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# Research of 3-DOF Active Rotational Ball Joint

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***Abstract*—This paper develops a 3-DOF active rotational ball joint with a simple and compact mechanism, which can realize a rotation around an any-direction rotational axis with a well manipulability and can change its direction of rotational axis smoothly and arbitrarily when it is on rotating. The mechanism principle of this joint is proposed and analyzed. Then the ball joint is developed with good dynamics and lower friction and experimental verification on the proposed mechanism is performed. The effectiveness of the mechanism principle is outlined by some experimental results.**

***Index Terms*—Three-DOF Ball Joint, Active Rotation Joint, Parallel Mechanism.**

## I. INTRODUCTION

In recent years, with the advances in humanoid robotics it has become possible to assign them the work of humans. There is a demand for robots to move like humans in every respect. Therefore, the development of 3-DOF active rotational joints such as the neck and hip joints which support human movement is required. 3-DOF rotational motions are referred to roll rotation, pitch rotation and yaw rotation, whose rotational axes are at right angles one another. A 3-DOF rotational joint can realize a rotation, which is in combination with the 3 basic rotations in the same time, around an any-direction rotational axis and can change its direction of rotational axis smoothly when it is on rotating. So far, for realizing some 3-DOF active rotations, 3 one-DOF rotational joints, whose rotational axes are arranged at right angles one another, are used in some robotic mechanism, for example the hip joint mechanism of some humanoid robots. This kind of joint mechanism can realize the roll rotation, pitch rotation and yaw rotation respectively, however, it cannot realize a rotation around an any-directional axis.

Regarding 3-DOF rotational mechanisms, there are some kinds of ball joints which are passive but active (for example, see [1]). And parallel mechanisms equipped with many active actuators are developed [2] $\sim$ [6], whose effecter can move with 3-DOF rotation. However, while it may be possible to achieve high stiffness with parallel mechanisms they lack well manipulatability in different rotational directions, and are structurally complex and not compact. As a similar research, for realize a 3-DOF active rotation, a parallel mechanism where 3 one-axis rotational joints connect one another in serial and at right angles was proposed [7], but the mechanism may not realize a rotation around an any-directional axis and is not so compact. Besides, there is a 3-DOF active rotational joint developed at Toyama laboratory in the Tokyo University of Agriculture and Technology, which uses a spherical ultrasound motor but may not be able to output larger powers [8].

In this research, the objective is the development of a structurally simple and compact 3-DOF active rotational ball joint, which can realize a rotation around an any-direction rotational axis with a well manipulability and can change its direction of rotational axis smoothly and arbitrarily when it is on rotating. We present and elucidate the construction principles behind the 3-DOF active rotational ball joint, and we demonstrate the effectiveness of the proposed principles by means of motion analysis and practical experiments.

## II. CONSTRUCTION PRINCIPLES FOR THE 3-DOF ACTIVE ROTATIONAL BALL JOINT

### A. Construction principles

Fig.1 shows a model of the construction of joint device proposed in this research, which is a 3-DOF active rotational ball joint between a pair of links.

The construction principles of the device arrange the rotational axes of each of the three hollow shaft motors supplying the drive power orthogonally for active rotations. The axes of active rotation are denoted as $X_m$, $Y_m$ and $Z_m$

