Advanced Robotics, Vol. 19, No. 1, pp. 55–71 (2005)
© VSP and Robotics Society of Japan 2005.
Also available online - www.vsppub.com

Full paper

Development of a control system for an omni-directional vehicle with step-climbing ability

DAISUKE CHUGO *, KUNIAKI KAWABATA, HAYATO KAETSU, HAJIME ASAMA and TAKETOSHI MISHIMA

Department of Information and Mathematical Science, Faculty of Science and Engineering, Saitama University, 255 Shimo-Okubo, Saitama-Shi, Saitama, Japan

Received 12 December 2003; accepted 30 January 2004

Abstract—This paper proposes a control method for wheels to pass over rough terrain. In our previous work, we have developed a holonomic mobile mechanism capable of running over steps. The mechanism realizes omni-directional motion on a flat floor and passes over uneven ground in forward and backward directions. The vehicle has seven special wheels with cylindrical free rollers and two passive body axes that can adapt to rough terrain. Seven actuators are located in each wheel; therefore, our vehicle system requires the rotation velocity of each wheel to be coordinated. However, it is difficult to keep such coordination among the wheels — as the vehicle passes over the step, the load applied to the wheel tends to heavy and irregular. Therefore, we propose a new control system for synchronization among the wheels. In this paper, the following two topics are discussed: the load adjustment so as not to exceed the maximum torque of the actuator in some of the wheels and keeping the balance of rotation velocity among the wheels. Our novel control method adjusts the output value by referring to the state of the other wheels. The performance of our system is investigated by means of computer simulations and experiments using our prototype vehicle.

Keywords: Omni-directional; step-climbing; passive link; torque control; wheel synchronization.

1. INTRODUCTION

Mobile robot technologies are expected to perform various tasks in general environments such as nuclear power plants, large factories, welfare care facilities and hospitals. However, there are narrow spaces with steps and slopes in such environments, and it is difficult for general car-like vehicles to travel around them.

Generally, the mobile vehicle should have flexible mobility for effective task execution. Omni-directional mobility is especially useful for tasks in narrow spaces, because the vehicle can control its position and orientation independently.

*To whom correspondence should be addressed. E-mail: chugo@riken.go.jp

Furthermore, no holonomic constraint enables an omni-directional vehicle to move more quickly and smoothly than a holonomic vehicle [1, 2]. Step-climbing function is also necessary for the mobile vehicle to run over the irregular terrain. Thus, in order to enable the vehicle to run in a general environment that has narrow spaces with a non-flat floor, it is important to have both functions.

In related works, various types of omni-directional mobile robots have been proposed (legged robots, ball-shaped wheel robots, crawler robots, etc.). The legged robots [3, 4] can move in all directions and pass over rough terrain. However, in many cases, the mechanism is complicated and energy efficiency is poor. A robot with ball-shaped wheels can run in all directions [5]; however, it cannot run on rough ground. A special crawler mechanism [6] has also been proposed for the omni-directional mobile robot, but it cannot climb over large steps.

In our previous work, we developed a holonomic omni-directional vehicle with step-climbing ability [7, 8]. Our prototype vehicle utilizes the passive suspension system and also has seven wheels with actuators (DC motors). Thus, our vehicle has redundant actuation and it is important to synchronize the rotation of wheels. However, when the vehicle is climbing steps, a heavy load is applied on the wheels and it is difficult to synchronize them without slipping and blocking. Thus, we proposed a control system that maintains the rotation of each wheel.

When the vehicle passes over rough terrain, it is important that the control system prevents slippage and locking of the wheel. Slippage occurs based on the imbalance between the friction coefficient and driving force. The extraordinary torque to the wheel, which is applied when the vehicle climbs the obstacle, causes the wheel lock and such torque exceeds the permissible torque of the actuator. Therefore, we utilized the traction control approach. Several traction control methods for mobile robots to pass over the rough terrain have already been proposed [9, 10]. These methods only consider the control of a single wheel and do not discuss problems related to synchronization among multiple wheels.

