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Proceedings of the Japan Society of Mechanical Engineers (C edition)
Volume 78, Issue 790 (2012-6)

Original paper No.2011-JCR-0760

Development of sphere-driven omnidirectional movement mechanism*

Shuichi Ishida*1, Hiroyuki Miyamoto*1

Holonomic Omnidirectional Vehicle with Ball Wheel Drive Mechanism

Shuichi ISHIDA*1 and Hiroyuki MIYAMOTO

*1 Graduate School of Life Science and Systems Engineering, Kyushu Institute of Technology
2-4, Hibikino, Wakamatsu-ku, Kitakyushu, Fukuoka, 808-0196, Japan

A holonomic omnidirectional vehicle can instantly produce speed in any direction. It has a high level of mobility even on narrow spaces and expected to have a wide field of application. A lot of mechanisms have been developed to realize omnidirectional motions. However, no vehicle achieves an optimal balance between mechanism and control. We have been developed a holonomic omnidirectional vehicle with ball wheel drive mechanism. This mechanism has three ball wheels and three actuators, in which each ball wheel is driven by two actuators. This mechanism do not cause over constraint , because the number of actuators agrees with the number of motion freedom on a flat surface. It was realized to devise layout of ball wheels and actuators. Also this mechanism is simple, but it can easily be controlled and has a high level of mobility. A prototype vehicle was developed to perform experiments of absolutely necessary performance in practical use. In motion experiments, we confirmed step overcoming, gap traversing and slope climbing ability on riding an adult (approximately 5[6kg]).

Key words: Moving Robot, Mechanism, Kinematics, Omnidirectional Vehicle, Ball Wheel Drive Mechanism

1. At the beginning

Currently, the most popular transportation mechanism is the wheel-type transportation mechanism. These are characterized by high energy efficiency, simple structure and control, and the accumulation of know-how over many years. However, many wheel-type moving mechanisms are non-holonomic systems, and the mechanism's non-holonomic constraints prevent it from being flat.3Degrees of freedom motion (translational2degree of freedom, posture1It is not possible to move in any direction within the degrees of freedom).3In order to move freely with controlled degrees of freedom, complex route planning such as turning back and forth is required. To overcome this restriction on movement direction,1An all-wheel steering type omnidirectional movement mechanism was devised that allows independent control of the drive wheels and steered wheels on two wheel units.(1). . However, since it is necessary to align the wheels in the direction of travel before moving, it takes time to move in all directions.

On the other hand, holonomic omnidirectional movement mechanisms that can instantaneously generate speed in any direction have a high degree of mobility and are being widely studied.(twenty three). . offset drive wheels2Omnidirectional movement mechanism equipped with wheels(Four)A mechanism has been developed that gives the drive wheels the ability to passively rotate in a specific direction. In this case, there are various mechanisms depending on the shape and arrangement of the driven wheel, and there is a mechanism called an omniwheel, which is a special wheel with multiple free rollers arranged around the circumference of the wheel.(5) (6)(figure1), a mechanism using spherical free rollers(7) (8), Crawler type equipped with multiple free rollers(9) (10)etc. Among these, omnidirectional movement mechanisms using omni-wheels are relatively easy to handle and are therefore widely used, mainly in research institutions. Using multiple omni-wheels, the direction of each driving speed vector is fixed and only the magnitude is changed. For plane 3-degree-of-freedom motion, the directions are different.3It is sufficient to have one driving velocity vector. By combining these velocity vectors, the moving velocity vector of the entire mechanism is obtained. Therefore, due to factors such as uneven floor surfaces, slopes, and movement of the center of gravity of the entire mechanism, friction with the floor surface may occur.

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* Manuscript reception2011Year9Month12Day

*1 Member, Department of Neuroinformatics, Graduate School of Bioengineering, Kyushu Institute of Technology (〒808-0196Hibikino, Wakamatsu Ward, Kitakyushu City, Fukuoka Prefecture2-4) E-mail: ishida-shuichi@edu.brain.kyutech.ac.jp

