Moving Properties and Simulations of an Omnidirectional Spherical Mobile Robot

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Shoichiro FUJISAWA*, Toshitaka UMEMOTO*, Takeo YOSHIDA*, and Akihiro NISHIKAWA**

ABSTRACT

This paper presents the concept of a new type of holonomic wheeled platform that has a feature of full omnidirectionality with instant movements. It was reported that an "all direction steering type mobile robot" having a spherical wheel had been developed. The robot has a spherical body, and a two wheel driven vehicle is installed in it. As it has non-holonomic restraint because of its structure, arbitrary instantaneous movements are impossible. We have already developed a four-wheel driven omnidirectional mobile robot, and the robot was applied to a spherical mobile robot. It has a holonomic restraint property and it can move into arbitrary directions instantaneously. This paper describes a development concept, mechanisms of the robot, and the experimental results. This robot has very excellent property concerning airtight. It can be expected to become one of the future generation's industrial robots.

Key Words: omnidirectional mobile robot, holonomic restraint, spherical mono-wheel, spherical mobile robot

I. INTRODUCTION

Recently the necessity of mobile robots has increased and many kinds of mobile robots have been proposed and developed. It means that the demand for robots has shifted from installed robots to mobile robots, i.e., from inside the factory to outside the factory. The fields which need these mobile robots are very wide from industrial use to individual hobby. And also the new type of robots, which are called the future generation robots, are widely noticed by many researchers [1]. A spherical shaped robot was reported to be developed for one of the example of these robots. The feature of this robot is that the wheel is made of a sphere and is equipped with two wheels in it. As the two wheels change their directions freely in the sphere, it can move to all directions. So it can be called an all-direction steering-type mobile robot [2] [3]. That is to say, it is a single-wheel type omni-directional mobile robot which is made of spheres equipped with two wheel built-in driving mechanisms. It is a notable robot but it has a defect to take some time for changing its directions. So it is impossible to change its directions instantaneously in the case of moving crank shaped roads. In that case, the driving wheels have to change its directions by some mechanical method. These movement is called non-holonomic restraint. We have developed an omnidirectional mobile Vehicle (ODV) with holonomic restraint, which can move to all directions instantaneously [4]. So, the ODV was used as the wheel built-in driving mechanisms of a spherical robot [5] and the driving properties of the robot were tested. In particular, the feature of this apparatus which can easily move to arbitrary directions without changing its body direction was examined. As a result, holonomic running was examined to be done easily, although the movement was a little bit unstable because the position control of the wheel built-in driving mechanisms was not performed. Then, the motion formula of the sphere robot was drawn by using the formula of omnidirectional vehicle. Finally, the instantaneous direction change of this apparatus was also confirmed by simulation.

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II. MECHANISM OF SPHERICAL SHAPED ROBOT

A. Omnidirectional Wheel

In general, there are three methods to drive vehicles on land; by wheels, floating, and feet. The most popular one in these methods is by wheels because they are easy to make and easy to control, and also they have superior transfer efficiency. However, this method is unsuitable for vehicles to change its directions instantaneously because wheels can move to only one direction. In order to drive vehicles back-and-forth and right-and-left with those wheels, some mechanisms to move axial direction are needed. We solved this problem by installing many rollers on each wheel. These rollers move perpendicularly to the wheel. As shown in Fig. 1, the circumference of the wheel is equipped with rollers. When the axle shaft is driven, the rollers don't rotate but contribute to drive the vehicle. When the wheel is pushed to the axle direction, the rollers rotate freely. Thus, the wheels move to back-and-forth and right-and-left simultaneously. We call this wheel an "Omnidirectional wheel (ODW)". The vehicle shown in Fig. 3 was equipped with four ODWs. As a result, the vehicle can move to all directions.

B. Mechanism of Driving Force

Mechanism to generate the driving torque of spherical robot is the wheel built-in driving mechanisms installed in the spherical mono-wheel.

