The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

1-DOF Spherical Mobile Robot that can Generate Two Motions

*Teppei TOYOIZUMI, The Universty of Tokyo
Shogo YONEKURA, The University of Tokyo
Akiya KAMIMURA, National Institute of Advanced Industrial Science and Technology (AIST)
Riichiro TADAKUMA, Yamagata University
Yoichiro KAWAGUCHI, The University of Tokyo

Abstract— **A spherical mobile robot has been developed with a 1-DOF mechanism that can generate two motions, translational and rotational, using only one motor. The basic concept is to attach vinyl strips to the sphere at regular intervals and to change the driving modes of the motor to produce the desired motion. For example, placing the motor in vibration mode causes the trajectory of the contact point between the sphere and ground to follow a specified closed path, such as an elliptical path, which makes the sphere rotate against the ground. Testing of this concept using a self-developed simulator confirmed that rotational motion is generated by the interactions between the surface attachments and the ground. On the basis of these results, a prototype spherical mobile robot was developed, and testing confirmed that switching the motor driving mode generated two different motions.**

I. INTRODUCTION

Various types of robot have been developed for space exploration. The most common type is the rover type, which has been used by NASA with great success in its Mars exploration program. Another type is cylindrical [1], which has a unique driving mechanism based on center of gravity movement. Both type generally require more than two motors for locomotion, which increases the chances of mechanical problems and reduces the robustness of the system. Therefore, an important objective in the field of exploration robots is to reduce the number of motors and thereby simplify the robot's mechanism. We have developed a simple exploration robot that has a spherical shape and only one motor that can generate two motions. This design reduces the chance of mechanical problems and makes the robot smaller and cheaper.

A number of such robots loaded onto a rocket and delivered to a planet would greatly benefit space exploration. Spherical mobile robots, which have been well studied, are considered practical and useful because they can generate omnidirectional motion, can readily traverse rough terrain without getting stuck, and can withstand significant shocks due to their tough structure. Spherical robots are grouped into several types on the basis of their driving mechanism or number of actuators. For example, a 1-DOF-type robot is controlled by a 1-DOF actuator and cannot generate 2-DOF locomotion [2]. A car type robot is controlled by a car actuatr in the sphere [3][4], a rotor-type robot is controlled by conservation of angular momentum using a rotor [5][6][7], and a pendulum-type robot is controlled by swinging a spindle in the sphere to change its barycentric position [8]. However, none of the spherical mobile robots developed so far can generate 2-DOF locomotion with only a 1-DOF input actuator.

Various motions of a spherical body can be realized by controlling the contact point between the sphere and a plane by using the holonomy of a specified closed path [9]. Therefore, if a closed path were specified for the contact point, a 1-DOF robot controlled by center of gravity movement could generate two motions translational and rotational by using the specified closed path. We have developed a spherical mobile robot equipped with only one motor that can generate two motions. We tested the concept by using computer simulation and tested a prototype based on this concept experimentally. In the next section, we describe the basic concept. In section Ⅲ we present the simulation results, and in section Ⅳ we describe the prototype and present the experimental results. We end with a summary of the key points and a look at future work.

T. Toyoizumi: Graduate School of Interdisciplinary Information Studies, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, Japan, e-mail:Teppei.Toyoizumi@jp.sony.com

S. Yonekura and Y. Kawaguchi: Interfaculty Initiative in Information Studies, The University of Tokyo,7-3-1, Hongo, Bunkyo-ku, Tokyo, Japan, e-mail:(yonekura,yoichiro)@iii.u-tokyo.ac.jp

A. Kamimura: National Institute of Advanced Industrial Science and Technology(AIST),1-1-1 Umezono, Tsukuba, Ibaraki, 305-8568 Japan, e-mail:kamimura.a@aist.go.jp

R. Tadakuma: Faculty of Engineering, Yamagata University,4-3-16 Jonan, Yonezawa, Yamagata, Japan, e-mail:tadakuma@yz.yamagata-u.ac.jp

II. BASIC CONCEPT

Translational and rotational motion are needed to achieve omnidirectional motion on a plane. Here, we describe the methods used to generate these motions using only one motor.