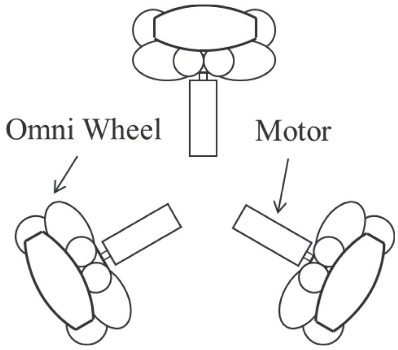


Fig. 1 Omni Wheel

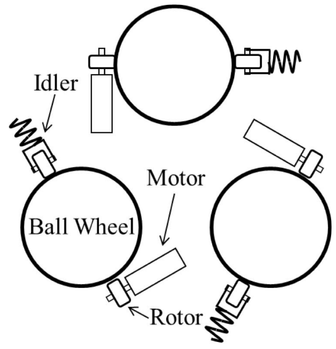


Fig. 2 3 Ball Wheels-3 Actuators

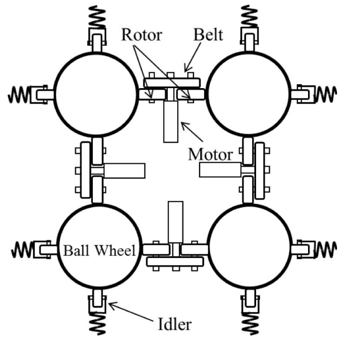


Fig. 3 4 Ball Wheels-4 Actuators

In situations where the friction varies, the direction of the composite vector tends to become unstable. In such cases, driving stability deteriorates, such as the ability to travel straight. In addition, it has been pointed out that the complexity of the structure due to the special wheel shape, vibration during running, low load capacity, and poor ability to overcome bumps due to the dependence on small-diameter free rollers have been cited as disadvantages, which have hindered practical application. ing(11)．．

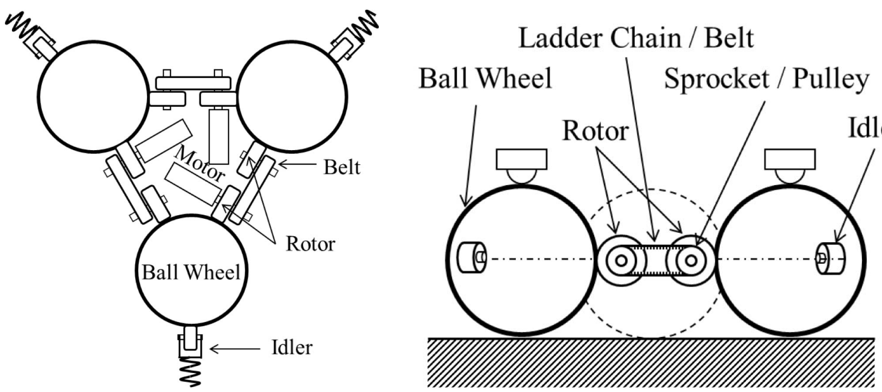
Although there are few research examples, a sphere-driven omnidirectional movement mechanism has been proposed.(12)~(16)．． Mechanisms using spheres are suitable for omnidirectional movement due to their shape.(2), low vibration, low noise, and high ability to climb over steps can be expected. The sphere drive method depends on the direction in which the sphere is driven.2It can be broadly classified into the following methods. One is a sphere1This is a method in which only one direction is driven, and the perpendicular direction is passively rotated.(12)~(15)．． Matsumoto et al.,Fig.2We have developed an omnidirectional movement mechanism configured as follows.(13)．． However, the principle of using passive rotation is basically the same as the omniwheel, and it can be said to be vulnerable to irregularities on the floor. The other is a sphere.2This is a method that drives the motor in more than one direction. In this method, the driving velocity vector of each sphere matches the velocity vector at each sphere grounding point of the mechanism. Therefore, running stability is high even when there are factors such as uneven floors, slopes, and movement of the center of gravity of the entire mechanism. As an example of this method, Fig.3likeFourtwo spheres andFourThere is a mechanism consisting of two actuators.(16)．． In this mechanism,FourConsists of two actuators1Overconstraint occurs due to redundancy of degrees of freedom. Mechanisms with overconstraint problems require precise synchronization of movements between actuators. If this collapses, an excessive load will be placed on the drive system and slippage will occur between the sphere and the running surface. In order to avoid this over-constraint problem, Asama et al.3with two actuatorsFourWe are proposing a wheel-type drive transmission mechanism that drives wheels.(Five)．． However, due to its complex structure, issues remain in adjustment and maintenance. As described above, a mechanism with holonomic omnidirectional movement capability has a trade-off in the relationship between mechanism and control.(2)．．

In this paper, we solve this problem by devising the arrangement of actuators and3by two actuators3each of the two spheres2We propose a holonomic omnidirectional movement mechanism that drives the object in more than one direction.3By using two actuators, the overconstraint problem is avoided, and although the mechanism is simple,3It is characterized by the fact that all three spheres are constantly driven wheels. onwards,2In Chapter 2, we show the structure of the mechanism and derive the kinematic model.3In this chapter, we will explain the developed omnidirectional movement mechanism and confirm its ability to climb over steps, ditches, and climb hills, which are obstacles to practical application. Furthermore, we will conduct a similar experiment with an adult on board to verify the effectiveness of the mechanism.Four Section concludes the paper.

