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

Development of a Ball Drive Unit using Partially Sliding Rollers
— An alternative mechanism for semi-omnidirectional motion —

Masaaki Kumagai

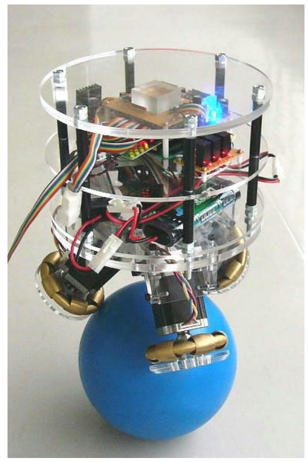
Abstract— **There are several works on mobile robots that employed a single ball as their wheel. Each of them used a kind of inverted pendulum control and a specific ball drive mechanism. The requirement for the mechanism is to roll the ball in two orthogonal directions for maintaining robot attitude and traveling on a two dimensional surface. In addition to these rolling motions, rotation around a vertical axis is useful for turning the robot body. The author developed robots that used wheels for omnidirectional motion of the ball in previous works. However, the wheel was complex to produce in large quantities and expensive. The purpose of the work described in this paper is to develop a new simpler mechanism with drivability almost comparable to previous driving mechanism but lower in cost. The idea of a roller with semi-passive features and a ball drive mechanism are described as well as experimental results using a robot with the proposed mechanism.**

I. INTRODUCTION

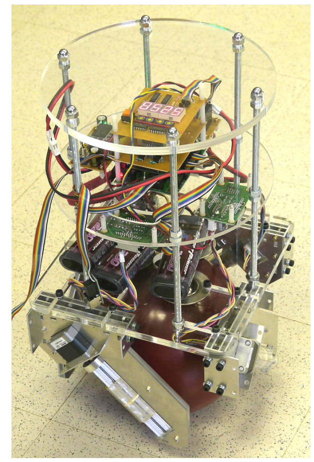
There are several previous efforts on robots using a single ball and balancing control to maintain their stability based on a different motivation. The famous *ballbot* project by Hollis et al.[1], [2] focuses attention on realizing a dynamically stable skinny robot with enough height that can be of service to a human. It used an inverse mouse-ball drive mechanism to drive the ball. Another project of *B.B.Rider*[3] had the purpose to develop an omnidirectional wheel-chair-like vehicle. They tried to use an omnidirectional mechanism to drive a ball, and theoretically it can not only travel in any direction but can also turn around a vertical axis. The author and colleague also developed a series of robots that balanced on their balls[4], [5], [6] as shown in Fig. 1(a), recently named *BallIP*. Though the first motivation was just for amusement to develop such kind of robot, the robot was refined so that it could carry some loads on top, and experiments with three robots were carried out. The robot employed three wheels mainly used for omnidirectional mobile robots invented by Asama et al.[7], [8].

The attitude controls of all robots are not so different. They feedback lean angle and its angular velocity as inputs to the system while there is a difference that the *ballbot* and *B.B.Rider* used torque commands to the ball as system input whereas *BallIP* used acceleration of the ball. However, a large difference can be found on their driving mechanisms. The *ballbot* used two orthogonal pairs of two parallel rollers to drive its ball. Therefore, it can only drive the ball in a traveling direction, not around a vertical axis while the mechanism is quite simpler than others. Because of simplicity,

Masaaki Kumagai is with Faculty of Engineering, Tohoku Gakuin University, Tagajo 985-8537 Japan, and is a visiting prof. at The Robotics Institute, Carnegie Mellon University, Pittsburgh, PA 15213, USA
kumagai@tjcc.tohoku-gakuin.ac.jp



(a) *BallIP*(–W), previously developed[5], [6].

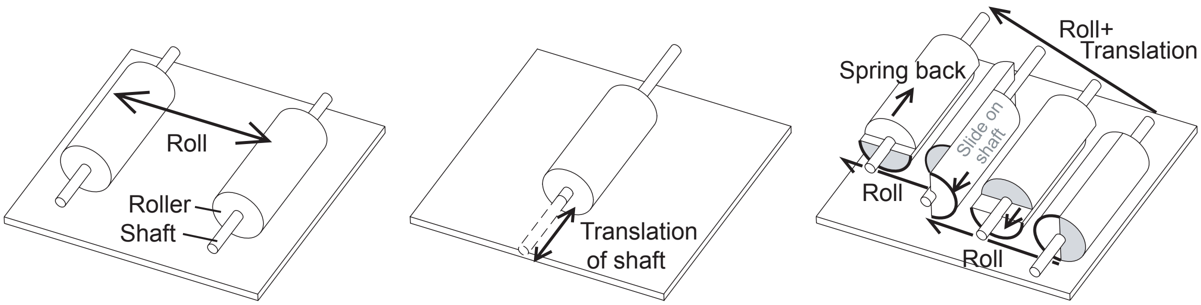


(b) Proposed one in this paper with PSR mechanism.

