# An Omnidirectional Vehicle on a Basketball

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***Abstract*— This paper is about development of an omni directional vehicle on a spherical tire. The vehicle moves by rolling a spherical tire and balancing on it. We selected a basketball as a spherical tire, because basketball is made of rubber. In general, rubber tire has three features, which are durability, adaptabilities to the ground surface and force transmissivity. We think that using a basketball as a spherical tire is low-cost and advantageous. Next, we describe how to calculate torque and angular velocity, which motors generate to roll a basketball. They need for driving motors and dynamic simulations. Finally, we propose an interface to operate the vehicle. One, who rides on the vehicle, can moves to all directions by shifting one's the center of mass. A six-axis force-torque sensor senses weight shift.**

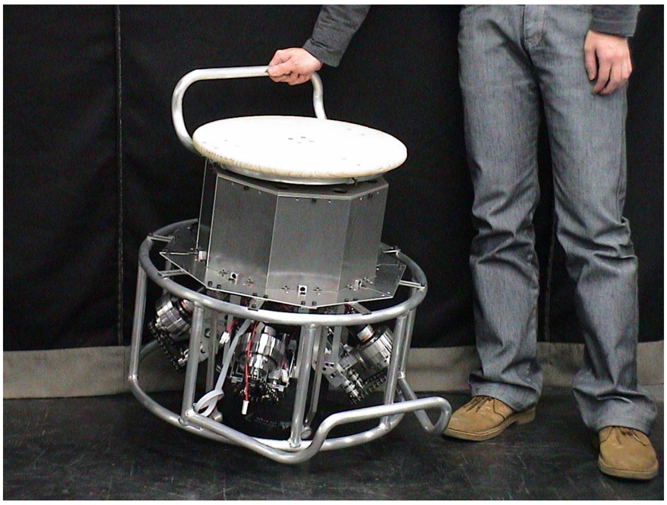

Fig. 1. Overview of ”B. B. Rider”. The robot has four force-transfer-mechanisms to roll a basketball. And its specifications are described in section two.

## I. Introduction

What are features of convenient wheeled vehicles? If we recounted all features, the number of them would be boundless. Now, we think about only three features. Three features are about being omni-directionality, adaptivity to the ground surface and easy maneuverbility. Those three features are important about vehicles, and we think only those features.

Vehicles need omni-directionality not to constrain desired paths. And they need to be robust on rough terrains to be stable. In general[9], it is difficult for wheeled mobile robots to have the two features. Mechanism of omni-directional vehicle tends to be complex. Due to the fact, use of omni-directional wheels for a personal vehicle results in rather small diameter of wheels and, therefore reduces the adaptability to unevenness of the ground surface. There are many omni-directional vehicles reported, but they haven't solved the problem in full.

There is automobile in vehicles, which is studied for the long time. What helps stability of automobiles? We think that it is rubber tires. Automobiles have them. Rubber tire has three good features[10]. First, rubber tire is durability. Second, it is adaptabilities to the ground surface. Last, it is force transmissivity. Those features are useful for omni-directional vehicles.

”Segway”[5] is known for its simple maneuverbitily. One, who rides on Segway, moves it by shifting one's the center of mass. The simple operations are useful for everyone. And we adopted the operations for the vehicle, which we developed. Specifically, a six-axis force-torque sensor, which is mounted in the vehicle, senses shifting one's the center of mass. Then, data sensed by the sensor are used as desired directions.

There are many omni-directional vehicles.

”Shakey”[7] was the omni-directional robot with nonholonomic driving mechanism developed in The SRI (Stanford Research Institute) in 1966. It had two driving wheels and two steering wheels. ”Swedish wheel”[8] was developed for holonomic omni-directional wheel. Ilon invented it in 1973. It has wheels, which transmit no force. Its idea has been used in various omni-directional vehicles. It's been improved by many researchers' ideas. La[13] and Bradbury[14] independently a unique omni directional vehicle in 1980. Those vehicles can move under holonomic constrains. Their ideas are used in many vehicles. Furthermore, Killough et.al[11] proposed ”orthogonal wheel”, which we use in our robot, too. They designed an omni-directional vehicle adapting orthogonal wheels.