2.Design of sphere-driven omnidirectional movement mechanism

2・1Mechanism configuration

The configuration diagram of this proposed mechanism is shown below.FourIt is shown in1Two actuators drive adjacent spheres simultaneously. figure4(b)As shown in Figure 2, the drive from the actuator is transmitted to the rotor by a belt, and a pressure contact drive method is used in which the sphere is pressed against the rotor by an idler with a spring. The rotor and idler have contact points with the sphere in the horizontal plane that includes the center of the sphere. The rotation of the spheres is maintained using ball casters placed at the top of each sphere. With these arrangements, the rotation direction vector of the sphere points to an arbitrary horizontal plane. Each sphere is driven simultaneously2The direction of rotation is determined by the vector sum of the rotational motions generated by the two rotors. moreover,3Due to the resultant force of the rotational motion of the two spheres, the plane of the moving mechanism3Movement with degrees of freedom can be realized.



(a) Top view (b) Side View

Fig. 4 Vehicle construction

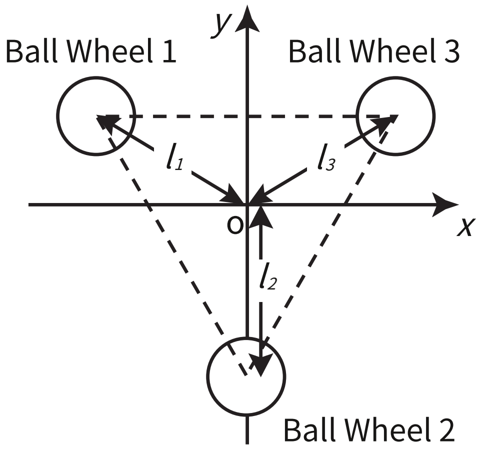


Fig. 5 Vehicle Coordinate System

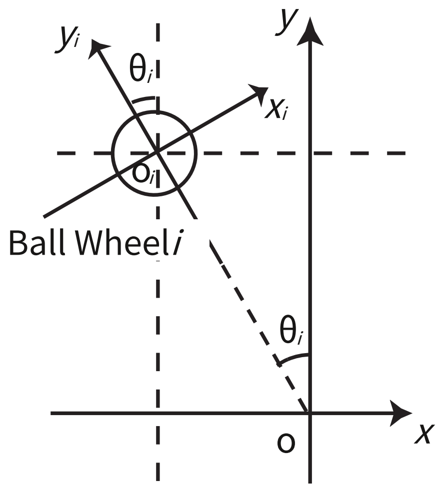


Fig. 6 Ball Wheel Coordinate System

2・2kinematics

figureFiveDefine a coordinate system fixed to the moving mechanism as shown in .3two driving spheres1～3at each vertex of the triangle, and the origin is inside this triangle.oTake.yThe axis is a sphere2From the grounding point to the origin,xThe axis is$y$Take each direction perpendicular to the axis. sphere number of spheres1Give more counterclockwise. Furthermore, the originoeach sphere from$i$distance tol_i[m]That is. subscript here$i$represents the number of the sphere. (i=1,2,3)

Then each sphere$i$Diagram the coordinate system for6Define it as shown below. each sphere$i$The origin is the grounding point of$o_i$and the origin in the coordinate system of the moving mechanismofrom$o_i$in the direction of$y_i$axis, perpendicular to thisx_iTake each axis. The rotation angle of each sphere from the moving mechanism coordinate system isθ_i[rad]Suppose that Each sphere in the moving mechanism coordinate system$i$grounding pointo_iThe coordinate system of is the originodistance from$l_i$and$y$ axis and o−$o_i$angle formed byθ_iIt can be expressed as (Counterclockwise direction is positive)

figure7shows the speed definition of the moving mechanism. The origin of the moving mechanismoof translational velocity at$x$axial componentv_x[m/s]，$y$axial componentv_y[m/s],originoThe counterclockwise rotational angular velocity of the surroundingω[rad/s]Suppose that Here each sphere grounding point$o_i$of the movement mechanism in $x_i$axial componentv_{xi}[m/s]，$y_i$axial componentv_{yi}[m/s]Then, the following relationship holds true.

$$\begin{aligned} v_{xi} &= v_x\cos\theta_i + v_y\sin\theta_i - l_i\omega \\ v_{yi} &= -v_x\sin\theta_i + v_y\cos\theta_i \end{aligned} \tag{1}$$