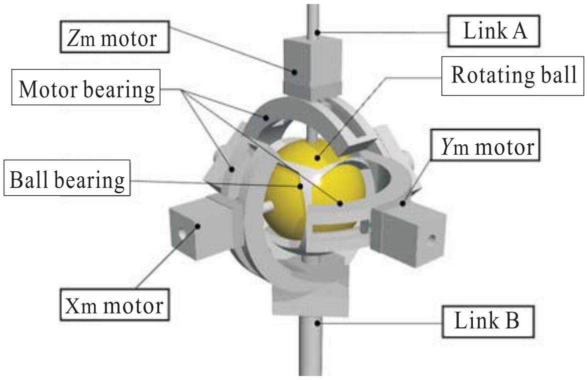


Fig. 1 Structure of 3-DOF active rotational ball joint

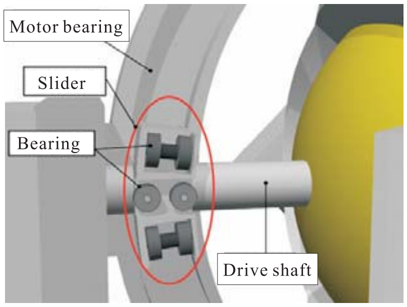


Fig. 2 Internal structure of the motor bearing

which are at right angles one another. The power output for the $X_m$ axis, the $Y_m$ axis and the $Z_m$ axis are compounded, and aligned at the centre of the joint in the manner of a ball joint. By setting the internal component as a rotating ball, the position of the ball can be kept still while rotational motion as a spherical bearing is permitted. Then, while regulating the rotation around the axes of each of the motors individually and permitting the 2 other orthogonal axes to perform passive rotation in sphercial 2-DOFs, a rotation around an any-directional axis can be realized. Lastly, by using the clamp supporting each of the motor axes to make the motor bodies not rotate around themselves axes but able to rotate around 2 other orthogonal axes, a 3-DOF active rotational joint can be formed.

Also, regarding the drive power of the $X_m$, $Y_m$ and $Z_m$ axes of the device, three drive shafts are used and the two ends of the drive shafts are inserted into the rotating ball and motor's hollow shaft respectively to connect the ball and motors. And the device is constructed such that the axial lines of each of the 3 hollow shaft motors align at a point in orthogonal directions. Furthermore, using a structure where a drive shaft extending from the frontal extremity of one of the hollow shaft motors to one of the links by passing through the motor's hollow, the movement of the rotating ball can be transmitted out to the link. Thereby, arbitrary 3-DOF relative rotational motion between the 2 links is possible.

## III. THE FUNDAMENTAL MOTION OF EACH PART

### A. Rotating ball

The rotating ball is arranged so that its center coincides with the origin of the orthogonal $X_0$, $Y_0$ and $Z_0$ axes. Also, the configuration is such that there are three mutually orthogonal bore holes, and the drive shafts which have the hollow shaft motors applied to them are inserted into these bore holes and fixed with pins, etc., so that the motors are transmitted via the bore holes, and combine to produce a rotating ball.

The output shaft to the link is fixed to the rotational shaft of the $Z_m$ axis motor. The movement of the rotating ball is output to the link via the rotational shaft of the $Z_m$ axis motor, passing through its hollow bore.