Muir et.al[2] showed a kinematics model of an omni-directional wheeled mobile robot ”Uranus”. They calculated the robot position in real-time. Damoto et.al[1] developed the omni-directional vehicle ”VutonII” using four ”Omni-disc”. ”Omni-disc” is a disc, which rotates eccentric and has eight casters. Only one caster in one disc contacts with ground to transmit force. Four casters contact with ground in usual. Therefore, that robot can move to all directions. Wada et.al[6] designed and developed the variable footprint vehicle with ball wheels. Their vehicle can move to all directions and climb slopes. Holmberg et.al[12] developed a wheeled holonomic robot for mobile manipulation tasks. The robot has casters,

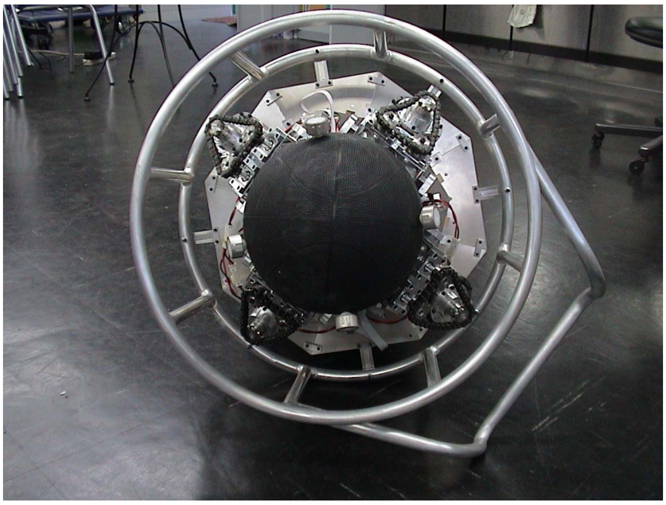

Fig. 2. A downside of ”B. B. Rider”. There is a basketball in the center of the robot.

which can change each direction of free rotation.

Omni-directional vehicles are useful for various environments. For instance, they are used in medical, transport, amusement and remote control. Therefore, many researchers worked on their development. To develop available vehicles is very important.

Our goal is to develop a small-size omni-directional vehicle for personal mobility. It would be useful for many people.

## II. Specifications of ”B. B. Rider”

### A. Devices built-in ”B. B. Rider”

In this section, we describe our robot that we named ”B. B. Rider” (Basketball Rider). We named our robot after riding on a basketball.

Fig.1 and Fig.2 show overview and downside-view of ”B. B. Rider”. Fig.3 shows the robot's side view diagram. Fig.4 shows PC structure in the robot. TableI shows specifications of the robot. And tableII shows control PC's specifications.

The seat, which is mounted on our robot, is made of tree. A human, who rides on the robot, can sit on it.

There is a force torque sensor mounted under the seat. It is to sense forces and torques, when one riding on the robot shifts the center of mass. If he/she wants to go somewhere, he/she just shifts his/her weight to a direction desired. Therefore, the robot has no levers or other devices to operate. The robot moves while behaving like an inverted pendulum.

In Fig.1 and Fig.2, there is a frame to protect against objects around the robot. One, who rides on our robot, can put on it his/her feet. Its material is aluminum.

Our robot has a PC for controlling it. The PC consists of a CPU board, a back plane board and three extended boards.

There are four force-transfer-mechanisms to drive a basketball. They have a motor and an encoder, respectively. The force-transfer-mechanism is described in next section.