Here is the origin of the movement mechanismovelocity vector at$v$of,

$$v = \begin{bmatrix} v_x & v_y & \omega \end{bmatrix}^T \tag{2}$$

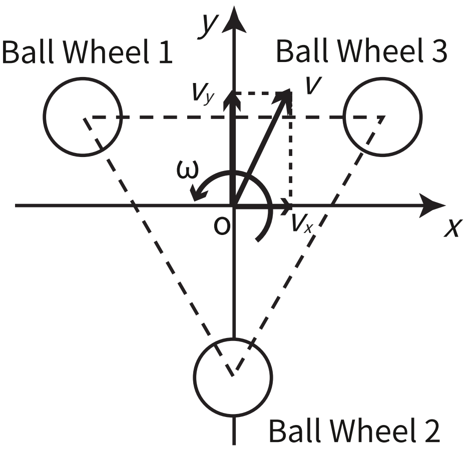


Fig. 7 Velocity of vehicle

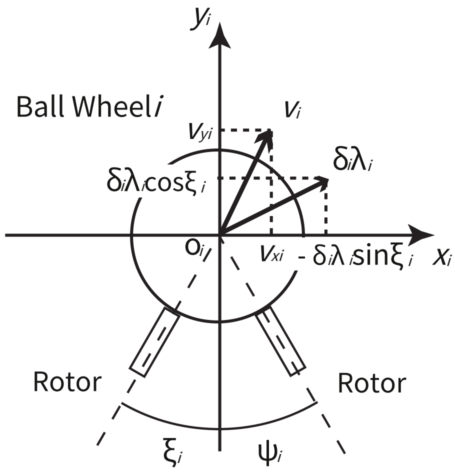


Fig. 8 Angular Velocity of Ball Wheel

Then, at each ball contact point, x_i axial component, y_i Vector that summarizes each axial component v_x, v_y teeth

$$v_x = \begin{bmatrix} v_{x1} & v_{x2} & v_{x3} \end{bmatrix}^T, \quad v_y = \begin{bmatrix} v_{y1} & v_{y2} & v_{y3} \end{bmatrix}^T \tag{3}$$

It is expressed as . Expression (1)The expression (2)，(3)When rewritten using , the following relationship holds true.

$$v_x = \mathbf{P_x} v, \qquad \text{(Four)}$$

$$\mathbf{P_x} = \begin{bmatrix} \cos\theta_1 & \sin\theta_1 & -l_1 \\ \cos\theta_2 & \sin\theta_2 & -l_2 \\ \cos\theta_3 & \sin\theta_3 & -l_3 \end{bmatrix}$$

$$v_y = \mathbf{P_y} v, \qquad \text{(Five)}$$

$$\mathbf{P_y} = \begin{bmatrix} -\sin\theta_1 & \cos\theta_1 & 0 \\ -\sin\theta_2 & \cos\theta_2 & 0 \\ -\sin\theta_3 & \cos\theta_3 & 0 \end{bmatrix}$$

figure8shows the velocity component at the point of contact with the sphere. sphere1and sphere2The rotational angular velocity of the rotor that drives λ_1[rad/s],sphere2and sphere3The rotational angular velocity of the rotor that drives λ_2[rad/s],sphere3and sphere1The rotational angular velocity of the rotor that drives λ_3[rad/s]That is. here λ_i When looking at the moving mechanism from the outside, the counterclockwise direction is positive, and the vector that combines these is λ is expressed as follows.

$$\lambda = \begin{bmatrix} \lambda_1 & \lambda_2 & \lambda_3 \end{bmatrix}^T \tag{6}$$

The effective radius of the rotor δ_i[m]Then, the circumferential speed of the rotor transmitted to drive each sphere is $\delta_i\lambda_i$[m/s]is at the grounding point of the sphere2two rotors x_i axial component, y_i Since it can be decomposed into axial components, the following relationship holds.

$$\begin{bmatrix} v_{x1} \\ v_{x2} \\ v_{x3} \end{bmatrix} = \begin{bmatrix} \delta_1\lambda_1\sin\xi_1 + \delta_3\lambda_3\sin\psi_1 \\ \delta_2\lambda_2\sin\xi_2 + \delta_1\lambda_1\sin\psi_2 \\ \delta_3\lambda_3\sin\xi_3 + \delta_2\lambda_2\sin\psi_3 \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} v_{y1} \\ v_{y2} \\ v_{y3} \end{bmatrix} = \begin{bmatrix} \delta_1\lambda_1\cos\xi_1 - \delta_3\lambda_3\cos\psi_1 \\ \delta_2\lambda_2\cos\xi_2 - \delta_1\lambda_1\cos\psi_2 \\ \delta_3\lambda_3\cos\xi_3 - \delta_2\lambda_2\cos\psi_3 \end{bmatrix} \tag{8}$$

