# A Spherical Haptic Interface with Unlimited Workspace

Yuichi Tsumaki
Department of Mechanical Systems Engineering
Yamagata University
4-3-16 Jonan Yonezawa, Yamagata, JAPAN
Email: tsumaki@yz.yamagata-u.ac.jp

Takeshi Ohgi
Hino Motors, Ltd.
3-1-1 Hino-dai Hino, Tokyo, JAPAN
Email: ta.ougi@hino.co.jp

Arata Niiyama
U-Shin, Ltd.
1-1-30 Shibadaimon Minato-ku, Tokyo, JAPAN
Email: niiyama107025@u-shin.co.jp

***Abstract- Over the last two decades, various haptic interfaces have been developed. However, their workspace has been mechanically restricted. This limited workspace reduces operationality, because operation should be suspended at the boundary. In this paper, to tackle this problem, a spherical haptic interface is developed, which utilizes a ball as an interface with the human. The ball is driven by three DC motors through omni wheels. Consequently, unlimited workspace is achieved for orientation. Furthermore, a novel artificial sensation is implemented by rolling the ball with the palm.***

**Index terms: Haptic interface, virtual reality, human interface, joystick, teleoperation,**

## I. INTRODUCTION

To date, various haptic interfaces have been developed. An ideal haptic interface should have a transparent property, meaning the operator does not perceive the presence of the haptic interface.

To accomplish such ideal haptic interface, both a wide workspace and quick motion ability should be required. The former provides seamless operation, and the latter reduces the effect of its impedance. Accordingly, a wide workspace is one of the most desirable characteristics of the haptic interface.

The so-called early master arm, which was a primitive form of the haptic interface, had a wide workspace with a huge body [1], [2]. Hayward introduced redundancy into the haptic interface to improve rigidity and workspace [3]. Borro, meanwhile, developed a large haptic device for aircraft engine maintainability [4], while VISHARD10 also achieved a wide workspace with several redundant joints [5], although these haptic interfaces are bigger than humans.

Nevertheless, the workspace of any conventional haptic interface is subject to mechanical limitations. A wearable haptic interface can be considered as one of the solutions to achieve unlimited workspace [6]. However, the reactive force, which should be absorbed somewhere on the body, causes an unpleasant feeling.

On the other hand, Tsumaki introduced a compact haptic interface with relatively wide workspace using a hybrid parallel structure [7]. This type of desktop size haptic interface has the potential to become an advanced PC interface. From this perspective, the compactness of the haptic interface is also a preferable property, although such requirement conflicts with that mentioned previously.

To tackle this problem, in this paper we propose a novel desktop size haptic interface with unlimited workspace [8]. A ball is employed as an interface with a human to display three moments and rotational motions. We call it a spherical haptic interface. It resembles a track ball but with three actuators. Such a concept of motor driven 3-DOF track ball can be found in [9]. However, reasonable mechanisms have not been discussed to achieve real 3-DOF motions with wide touching area that is one of preferable properties for a haptic interface.

We would like to emphasize that it can also display each two directional forces in an arbitrary plane, while also providing a new feeling of the ball being rolled by the palm. Details of the design and fundamental experiments are described.

## II. A DESIGN CONCEPT OF A SPHERICAL HAPTIC INTERFACE

To achieve unlimited workspace, we utilize a ball as an interface with humans, since it is capable of infinite rotation in any direction. If the ball is driven by three actuators, it can display three axis moments and motions. In addition, it can also display two dimensional forces in the arbitrary tangential plane as shown in Fig. 1. Fig. 2, meanwhile, shows a novel developed spherical haptic interface. As you can see, compactness can be also achieved. The diameter of the ball is 57.1 mm which is the same as that of a billiard ball. The next section describes details of the mechanical design.