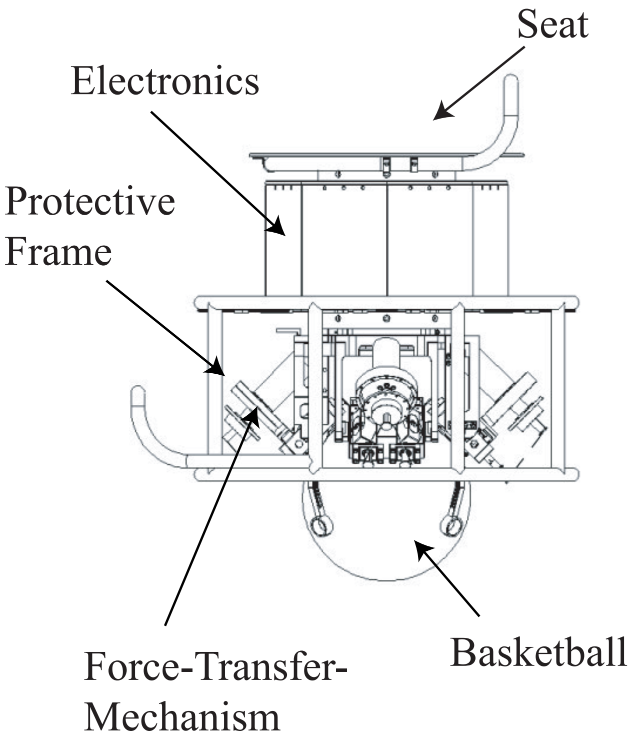


Fig. 3. A sideview diagram of ”B. B. Rider”

| | |
|---|---|
| Height | 0.63 [ $m$ ] |
| Width | 0.57 [ $m$ ] |
| Weight | 25 [ $kg$ ] |
| Basketball's Diameter | 0.245 [ $m$ ] |
| Basketball's Inner Pressure | 500-600 [ $Pa$ ] |
| Basketball's Weight | 0.5 [ $kg$ ] |
| DC Motor's Output | 150 [ $W$ ] |
| Gear Ratio (Harmonic Drive Gear) | 100 |
| Maximum Payload | 75 [ $kg$ ] |
| Rotary Encorder | 4 |
| Force Torque Sensor | 1 |
| Gyro | 1 |
| Battery | 16 [ $V$ ], 6 [ $Ah$ ] |

TABLE I
SPECIFICATIONS OF ”B. B. RIDER”

A gyro, which is mounted in our robot, can measure the robot's orientation. And its data are used for controlling the robot.

Our robot has two batteries, which are mounted with series. But we can select both batteries and outer power supplies.

Structural members' materials are made from extra super duralumin, aluminum and magnesium alloy. We used extra super duralumin at parts, which need stiffness. And we used aluminum and magnesium alloy at other parts, which don't need stiffness, through considering price.

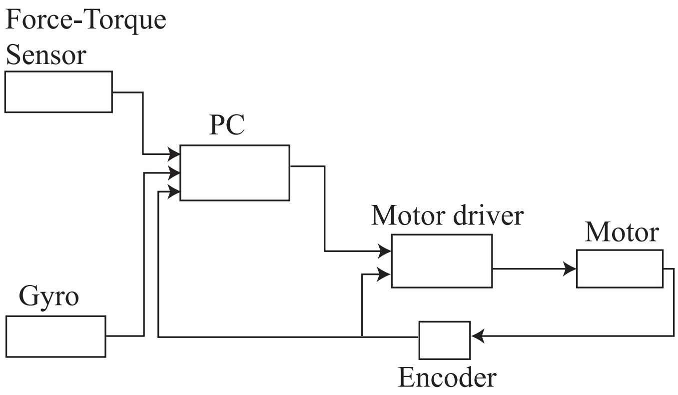


Fig. 4. A diagram of structure about PC and sensors

| | |
|---|---|
| CPU Clock | Pentium4 2.4 [ $GHz$ ] |
| Memory Size | 512 [ $MB$ ] |
| OS | Windows 2000 |
| Extended Serial Interface Board | 1 |
| Force Torque Sensor Board | 1 |
| AD Board | 1 |

TABLE II

CONTROL COMPUTER'S SPECIFICATIONS

### *B. A basketball built-in "B. B. Rider"*

In this section, we describe why we selected a basketball as a spherical tire.

A basketball, which our robot has, isn't particular kind of stuff. It is commercially available and cheap price. We can obtain it anywhere.

Why do we use a basketball? There is much stuff, which can regard as a spherical tire (volleyball, dodge ball, soccer ball and so on). We have some reasons about it.