Expression (7)and the expression (8)The expression (3)and the expression (6)Rewriting using

$$v_x = \mathbf{U_x}\lambda, \tag{9}$$

$$\mathbf{U_x} = \begin{bmatrix} \delta_1 \sin\xi_1 & 0 & \delta_3 \sin\psi_1 \\ -\delta_1 \sin\psi_2 & \delta_2 \sin\xi_2 & 0 \\ 0 & \delta_2 \sin\psi_3 & \delta_3 \sin\xi_3 \end{bmatrix}$$

$$v_y = \mathbf{U_y}\lambda, \quad \text{(Ten)}$$

$$\mathbf{U_y} = \begin{bmatrix} \delta_1 \cos\xi_1 & 0 & -\delta_3 \cos\psi_1 \\ -\delta_1 \cos\psi_2 & \delta_2 \cos\xi_2 & 0 \\ 0 & -\delta_2 \cos\psi_3 & \delta_3 \cos\xi_3 \end{bmatrix}$$

obtain. Also, from the geometrical relationship, the formula (Four)and (9)can be summarized as follows.

$$\mathbf{P_x} v = \mathbf{U_x}\lambda \tag{11}$$

Expression (11)Translational and rotational angular velocity of the moving mechanism vThe rotational angular velocity of the rotor λTo find by, $\mathbf{P_x}$ and $\mathbf{U_x}$ must be regular. A necessary and sufficient condition for regularity is that the determinant is nonzero, but depending on the arrangement of the spheres, there are variables whose determinant becomes zero. Therefore, in the proposed mechanism, by selecting an arrangement where the determinant is non-zero, it is possible to obtain the inverse matrix as follows.

$$v = \mathbf{P_x}^{-1}\mathbf{U_x}\lambda \tag{12}$$

In addition, conversely, the rotational angular velocity of the rotor λ is the translational/rotational angular velocity of the moving mechanism v It can be found as follows.

$$\lambda = \mathbf{U_x}^{-1}\mathbf{P_x} v \tag{13}$$

When each spherical grounding point is placed at the vertex of an equilateral triangle as in the proposed mechanism, that is, $\delta=\delta_1=\delta_2=\delta_3$, $\theta_1=\pi/3$, $\theta_2=\pi$, $\theta_3=5\pi/3$, $l=l_1=l_2=l_3$, $\xi=\phi=1/6\pi$ When , the expression (Four), expression (9)of $\mathbf{P_x}$, $\mathbf{U_x}$ becomes simple as follows.

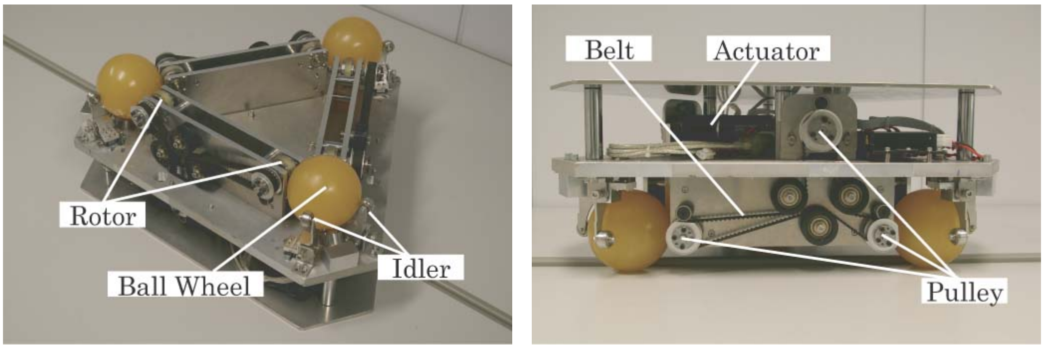
$$\mathbf{P_x} = \frac{1}{2}\begin{bmatrix} 1 & \sqrt{3} & -2l \\ -2 & 0 & -2l \\ 1 & -\sqrt{3} & -2l \end{bmatrix}, \quad \mathbf{U_x} = \frac{\delta}{2}\begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix} \tag{14}$$

$$\mathbf{P_x}^{-1}\mathbf{U_x} = \frac{\delta}{6}\begin{bmatrix} -1 & -1 & 2 \\ 2\sqrt{3} & -2\sqrt{3} & 0 \\ -\frac{2}{l} & -\frac{2}{l} & -\frac{2}{l} \end{bmatrix}, \quad \mathbf{U_x}^{-1}\mathbf{P_x} = \frac{1}{\delta}\begin{bmatrix} -1 & \sqrt{3} & -l \\ -1 & -\sqrt{3} & -l \\ 2 & 0 & -l \end{bmatrix} \tag{15}$$