Fig. 1. Robots balanced on single balls.

there are robots with a similar mechanism[9] even developed using LEGO blocks. It is enough for many applications although it requires an additional yaw drive mechanism[2] if it wants to turn. *B.B.Rider* and *BallIP* used omnidirectional drive mechanisms previously used in omnidirectional mobile robots, which also enable turning motions. However, the driving mechanisms become rather complex. One wheel[7] used for *BallIP* consisted of more than 120 parts including screws and bearings, and some of the parts had strange shapes that were not easy to manufacture, which required more cost to materialize (more than $150 USD only for materials and bearings). Therefore, the author recognized a necessity to develop an alternative mechanism for the ball drive. The new mechanism must be less expensive, easy to manufacture and have a similar function to the original one of *BallIP*. Other candidates for driving the ball are direct spherical actuators[10], [11], [12]. However, none of those types have achieved enough capability for our purpose, and a mechanical drive is discussed in this paper. There are more works using balls as wheels of omnidirectional robot[13], [14], which distributed active degrees of freedom to sets of a ball and roller(s) to solve interference between drives. They are useful for multiply-supported robots though the goal of this paper is to achieve the robot with only one ball.

This paper describes a simple mechanism with a comparable function developed for this need. Similarity is a key point of this paper, as illustrated by the similar robots shown in Fig. 1. A new mechanism named *Partially Sliding Roller* was introduced as a roller drive with semi-passive characteristics.



(a) Rolling motion (b) Slide motion (c) Concept of PSR

Fig. 3. Motion of a roller mechanism which slides along a shaft.

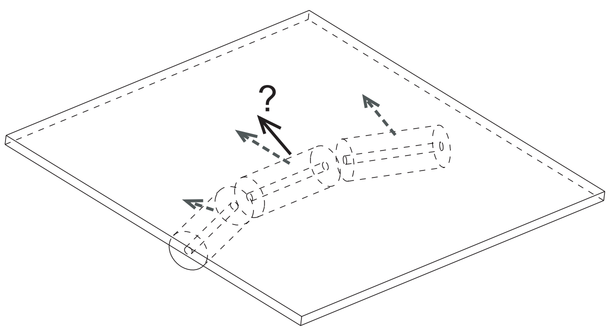


Fig. 2. Driving a plate using three rollers whose roll axes are in different directions.

With this mechanism, the driving system became simpler and less expensive with no significant degradation of the stability. This special roller mechanism may have a place between the complex mechanism of the omnidirectional type drive and the simple *ballbot* drive. The idea of the roller is described first, followed by the ball drive mechanism using the roller, a modified type of *BallIP*, Fig. 1(b), and finally experimental results are presented. To distinguish between the previous robot and the one proposed in this paper, the previous robot *BallIP* is referred as BallIP–W(wheel) hereafter.

II. PARTIALLY SLIDING ROLLER

The requirement for a mechanism that drives a ball for the robot is a kind of two-dimensional omnidirectional drive. The motion of the ball is three dimensional but each driver faces the ball surface, which can be assumed locally as having only two dimensions. Therefore we first discuss the driving mechanism with a two-dimensional model in this section and then apply it to the three-dimensional ball drive. A mechanism named *Partially Sliding Roller* (PSR) is introduced in this section.

A. *Concept of PSR*

A situation where a plate is driven by several rollers as shown in Fig. 2 is assumed. The rotations of the rollers are controlled independently so that they can drive the plate contacting them in two-dimensional motion. The motion of the plate is of course governed by the arrangement of rollers and dynamic properties such as friction between the rollers and the plate. It is difficult to control the motion of the plate without a feedback control based on a position measurement of the plate when we use ordinary rollers. The motion of the plate should be described by equation of motions whose horizontal force input is unpredictable frictional forces, whereas it will simply coincide with motion of the roller(s) if the plate is driven by one roller (or identical rollers whose axes are in same direction). The problem is that the driving motion of one roller is prevented by friction with the other rollers. These frictional forces depend on the surface condition and the normal forces between the rollers and the plate, among other effects. It is especially difficult to estimate the normal forces in the over constrained case because small distortions of the plate can effect these forces. Therefore it is difficult to control the two dimensional motion of the plate using ordinary rollers. This problem is due to interference by the other rollers, which can be solved if each roller is passive to motions of the other rollers. As is the case for many wheels for omnidirectional mobile robots, passivity along the rotating axis, i.e. perpendicular to the driving direction, permits two-dimensional motion.