First, basketball is made of rubber. Rubber tire's features are shown by the reference[10]. Second, we hope that components of a robot are as few as possible. Then, we think up a spherical tire, which is made of rubber. Basketball satisfies those requests, moderately. Therefore, we propose using a basketball as a spherical tire.

We think that a basketball is better one of the selections for our robot. To use a basketball is one of unique points in our research.

There might be ideas that we had better reduce costs of other devices. But it is too difficult to reduce ones of electronics, in general. Electronics is defined by objects, which robots need. Therefore, to reduce costs of electronics isn't a realistic way. If we selected the way, our robot's cost would be very high price. And we hope that design and structure of devices are simple. Therefore, we selected a basketball.

## III. A MECHANISM OF FORCE TRANSMISSION

### *A. Structure of force transmission*

In this section, we describe a mechanism of transmitting force to a basketball as a spherical tire.

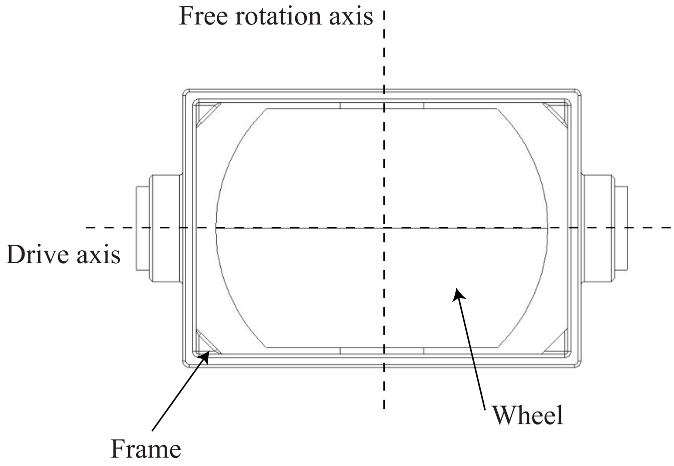


Fig. 5. A frame and a wheel in a force-transfer-mechanism

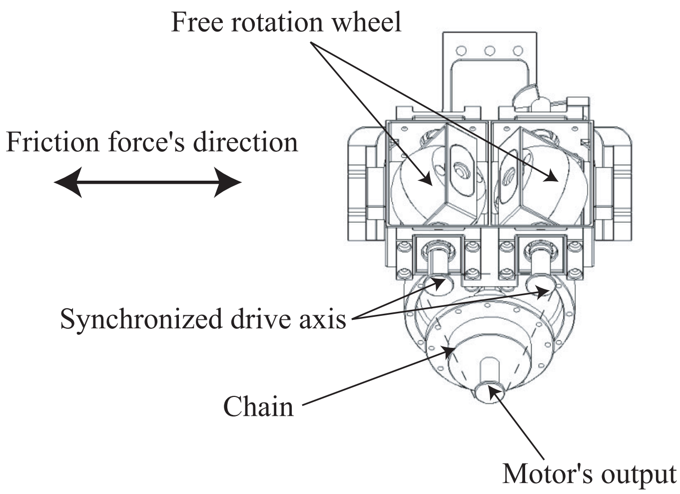


Fig. 6. A downview of a force-transfer-mechanism

We show a force-transfer-mechanism, which we developed, in Fig.5 and 6. However, forces are friction forces between wheels and a basketball. In Fig.5, a drive axis and a free rotation axis are shown. A drive axis is to transmit force on a basketball, and a free rotation axis isn't to transmit force on it. Two axes are orthogonal. And a wheel is sliced on both sides.

In Fig.6, two wheels are shown. A DC-motor drives two frames, which have a drive axis, respectively. Then, a chain synchronizes two frames and a DC-motor. And wheels, which frames have, contact on a basketball, either-or or both. It's no problem that wheels contact both. Since, wheels are synchronized, and they transmit the same forces and velocities. We don't need to know which wheels contact. This useful feature is used in calculations of motors' torques and angler velocities. Those methods are described in next section.