3. fruit experience

3・1 Prototype of omnidirectional movement mechanism

An overview of the developed prototype machine9It is shown in figure9(a)The vehicle is as shown in3Two spheres are attached, each sphere2 It is driven by two actuators. The rotation transmission from the actuator to the rotor is shown in the figure.9(b)As shown in Figure 2, the rotation from the actuator attached to the mechanism base is transmitted through the belt.2It drives two rotors. The ball caster at the top of each sphere is positioned from the north pole of the sphere to stabilize the contact force between the sphere and the rotor.10 [mm]It is placed outside. figureTenshows the arrangement of the sphere and actuator. In motion input to the vehicle3Translation speed with joystick degrees of freedom v_x, v_y, originorotational angular velocity around ω It is possible to generate a speed command of The speed command is expressed by the formula (13), the rotational angular velocity of the rotor is determined, and a speed command is given to each actuator via the motor driver. The specifications of the prototype are listed below.1As shown in



(a) Perspective viewe (b) Side View

Fig. 9 Whole View of Omnidirectional Vehicle

Table 1 Specification of Omnidirectional Vehicle

Height	220 [mm]
Width	553.6 [mm]
Weight	28.4 [kg]
Ball Wheel's Diameter	98 [mm]
Ball Wheel's Weight	0.56 [kg]
Ball Wheel's Material	Urethane shore 9 0
Rotor's Diameter	40 [mm]
Rotor's Material	Urethane shore 9 0
DC Motor's Output	150 [W]×3
Gear Ratio	74

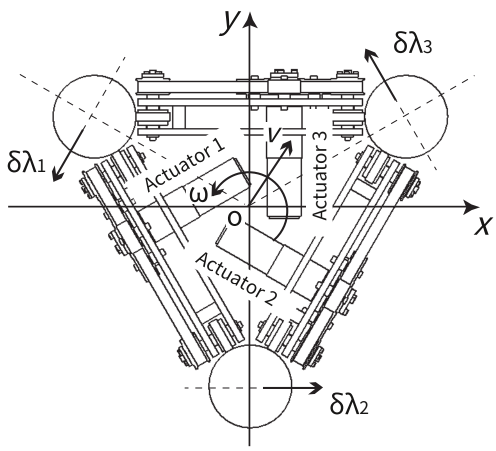
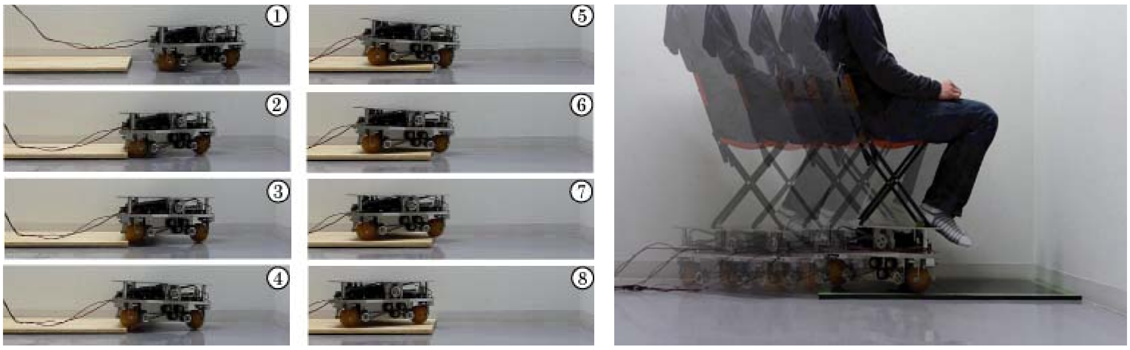


