vector of the rotational axes and $\theta$ is an angle of rotation of the basis transformation from $S$ to $R^{(i)}$.

$$K_{Ri} = \begin{bmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{bmatrix}$$

$$k_{11} = n^2_1 (1 - \cos \theta) + \cos \theta$$
$$k_{12} = n_1 n_2 (1 - \cos \theta) - n_3 \sin \theta$$
$$k_{13} = n_2 n_1 (1 - \cos \theta) + n_2 \sin \theta$$
$$k_{21} = n_1 n_2 (1 - \cos \theta) + n_3 \sin \theta$$
$$k_{22} = n^2_2 (1 - \cos \theta) + \cos \theta$$
$$k_{23} = n_2 n_3 (1 - \cos \theta) - n_1 \sin \theta$$
$$k_{31} = n_3 n_1 (1 - \cos \theta) - n_2 \sin \theta$$
$$k_{32} = n_2 n_3 (1 - \cos \theta) + n_1 \sin \theta$$
$$k_{33} = n^2_3 (1 - \cos \theta) + \cos \theta$$

Fig. 1. Rotor coordinate system and stator coordinate system.
Eq. (5) is derived from Rodrigues’ rotation formula (6).

\[ K_{Ri} = I + N^2(1 - \cos \theta) + N \sin \theta \]  

(6)

where

\[ N = \begin{bmatrix} 0 & -n_3 & n_2 \\ n_3 & 0 & -n_1 \\ -n_2 & n_1 & 0 \end{bmatrix} \]  

(7)

\[ N^2 = \begin{bmatrix} -n_2^2 - n_3^2 & n_1n_2 & n_3n_1 \\ n_1n_2 & -n_2^2 - n_1^2 & n_2n_3 \\ n_3n_1 & n_2n_3 & -n_1^2 - n_2^2 \end{bmatrix} \]  

(8)

As these characteristics of \( K_{Ri} \) are convenient to represent the vector rotation, rotor posture is represented by \( K_{Ri} \) in this paper.

2.2 Sensor Coordinate Systems

Two mouse sensing devices are arranged at the arbitrary positions on a stator \((p_1)_S\) and \((p_2)_S\). Each mouse sensor measures two circumferential speed \((v_{j1}, v_{j2})\) along the unit vectors of sensing directions \((u_{j1}, u_{j2})_S\).

The basis of the sensor coordinate system \( M = \{(m_1, m_2, m_3)\} \) is introduced. \( m_1, m_2, \) and \( m_3 \) are determined by Eqs. (9) to (11).

\[ m_1 = \frac{(p_1)_S}{(p_1)_S} \]  

(9)

\[ m_3 = \frac{(p_1)_S \times (p_2)_S}{(p_1)_S \times (p_2)_S} \]  

(10)

\[ m_2 = m_3 \times m_1 \]  

(11)

Then, \( K_M \), which is the basis transformation matrix from \( S \) to \( M \), is \([m_1, m_2, m_3]\). As the mouse sensing devices are fixed on the stator, \( K_M \) can be calculated previously.

Fig. 2. Sensor coordinate system and mouse sensors.

\((p_1)_M\) and \((p_2)_M\), which are the position vectors of the mouse sensors on \( M \), are easily derived as \( K_M(p_j)_S \) and \( K_M(p_j)_S \cdot (u_{j1}, u_{j2})_M \), which are the unit vectors of sensing direction of mouse sensor \( j \) on \( M \), are represented as \( K_M u_{j1}, K_M u_{j2} \). Fig. 2 shows the sensor coordinate system \( M \).

2.3 Obtain Current Posture of the Rotor from the Sequence of the Basis Transformation Matrices

At first, the rotor coordinate system \( R^{(0)} \) is set equal to the stator coordinate system, and at every sensing time interval \( \Delta t \), the rotor coordinate system \( R^{(i)} \) is set to equal to the stator coordinate system after rotation. In other words, the rotor coordinate system \( R^{(i-1)} \) is equal to the stator coordinate system \( S \) before rotation.

Therefore, the basis vectors \( r_1^{(i)}, r_2^{(i)}, r_3^{(i)} \) of the rotor coordinate system after rotation is represented by Eq. (12). Eq. (13) is obtained from Eq. (12).

\[ [r_1^{(i)}, r_2^{(i)}, r_3^{(i)}] = [r_1^{(i-1)}, r_2^{(i-1)}, r_3^{(i-1)}] K_{Ri} \]  

(12)

\[ [r_1^{(i-1)}, r_2^{(i-1)}, r_3^{(i-1)}] = [r_1^{(i)}, r_2^{(i)}, r_3^{(i)}] K_{Ri} \]  

(13)

After the rotor rotates \( h \) times from the initial posture, the basis vectors of the initial posture of the rotor \( r_1^{(0)}, r_2^{(0)}, r_3^{(0)} \) are represented by Eq. (14).

\[ [r_1^{(0)}, r_2^{(0)}, r_3^{(0)}] = [r_1^{(1)}, r_2^{(1)}, r_3^{(1)}] K_{R1} \]  

(14)

\[ K_{R} = K_{R1} K_{R2} \ldots K_{Rh} \]  

(15)

By introducing matrix \( K_R \) defined by Eq. (15), Eq. (14) is simplified to Eq. (16).

\[ [r_1^{(h)}, r_2^{(h)}, r_3^{(h)}] = [s_1, s_2, s_3] K_R \]  

(16)

As \( R^{(h)} \) is equal to the stator coordinate system after \( h \) time rotation, equation (17) is obtained.

\[ [r_1^{(0)}, r_2^{(0)}, r_3^{(0)}] = [s_1, s_2, s_3] K_R \]  

(17)

\( K_R \) is the basis transformation matrix from \( S \) to \( R^{(0)} \) after \( h \) rotation. Therefore, the current posture of the rotor is represented by \( K_R \).