A. Translational motion generation

The spherical robot developed by Zhan et al. [8] generates translational motion by using center of gravity movement. The input torque of the motor is transferred to the center shaft, which is connected to the mass, and this moves the center of gravity (Fig. 1). If the robot moves at a constant velocity along a straight trajectory, input moment τ is expressed as

$$\tau = mgl_x = -fr. \quad (1)$$

978-1-4244-6676-4/10/$25.00 ©2010 IEEE

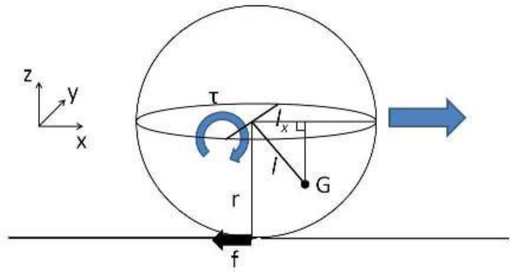

Fig. 1. Translational motion generation

where m is the mass, l_x is the projection vector of length l on axis x, f is the friction vector imposed on the robot by the plane, g is the acceleration of gravity, and r is the radius of the sphere. We use this method to generate translational motion in our robot.

B. Rotational motion generation

Rotational motion is generated using the same input actuator used for generating the translational motion.

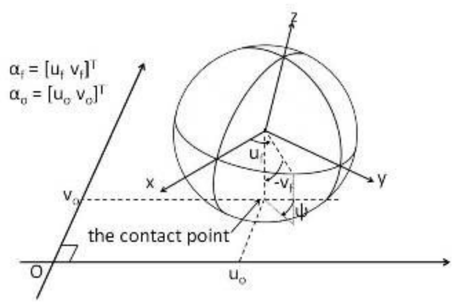

Fig. 2. Schematic of sphere rolling on plane

1) Specified closed path: Nakashima, et al. [9] developed a method for changing the position and pose of a sphere by using a closed path for the contact point. The configuration of the system is expressed as

$$\eta = [\alpha_f^T \alpha_o^T \psi]^T \in R^5. \tag{2}$$

where α_f is the contact point on the sphere, α_o is the contact point on the plane, and ψ is the angle between the directions of u_o and the projection of the latitude (u_f) on the plane (Fig. 2). Here, rolling contact is assumed to be pure rolling contact. Therefore, the kinematic model, which represents the relationship between $\dot{\eta}$ and $\dot{\alpha}_f$, is as follows [10]:

$$\dot{\eta} = \begin{bmatrix} \dot{\alpha}_f \\ \dot{\alpha}_o \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ r\mathbf{cos}v_f\mathbf{cos}\psi & -r\mathbf{sin}\psi \\ -r\mathbf{cos}v_f\mathbf{sin}\psi & -r\mathbf{cos}\psi \\ \mathbf{sin}v_f & 0 \end{bmatrix} \dot{\alpha}_f. \tag{3}$$

Now, let us consider a closed path on the sphere for the regulation, as shown in Fig. 3. The diagram on the left illustrates a closed path on the sphere (α_f), and the one on the right illustrates a closed path on the plane (α_o). The contact point on the sphere at the start is A_f, and the corresponding point on the plane is A_o. The closed path along the path α_f:$A_f \to B_f \to C_f \to D_f \to E_f(A_f)$ is characterized by parameters θ and L.