One possible idea to add passivity to the roller is to make it possible for the roller to slide along the roller shaft as shown in Fig. 3(a,b). These figures depict the shaft as a thin plain cylinder though a splined shaft is one example of a mechanism that can transmit rotation of the shaft to the roller while the roller and the shaft slide over each other. Because we are concerned only with the relative motion between the plate and the drive mechanism, i.e. the shaft, we can consider the plate to be fixed and only motion of the shaft will be considered hereafter in this section.

The shaft can move in the direction perpendicular to its axis as shown in Fig. 3(a). This is the ordinary active motion of the roller. The shaft can also move along its axis as shown in (b) with the idea of a passive slide. However, the sliding motion will be limited because it is impossible to design a mechanism that can slide infinitely along a shaft. The practical design of the mechanism will limit its motion to a small amount of displacement.

The idea of the PSR is introduced to solve this limitation to some extent. A conceptual design of the PSR is illustrated in Fig. 3(c). The PSR consists of a shaft and several partial

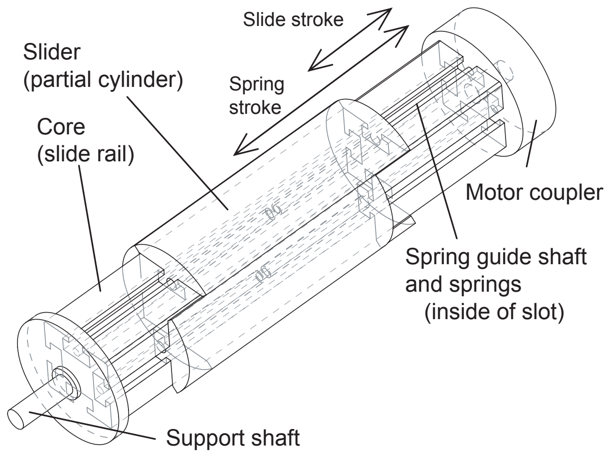


Fig. 4. A practical design of PSR used for the robot.

cylindrical faces of a roller sliding on the shaft that make up a whole cylinder. Two semicircular cylindrical parts (called sliders) are used in the figure. As with the normal roller, the shaft of the PSR can move from right to left while rolling over the plate. When the shaft moves along the axis, the slider that is contacting the plate does not slip on the plate but slides along the shaft (denoted as small arrow). The other slider remains in the middle of the shaft because it is pushed into the center by weak springs from either side. When the PSR rolls to the boundary of the contacting slider, the duty of that slider ends and the next slider begins to contact (third PSR from right). Then the new slider starts rolling on the plate and the released slider will spring back to the middle of the shaft. The translational motion of the shaft can be continued on the new slider. Therefore, the slider's cylindrical face does not slide (slip) on the plate during contact and the shaft can also move along the axis continuously by switching sliders. The shaft can move not only in the rolling direction but also can move in a skewed direction though the geometrical parameters of the PSR limit the angle of direction.

A practical design of the PSR is shown in Fig. 4, which is used for the robot described later. The cylindrical surface is divided into four sliders, i.e. 90 degrees center angle. A core, corresponding to the shaft, is an aluminum frame for machine construction (Yamato aluminum frame □20 × 120 mm) and the slider is made of an acrylic plastic (62 mm in length, 15 mm in radius), which has the cross-section fit to the slot of the frame. Two weak springs are inserted in the slot on both sides of the slider with a guide shaft. The slider can move on the full length of the rail because the spring will be pushed into a hole in the slider (one end of the spring is almost in the center of the slider).

B. Design Parameter of PSR

The driving characteristic of the PSR is limited by its geometric parameters. As shown in Fig. 5, there are four major parameters: the diameter of the roller D, the number of sliders N, the length of each slider (half) l_s, and the range of translational motion of the slider l_t. For simplicity,

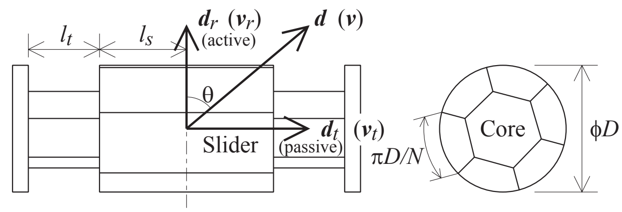


Fig. 5. Design parameter of PSR ($N = 6$).

we assume there is no slip between the PSR and an object driven by it, and the motion of direction of the object is almost constant.