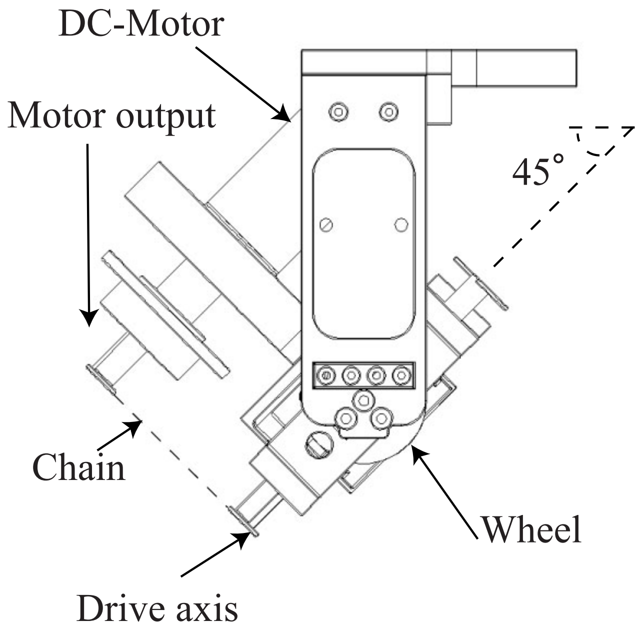


Fig. 7. A leftside diagram of a force-transfer-mechanism

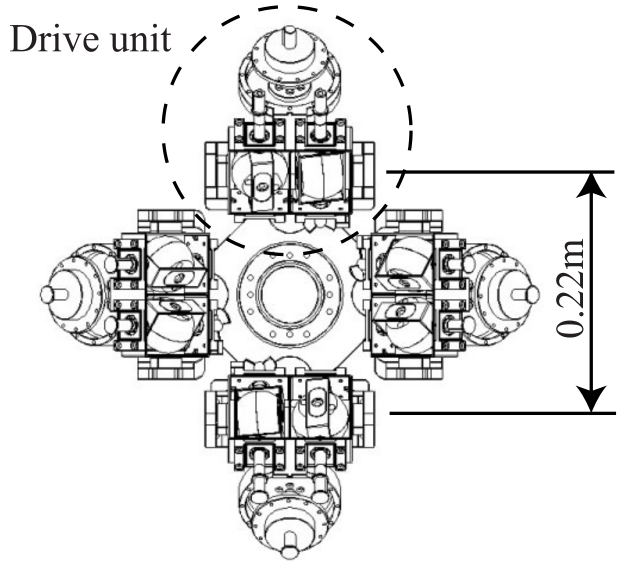


Fig. 8. An alignment diagram of force-transfer-mechanisms

In Fig.8, an alignment of drive units is shown. Drive units are aligned at even intervals. And each drive unit is attached at forty-five degrees from a vertical direction, in Fig.7. Since, that is to contact a basketball. In summary, the basketball has four independent drive axes.

Therefore, a basketball as a spherical tire can make the robot moved to all directions with holonomic constrains.

### *B. How to calculate angular velocities and torque to drive a basketball with four omnidirectional wheels*

In this section, we describe how to calculate velocities and torque that motors generate on a basketball.

In Fig.9, we show that a relationship of a wheel and a basketball for explaining the calculation. Variables, which we use, are defined as follows:

- $\omega_i$ is a wheel's angular velocity (i.e. a angular velocity generated by a drive axis and a free rotation axis).
- $r_i$ is a position vector of the wheel.
- $\omega_b$ is a basketball's angular velocity.
- $r_b$ is a position vector of the basketball.
- $e_i$ is a velocity's unit vector, which is generated by the wheel and the basketball.