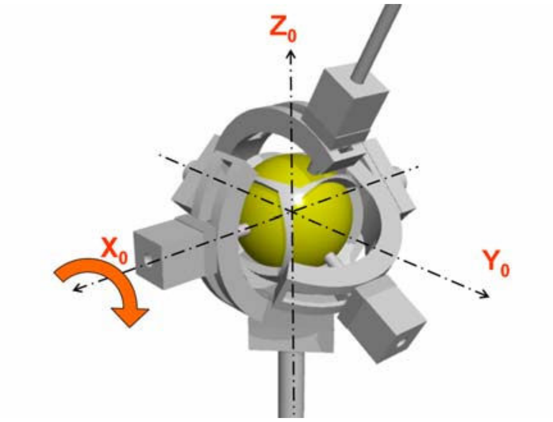


Fig. 3 When the $X_m$ axis motor is rotated

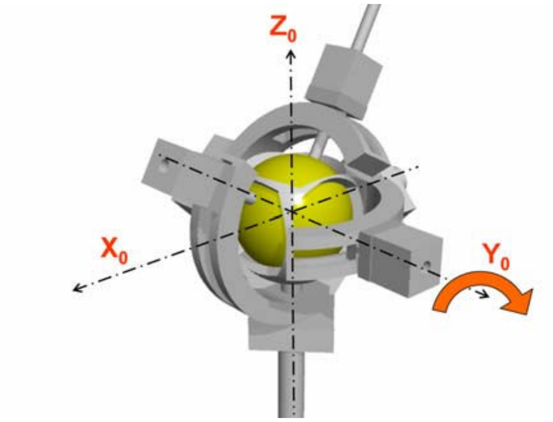


Fig. 4 When the $Y_m$ axis motor is rotated

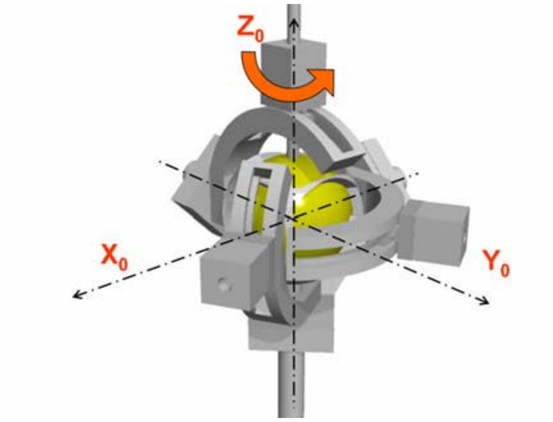


Fig. 5 When the $Z_m$ axis motor is rotated

### B. The ball's bearing and clamp

The bearing of the ball is constituted by the hollow sphere formed by the rotating ball and its concentric sphere. It functions as a spherically-sliding axis-bearing supporting the rotational motion of the rotating ball in an arbitrary direction. According frames of latitude and longitude in terms corresponding to the Earth, the ball's bearing is such that around the $X_m$, $Y_m$ and $Z_m$ output shafts a reduced quadrilateral aperture is formed. This bearing is supported by means of the clamps.

In addition, the clamps fix the bearing, and function to support the motor bearings which support each motor by means of the attachment extremities located on the 3 orthogonal axes stated above.

### C. Motor bearings

We now focus on and explain the motor bearing supporting the $X_m$ axis motor shown in 1.

This motor bearing is formed by the great circle of the rotating ball and the concentrically curved hollow cylinder component. Also, for the surface on the side of the $X_m$ axis motor, and the surface on the side of the rotating ball, a long hole is formed in a longitudinal direction with the insertion width of the hollow motor output axis.

Also, a component known as a slider is incorporated into the hollow part of the motor bearing (see Fig.3). There are a number of bearings located in the slider. The dimensions of these bearings are set so that there cannot be any gap between the inner surface of the hollow part of the motor bearing, the inner surface on the motor side, and the inner surface of the rotating ball. The slider ensures that the internal components do not jiggle in any direction.

In this way the slider, by means of the rolling motion between each inner surface of the internal components yielded by the bearings, makes it is possible for the inner part of the motor bearing to slide with low friction in a longitudinal direction while keeping the rotating ball at a constant distance.

The anterior end of the $X_m$ axis motor is fixed via a support plate coupled with the slider. In this case, the output axis extending from the anterior end of the $X_m$ axis motor passes through the slider and is joined to the rotating ball.

According to the structure stated above, there is no jiggling in the $X_m$ axis motor between the slider and the hollow part of the motor bearing, so the rotation is regulated around the axial direction of this part itself (see Fig. 3). Moreover, due to the slider there can be no reciprocation along the motor bearing, so among the other 2 orthogonal axes the $X_m$ axis motor can turn around the $Y_0$ axis (see Fig.4).

With this type of motor bearing, the ends are fixed to the rotation axes, and there is axial support in such a way that rotation is possible at the support-end located on the $Z$ axis of the clamp. There are two bearings installed internally in the support-end, and by aligning the two bearings in the axial direction of the rotation axis, even when an external force is applied to tilt the rotation axis the two bearings act together to support the rotation axis and prevent it from tilting.

According to the structure stated above, among the other 2 orthogonal axes, the motor bearing, i.e., the $X_m$ axis motor, can rotate about the $Z_0$ axis (see Fig.5).

We focused on and explained the motor bearing supporting the $X_m$ axis motor, but the explanation regarding the motor bearings supporting the $Y_m$ axis and $Z_m$ axis motors is the same.