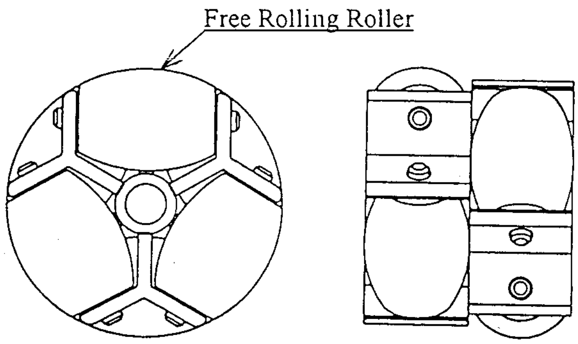


Fig. 1. An omnidirectional wheel.

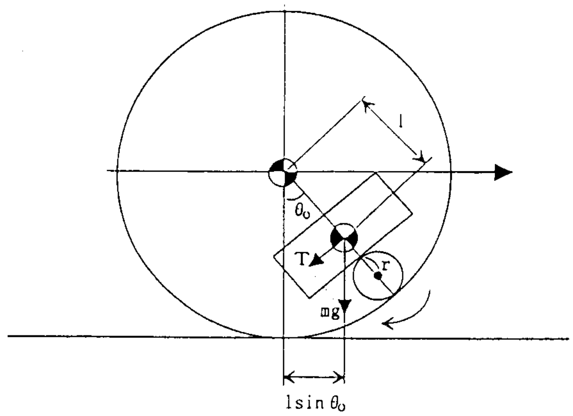


Fig. 2. Mechanism of driving force.

The movement of this wheel is explained as a pendulum. The restoring force of the movement is shown as formula (1) when the amplitude angle is θ_0.

$$T = mgl\sin\theta_o \qquad (1)$$

This is the driving torque of this wheel.

C. Kinematics of Omnidirectional Movement

To analyze the movements of the omnidirectional vehicle, we used a mechanical model which has driving power applied to only the wheels. As shown in Fig. 3, origin G(0,0) was fixed to the center of the vehicle.
Where,

1, 2, 3, and 4 are omnidirectional drive wheels.
G(0,0) is fixed to the center of the vehicle.
IC(Cx,Cy) is instantaneous center of rotation.
Vx,Vy are velocities of the vehicle.
$\dot{\varphi}$ is the rotating angular velocities of the vehicle.

Fig.4 shows the arrangement of the ODV into the spherical mono-wheel. In order to control the moving

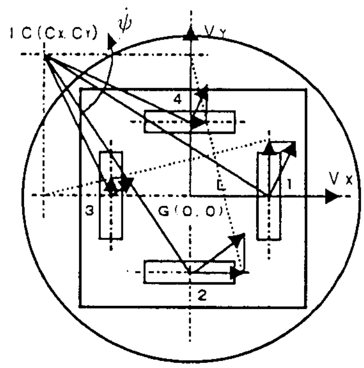


Fig. 3. Rotation speed of wheel in an arbitrary turning center.

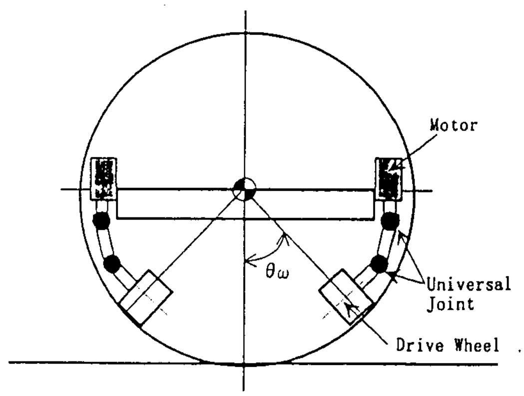


Fig. 4. Arranged drive wheel.

distance L, so as to be the same as that of the spherical robot, θ_w should satisfy formula (2).

$$L = 2\pi r \cos\theta_w \cdot \dot{\theta}_j t \tag{2}$$

Where, $\dot{\theta}_j$ (j=1,2,3,4) are the rotating angular velocities of the wheels.