For simplicity, we assume that $\dot{\alpha}_f$ can be controlled directly. Consequently, the control problem is reduced to the regulation of

$$\tilde{\eta} = [\alpha_o^T \psi] \in R^3 \tag{4}$$

by adjusting the closed path on the sphere. Integrating (3) along the closed path given the initial conditions results in the incremental distances being given by

$$\Delta\tilde{\eta}(\theta, L) = \begin{bmatrix} \Delta\alpha_o^T & \Delta\psi \end{bmatrix}^T \in R^3. \tag{5}$$

where

$$\Delta\alpha_o(\theta, L) = \begin{bmatrix} \Delta u_o \\ \Delta v_o \end{bmatrix}$$

$$= \begin{bmatrix} \{r\mathbf{cot}(\frac{\pi}{2} - \frac{L}{\mathbf{r}}) - L\}\{\mathbf{cos}(2\theta - \theta\mathbf{cos}\frac{L}{r}) - \mathbf{cos}\theta\} \\ +r\mathbf{cot}(\frac{\pi}{2} - \frac{L}{\mathbf{r}})\{\mathbf{cos}(\theta - \theta\mathbf{cos}\frac{L}{r}) - \mathbf{cos}(2\theta - 2\theta\mathbf{cos}\frac{L}{r})\} \\ \\ \{r\mathbf{cot}(\frac{\pi}{2} - \frac{L}{r} - L\}\{\mathbf{sin}(2\theta - \theta\mathbf{cos}\frac{L}{r}) - \mathbf{sin}\theta\} \\ +r\mathbf{cot}(\frac{\pi}{2} - \frac{L}{r})\{\mathbf{sin}(\theta - \theta\mathbf{cos}\frac{L}{r}) - \mathbf{sin}(2\theta - 2\theta\mathbf{cos}\frac{L}{r})\} \end{bmatrix} \tag{6}$$

$$\Delta\psi(\theta, L) = -\mathbf{2}\theta(\mathbf{1} - \mathbf{cos}(L/r)) < 0. \tag{7}$$

Consequently the pose of the sphere is represented by $\Delta\psi$. Because $\Delta\psi$ is smaller than zero, the pose is counterclockwise rotation.

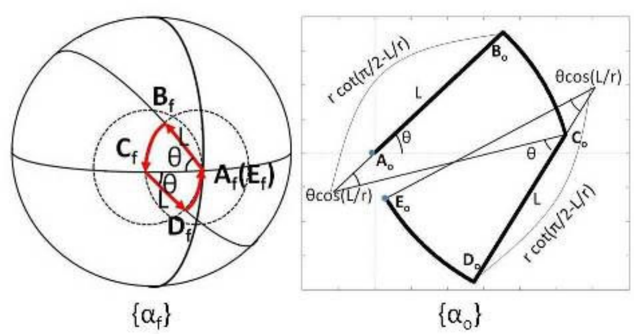

Fig. 3. Specified closed path on sphere (left) and on plane (right)

2) Closed path creation: The closed path is created by placing several attachments on the surface of the sphere at regular intervals. The shape of the attachments is shown at the upper left in Fig. 4. When motor torque τ is input in the direction of the y axis, friction force is added to the surface of the sphere in the x-z plane direction. The center of gravity is located at (0,0,-l), and gravity acts in the -z direction. The contact point on the sphere passes through position (0,0,-r) and a surface attachment. When it passes through the attachment in the direction $1 \rightarrow 2 \rightarrow 3$ (shown in the left diagram in Fig. 4), force F is added to the attachment in proportion to its bonding angle $\phi(0° \leq \phi \leq 90°)$. When the contact point passes through in the opposite direction, the force is added in the opposite direction because of point symmetry. The force is added to the surface attachment back and forth as the spherical body vibrates. The prospective trajectory of the contact point is shown in the right diagram of Fig. 4. It is like the trajectory shown in Fig. 3, so it would generate counterclockwise rotational motion. Clockwise rotational motion can be generated by changing the bonding angle of the surface attachment $\phi(90° \leq \phi \leq 180°)$.