The displacement of the driven object $\boldsymbol{d}$ can be decomposed into two components, $\boldsymbol{d}_r$ along the roller driving direction and $\boldsymbol{d}_t$ along the sliding direction (along the PSR axis). The former is the active motion and the latter is the passive motion. While the object is in contact with only one specific slider, the PSR will rotate $2\pi/N$ radians and the object will move $|\boldsymbol{d}_r| = \pi D/N$ in the active direction. The slider must slide $|\boldsymbol{d}_t| = (\pi D/N)|\tan\theta|$ simultaneously with the object if the direction of motion of the object is θ as in the figure.

The design condition for two parameters l_s and l_t are simple:

$$l_t > (\pi D/N)|\tan\theta|, \quad l_s > (\pi D/N)|\tan\theta| \qquad (1)$$

The range of motion must be long enough to slide. The length of the slider should be longer in the case that the object is small (narrow) and it is in contact with the central region of the PSR, for example the ball drive mechanism discussed later. If the object is large enough, the latter condition is not necessary. Under these conditions, the object switches between contacting sliders and can continue motion to the direction θ. The PSR cannot be used for a completely omnidirectional purpose because of this requirement. It would require an infinite range of the slide if we want make $\theta = \pi/2$. Therefore, it is semi-omnidirectional.

From another point of view, if we want to drive the target object in the θ direction with velocity of $\boldsymbol{v}$, the circumferential speed of the roller should be controlled to $v_r = |\boldsymbol{v}|\cos\theta$. With the sliding speed $v_t = |\boldsymbol{v}|\sin\theta$ which will be provided by other PSRs, the relative speed between the PSR and the object becomes $\boldsymbol{v}$. The calculation of the velocity of the PSRs is very easy in the case shown in Fig. 2. The relative angle between the object driving direction and each PSR is calculated first, and then the circumferential speed, i.e. the angular velocity of the core is derived. By using the PSRs, the unpredictable motion with slip turns into definite motion.

The advantages of the PSR are its continuous behavior to the target object driven by the PSRs and the simple structure. There are many types of wheels for the omnidirectional mobile robots although many of the wheels have incomplete continuous motion with partially continuous trajectories. The latter means it is easy to manufacture with low cost. In addition, the PSR 'roller' has a smaller diameter than those of ‘wheels,’ which can make mechanisms thinner (of course, it makes the mechanism longer than those using wheels).

There is a disadvantage with the PSR. It has the limitation in the direction of relative motion as in (1). It requires a longer range of the slide for larger θ. Improvements for this problem are to have a smaller diameter for the roller and a larger number of sliders, which make $(\pi D/N)$ smaller.

Despite the disadvantage, the PSR can be used for the semi-omnidirectional object drive. The usage of the PSR for the ball drive mechanism is described next.

III. BALL DRIVE MECHANISM USING PSR

A. Driving a ball in 3 DOF using PSR

The ball drive mechanism for the robot is designed as shown in Fig. 6. The arrangement and the basic motion principle of this mechanism is similar to the ‘inverse mouse-ball drive mechanism’ (hereafter IMBD) of *ballbot*[1] except that the robot described in this paper uses the PSRs and the PSRs are arranged at a tilt. The largest difference is that the IMBD only drives the ball around the x and y axes (2 DOF), while this mechanism can also drive around the z axis (3 DOF), which enables the robot to rotate it around a vertical axis without other mechanisms.