When the vehicle is directed to turn around the arbitrary point IC(Cx,Cy), the rotating angular velocities of the wheels $\dot{\theta}_j$ (j=1,2,3,4), velocities of the vehicle (Vx,Vy), and rotating angular velocities $\dot{\theta}_j$ are described as follows:

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} = \frac{1}{2\pi r \cdot \cos\theta_w}[R]\begin{bmatrix} V_X \\ V_Y \\ \dot{\varphi} \end{bmatrix} \tag{3}$$

$$[R] = \begin{bmatrix} 0 & 1 & L-C_Y \\ 1 & 0 & L-C_X \\ 0 & -1 & L-C_Y \\ -1 & 0 & L-C_X \end{bmatrix} \tag{4}$$

In this equation, r represents the radius of the wheel. The equation holds subject to $\frac{\dot{\theta}_1+\dot{\theta}_3}{2} = \frac{\dot{\theta}_2+\dot{\theta}_4}{2}$.

The velocities of the vehicle are derived as follows:

$$\begin{bmatrix} v_X \\ v_Y \\ \dot{\varphi} \end{bmatrix} = 2\pi r \cdot \cos\theta_w [\bar{R}] \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \end{bmatrix} \tag{5}$$

$$[\bar{R}] = \begin{bmatrix} 0 & \frac{1}{2} & 0 & -\frac{1}{2} \\ \frac{1}{2} & 0 & -\frac{1}{2} & 0 \\ \frac{1}{4(L-C_Y)} & \frac{1}{4(L-C_X)} & \frac{1}{4(L+C_Y)} & \frac{1}{4(L+C_X)} \end{bmatrix} \tag{6}$$

From this equation, we can easily obtain the motions of this vehicle by substituting the value of the rotating center.

D. The Modes of Movement

1) Straight mode

As shown in Fig. 2, when wheels 1 and 3 are driven simultaneously, the rollers on wheels 2 and 4 rotate and the ODV moves back and forth. When wheels 2 and 4 are driven, the rollers on wheels 1 and 3 rotate, and the ODV moves right and left. If the back-and-forth movement and right-and-left movement are combined, the vehicle can move in all directions. If the driving speeds differ between back and forth movement and right and left movement, the vehicle moves in arbitrary directions.

2) Omnidirectional mode

If the back-and-forth and right-and-left movements are combined, the vehicle can move in all directions. In this case, each roller on the wheels not only contributes to driving the vehicle, but also rotates itself at the same time. If the driving speeds differ between back and forth and right and left, the vehicle moves in arbitrary directions.

3)Spinning mode

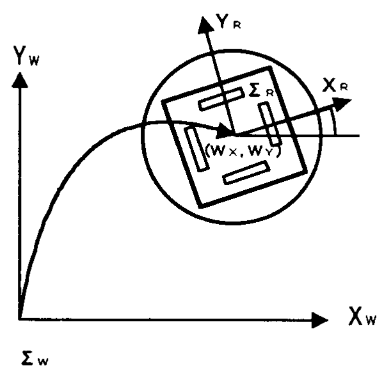
When wheels 1, 2, 3, and 4 are all driven at the same time, the vehicle rotates around its center. So, the spherical monowheel does not move but stay still.

4)Turning mode

If spinning mode is added to straight mode or to omnidirectional mode, the vehicle can move to arbitrary directions. I some cases, it became car mode. The details of this mode are described later.

E. Moving Simulations

The coordinates are defined as shown in Fig. 3. Using formula (3) to (6), the velocity (Vx,Vy) and the rotating angular velocity $\dot{\varphi}$ of the vehicle are obtained. So, the angles in the world coordinate are obtained as



ΣW: world coordinate
ΣR: robot coordinate

Fig. 5. Coordinates of omnidirectional vehicle.

formula (7) when the sample time is Δt. Here, the initial conditions are $t=0$ and $\varphi=0$.

$$\begin{aligned} t_j &= t_{j-1} + \Delta t \\ \varphi_j &= \varphi_{j-1} + \dot{\varphi}\Delta t \end{aligned} \tag{7}$$