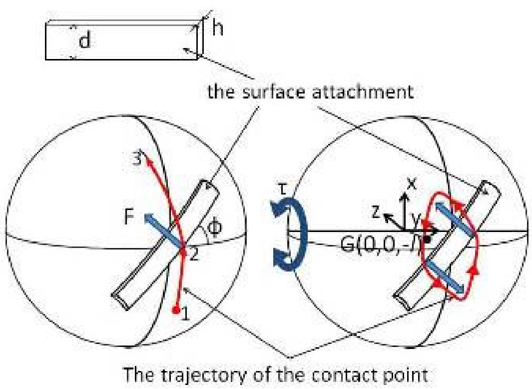

Fig. 4. Schematic of representative surface attachment on sphere. Trajectory of contact point and force vector F during rotation

3) Effect of attachments on translational motion: The surface attachments affect the translational motion. If the motor is in constant velocity mode for generating translational motion, the sphere turns to the right or left due to the attachments. This effect is avoided by using two different bonding angles for the attachments, as shown on the left in Fig. 5: Angle A ($0° \leq \phi_A < 90°$) and Angle B ($\phi_B = 180° - \phi_A$). An equal number of attachments are used for both angles. As a result, the effects of the attachments on the translational motion are mutually canceled, so the average trajectory is straight.

III. Simulation

A. Model

We developed a simulator to test whether a robot can generate rotational motion when the motor is in vibration mode. Sphere radius r was set to 120 mm, the center of gravity was set to (0,0,-100 mm), motor torque τ was set to

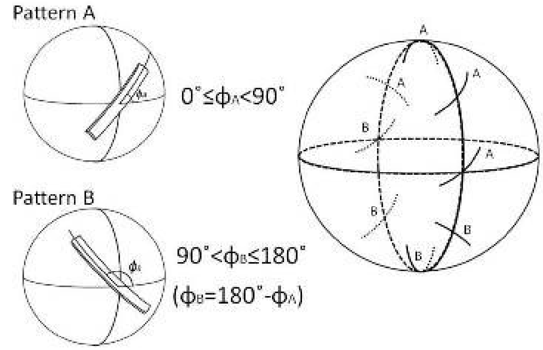

Fig. 5. Surface attachments placed at two different angles to mutually cancel their effects on translational motion

±1.0 N (rectangular wave), and the frequency was set to 2 Hz. The surface attachments were vinyl strips, 1 mm thick and 10 mm wide. We adjusted these parameters so that the trajectory of the contact point passed through only the one with Angle A(ϕ_A = 0°,45°,60°).

h	1mm
d	10mm
τ	±1.0N
r	120mm
l	100mm
ϕ_A	0°,45°,60°

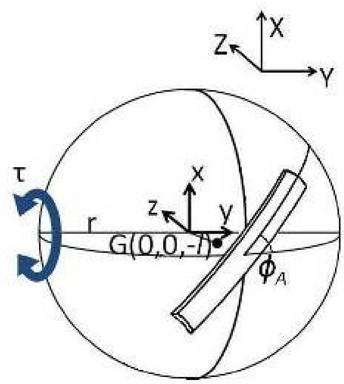

Fig. 6. Simulation model for 1-DOF spherical mobile robot

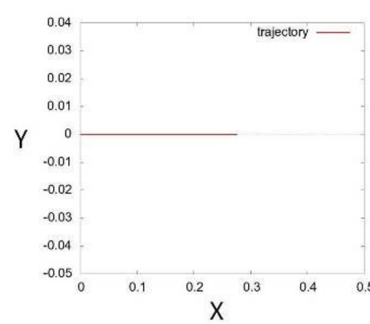

Fig. 7. Trajectory of robot without attachments

B. Results

1) Trajectory of contact point on plane: The trajectory of the contact point on the plane when there were no surface attachments is shown in Fig. 7. The sphere had a unidirectional trajectory affected by only input τ to the motor and did not generate rotational motion.