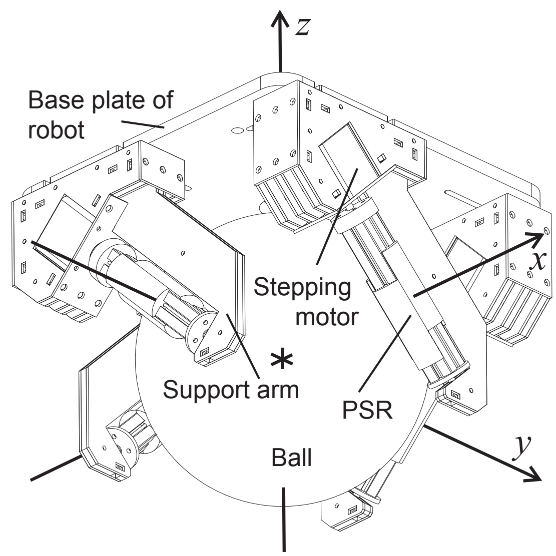
The driving principle of this mechanism around the x and y axes are the same as the IMBD. For example, the ball will rotate around the y axis when PSR0 and PSR2 in Fig. 6(c) are driven in the opposite directions and the same speed by the motors. Note that the sliders of each PSR slide along the relative motion between that PSR and the ball because of the tilt arrangement of that PSR. In this motion around the y axis, the ball slips on PSR1 and PSR3 as does the IMBD. As an additional feature of this mechanism, the ball can be rotated around the z axis by rotating all PSRs in the same direction with the same speed.

The details of the calculation are described below. Note that the restriction of the PSR mentioned above of course limits the drivability of the ball. The motion around the x and y axes can be combined without restriction because they are independent of each other. But motion around the z axis and other axes share the range of motion of the sliders, which restricts combined motion (in some unusual combined cases, it requires infinite slides). However, this restriction is not serious for the application of our robot because the robot usually uses the x and y motion for the balancing motion and the traveling motion, and the z rotation is used only in a particular motion for heading the robot in any direction (the robot is omnidirectional without z rotation).

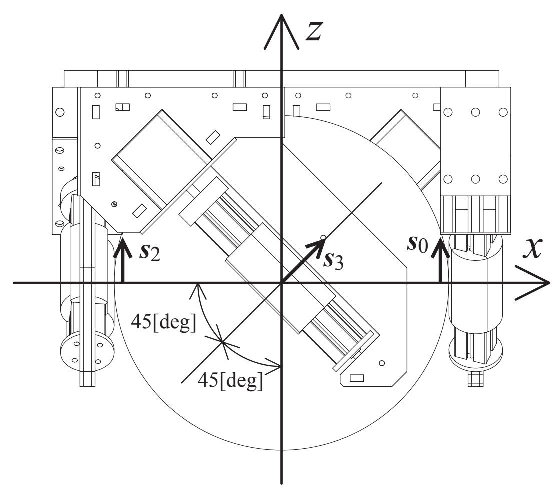
B. Calculation of rotational speed of PSRs

The calculation scheme of the rotational speed of the PSRs is almost same as that of BallIP–W[6]. Therefore the method is briefly described here.

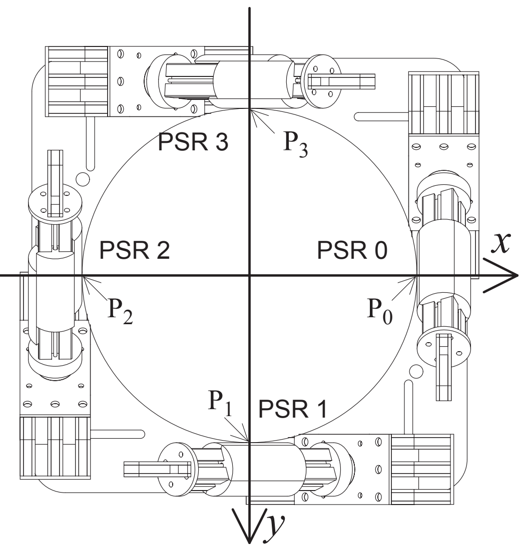
For controlling the robot, it is required to convert the desired ball angular velocity to the circumferential speed of the PSRs, i.e. the angular velocity of the motor. On the ball coordinate frame shown in Fig. 6, let the contact points between the ball and the PSRs be P_i whose position vectors



(a) Overall view



(b) Side view



(c) Bottom view

Fig. 6. Ball drive mechanism using the PSR and the definition of the mechanism axes. (Ball support, a set of three ball transfers, are omitted)

TABLE I

GEOMETRICAL PARAMETER OF THE BALL DRIVE MECHANISM.

i	$\boldsymbol{p}_i$	$\boldsymbol{s}_i$	$\boldsymbol{p_i} \times \boldsymbol{s}_i$
0	$(\ R,\ 0, 0)$	$(\ 0,\ 1/\sqrt{2}, 1/\sqrt{2})$	$(0, -R/\sqrt{2}, R/\sqrt{2})$
1	$(\ 0,\ R, 0)$	$(-1/\sqrt{2}, 0, 1/\sqrt{2})$	$(R/\sqrt{2},\ \ 0, R/\sqrt{2})$
2	$(-R, 0, 0)$	$(0, -1/\sqrt{2}, 1/\sqrt{2})$	$(0,\ \ R/\sqrt{2}, R/\sqrt{2})$
3	$(0, -R, 0)$	$(\ 1/\sqrt{2},\ 0, 1/\sqrt{2})$	$(-R/\sqrt{2}, 0, R/\sqrt{2})$