As seen in Fig. 5, the parameters are given by the robot coordinate. Therefore, the velocities in the world coordinate are given as follows:

$$\begin{bmatrix} X_W \\ Y_W \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\varphi & -\sin\varphi & w_X \\ \sin\varphi & \cos\varphi & w_Y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_R \\ Y_R \\ 1 \end{bmatrix} \tag{8}$$

The coordinate values of the vehicle P(Xw,Yw) are given by the formula (9) in the form of discrete values.

$$\begin{aligned} P_j &= P_{init} + \sum_{i=1}^{j} \Delta p_i \\ \Delta p_i &= v_{j-1}\Delta t \end{aligned} \tag{9}$$

The results of these analyses by using the equations are shown in Figs. 6-8. Figure 6 shows the simulation of the movements when the rotating center is the same as the center of the vehicle and the vehicle is running in omnidirectional mode. The direction of the vehicle remains unchanged. Figure 7 shows the result when the rotating center is changed from the center of the body to arbitrary positions. This result indicates that the locations and directions of the vehicle can be set up arbitrarily. Figure 8 shows the result of a car movement. This car mode running is obtained by adding the condition $\frac{\dot{\theta}_1 - \dot{\theta}_3}{4} = \pm\dot{\theta}_2 = \mp\dot{\theta}_4$ to the turning mode. The vehicle appears to demonstrate these movements easily.

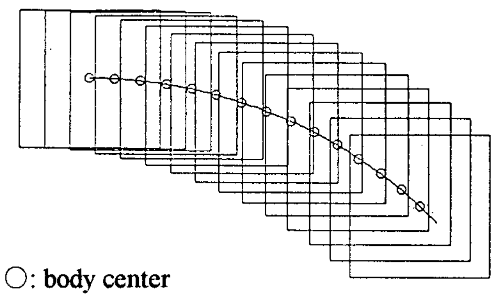


Fig. 6. Simulation of omnidirectional mode.

In this figure, only the trajectory of the wheel built-in driving mechanisms was shown. The center of the body coincident with the center of the spherical robot.

III. CONSTRUCTION OF VEHICLE AND ODV

In this section, the components of vehicle and ODV are shown.

A. Mechanisms of the Driving Unit

DC motors were used for driving power to obtain accurate movement and positioning. It is noted that the center of the body and the center of the gravity should be the same point. If they were different, the driving forces to the wheels would differ from each other. The wheels were equipped with motors and reduction gears. The motor speed was reduced by the reduction gear. All these parts were combined into driving units. The driving units were attached to the body through suspensions to ensure even grasp forces and the ability to proceed on uneven ground. In this way, effective performance is achieved from a simple mechanism. The total figure was shown in Fig. 9. Fig. 10 shows the driving unit. As shown in this figure, two driving shafts were connected by a universal joint because the motor and wheel were arranged along the sphere. In order to strengthen the gripping ability, rubber sheets were pasted around the roller in addition to installing the suspensions.

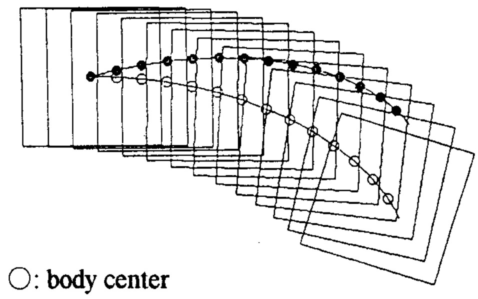


Fig. 7. Simulation of spinning mode.

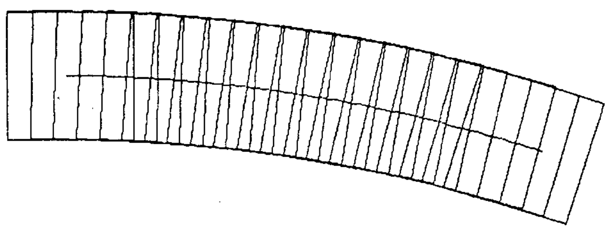


Fig. 8. Simulation of car mode.