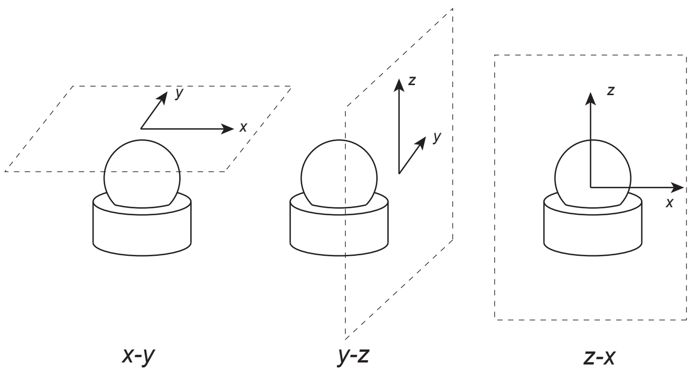


Figure 1. Forces in the tangential plane

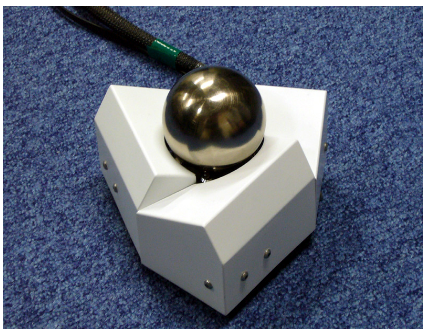

Figure 2. Photo of the spherical haptic interface

## III. MECHANICAL DESIGN

The surface of the ball should be exposed as widely as possible, with accessibility in mind. However, more than the half of the surface of the ball is usually covered to retain its position, as shown in Fig. 3 (A) like a trackball. This configuration introduces difficulties to grip the ball for the operator. On the other hand, a configuration of Fig. 3 (B) is preferable for a haptic interface. To achieve this configuration, both driving and holding mechanisms should be developed.

To date, several sphere driving mechanisms have been proposed. Yano developed a spherical stepping motor which achieved three-axis rotational motions [10]. However, a ball should be covered like Fig. 3 (A). Takemura used an ultrasonic actuator to drive a small ball. However, it lacks backdrivability, which is one of the significant properties for a haptic interface [11] . Consequently, we decide to utilize conventional DC motors to retain backdrivability as below.

### A. Driving Mechanisms

For the sphere driving mechanism, three sets of combinations of both an omni wheel and a DC motor are employed. It is well known that the omni wheel provides one degree of freedom actuation without interference in an orthogonal direction. Fig. 4 shows details of the omni wheel. Three sets of driving mechanisms are distributed at intervals of 120 degrees as shown in Fig. 5. Each axis of the omni wheel inclines 30 degrees against the ground as shown in Fig. 6. It is important to note that each normal line of the inclined plane at the center of the omni wheel should intersect at the center of the ball.

To ensure compactness, the omni wheel is driven by the DC motor via a belt and pulleys. The reduction ratio at the pulleys is 18.59:8.4 to ensure backdrivability, while the total reduction ratio between the actuator and ball is 6.32:1 because the diameter of the omni wheel is 20 mm. On the other hand, three poles with an artificial ruby ball are installed between the driving mechanisms to ensure stable motions, and an artificial ruby is selected because of its low friction coefficient.

We should point out that the current configuration is not absoluteness from the perspective of an exact geometric condition, because the omni wheel works well for flat surfaces. However, in the case of a sphere, a gap should be introduced. To tackle this problem, distance d in Fig.

4 is designed to be as short as possible. In addition, barreled rollers in the omni wheel are made by soft silicon rubber as shown in Fig. 7 to adapt to the gap.

On the other hand, several consistent mechanisms to drive a ball have been proposed [12], [13], although these are too complicated to make it small.

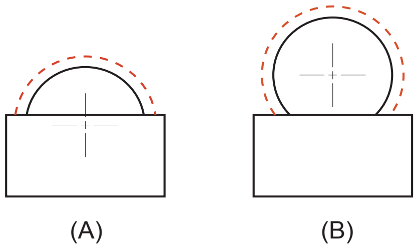


Figure 3. Touching area.