Our proposed control system realizes the passage over irregular terrain. The key idea of our method is that not only the single wheel state, but also the states of multiple wheels are utilized as feedback. We verify the performance of the proposed control method through computer simulations and experiments.

We discuss the mechanical design and the kinematic model of the robot in Section 2. In Section 3, the novel control method is proposed, and we show the implementation and discuss experimental results in Section 4. In Section 5, we conclude this paper.

2. SYSTEM CONFIGRATION

2.1. Mechanical design

Figures 1 and 2 show a prototype mobile mechanism [7] and also an advanced prototype vehicle system. The vehicle has seven wheels and each wheel is equipped

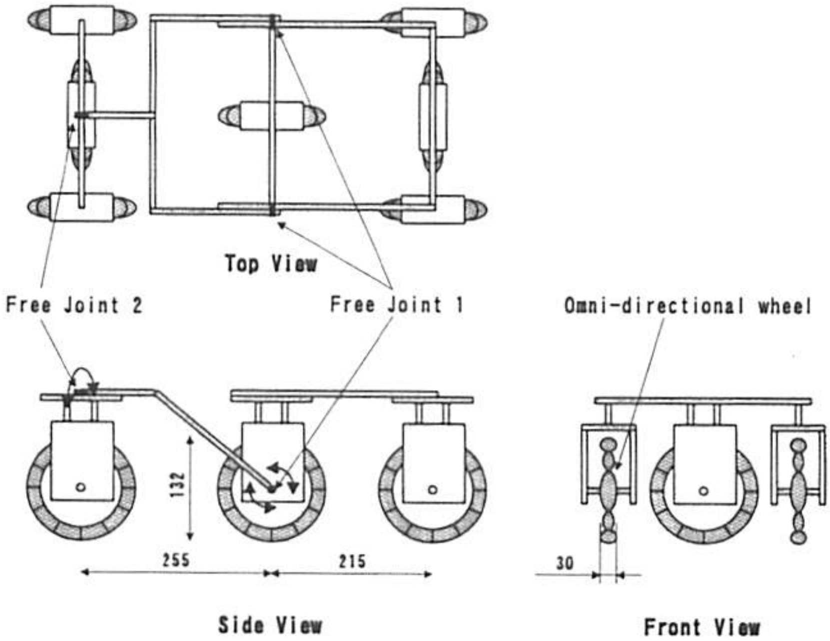


Figure 1. Overview of the mechanism.

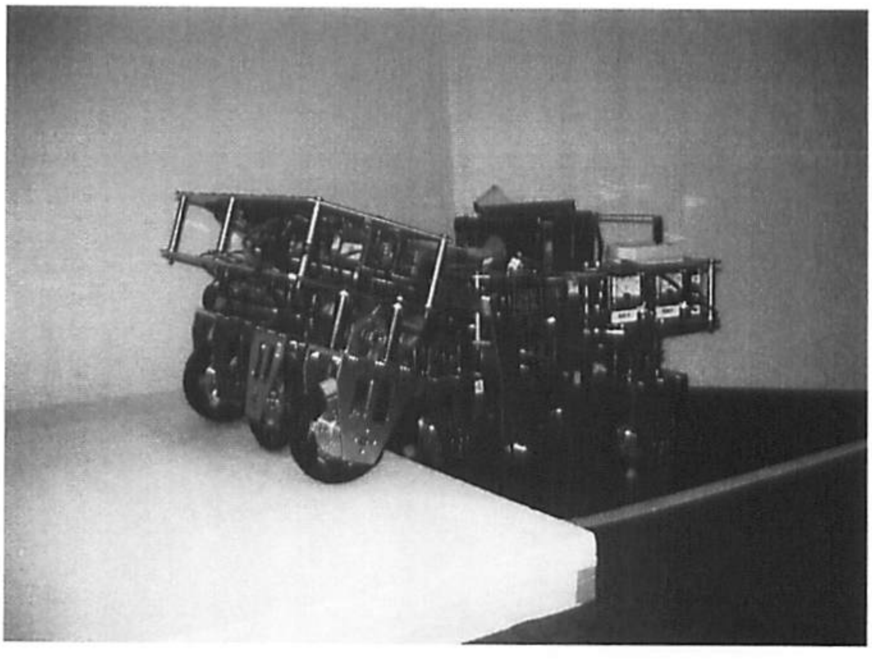


Figure 2. Prototype vehicle.