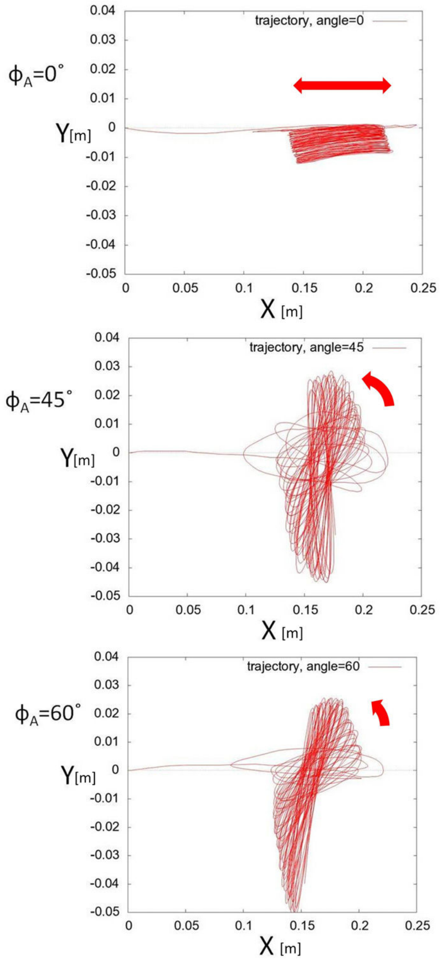

Fig. 8. Trajectory on plane with motor in vibration mode for ϕ_A=0°,45°, and 60°

The trajectories of the contact point on the plane when there were surface attachments and the motor was in vibration mode are shown in Fig. 8. When ϕ_A was 0° (top graph), rotational motion was not generated. When ϕ_A was 45° (middle) or 60° (bottom), the sphere generated rotational motion. It did this by rotating the plane of vibration for each vibrational motion. The rotation with ϕ_A = 45° was more effective than with ϕ_A = 60°. This is attributed to the difference in the amount of rotation during each vibration period.

2) Trajectory of contact point on sphere: The trajectory of the contact point on the sphere for ϕ_A=45° is shown in Fig. 9. The trajectory rotated counterclockwise elliptically. This is similar to the rotational motion described in II-B-2.

C. Discussion

Our simulation demonstrated that using surface attachments resulted in an elliptical trajectory for the contact point on the sphere, including a biased trajectory relative to the x axis. Consequently, using the attachments resulted in rotational motion. Photographs of the rotating sphere during the simulation are shown in Fig. 10.

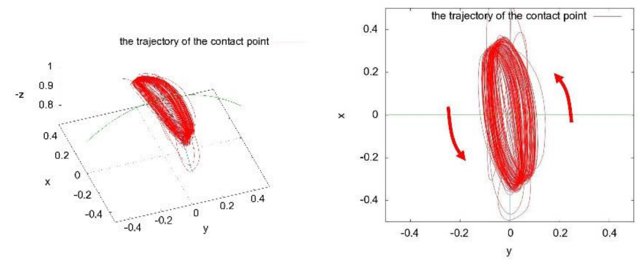

Fig. 9. Trajectory of contact point on sphere for ϕ_A=45° (3D (left) and 2D (right))

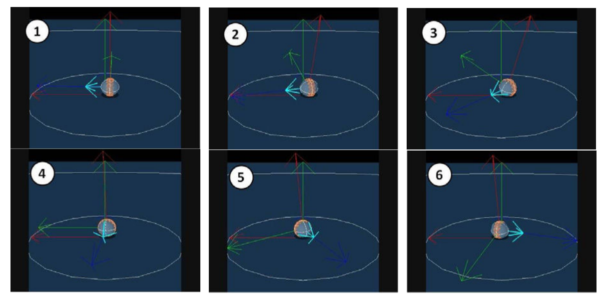

Fig. 10. Photographs of sphere generating rotational motion taken at 1-s intervals (ΔI = 20°, A = 88.0°, f = 6.4 Hz)