According to the structure stated thus far, the device has the functionality of a 3-DOF active rotational joint between a pair of links. According to these structural principles, if the $X_m$, $Y_m$, and $Z_m$ axis motors are rotated simultaneously and independently, rotational motion in an arbitrary direction is possible as a composition of motion in the direction of each DOF. Also, having a structure similar to a spherical joint, we can present a 3-DOF active rotational joint with a simple structure.

## IV. KINEMATICS OF THE 3-DOF ACTIVE ROTATIONAL BALL JOINT

The reference frame of the device is taken as $O-X_0Y_0Z_0$. The motor coordinate frame in terms of the three orthogonal axes of the motors is taken as $O-X_mY_mZ_m$.

The motor coordinate frame rotates along with the rotating ball. When the device is in the initial orientation, the $X_0$ axis coincides with the $X_m$ motor axis, as do the $Y_0$ and $Y_m$, and the $Z_0$ and $Z_m$ axes.

By using the Jacobian matrix, $J$, the relation between the rotational velocity about each of the axes of $O-X_0Y_0Z_0$ and the rotational velocity input form each of the motors can be obtained as follows. The angular velocity occurring about the $X_0$ axis of the reference frame is written as $\theta_{x_0}$, that about the $Y_0$ axis as $\theta_{y_0}$, and that about the $Z_0$ axis as $\theta_{z_0}$. The rotational velocity about the $X_m$ axis in the motor coordinate frame is written as $\phi_{x_m}$, that about the $Y_m$ axis is written $\phi_{y_m}$, and that about $Z_m$ is written $\phi_{z_m}$. Then we have:

$$\begin{bmatrix} \dot{\theta}_{x_0} \\ \dot{\theta}_{y_0} \\ \dot{\theta}_{z_0} \end{bmatrix} = J \begin{bmatrix} \dot{\phi}_{x_m} \\ \dot{\phi}_{y_m} \\ \dot{\phi}_{z_m} \end{bmatrix}, \tag{1}$$

$$J = \begin{bmatrix} C_{y_m}C_{z_m} & -C_{y_m}S_{z_m} & -S_{y_m}C_{z_m} \\ -C_{x_m}C_{z_m} & C_{x_m}C_{z_m} & -S_{x_m}C_{z_m} \\ -C_{x_m}S_{y_m} & -S_{x_m}C_{y_m} & C_{x_m}C_{y_m} \end{bmatrix}, \tag{2}$$

where, we take $C_{x_m} = \cos\phi_{x_m}$, $S_{x_m} = \sin\phi_{x_m}$, and $C_{y_m}$, $C_{z_m}$, $S_{y_m}$ and $S_{z_m}$ are set in the same way.

In addition, for inverse kinematics, when the velocities are calculated from the trajectory of the link tip, the inverse, $J^{-1}$, of the Jacobian matrix $J$ is obtained and then the angular velocity of axis' motor can be obtained by premultiplying both sides of Eqn.(1) with it. Then, by integrating the angular velocity of each axis' motor, the trajectories of each motor can be obtained from the trajectory of the link tip.

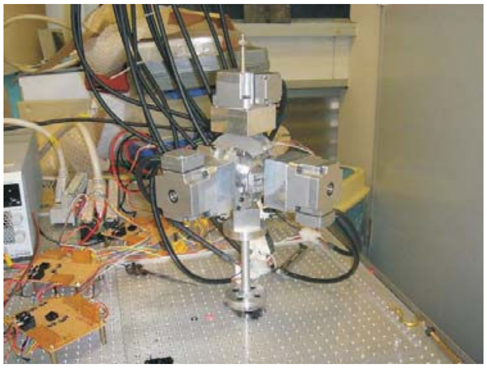
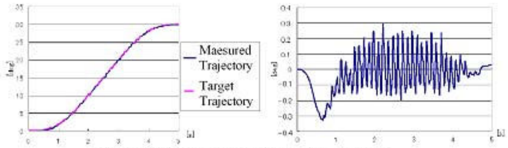
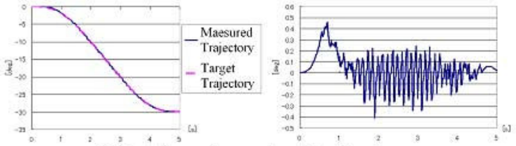