Note: R is the radius of the ball.

are $\boldsymbol{p}_i$, and let the unit vectors along the active driving direction at P_i be $\boldsymbol{s}_i$. The circumferential speed $\boldsymbol{v}_i$ of the ball at P_i which coincides with that of the PSR is obtained from the angular velocity vector of the ball $\boldsymbol{\omega}$.

$$\boldsymbol{v}_i = \boldsymbol{\omega} \times \boldsymbol{p}_i \tag{2}$$

Then the magnitude of the active component of $\boldsymbol{v}_i$ ($\boldsymbol{v}_r$ in Fig. 5) is derived.

$$\begin{aligned} \boldsymbol{v}_i &= \boldsymbol{v}_{ir} + \boldsymbol{v}_{it} && (3) \\ \boldsymbol{s}_i \cdot \boldsymbol{v}_i &= \boldsymbol{s}_i \cdot \boldsymbol{v}_{ir} + \boldsymbol{s}_i \cdot \boldsymbol{v}_{it} = v_{ir} + 0 \\ v_{ir} &= \boldsymbol{s}_i \cdot (\boldsymbol{\omega} \times \boldsymbol{p}_i) = \boldsymbol{\omega} \cdot (\boldsymbol{p}_i \times \boldsymbol{s}_i) && (4) \end{aligned}$$

The input of the calculation is $\boldsymbol{\omega} = (\omega_x, \omega_y, \omega_z)$ and the outputs are v_{ir} (scalars identical to $|\boldsymbol{v}_{ir}|$ with a sign for the direction). The vectors $\boldsymbol{p}_i, \boldsymbol{s}_i$ are constant and defined as shown in Table I from the mechanism design Fig. 6. The commands for each PSR can be derived as follows:

$$\begin{aligned} v_{0r} &= 0 - (R/\sqrt{2})\omega_y + (R/\sqrt{2})\omega_z \\ v_{1r} &= (R/\sqrt{2})\omega_x + 0 + (R/\sqrt{2})\omega_z \\ v_{2r} &= 0 + (R/\sqrt{2})\omega_y + (R/\sqrt{2})\omega_z \\ v_{3r} &= -(R/\sqrt{2})\omega_x + 0 + (R/\sqrt{2})\omega_z \quad (5) \end{aligned}$$

These equations confirm that there is no interference between ω_x and ω_y but there is with ω_z.

As shown in Fig. 6, the angle difference θ between the driving direction and the rolling direction in Fig. 5 is 45 degrees (to each of the x, y, and z axes), and the diameter of the PSR is 30 mm. The design equation (1) requires that the minimum range l_t and the length of the slider l_s are 23.6 mm. Therefore we designed the PSR used for the robot with l_s=31 mm and l_t=29 mm including a margin for the simultaneous motion of ω_x, ω_y and ω_z.

IV. A ROBOT BALANCED ON A BALL USING PSR

A. Robot hardware and brief control scheme

The ball drive developed above is used instead of the original drive with the wheels of BallIP–W to confirm the effectiveness and similarity as shown in Fig. 1(b). The other hardware such as the 16-bit micro-controller, the sensors (MEMS accelerometers and gyros), and the control equations are exactly the same as in BallIP–W[6], only the driving mechanism, the velocity conversion equations (5), and the feedback gains are different. In addition, the ball is not a rubber coated bowling ball[6] but a urethane coated ball borrowed from ballbot[1], which is more elastic. The robot body itself is also a little taller than BallIP–W while the total height including the ball is almost same (500 mm).

TABLE II

SET OF THE GAINS USED IN THE EXPERIMENT.

Gain	value and unit	internal(†)
K_A	597.4 (mm/s^2)/(deg)	2000
K_{AV}	95.6 (mm/s^2)/(deg/s)	8000
K_T	19.1 (mm/s^2)/(mm)	500
K_V	7.6 (mm/s^2)/(mm/s)	2500

†These are the internal gains used in the fixed-point control software on the robot, which were tuned roughly. The gains in the metric system are converted from these values.