IV. Experiments

A. Prototype robot

A structural image of the prototype 1-DOF spherical mobile robot we constructed on the basis of the simulation results is shown in Fig. 11. The input torque of the servo motor is transferred to the body through the center shaft via spur gears. The motor part is attached to the shaft by a bearing with rotational freedom, so the motor can rotate around the shaft. The actual hardware is shown in Fig. 12. The weight of the robot is approximately 1 kg, and the radius is 120 mm. The spherical body is made of acrylic plastic, and the surface attachments ([0.5 mm thick and 10 mm wide]) are made of vinyl plastic strips. The motor is directly controlled by a signal from a laptop PC using Bluetooth. It is powered by a lithium polymer battery. Two motions are generated by switching the motor driving mode. In the experiments, red and blue markers were attached to the left and right ends of the center shaft respectively to enable us to capture the motion and position of the robot by using a camera and image processing. There were two experiments, one for translational motion with the motor in constant velocity mode, and one for rotational motion with the motor in vibration mode.

B. Results

1) Translational motion: For the translational motion experiment, we used four motor speeds (11.1, 22.3, 33.4, and 44.6 rpm) and measured the velocity of the robot while the motor was driven for a fixed time. As shown in Fig. 13, there was a positive correlation between the motor speed and the average velocity. The error bars show the maximum

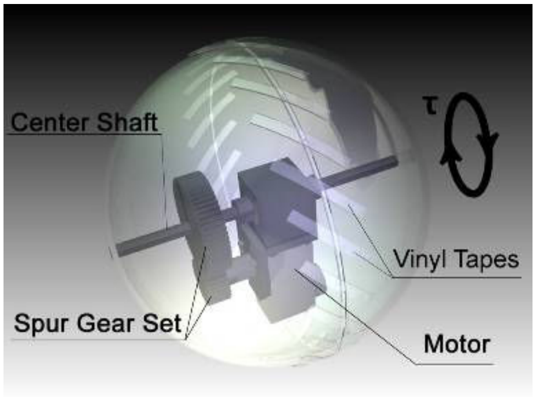

Fig. 11. Hardware design of 1-DOF spherical mobile robot

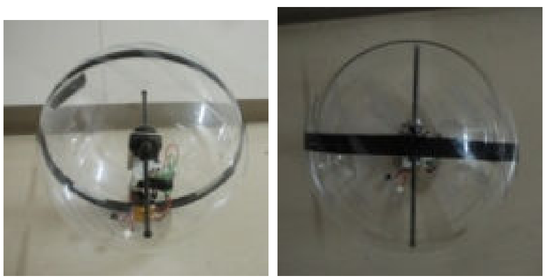

Fig. 12. Photos of 1-DOF spherical mobile robot

and minimum velocities for the nine experimental runs. The result has a large margin of error when the motor speed is too high, because the motor unit sometimes goes into a 360-degree roll in the initial acceleration stage. Photographs of taken during the experiment are shown in Fig. 14.

2) Rotational motion: For the rotational motion experiment, the bonding angle of the attachments (ϕ) was 45° and the bonding interval of the attachments (ΔI) was 15° or 20°. The motor frequency f was 6.4 Hz, and the amplitude of the motor A was 52.8° or 70.4°. For each experimental run, the motor and robot were initially in stop mode. The motor was then started and placed in vibrating mode. The motor remained in vibrating mode for 20 s and was then turned off.

Without the attachments, the average rotational velocities ω were zero, as shown in Fig. 15 (left). That is, a robot without attachments cannot rotate. The trajectories of the

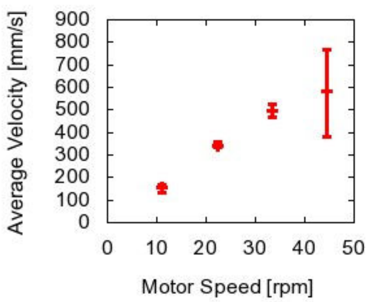

Fig. 13. Average velocity of robot with motor in constant velocity mode

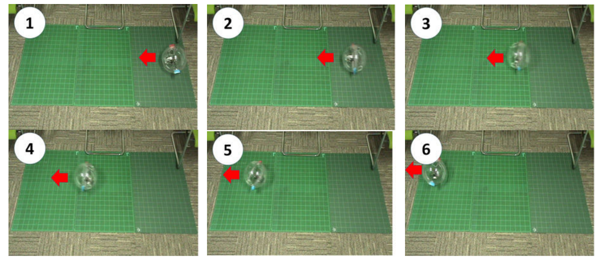

Fig. 14. Photographs of translational motion taken at 0.5 s intervals for motor speed of 33.4 rpm