Fig. 10 Control of Omnidirectional eVhicle

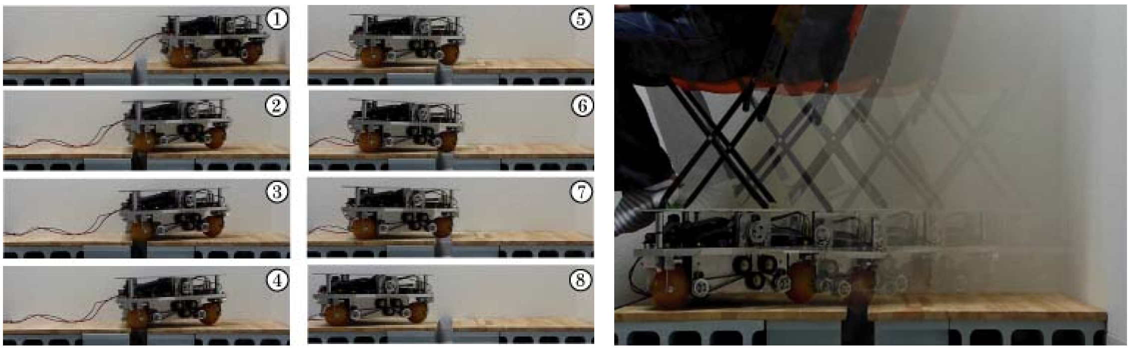
3・2 Driving experiment

Using a prototype machine, we will conduct experiments to evaluate the ability of this mechanism to climb over steps, ditches, and climb slopes. These evaluation items can be said to be essential abilities for the practical use of omnidirectional movement mechanisms. In addition, in each evaluation item, adults (approximately56 [kg]) was also carried out in a similar experiment. In addition, open-loop control was used to control the vehicle in the experiment, and the vehicle was0.15[m/s]It is performing a straight-line motion. When climbing over steps and ditches2Compared to the condition where two spheres enter at the same time, when the spheres enter one after the other or when rotational motion is added, it tends to be easier to climb over steps and cross ditches. In this experiment, the approach direction was2The direction in which the two spheres touch the steps, grooves, and slopes at the same time is unified. In the experiment, we captured continuous images of the vehicle while it was running using a video camera. In experiments involving only vehicles, images were shown in chronological order, and in experiments with adults on board, images were shown among consecutive images.FiveA composite image obtained by overlapping the images is shown as the experimental result.



(a) Step Height 24mm (b) Step Height 14mm

Fig. 11 Step Overcoming Motion



(a) Gap length 65mm (b) Gap Length 50mm

Fig. 12 Gap Traversing Motion

3・2・1 Movement over steps

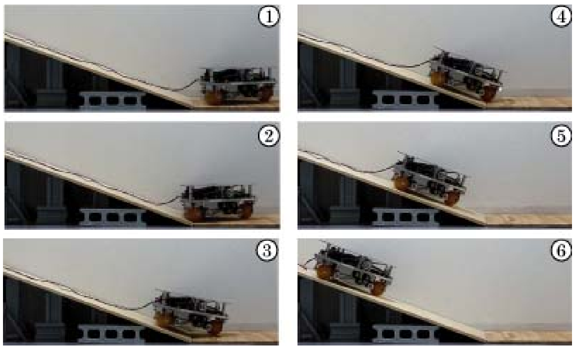
Figure 2 shows the vehicle's step-crossing operation experiment.11(a)I went like this. The level difference that the vehicle was able to overcome24 [mm]Met. In addition, when an adult is on board,11(b)as shown in14 [mm]It was the ability to get over steps. When vehicles are used for purposes other than specific purposes, it is assumed that they will be used indoors or in factories. Although the running surface is not completely flat, it can be said to be a leveled environment. The required ability to cross steps is several [mm]～Dozens [mm]The prototype's capabilities meet this requirement.

3・2・2 Ditch traversing movement

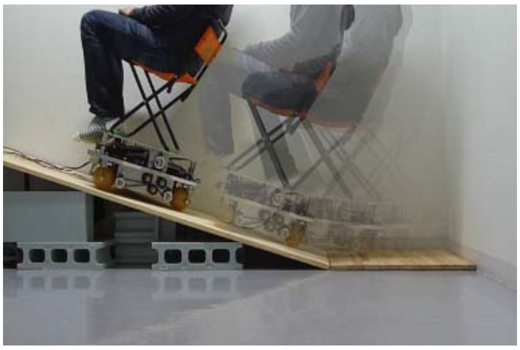
An example of where a groove-traversing motion is required is when running in a groove between an elevator and a floor. A wheel-type moving mechanism may be unable to get out of the groove depending on the direction of approach. Since this mechanism uses a sphere as the driving wheel, it is possible to cross a ditch at any angle of approach. The length of the groove between the elevator and the floor at the university to which the authors belong is approximately30 [mm]It was confirmed that the vehicle could traverse this without any problems. Furthermore, the figure for a single vehicle is12(a)It has the ability to traverse ditches as shown in65 [mm]It was possible to traverse the ditch. Similarly, if an adult is on board,50 [mm]Figure showing how to break through the ditch.12(b)I was able to confirm as follows.

3・2・3slope climbing exercise

figure13(a)As shown in , it was confirmed that the vehicle had slope climbing ability. The slope of the slope is20 degreesMet. Further figure13(a)InFiveIn the second image, the vehicle is temporarily stopped and then starts again from that state. Also, figure 13(b)An adult male is on board.15[deg]A similar ability was confirmed when climbing a hill.