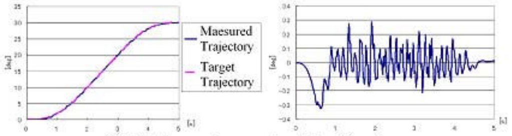
Fig. 6 Exterior appearance of the device



(a) Rotation and errors about the $X_0$ axis



(b) Rotation and errors about the $Y_0$ axis



(c) Rotation and errors about the $Z_0$ axis

Fig. 7 Rotation about the $X_0$, $Y_0$ and $Z_0$ axis during single axis rotation

## V. PROTOTYPE DEVICE AND PRACTICAL EXPERIMENTS

### A. Prototype device

A device was planned and experimentally manufactured based on the structural design stated above. A photograph of the actual completed device is shown in Fig.6.

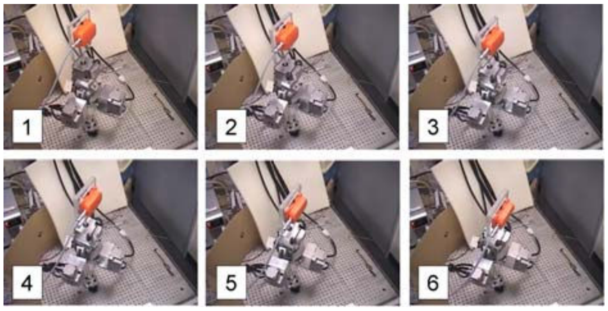
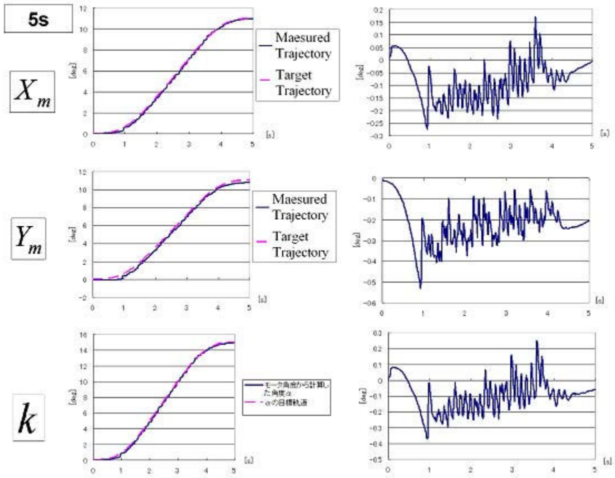


Fig. 8 The appearance of rotational motion with two axes



(a) Actual measured trajectory and target trajectory

(b) Error (Measured angle) - (Target angle)

Fig. 9 Rotation about the $X_0$, $Y_0$ and $k$ axis during dual axis rotation

### B. Rotational motion about a single axis of rotation

In order to confirm the principle motions using the completed device, a 3-DOF orientation sensor was installed on the tip of the link connected to the rotating ball. The experiments involved conducting motions from the initial orientation using the $X_m$ axis motor, the $Y_m$ axis motor, and the $Z_m$ axis motor one at a time. For each motor, a desired trajectory with S-shaped acceleration curve was applied to produce rotation within 5[s]. Each of the results is shown in Fig.7 (a), (b) and (c).

### C. Rotational motion about an arbitrary axis with 2 axes simultaneously

Next we conducted an experiment in which the $X_m$ and $Y_m$ axis motors were rotated simultaneously. This motion took a direction of $-45^\circ$ from the $X_0$ axis in the $X_0 - Y_0$ plane as the axis of rotation, and we adopted a link rotation of $20^\circ$ about this axis. That is to say, taking a rotation axis of $k = [\,-\sin 45^\circ\,,\ \cos 45^\circ\,,\ 0\,]^T$, the angle of rotation about