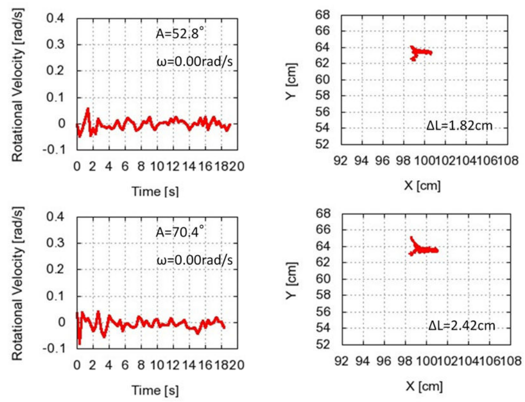

Fig. 15. Rotational velocity (left) and trajectory (right) of robot without attachments for A=52.8° and 70.4°

robot are shown in Fig. 15 (right). ΔL is the moving distance from the default position to the last position.

With the attachments, the average rotational velocities ω were positive, as shown in Figs. 16 and 17 (left). That is, a robot with attachments can rotate. Moreover, the stronger the vibration, the higher the rotational speed. This relationship was not affected by the value of ΔI. The average rotational velocity ω was 0.21 rad/s for ΔI = 20° and A = 70.4. This means that the robot can perform a 360° roll in approximately 30 s, which means that it can change its orientation to an arbitrary one within approximately 30 s. Photographs taken during the experiment are shown in Fig. 18.

C. Discussion

Our experiments using a prototype robot showed that a 1-DOF spherical mobile rbot can generate 2-DOF motions (translational and rotational) by switching the motor driving modes. The rotational motion generated was similar to that in the simulation. The results showed that the rotational velocity depends on a combination of parameters. Consequently, the translational and rotational motions are simply the results of location control and orientation control.

V. Conclusion

Our spherical mobile robot with only one motor generate both translational and rotational motion using only one input. This is achieved by attaching vinyl strips to the sphere.

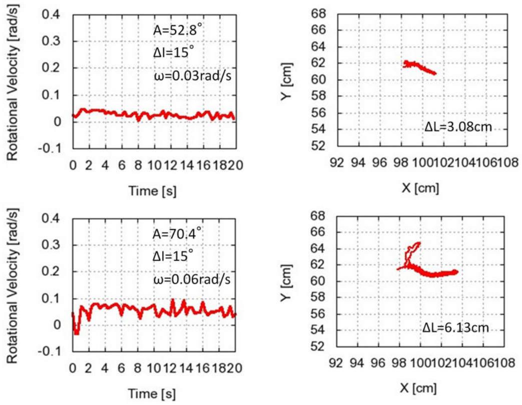

Fig. 16. Rotational velocity (left) and trajectory (right) of robot for ΔI =15° and A=52.8° and 70.4°

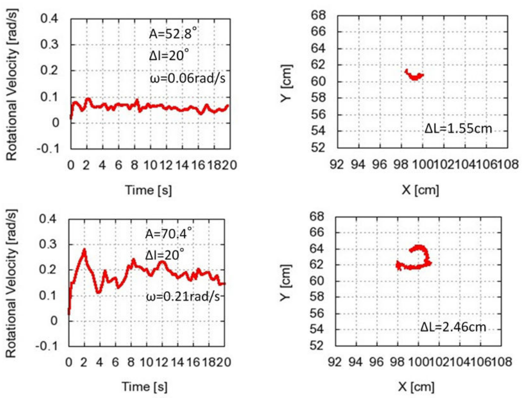

Fig. 17. Rotational velocity (left) and trajectory (right) of robot for ΔI =20° and A=52.8° and 70.4°

Placing the motor in constant velocity mode generates translational motion due to center of gravity movement. Placing the motor in vibration mode generates rotational motion along a specified closed path for the contact point due to interaction between the surface attachments and the plane. Simulation demonstrated that the surface attachments are needed for a robot to generate rotational motion. Prototype testing demonstrate that both motions can be generated using only one motor.