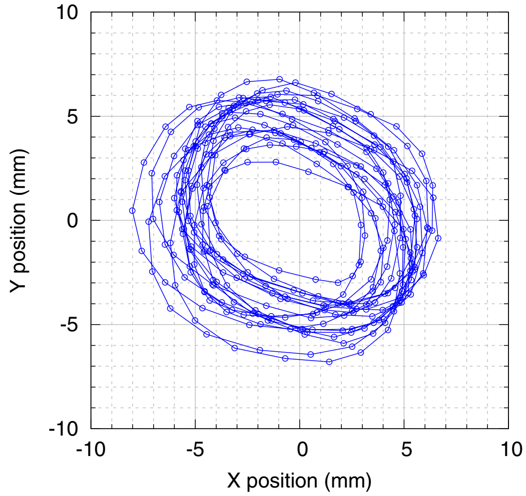
The robot is controlled using two inverted pendulum controllers around two horizontal axes separately.

$$\begin{aligned} a_x &= K_A\theta_x + K_{AV}\dot{\theta}_x + K_T(x - x_0) + K_V v_x \\ a_y &= K_A\theta_y + K_{AV}\dot{\theta}_y + K_T(y - y_0) + K_V v_y, \quad (6) \end{aligned}$$

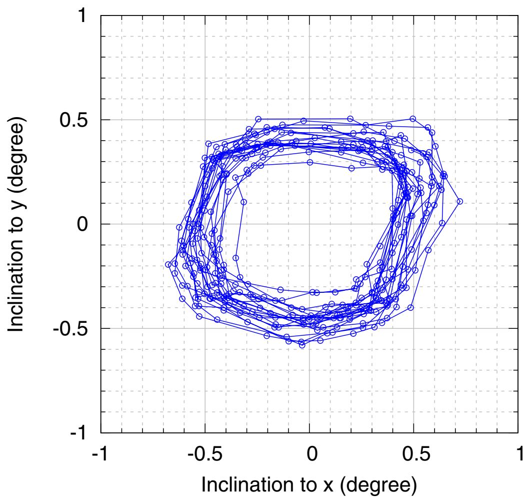
where a is the control input that commands the acceleration of the ball, θ is the inclination towards each axis (not the same θ as the PSR parameter), x and y are the traveling distances and v is the velocity of the ball. The subscripts x and y denote the related axes of the state variables, and Ks are the constant gains tuned through experiments. Actual values of the gains used in the following experiments are shown in Table II. v and x (y) were obtained by numerical integration of the accelerations a. In addition, x, y, v_x, v_y are estimated on the PSRs instead of on the world coordinate frame (e.g. $v_x = -R\omega_y, v_y = R\omega_x$). There is little difference between the motion on the floor and these values but there must be a discrepancy especially when the robot moves in a complicated path and the ball slips on the PSRs.

B. Experiments for evaluation

Experiments using the robot were carried out on a flat floor. The attached video contains the demonstration of the robot including turning motions around the vertical axis, a response to disturbances, and a traveling motion while balancing. A set of experimental results is shown in Fig. 7. It contains the position and the lean angle acquired from the robot while the robot was commanded to keep its station. The data were sampled with a 50 milliseconds interval lasting 20 seconds. Compared to the results of the latest BallIP–W[6], the range of fluctuation in position and lean angle are bigger; ±5 mm became ±8 mm and ±0.4 degrees became ±0.7 degrees. However, note that these were better than the first prototype of BallIP[4] that used a rigid ball and that the latest BallIP–W has excellent stability. The main reason should be due to the characteristics of the mechanism. The wheel driven mechanism of BallIP–W is completely passive to the other active motions of the wheels while this new mechanism has friction on the orthogonal pair of the PSRs which will cause transmission errors. The other issue is the stiffness of the ball. Other experiments done with BallIP–W showed that the ball with less stiffness caused larger vibration. The gain concerning the velocity K_V and that for



(a) Position of the robot



(b) Lean angle of the robot

Fig. 7. Experimental results while station control. The interval of the data plot is 50 milliseconds and the position is estimated from the velocity command of the motors.

the lean angular velocity K_{AV} were limited to avoid this vibration, which caused larger amplitudes in both position and inclination.

We had carried out other experiments on BallIP–W such as traveling motions on the floor at higher speeds, the passive behavior, or putting load on the top[5]. The passive characteristic and the load tolerance on the present robot were confirmed briefly and they were fine, but the traveling ability was limited to slower speeds, that was 100 mm/s in the command (600 mm/s for BallIP–W), because the stepping motors chosen have lower output and need to rotate in higher speed (due to smaller diameter) than those of the previous robot, which easily loose steps when the robot speeds up. This will require a re-design of the supporting frame of the motor and the PSR in the next production.