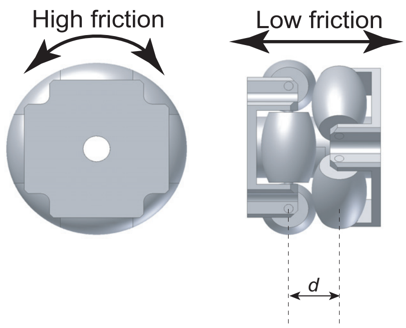


Figure 4. Details of the omni wheel.

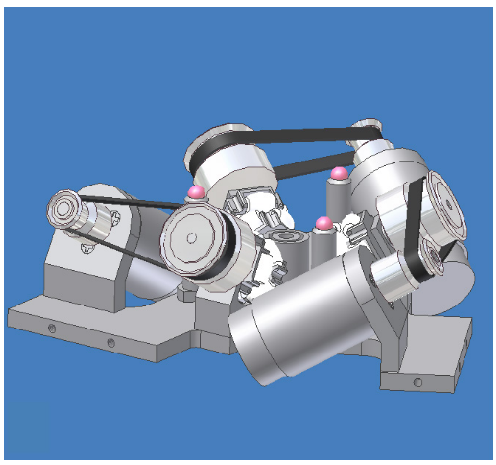

Figure 5. Distribution of driving mechanisms.

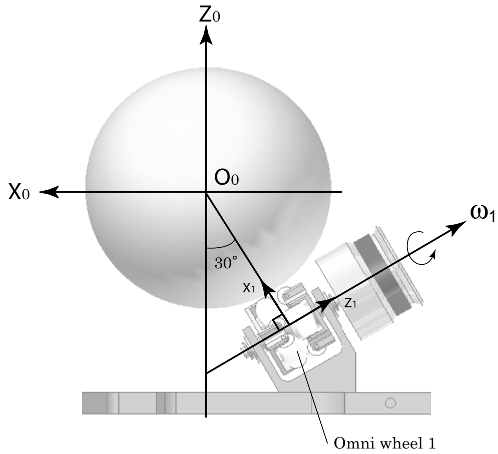


Figure 6. Inclination of the omni wheel.

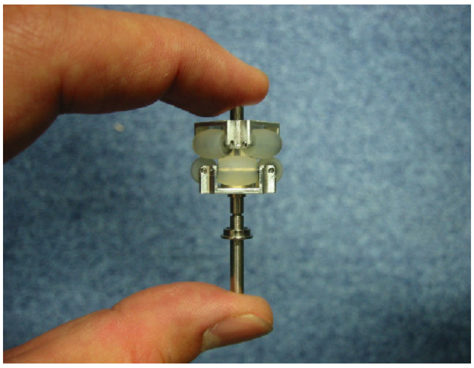

Figure 7. Photo of the omni wheel.

B. Holding Mechanisms

The driving mechanisms achieve stable motions of the ball. However, the ball is lifted if force exceeding its weight is exerted in a vertical upper direction. To handle this problem, both a steel ball and neodymium magnets are introduced as shown in Figs. 8 and 9, whereby the magnetic force attracts the ball beyond the small gap to retain its position. Consequently, although friction between the ball and ruby increases, a more stable motion can be obtained. To reduce the inertia of the ball, a midair shape is employed. The weight of the steel ball is 216 g, with magnetic force of almost 210 gf. Fig. 10 shows details of the inner design of the haptic interface.