This research, showed that the number of actuators in a spherical mobile robot can be reduced by simplifying the orientation control by modifying the body design. We are planning to develop a distributed autonomous system for space exploration using multiple robots.

VI. Acknowledgments

Special thanks to A.Kamimura who offered the actuator and its software, and to R.Tadakuma for his valuable comments about the concept of this research.

This research was supported by JST CREST.

References

[1] S. Shimoda, Y. Nakamura, and Y. Watanabe.: "Development of a Micro-Gravity Rover using Internal Magnetic Levitation," In Space '99 International Space Utilization Symposium, pp. 173-179, 1999.

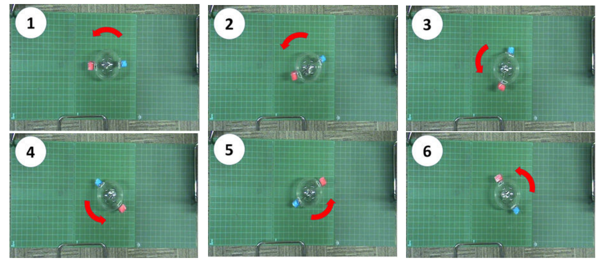

Fig. 18. Photographs of rotational motion taken at 1.0 s intervals for ΔI = 20°, A = 88.0°, and f =6.4 Hz

[2] A. Halme, T. Schonberg, and Y. Wang: "Motion Control of a Spherical Mobile Robot," Proceedings of Advanced Motion Control, pp. 259-264, 1996.

[3] A. Bicchi, A. Balluchi, D. Prattichizzo, and A. Gorelli,"Introducing the "SPHERICLE": An Experimental Testbed for Research and Teaching in Nonholonomy," Proceedings of IEEE Int. Conf. on Robotics and Automation, vol. 3, pp. 2620-2625, 1997.

[4] J. Alves and J. Dias, "Design and Control of a Spherical Mobile Robot," Proceedings of the IMechE Part 1: Journal of System Control Engineering, Vol. 217, pp. 457-467, 2003.

[5] B. Chemel and H. Schempf: "Cyclops: Miniature robotic reconnaissance system," IEEE Int. Conf. on Robotics and Automation(ICRA'99), Vol. 3, pp. 2298-2302, 1999.

[6] S. Bhattacharya and S. Agrawal, "Design, Experiments and Motion Planning of a Spherical Rolling Robot," Proceedings of 2000 IEEE Int. Conf. on Robotics and Automation(ICRA2000), Vol. 2, pp. 1207-1212, 2000.

[7] T. Otani, T. Urakubo, S. Maekawa, H. Tamaki, and Y. Tada, "Position and Attitude Control of a Spherical Rolling Robot Equipped with a Gyro," Proceedings of 9th IEEE International Workshop on Advanced Motion Control, pp. 416-421, 2006.

[8] Q. Zhan, T. Zhou, M. Chen, and S. Cai, "Dynamic Trajectory Planning of a Spherical Mobile Robot," Proceedings of IEEE Conf. on Robotics, Automation and Mechatronics, pp. 1-6, 2006.

[9] A. Nakashima, K. Nagase, and Y. Hayakawa, "Control of Contact Points of Two-Fingered Robot Hand with Manipulating an Object," Proceedings of ICASE/SICE, pp. 120-125, 2002.

[10] D.J.Montana, "The Kinematics of Contact and Grasp," Int. Journal of Robotics Research, Vol. 7, No. 3, pp.17-32, 1988.