The vector is orthogonal to $\omega_i$ and $r_i$. Subscript $i$ is the wheel's number for each drive unit. And wheels and a basketball don't slip. Then, equations of relationships about the velocity, which is generated by contact of the wheel and the basketball, are given by:

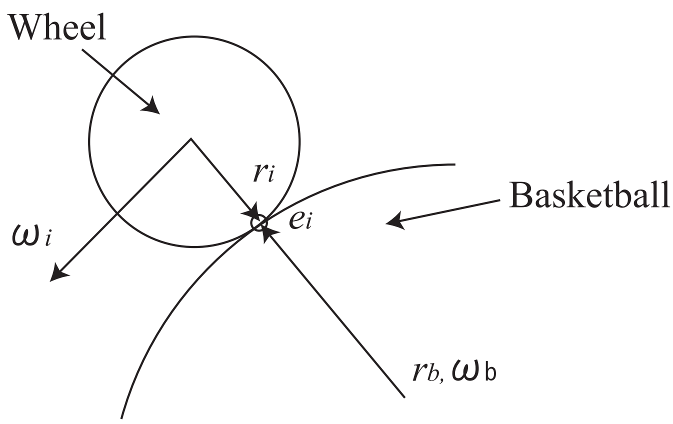


Fig. 9. A diagram of a relationship about a wheel and a basketball

$$e_i(\omega_i \times r_i) = e_i(\omega_b \times r_b) \quad (1)$$

$$\sum_{i=1}^{4} e_i e_i(\omega_i \times r_i) = \omega_b \times r_b \quad (2)$$

$$\sum_{i=1}^{4} e_i \omega_i (r_i \times e_i) = \omega_b \times r_b \quad (3)$$

$$\sum_{i=1}^{4} e_i \omega_i r_i = \omega_b \times r_b \quad (4)$$

Here, "$\times$" is outer product. Eq.1 is about a velocity that is generated by a wheel and a basketball. Then, a free rotation axis doesn't generate a velocity on the basketball. And both sides of this equation are scalar. Eq.2 is about velocities that are generated by wheels and the basketball. Since there are four force-transfer-mechanisms, both sides are summed up. And both sides of this equation are vector. Eq.3 is about changing Eq.2 by using scalar triple product. And each vector is orthogonal, then we obtain a relationship as follows:

$$\omega_i(r_i \times e_i) = \omega_i r_i \tag{5}$$

By putting together, we obtained Eq.4.

Then, rewriting Eq4 by matrixes, an equation is given by:

$$\begin{bmatrix} e_{1x} & \cdots & e_{4x} \\ e_{1y} & \cdots & e_{4y} \\ e_{1z} & \cdots & e_{4z} \end{bmatrix} \begin{bmatrix} \omega_1 r_1 \\ \vdots \\ \omega_4 r_4 \end{bmatrix} = \omega_b \times r_b \tag{6}$$

Here, $e_{ix}, e_{iy}, e_{iz}$ are elements of $e_i$ in three-dimension.

We need motors' angular velocities. And using a pseudo inverse matrix in Eq.6, an equation is given by:

$$\begin{bmatrix} \omega_1 r_1 \\ \vdots \\ \omega_4 r_4 \end{bmatrix} = \begin{bmatrix} e_{1x} & \cdots & e_{4x} \\ e_{1y} & \cdots & e_{4y} \\ e_{1z} & \cdots & e_{4z} \end{bmatrix}^{\dagger} \omega_b \times r_b \tag{7}$$

In case of our robot, wheels are designed as the same radius. Then, $r_1, r_2, r_3, r_4$ are scalar and we obtain a relationship as follows:

$$r_1 = r_2 = r_3 = r_4 = r_w \tag{8}$$

Here, $r_w$ is a wheel's radius, which we designed in our robot. Therefore, an equation to calculate motors' angular velocities is given by:

$$\begin{bmatrix} \omega_1 \\ \vdots \\ \omega_4 \end{bmatrix} = \begin{bmatrix} e_{1x} & \cdots & e_{4x} \\ e_{1y} & \cdots & e_{4y} \\ e_{1z} & \cdots & e_{4z} \end{bmatrix}^{\dagger} \omega_b \times \frac{r_b}{r_w} \tag{9}$$

Finally, we obtained Eq.9 to calculate motors' angular velocities. And we can command desired trajectories to motors. This equation is important about controlling our robot to roll the basketball.