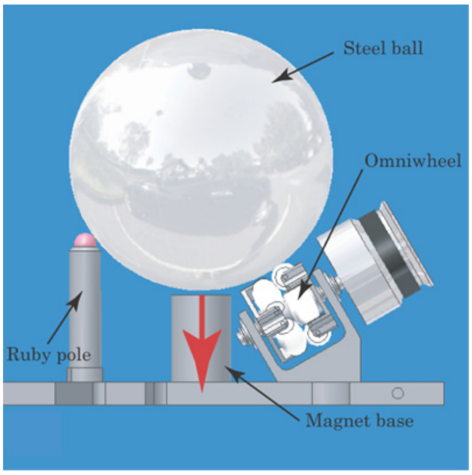


Figure 8. Concept of the mechanism

Figure 9. The steel ball

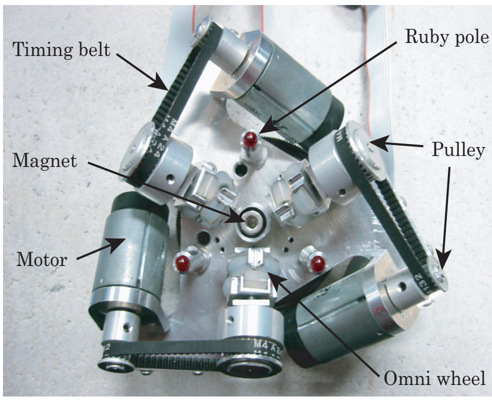


Figure 10. Details of the inner design

## IV. KINEMATICS

The angular velocity of the ball is decided upon by the composition of angular vectors of the omni wheels. This relation can be written as follows:

$$\boldsymbol{\omega}_b = \alpha(\boldsymbol{\omega}_1+\boldsymbol{\omega}_2+\boldsymbol{\omega}_3) \qquad (1)$$

where $\boldsymbol{\omega}_b$ is an angular vector of the ball and $\boldsymbol{\omega}_i$ is an angular vector of the $i$-th omni wheel. $\alpha$ is the reduction ratio based on the relation between the radius of the ball and that of the omni wheel. As a result, Jacobean J can be written as follows:

$$J = \frac{\alpha}{4}\begin{bmatrix} -2\sqrt{3} & \sqrt{3} & \sqrt{3} \\ 0 & -3 & 3 \\ 2 & 2 & 2 \end{bmatrix} \qquad (2)$$

$$\omega_b = J\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} \qquad (3)$$

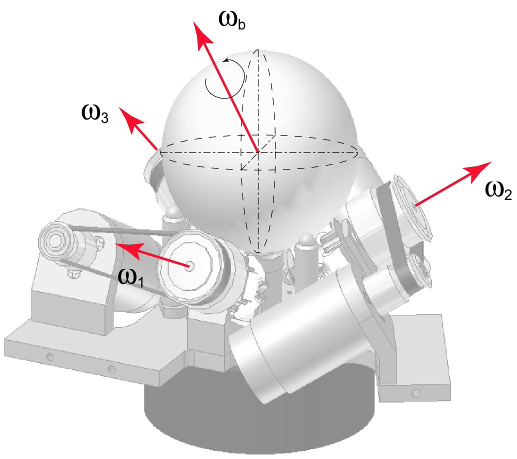


Figure 11. Relation of angular velocities

## V. CONTROL SYSTEM

Details of the control system are shown in Fig. 12. 11 W DC maxon-motors with 512 pulse MR encoders are employed for actuators. Each motor is driven by a Titech driver, and controlled through a Ritech interface card including D/A and counters. In addition, a 6-axis force/torque sensor is installed, thus allowing the haptic interface to also be utilized as a 6-axis force joystick. In other words, a combination with a rate joystick for translational command and a master arm for rotational command can be utilized for teleoperation. This combination is suited to a master device for a free-flying space robot or a 6-DOF manipulator.

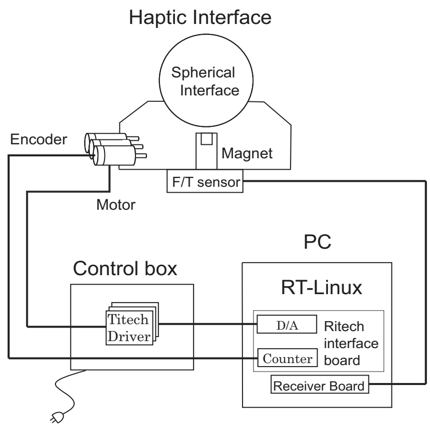


Figure 12. Control system

## VI. EXPERIMENTS

### A. Compensation for slip

The ball is driven by friction between the omni wheel and ball. Therefore, slip introduces significant position errors. To compensate for such errors, slip is measured using a digital camera to find the coefficient of error compensation. Consequently, it becomes clear that errors around both $x$ and $y$ axes are almost 10 percent. Errors around the $z$ axis are too small to be compensated for. Table 1 shows the coefficients for error compensation.