B. Control Unit and Programs for Driving Unit

A Z80CPU microcomputer was used to control the wheel built-in driving mechanisms. The signals to control four motors were sent from microcomputer to four driving circuits through 8255 parallel board. The four motors could move independently, omni-directional movement was obtained easily.

IV. MOVING PROPERTIES

The moving properties of the spherical robot we made was examined. Image treatment using CCD camera and image analysis software was performed in order to analyze the moving properties of the vehicle.

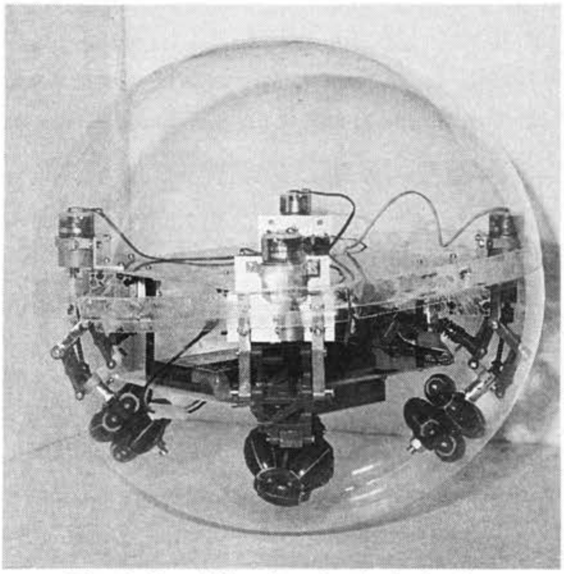


Fig. 9. Omnidirectional spherical robot.

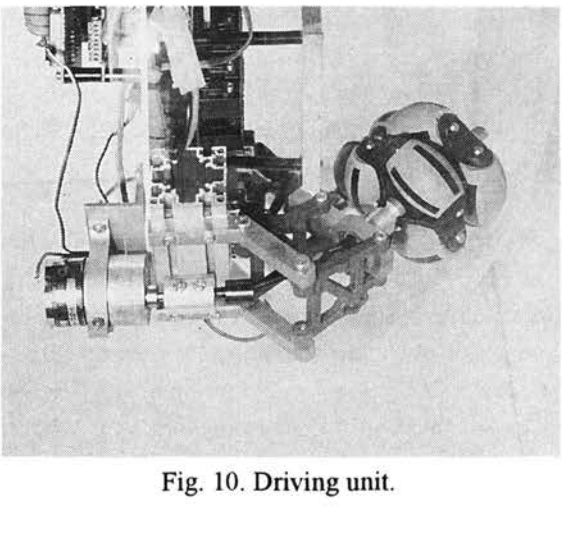


Fig. 10. Driving unit.

A. Straight motion property

The spherical robot was driven straight on an expanded polystyrene mat. The results were shown in Fig. 12. The points show the positions of the vehicle on every 1 second. We can see the vehicle moved nearly on straight lines. On the other hand, the velocities of the

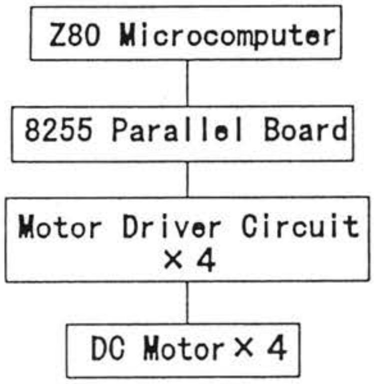


Fig. 11. Control circuit chart.

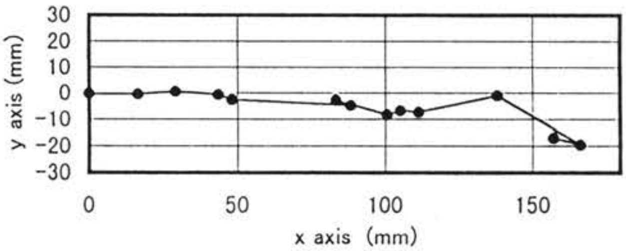


Fig.12. The property of straight motion.