We can think about equations in the way of the same kind. We explain how to calculate torque, which are generated by motors, to drive a basketball. Then, we obtain equations as follows:

$$e_i \frac{\tau_i}{r_i} = e_i \frac{\tau_b}{r_b} \tag{10}$$

$$\sum_{i=1}^{4} e_i e_i \frac{\tau_i}{r_i} = \frac{\tau_b}{r_b} \tag{11}$$

$$\sum_{i=1}^{4} e_i \frac{\tau_i}{r_i} = \frac{\tau_b}{r_b} \tag{12}$$

We think about force on a basketball by generated motors. And force, which is generated between a wheel and a basketball, is equal. $\tau_i$ is torque generated by a motor. $\tau_b$ is torque of a basketball. Other variables are the same. But position vectors $r_i$ and $r_b$ are scalar.

With this situation in mind, Eq.10 is about a force's relationship of a wheel and a basketball. Then, both sides of this equation are scalar. Eq.11 is about all wheels and the basketbal. Because there are four force-transfer-mechanisms, both sides are summed up. Then, both sides of this equation are vector. Besides, we obtain a relationship as follows:

$$e_i \frac{\tau_i}{r_i} = \frac{\tau_i}{r_i} \tag{13}$$

Since, a direction of $\tau_i$ and a direction of $e_i$ is equal. By using this relationship, we obtain Eq.12.

By rewriting Eq.12 with using matrixes, an equation is given by:

$$\begin{bmatrix} e_{1x} & \cdots & e_{4x} \\ e_{1y} & \cdots & e_{4y} \\ e_{1z} & \cdots & e_{4z} \end{bmatrix} \begin{bmatrix} \frac{\tau_1}{r_1} \\ \vdots \\ \frac{\tau_4}{r_4} \end{bmatrix} = \frac{\tau_b}{r_b} \tag{14}$$

We need an equation to calculate motors' torque. We can obtain the equation by using a pseudo inverse matrix and the relationship of Eq.8. The equation is given by:

$$\begin{bmatrix} \tau_1 \\ \vdots \\ \tau_4 \end{bmatrix} = \begin{bmatrix} e_{1x} & \cdots & e_{4x} \\ e_{1y} & \cdots & e_{4y} \\ e_{1z} & \cdots & e_{4z} \end{bmatrix}^{\dagger} \tau_b \frac{r_w}{r_b} \tag{15}$$

Finally, we obtained the equation to calculate torque, which is generated by motors. This equation is important for dynamic simulations.

We find out that Eq.9 and Eq.15 give an interesting result. They show relationships like gear ratio between wheels and the basketball. When a relationship of the wheel's radius and the basketball's radius is $r_w < r_b$, a angular velocity of the basketball is slowing down than wheels' velocities and torque of that increases than wheels' torque, vice verse. This angular velocity's relationship is a kind of inverse kinematics.

## IV. How to ride on "B. B. Rider"

In this section, we describe how to ride on our robot.

Our robot has a seat for transporting one. There is a six-axis force torque sensor under the seat of our robot. Omni-directional motion is consist of three movements (x-axis direction, y-axis direction and z-axis rotation) on the ground surface. The robot only knows those movements. When one wants to go ahead, all one have to do is to shift one's the center of mass to ahead. If one wants to rotate on z-axis, all one have to do is to twist the seat. Data sensed by the sensor are used by control methods. Then, our robot moves while behaving motions like an inverted pendulum. In summary, our robot stabilizes itself while moving to somewhere.

## V. Conclusions

We proposed and described "B. B. Rider", which can move to all direcitons and transport a person.

Our robot has a basketball as a spherical tire. A spherical tire is possible to compose a robot with few parts. And a basketball has big three features, which are low-cost, simple structure and adaptivity to the ground surface. Then, those features satisfy our goal, which is to develop a useful omni-directional vehicle. We assume a basketball as a spherical rubber tire like auto cars' tire. And our robot moves while behaving like an inverted pendulum by using a six-axis force-torque sensor.

We designed and developed our robot. We used orthogonal wheels to drive a basketball. And we showed those mechanisms.

We explained how to calculate angular velocities and torque of motors. Simulations and experiments need them.

We need to control our robot by using the methods, which we described in this paper. And we will have got to do several experiments to verify our robot. We are looking forward to obtaining many interesting results from experiments and demonstrating.

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