After compensation, the motions of the haptic interface are shown in Fig. 13. 1 to 3 show 60 degrees of rotational motions around the $x$-axis. 3 to 5 show reverse motions. 5 to 7 show 60 degrees of rotational motions around the $y$-axis. Subsequently, 7 to 10 show 180 degrees of rotational motions around the $z$-axis. Finally, 10 to 12 show 60 degrees of rotational motions around the $y$-axis. The final position of a red point is almost the same as the initial position. In this way, the compensation works well.

Table 1: Coefficients for compensation.

| Parameter | Compensation ratio |
|---|---|
| $x$ | 1.088 |
| $y$ | 1.115 |
| $z$ | 1.000 |

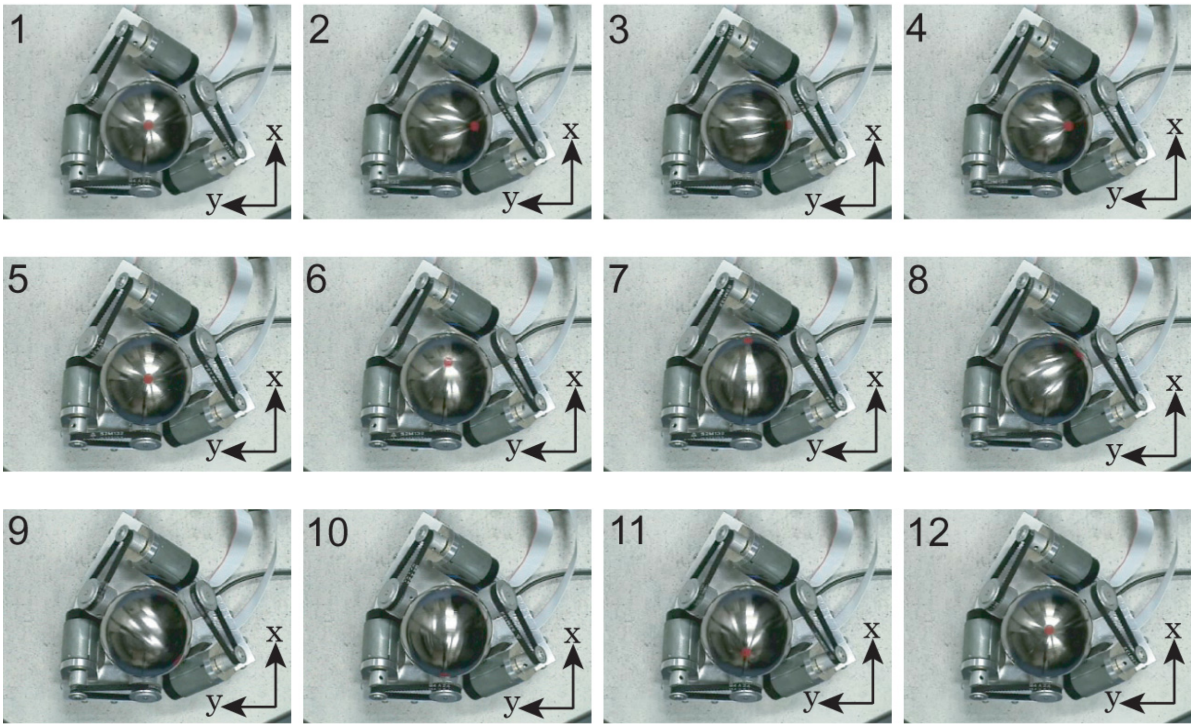


Figure 13. Motions in experiment

B. Current torque capability

Output torque is measured by a digital force gauge at intervals of 60 degrees as shown in Fig. 14. Figure 15 shows average of result of measurement 10 times. Unfortunately, the current torque is insufficient to display significant moment to the operator because of slip between the ball and omni wheel. In addition, it is clear that maximum torque depends on direction, because of configuration of omni wheels and ruby polls. Revision for material of the omni wheel should be required to increase the output torque. In addition, the current initial (static) friction is too big to display sensitive moment. To reduce it, the accuracy of the omni wheel should be improved.