(a) Slope Angle 20 degrees



(b) Slope Angle 15 degrees

Fig. 13 Slope Climbing Motion

Four.in conclusion

In this research3two spheres and3We proposed a holonomic omnidirectional movement mechanism consisting of two actuators. Although it is a holonomic omnidirectional movement mechanism with a high degree of mobility, there have been few practical studies regarding the complexity of the structure and control, and obstacles in actual use such as climbing over steps, ditches, and climbing slopes, and it has not been put into practical use. was late. This mechanism avoids the over-constraint problem by carefully arranging the actuators, and achieves omnidirectional movement with a simple structure and control. Furthermore, assuming actual use, we conducted experiments with a single vehicle and with an adult on board, and were able to confirm that this mechanism is effective in actual use. As a future work, we plan to verify the durability of the ball, rotor, and support by taking into account the wear caused by pressure contact drive.

Thank you words

This research is supported by Grant-in-Aid for Scientific Research (21560265).

Sentence dedication

(1) Nakano, E. and Koyachi, N., "An Advanced Mechanism of the Omni-Directional Vehicle(ODV) and Its Application to the Working Wheelchair for the Disabled",*Proceedings of the 1983 International Conference on Advanced Robotics*, (1983), pp.277-284.

(2)Jun Yamashita, Hajime Asama, Tamio Arai, Jun Ota, Toru Kaneko, "Research Trends on Robot Locomotion Mechanisms", Journal of the Robotics Society of Japan,Vol. 21, No. 5 (2003), pp.282-292.

(3)Kenjiro Tadakuma, "Omnidirectional movement/drive mechanism", Journal of the Robotics Society of Japan,Vol. 29, No. 6 (2011), pp.516-519.

(4) Wada, M. and Mori, S., "Holonomic and Omnidirectional Vehicle with Conventional Tires", *Proceedings of the 1996 IEEE International Conference on Robotics and Automation*, (1996), pp.3671-3676

(5) Asama, H., Sato, M., Bongoni, L., Kaetsu, H., Matsumoto, A., and Endo, I., "Development of an Omni-Directional Mobile Robot with 3 DOF Decoupling Drive Mechanism", *Proceedings of the 1995 IEEE International Conference on Robotics and Automation*, (1995), pp.1925-1930.

(6)Shoichiro Fujisawa, Keiji Okubo, Yasunari Shidama, Hiroo Yamaura, "Kinematics and running characteristics of four-wheel independently driven omnidirectional mobile robot", Nippon Kikai Proceedings of academic conferencesCed.,Vol. 62, No. 604 (1996), pp.149-155.

(7) Pin, FG, and Killough, SM, "A New Family of Omnidirectional and Holonomic Wheeled Platforms for Mobile Robots", *IEEE Transactions on Robotics and Automation*, Vol. 10, No. 4 (1994), pp.480-489.

(8) Tadakuma, K., Tadakuma, R., and Berengeres, J., "Development of Holonomic Omnidirectional Vehicle with "Omni-Ball": Spherical Wheels", *Proceeding of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, (2007), pp.33-39.

(9) West, M. and Asada, H., “Design of a Holonomic Omnidirectional VehicP ler” o,ceeding of the 1992 IEEE International Conference on Robotics and Automation, (1992), pp.97-103.

(Ten)Shigeo Hirose, Shinichi Amano, “Development of large-load, high-efficiency omnidirectional vehicle”, Japan Society of Mechanical Engineers Robotics and Mechatronics Conference'93Collection of lecture papers, (1993), pp.350-355.

(11) Ferrerì re, L., Raucent, B., and Campion, G., “Design of Omnimobile Robot WhePerlosc”,eedings of the 1996 IEEE International Conference on Robotics and Automation, (1996), pp.3664-3670.

(12) West, M. and Asada, H., “Design and Control of Ball Wheel Omnidirectional VehicleP ersо” c,eeding of the 1995 IEEE International Conference on Robotics and Automation, (1995), pp.1931-1938.

(13)Naoki Matsumoto, Shigeru Takeda, Shinji Iida, Masaatsu Ito, “3Motion and control of omnidirectional moving mechanism using two balls”, Transactions of the Japan Society of Mechanical EngineersCed., Vol. 60, No. 576 (1994), pp.266-273.

(14) Ferrerìre, L., Campion, G., and Raucent, B., “ROLLMOBS, a new drive system for omnimobile rob Rootbso”,tica(2001), 2001 Cambridge University Press, Vol. 19 (2001), pp.1-9.

(15) Lee, YC, Danny, Lee, DV, Chung, JH, and Velinsky, SA, “Control of a redundant, reconfigurable ball wheel drive mechanism for an omnidirectional mobile platform R” o,botica(2007), 2006 Cambridge University Press,eVsosl. 25 (2007), pp.385-395.

(16)Kensuke Yamada, Kyosei Miyamoto, Seiichi Usui,“Four “Study on omnidirectional movement mechanism using individual balls”, Transactions of the Japan Society of Mechanical EngineersCed.,Vol. 71, No. 708 (2005), pp.127-132.