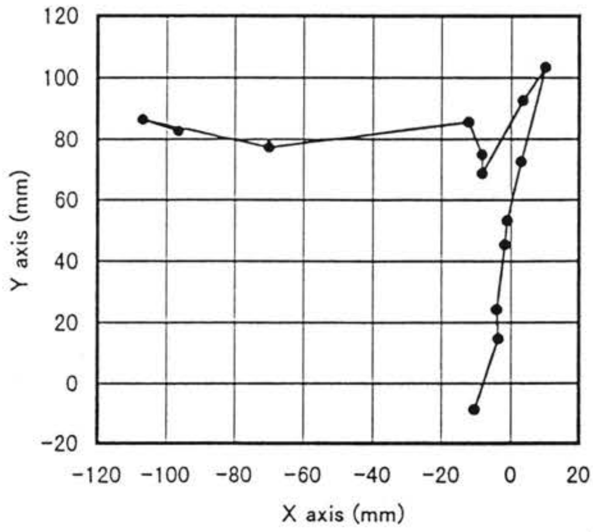


Fig.13. The property of clank motion.

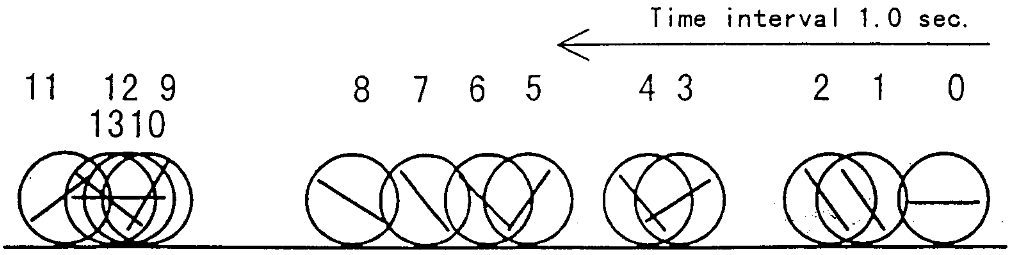


Fig. 14. Behavior of spherical robot.

vehicle were not constant, so the rotating speeds of the wheels seemed to be irregular. It is due to the differences between the revolution of the spherical robot and velocity of the ODV. The figure also shows that the position of the end point was largely out of line. It was because the spherical wheels continued to roll even after the driving unit had stopped moving.

B. The property of clank motion

Crank motion after straight running, which the vehicle moves the right angled corner after straight line, was examined. The result was shown in Fig. 13. holonomic restraint movement which the vehicle can change the directions instantaneously, that was our original purpose, was assumed to be done easily. But as seen in the figure, overshooting and undershooting occurred when the vehicle changed the directions. It was due to the lack of position control and velocity control.

C. Behavior of Spherical Robot

Fig. 14 shows the side view of the performance of the spherical robot and ODV, when they are driven to the straight line. During the time when the ODV moves on the part 0～2 in Fig. 14, starting torque works efficiently and there are no slip. As the distance between the center of the ODV and the center of the mono-wheel is only 16 mm, it is rather small compared with the radius of the mono-wheel, 250mm. So, in order to generate the sufficient torque, large amplitude was needed. It occurred the large swing as seen in Fig. 14. The maximum swing angle of the ODV was 44 degree. The spherical robot runs by the rotation torque. As the velocity of the ODV was constant, the ODV was delayed to the movement of the spherical robot at the part of 2～3 in Fig. 14. The running of the spherical robot was the repetition of this movement. Part 10～13 in Fig. 14 is the movement of the spherical robot from starting point to the end point.

V. CONCLUSION

As the result of installing the four-wheel-drive omnidirectional vehicle into Mono-wheel, the spherical robot performed a holonomic restraint movement although the running property and behavior of the ODV were not so stable. This time, we can only present the concept of the apparatus. We have to study more how to establish the stable running by controlling the position and velocity of the apparatus. In addition to it, lowering the center of gravity, reforming the driving unit etc. were needed.

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