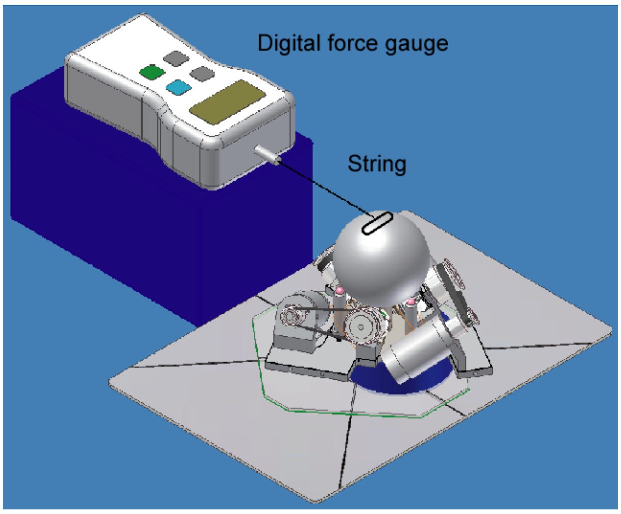


Figure 14. Measurement for output torque

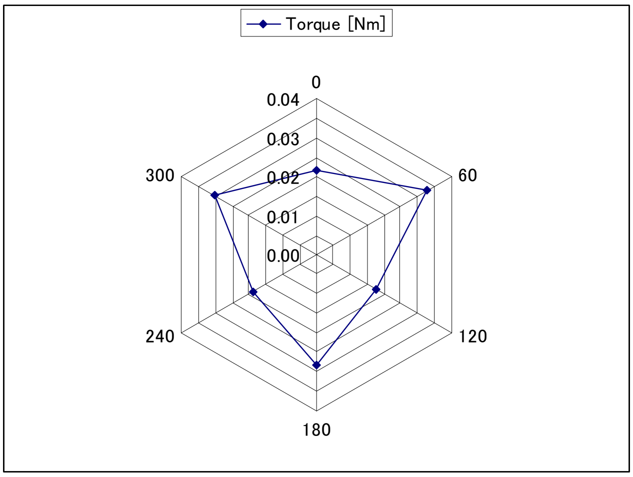


Figure15. Maximum torque

### C. VR simulator

Finally, Fig. 15 shows a Virtual Reality simulator using the spherical haptic interface. Motions of a virtual ball corresponds with that of the spherical interface. An operator rotates a virtual ball using his palm, which is another aspect of the developed haptic interface.

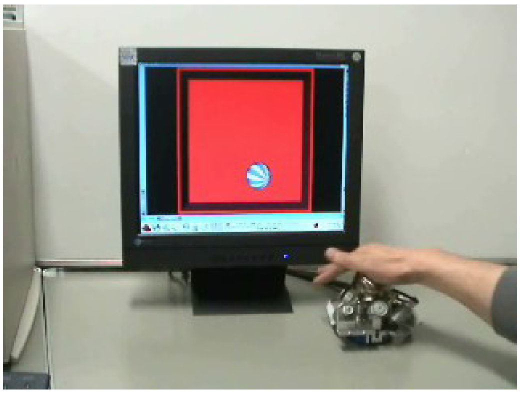

Figure 15. A VR simulator with the spherical haptic interface

## VII. CONCLUSIONS

A novel desktop spherical haptic interface is designed and developed, which consists of a ball and three sets of driving mechanisms, including the omni wheels. Furthermore, neodymium magnets and the steel ball are employed to retain stable motion. As a result, three axes of moments and motions can be displayed via the haptic interface with unlimited workspace.

Increasing the driving force dependent on the friction between the omni wheel and ball represents the next challenge.

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