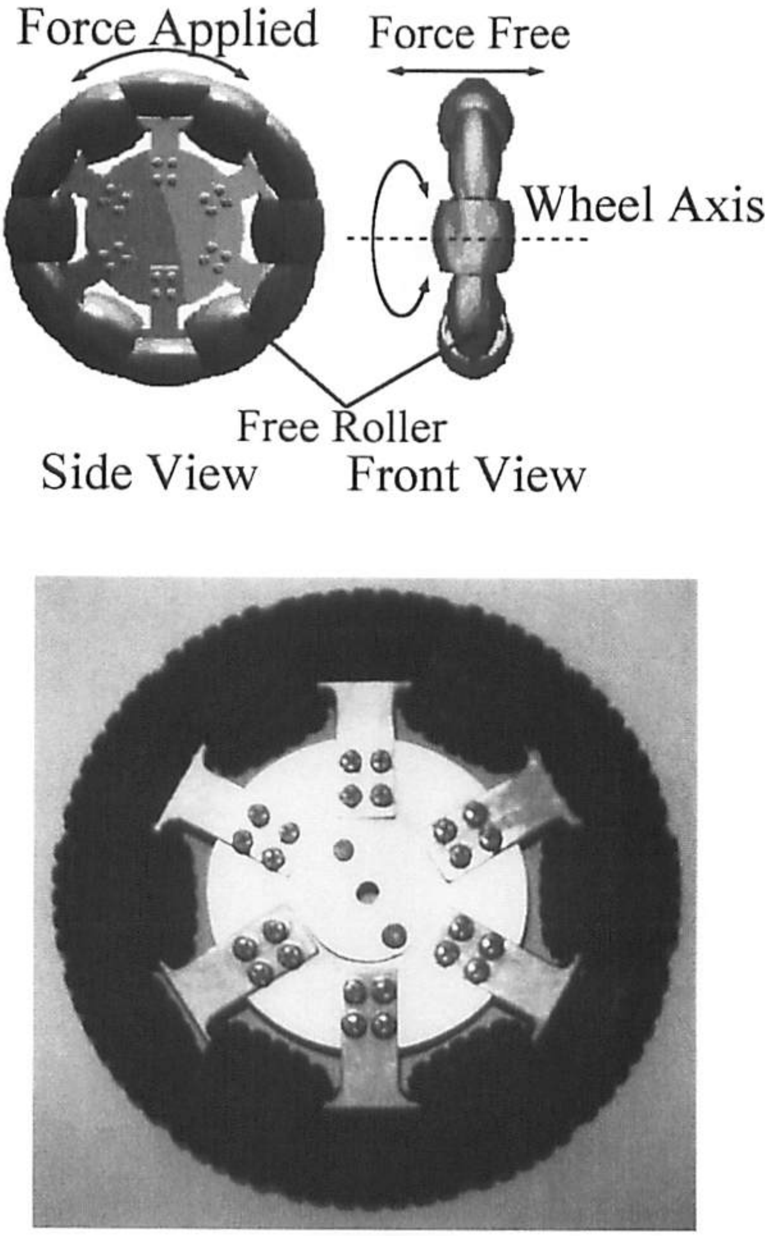


Figure 3. Special wheel.

with a DC motor. The size of the vehicle is 750 mm (L) × 540 mm (W) × 520 mm (H).

The mobile mechanism consists of seven special wheels with free rollers and a passive suspension system. The special wheels consist of 12 cylindrical free rollers (Fig. 3) [11] and generate the omni-directional motion. Generally, running on structured terrain [12], the energy efficiency of the wheeled mobile system is better than those of the other type of mobile systems (e.g. legged or crawler type). This special wheel helps us to realize omni-directional mobility.