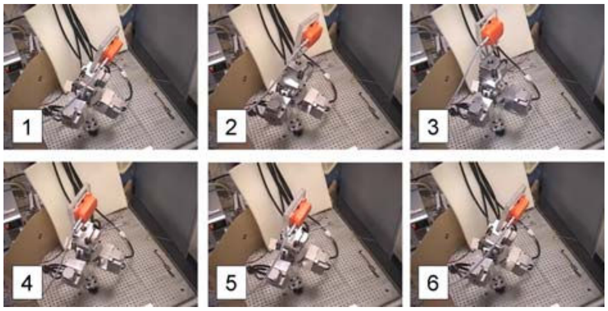
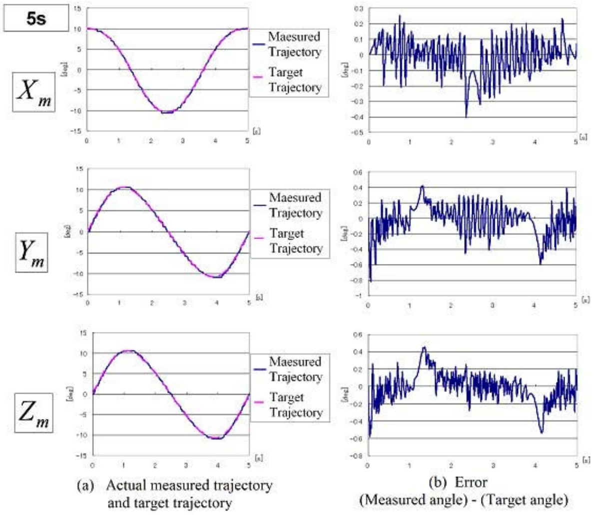


Fig. 10 The appearance of rotational motion with 3 axes



(a) Actual measured trajectory and target trajectory

(b) Error (Measured angle) - (Target angle)

Fig. 11 Rotation about the $X_0$, $Y_0$ and $Z_0$ axis during triple axis rotation within 5[s]

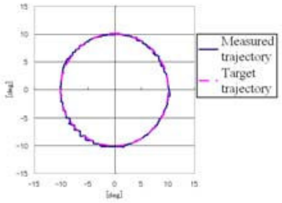
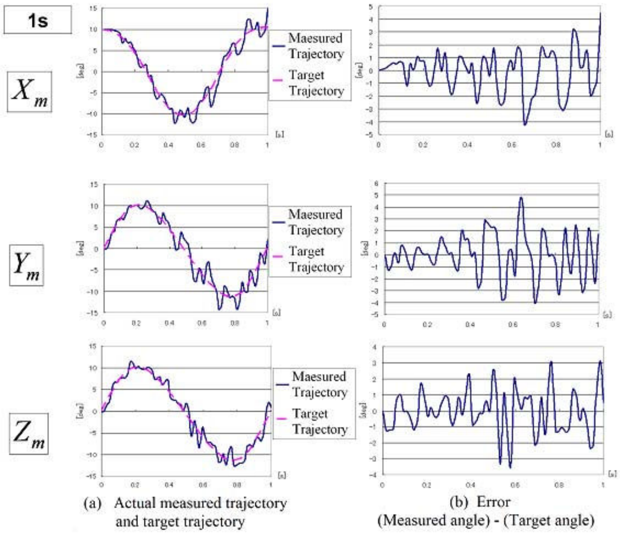


Fig. 12 Link-tip trajectory during triple axis rotation within 5[s]

this axis, $\alpha$, was taken as $\alpha = 15°$. Using a single axis rotation method, a desired trajectory describing an S-shaped acceleration curve was applied within 5[s]. The appearance of this motion is shown in Fig.8, and the results in Fig.9.



(a) Actual measured trajectory and target trajectory

(b) Error (Measured angle) - (Target angle)

Fig. 13 Rotation about the $X_0$, $Y_0$ and $Z_0$ axis during triple axis rotation within 1[s]