2.4 Calculation of the Basis Transformation Matrix

In this section, a basis transformation matrix \( K_{Ri} \) is calculated.

Three circumferential speeds among four measured circumferential speeds \((v_{11}, v_{12}, v_{21}, v_{22})\) are chosen such that three corresponding unit vectors of sensing
direction are not in parallel. Assume that \((v_{11}, v_{12}, v_{21})\) are selected. Then, \(\omega_M\) is obtained by solving Eq. (18) [18].

\[
v = A\omega_M \tag{18}
\]

where

\[
v = \begin{bmatrix} v_{11} \\ v_{12} \\ v_{21} \end{bmatrix}, \quad A = \begin{bmatrix} (p_1)M \times (u_{11})M \\ (p_1)M \times (u_{12})M \\ (p_2)M \times (u_{21})M \end{bmatrix} \tag{19}
\]

Rotor angular velocity vector on M is transformed on S by Eq. (20)

\[
\omega_S = \omega_M \tag{20}
\]

Rotation angle \(\theta\) and \(n_S\) are calculated by Eqs. (21) and (22).

\[
n_S = \frac{\omega_S}{|\omega_S|} \tag{21}
\]

\[
\theta = |\omega_S| \tag{22}
\]

\(K_R\) is obtained by calculate Eq. (5), and \(K_R\) is obtained from Eq. (15).

3. Experimental Results

3.1 Representation of the Rotor Posture

Fig. 3 shows the developed spherical motor. Eight permanent magnets are attached on the rotor such as the North poles and South poles appear alternatively at the vertexes of the hexahedron subscribed in the rotor. Twenty-five coils are attached on the stator at the vertexes, centers of edges, and centers of planes of the octahedron subscribed in the rotor. The rotor can be driven in any direction by the control currents of the coils. The rotor is sphere and the diameter \(d\) is 78mm. For position feedback control of the developed motor, the mouse sensor should read the data at 300 rpm rotational speed and the angle resolution should be less than 0.01 deg.

The calculation results of the rotor speed of the developed spherical motor to the tracking speed of the mouse sensor is shown in Fig. 4, and the angle resolution of the developed spherical motor to the XY resolution of the mouse sensor is shown in Fig. 5. In Fig. 4 and Fig. 5, \(d\) is the diameter of the rotor.

The mouse sensing devices are connected at the USB ports. The data is obtained through Windows 7 OS. Therefore, the data acquirement interval is not controlled. So, for checking the reliability of the obtained mouse data, the resolution of the mouse data is tested to put a mouse sensor on the XY precision linear stage. Fig. 7 shows the test results. The upper graph shows the large movement and the lower graph shows the small movement.
Fig. 7. Mouse count to the stage movement.

The mouse counts are 15 pixels short for 620 pixels at X direction and 9 pixels short at Y direction, which are 2.41% and 1.13% of the 620 pixels. For the small movement, the mouse counts are within 4 pixels from the ideal count line. The test results show that the mouse sensor is useful for the sensing device of the spherical posture sensor.

3.2 Experimental Setup

Two mouse sensing devices are set on the armature coil holders of the spherical motor stator. The spherical motor is set on the spherical motor testing stage as Fig. 8.

The output shaft of the spherical motor rotor is fixed on the base of the testing stage and the stator is fixed on the jimbal mechanism of the testing stage. The stator is supported to rotate around X, Y, and Z axis of the jimbal mechanism. The mouse sensing devices are set at the position vectors \((p_1)_S\) and \((p_2)_S\) in equation (23).

\[
(p_1)_S = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \quad (p_2)_S = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}
\]  

Therefore, the basis vectors of the sensor coordinate system are represented by Eq. (24).

\[
\begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
\]  

\( (u_{11}, u_{12}, u_{21}, u_{22})_M \), the unit vectors of sensing direction on the sensor coordinate, are set as Eq. (25).

\[
(u_{11}, u_{12}, u_{21}, u_{22})_M = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix}
\]

3.2 Experimental Results

A posture calculation program is developed. Visual C++ language is used to develop the program. The display part of the posture sensing program is shown in Fig. 9. The 3D rotor posture is graphically displayed at the lower right.

The measurement error of the rotor posture is evaluated by rotating the rotor around Z axis by hand and the rotation angle is measured by an encoder fixed on the output shaft. The measurement rotational angles are shown in Fig. 10. The maximum measurement error is 12.6 degrees. As the mouse sensing device is an incremental sensor, the measurement value need to be reset after long term measurement times. For avoiding the measurement error integration, the reference posture marker which resets the measurement error or an absolute posture sensor should be used in parallel.

Fig. 8. Mouse sensing devices on the spherical motor and the spherical motor testing stage.

Fig. 9. Display of the rotor posture.
4. Conclusion

Researchers of the posture sensors for the spherical motor are reviewed. A posture sensor with two mouse sensing devices is developed. The basic ideas for getting the posture from the data of two mouse sensing devices are presented. Two mouse sensing devices are set on the armature coil holders of the spherical motor stator and the basic performance of the rotor posture measurement is evaluated. As the mouse sensing device is an incremental sensor, the measurement error increases during sensing. The reference posture marker to reset the error or some absolute posture sensors as Hall device position sensors should be used with the developed posture sensor in parallel.

In the near future, an automatic rotor posture evaluate stage will be developed and more precise data are obtained. The Hall device absolute position sensors will be also used with this sensor.

The developed spherical motor is also controlled by position feedback with the developed rotor posture sensor.

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References