V. CONCLUSIONS

An alternative mechanism for driving a ball is proposed and evaluated in this paper. The purpose of this work was to make the complex mechanism of a robot balanced on a ball be much simpler to reduce costs. The mechanism has a 3 DOF driving ability, for balancing and traveling on the floor and turning around a vertical axis. For this mechanism, the idea of the partially sliding roller was introduced. The PSR can be used not only for a ball but also for a two dimensional horizontal load transfer. A set of more than one PSR can continuously move an object in an arbitrary direction within the designed sliding limit. The cost became about 1/10 of that of the omnidirectional wheel used for the previous robot and the parts become much easier to manufacture and assemble. A new practical option of mechanism for the robots with balls is added.

The possibility and the effectiveness of the proposed idea were confirmed in this paper which can be improved by future works. Applications for other purposes such as industrial systems will also be investigated.

VI. ACKNOWLEDGMENTS

The most of this work were done in the Microdynamic Systems Laboratory, The Robotics Institute, CMU. I'm grateful for the help of Professor Ralph Hollis and other people. Most of the mechanical parts were manufactured by engineers in the workshop of Tohoku Gakuin University. I also thank them for their help.

REFERENCES

[1] T.B.Lauwers, G.A.Kantor, R.L.Hollis, "A Dynamically Stable Single-Wheeled Mobile Robot with Inverse Mouse-Ball Drive," *Proc. ICRA 2006*, 2006, pp 2884–2889

[2] U.Nagarajan, M.Anish Mampetta, G.Kantor, R.Hollis, "State Transition, Balancing, Station Keeping, and Yaw Control for a Dynamically Stable Single Spherical Wheel Mobile Robot," *Proc. ICRA 2009*, 2009, pp 998–1003

[3] T.Endo, Y.Nakamura, "An Omnidirectional Vehicle on a Basketball," *Proc. ICAR'05*, 2005, pp 573–578

[4] M.Kumagai, T.Ochiai, "Development of a Robot Balancing on a Ball," *Proc. ICCAS 2008*, 2008, pp 433–438

[5] M.Kumagai, T.Ochiai, "Development of a robot balanced on a ball – Application of passive motion to transport –," *Proc. ICRA 2009*, 2009, pp 4106–4111

[6] M.Kumagai, T.Ochiai, "Development of a Robot Balanced on a Ball –First Report, Implementation of the Robot and Basic Control–," *J. of Robotics and Mechatronics*, vol.22 No.3, 2010, pp 348–355 (downloadable at `http://www.fujipress.jp/JRM/`)

[7] D.Chugo, K.Kawabata, H.Kaetsu, H.Asama, T.Mishima, "Development of Omni-directional Vehicle with Step-Climbing Ability," *Proc. ICRA 2003*, 2003, pp 3849–3854

[8] H.Asama, H.Kaetsu, I.Endo, M.Sato, "Wheel for Omnidirectional Mobile Robot," JP-patent no.3421290, 2003

[9] Search results of 'ballbot' on YouTube `http://www.youtube.com/` and Google. Not published in literature, but several ballbot-type robots can be found.

[10] K.Davey, G.Vachtsevanos, R.Powers, "The Analysis of Fields and Torque in Spherical Induction Motors," *IEEE trans. on Magnetics*, vol.MAG-23 No.1, 1987, pp 273–282

[11] G.Chirikjian, D.Stein, "Kinematic Design and Commutation of a Spherical Stepper Motor," *IEEE/ASME trans. on Mechatronics*, vol.4 No.4, 1999, pp 342–353

[12] B.Dehez, G.Galary, D.Grenier, B.Raucent, "Development of a Spherical Induction Motor With Two Degrees of Freedom," *IEEE trans. on Magnetics*, vol.42 No.8, 2006, pp 2077–2089

[13] L.Ferrière, G.Campion, B.Raucent, "ROLLMOBS, a new drive system for omnimobile robots," *Robotica*, vol.19 No.1, 2001, pp 1–9

[14] Y.C.Lee, D.V.Lee, J.J.Chung, S.A.Velinsky, "Control of a redundant, reconfigurable ball wheel drive mechanism for an omnidirectional mobile platform," *Robotica*, vol.25 No.4, 2007, pp 385–395