Our mechanism utilizes a passive suspension system that consists of two passive body axes. Thus, the system can adapt the body configuration to rough terrain [12–14]. When the vehicle climbs a step as shown in Fig. 4, the body axis is adjusted passively and changes the body configuration depending on the shape of the ground. No sensors and no additional actuators are required to pass over irregular terrain. In general environments, it is not an easy task to estimate terrain conditions precisely. Our system realizes such an estimate function using only the passive body axis [15].

2.2. Kinematics

The kinematics of the developed vehicle are covered in this section. The coordinates, the length of each link and the rotation speed of each wheel when the vehicle is on a flat floor are defined in Fig. 5.

Here, (1) indicates the wheel rotation velocity ω_i when the actuator i rotates at v_i:

$$\omega_i = kv_i, \quad (i = 1, \dots, 7), \tag{1}$$

where ω_i is rotation velocity of the wheel i and k is gear ratio value of the actuator.

Now we consider the relation between the velocity of the vehicle body and the rotation velocity of each wheel. The rotation velocity of wheel 5 must be equal to the rotation velocity of wheel 1, because wheel 1 and wheel 5 are on the same straight line [16]. The speed of wheel 7 is equal to the speed of wheel 3, too. Thus, (2)–(5) are calculated as follows.

$$\omega_1 = \omega_5 \quad \text{and} \quad \omega_3 = \omega_7, \tag{2}$$

$$\dot{x} = \frac{1}{5}(r\omega_1 + r\omega_3 + r\omega_4 + r\omega_5 + r\omega_7), \tag{3}$$

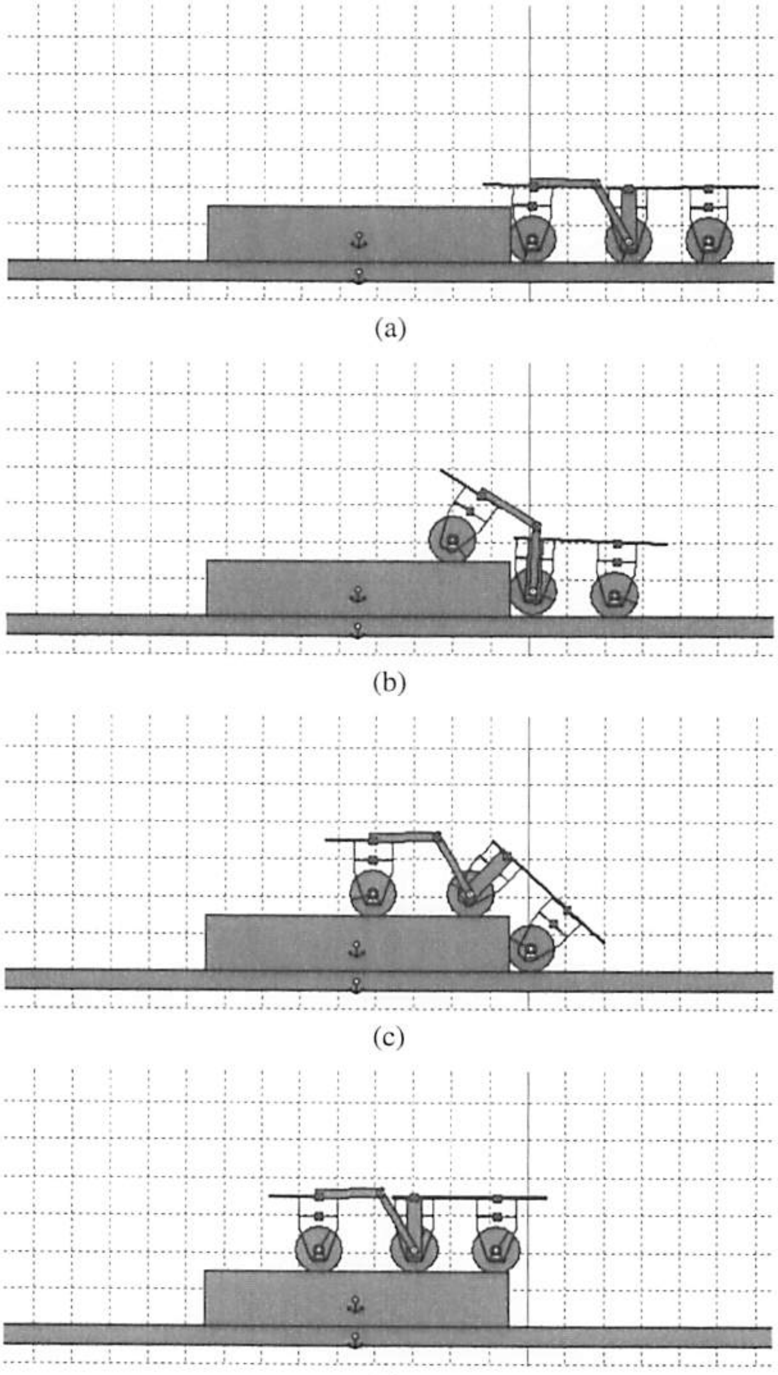
$$\dot{y} = \frac{1}{2}(r\omega_2 + r\omega_6), \tag{4}$$

