1. Introduction

Recently, redundant manipulators are highly regarded for having a lot of inherent advantage. However, the redundant manipulators mostly constitute a linkage mechanism installed redundant actuators at redundant joints for driving the redundant linkages, so, redundant manipulators become more bulky and projections for the actuators impede the motion of the manipulators. Moreover, as the driven axes for the actuators are intersect at the centre of the joint, structure of the redundant joint is more intricate. For the solution of these inconvenient, some spherical motors have been developed. One spherical motor is consist of a spherical cell made of steel and four ultrasonic motors. Other spherical motor composes a special planet gear mechanism. These spherical motors are still intricate and control algorithms are complicated.

In this paper, we present a novel spherical motor manipulated by four wires. The spherical motor can drive into three directions in rotation (i.e., pitch, roll and yaw). Structure of the spherical motor is compact and its mechanism is not intricate. Posture of the spherical motor is controlled by a simple algorithm in which lengths of four wires are regulated to reference lengths. The reference is calculated by a simple formula. The structure of the spherical motor manipulated by four wires and the principles of drive algorithm are described in this paper. Relationship between posture of the spherical motor and length of the wires are analyzed in theoretically. Optimal points to fix the tips of wires on the spherical cell and optimal points to pull the wires into the spherical concave shell are investigated in numerical calculations.

2. Structure and drive algorithm of the spherical motor

The spherical motor is consisted of a spherical cell, a spherical concave shell and four wires as shown in figure 1. The spherical cell is fitted on the spherical concave shell and slides on the spherical concave shell.
shell like a spherical slide bearing. The tips of the wires are fixed on the spherical cell symmetrically and the wires are respectively guided into small holes around a rim of the spherical concave shell. Each wire is stretched between the fixed point on the spherical cell and the hole of the spherical concave shell. The wires lie on the spherical cell with the shortest wire in length without slacking the wires. Four wires are pulled or loosened by stepping motors respectively. The spherical cell rotates in the direction of the resultant tensions for four wires. Length of the wires decides the posture of the spherical motor.

The spherical motor is driven as shown figure 3. Coordinates frame and standard posture of the spherical motor are defined as shown in figure 3-1. If the wires of B and D are pulled/loosened and the wires of A and C are loosened/pulled simultaneously, the spherical cell rotates against the X-axis as shown in figure 3-2. If the wires of A and B are pulled/loosened and the wires of C and D are loosened/pulled simultaneously, the spherical cell rotates against the Y-axis as shown figure 3-3. If the wires of B and C are pulled/loosened and the wires of A and D are loosened/pulled simultaneously, the spherical cell rotates against the Z-axis as shown in figure 3-3.

3. Posture of the spherical motor and length of the wires

A certain posture of the spherical motor is represented by three angles as shown in figure 4. $v$ represents tilted angle between Z-axis of the coordinates frame and the output axis of the spherical cell. $h$ represents rotated angle against Z-axis of the coordinates frame after the tilt of $v$ is accomplished. $r$ represents spun angle against the output axis of the spherical cell after the tilt of $v$ and rotation of $h$ are accomplished.

In the standard posture, if the tip of the wire is fixed at a point of (P) which coordinates components against the coordinates frame are (Px, Py, Pz) and if the wires are pulled into a point of (Q) which components against the coordinates frame are (Qx, Qy, Qz), the wire length Lo becomes as follows;

$$Lo = R \times \cos^{-1}\left(\frac{\mathbf{x} \cdot \mathbf{y}}{R^2}\right),$$

where $R$ is radius of the spherical cell.

When the spherical cell is driven from the standard posture to the posture which posture is represented by ($v$, $h$, $r$), the fixed point of the wire moves to the point which coordinates components are (Pxa, Pya, Pza). The wire length La becomes as follows;

$$La = R \times \cos^{-1}\left(\frac{\mathbf{x} \cdot \mathbf{y}}{R^2}\right),$$

where Pxa, Pya and Pza are calculated by a following translate equation;

$$\begin{align*}
\begin{pmatrix}
Pxa \\
Pya \\
Pza
\end{pmatrix}
&= \begin{pmatrix}
ACos + BCos + v - Bsin \\
Bcos + BCos + v - ASin \\
Bcos + BCos + v - ASin
\end{pmatrix} \\
&= \begin{pmatrix}
Px \\
Py \\
Pz
\end{pmatrix}
\end{align*}$$

where $v = Cos + BCos + Sin + Bsin$ and $h = ASin + Bcos + v$.

Therefore, if the wire is pulled subtracted distance between Lo and La, the spherical cell is moved from the standard posture to the posture. Additionally, if the spherical cell moves from the posture to a
posture, wire length (Lb) is calculated and the wire is pulled subtracted different between La and Lb in the same way.

4 Manipulated range of the spherical motor

The spherical motor can move in restricted range. The restricted range is defined by some geometrical necessities and some kinematical requirements. They are as follows; 1)the wires can not stretch over the half length of the outer circumference of the spherical cell because the wires are stretched along the shortest track of the spherical cell by its tension, 2)the wires are not tangled, 3)the tip on the wires are not moved under the guided holes around the rim of the spherical concave shell, 4)all of three components of the wire’s tension distributed to the direction of v, h and r at the tip of wire must exist because the spherical cell can not drive to all directions of v, h and r if one of these components does not exit. Distributed wire’s tensions at the fixed point on the spherical cell are shown in figure 5.

The manipulated range in which the spherical motor can move to all directions of v, h and r and other geometrical necessities are obtained satisfactory is numerically analyzed. If the tip of wires fixed at the point which setting angles are v and h as shown figure 6, the manipulated range are shown in figure 7, figure 8 and figure 9. In these figures, the manipulated range depends on the setting angles of v and h. The manipulated range about v and h is estimated in figure 10. Total spaces on each v-h plane, which mean that the spherical motor can move to the three directions, are plotted in figure 10. When v is 5 degree and h is 5 degree about the setting angles, manipulated range about r becomes biggest. The manipulated range about range r is estimated in figure 11. Total volumes, which mean that the spherical motor can move to the three directions, are plotted in figure 11. When v is 5 degree and h is 5 degree about the setting angles, manipulated range about r becomes biggest.

5. Conclusions

The novel spherical motor manipulated by four wires is developed. The structure of the spherical motor is compact and its drive algorithm is simple. The spherical motor is manipulated into the goal posture by controlling length of the wires. The manipulated range become largest when v is 5 degree and h is 5 degree about the setting angles.

References

Figure 6. Setting angles (v, h) for the wires

Figure 7. Manipulated range (v=45°, h=0°)

Figure 8. Manipulated range (v=45°, h=0°)

Figure 9. Manipulated range (v=45°, h=0°)

Figure 10. Estimation of the manipulated range for v and h

Figure 11. Estimation of the manipulated range for r