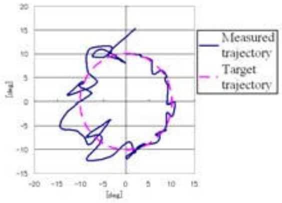


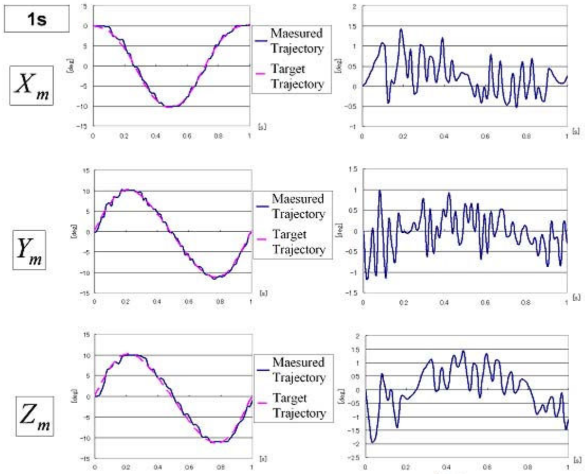
Fig. 14 Link-tip trajectory during triple axis rotation within 1[s]

## D. Rotational motion about an arbitrary axis with 3 axes simultaneously

Next we conducted an experiment in which the $X_m$ axis, $Y_m$ axis, and $Z_m$ axis motors were rotated simultaneously within 5[s]. For this motion, the target trajectories for each axis' motor were assigned so as to make the link describe a circular trajectory. The desired trajectory was taken as $\phi_x = 10\cos(\omega t)$, $\phi_y = 10\sin(\omega t)$, and $\phi_z = 10\sin(\omega t)$. The appearance of the motion is shown in Fig.10 and the results in Figs.11.

## E. Rotation with considering dynamics and friction

In order to test the joint's characteristic with high speed rotation, we give a high speed desired trajectory with acceleration, constant speed and deceleration, where, each axis'



(a) Actual measured trajectory and target trajectory

(b) Error (Measured angle) - (Target angle)

Fig. 15 Rotation about the $X_0$, $Y_0$ and $Z_0$ axis during triple axis rotation within 1[s] by considering dynamics and friction

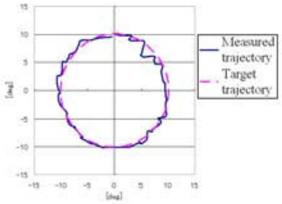


Fig. 16 Link-tip trajectory during triple axis rotation within 1[s] by considering dynamics and friction

motor were assigned so as to make the link describe a circular trajectory within 1[s].

We identified the joint's dynamics and dynamic friction with some experiments, and confirmed that the joint's moments of inertia and dynamic friction in $O - X_mY_mZ_m$ almost do not change with any different orientations of joint. By considering the identified dynamics and dynamic friction of joint, some experimental results are obtained as shown by Fig.16. And for comparison, Fig.14 shows a result with the same experiment within 1[s] but not considering the dynamics and dynamic friction. We can see that the errors about Fig.14's result are very large, but that in Fig.16 is very well since the dynamics and dynamic friction are considering.

Lastly, we give an result of an experiment within 1[s] shown by Fig.17 where only the dynamics has been considerred . The result is also very well, which means the friction in the joint is very small so that it can been ignored. From these result, we can see that the proposed 3-DOF rotation joint will be able to realize high speed rotations with a good accuracy.

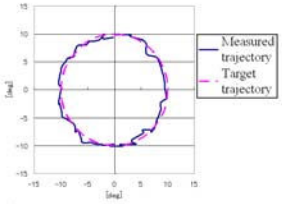


Fig. 17 Link-tip trajectory during triple axis rotation within 1[s] by only considering dynamics

## VI. CONCLUSION

The simple and compact 3-DOF active rotational ball joint proposed in this paper has a structure similar to a spherical joint, and its ability to rotate with 3-DOFs facilitates movements similar to those of human hip joints. The rotational joint can realize a rotation around an any-direction rotational axis with a well manipulability and can change its direction of rotational axis smoothly and arbitrarily when it is on rotating. In addition, 3-DOFs are provided by a single joint, making the miniaturization of the device a possibility, and by joining together these joints many DOFs can be obtained. From the experimental results it can be seen that each motor was capable not only of performing single axis rotations, but also rotations using two or three axes simultaneously without problems. It was thus confirmed that the device operated according to the structural principles established in this research.

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