$$\dot{\theta} = \frac{1}{6}\left(\frac{r\omega_1}{R_2} + \frac{r\omega_2}{R_1} + \frac{r\omega_3}{R_2} + \frac{r\omega_5}{R_2} + \frac{r\omega_6}{R_1} + \frac{r\omega_7}{R_2}\right), \tag{5}$$

where r is the radius of a wheel.

After substituting (1) for (2)–(5), we can get (6) that indicates the relation between the rotation velocity of the wheel $V = [v_1 \ \cdots \ v_7]^{\mathrm{T}}$ and the velocity of vehicle body $\dot{X} = [\dot{x} \ \dot{y}, \dot{\theta}]^{\mathrm{T}}$.

$$\dot{X} = J \cdot V, \tag{6}$$



(a) (b) (c) (d)

Figure 4. The process of climbing up a large step.

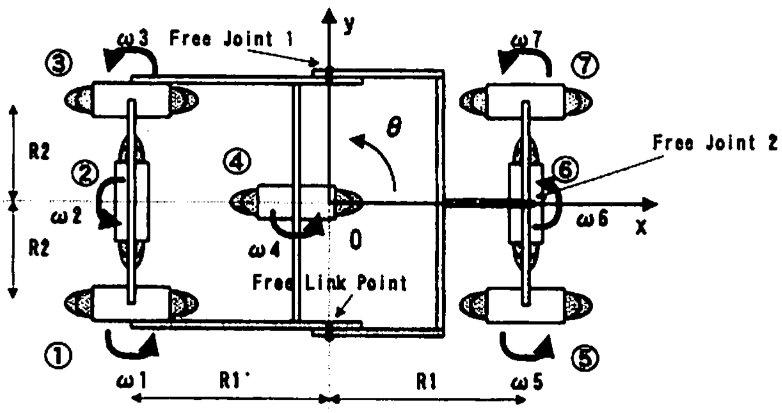


Figure 5. Coordination and parameters. R1 and R2 are the length of each link.

where J is the Jacobian matrix:

$$J = \begin{bmatrix} \frac{kr}{5} & 0 & -\frac{kr}{5} & \frac{kr}{5} & \frac{kr}{5} & 0 & -\frac{kr}{5} \\ 0 & -\frac{kr}{2} & 0 & 0 & 0 & \frac{kr}{2} & 0 \\ \frac{kr}{6R_2} & \frac{kr}{6R_1} & \frac{kr}{6R_2} & 0 & \frac{kr}{6R_2} & \frac{kr}{6R_1} & \frac{kr}{6R_2} \end{bmatrix}. \quad (7)$$

Therefore, the reference value of each actuator can be calculated by the following equation:

$$V = J^{+} \cdot \dot{X}, \quad (8)$$

where J^{+} is pseudo-inverse of Jacobian matrix:

$$J^{+} = (J^{\mathrm{T}}J)^{-1}J^{\mathrm{T}} = \frac{1}{kr} \cdot \begin{bmatrix} 1 & 0 & R_2 \\ 0 & -1 & R_1 \\ -1 & 0 & R_2 \\ 1 & 0 & 0 \\ 1 & 0 & R_2 \\ 0 & 1 & R_1 \\ -1 & 0 & R_2 \end{bmatrix}. \quad (9)$$

Thus, the vehicle must synchronize the rotational velocity of each wheel according to (8) and in this paper we propose the control system for synchronization.

3. CONTROL SYETEM

3.1. Problem specification

The vehicle developed has a redundant actuation system using seven wheels. Thus, our system has to synchronize the wheel rotation based on a control reference,

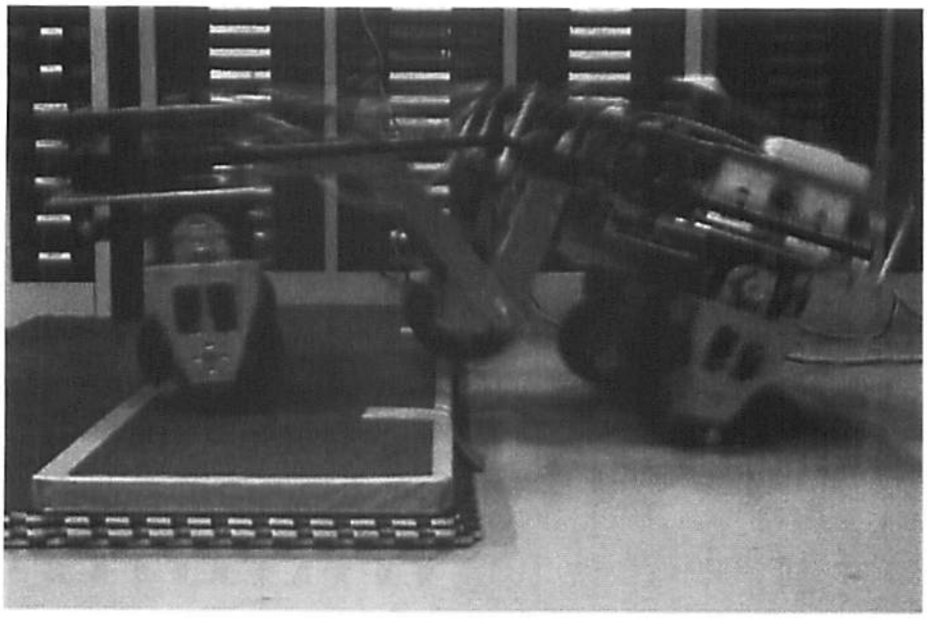


Figure 6. The off-balance situation on irregular terrain.

which is calculated by (8). However, when the robot passes over irregular terrain, it is important to consider how to distribute the load to the wheel. There is no synchronization scheme among the wheels and the vehicle loses the balance of the body posture as shown in Fig. 6.

Thus, each wheel has to synchronize with the others when the vehicle runs on rough terrain. In related works, traction control methods for single wheel have already been proposed [10]. However, they do not discuss synchronization control for multiple wheels running on rough terrain. We describe our proposed method in this section.

3.2. Proposed method

In order to coordinate wheel rotation when the vehicle passes over a step, we consider the following points.

- If a extraordinary load is applied to the wheel(s) or the torque reference exceeds the maximum value of the actuator, the control system cannot drive the wheels accurately. Thus, the calculated torque reference value should not exceed the maximum torque value of the actuator.
- The control reference of each actuator is calculated by the kinematics of the wheel as shown in (8). In particular, the rate of wheel rotation velocities affects the posture stability and the advance direction of the vehicle. Therefore, it is important to maintain the rate of the control reference.

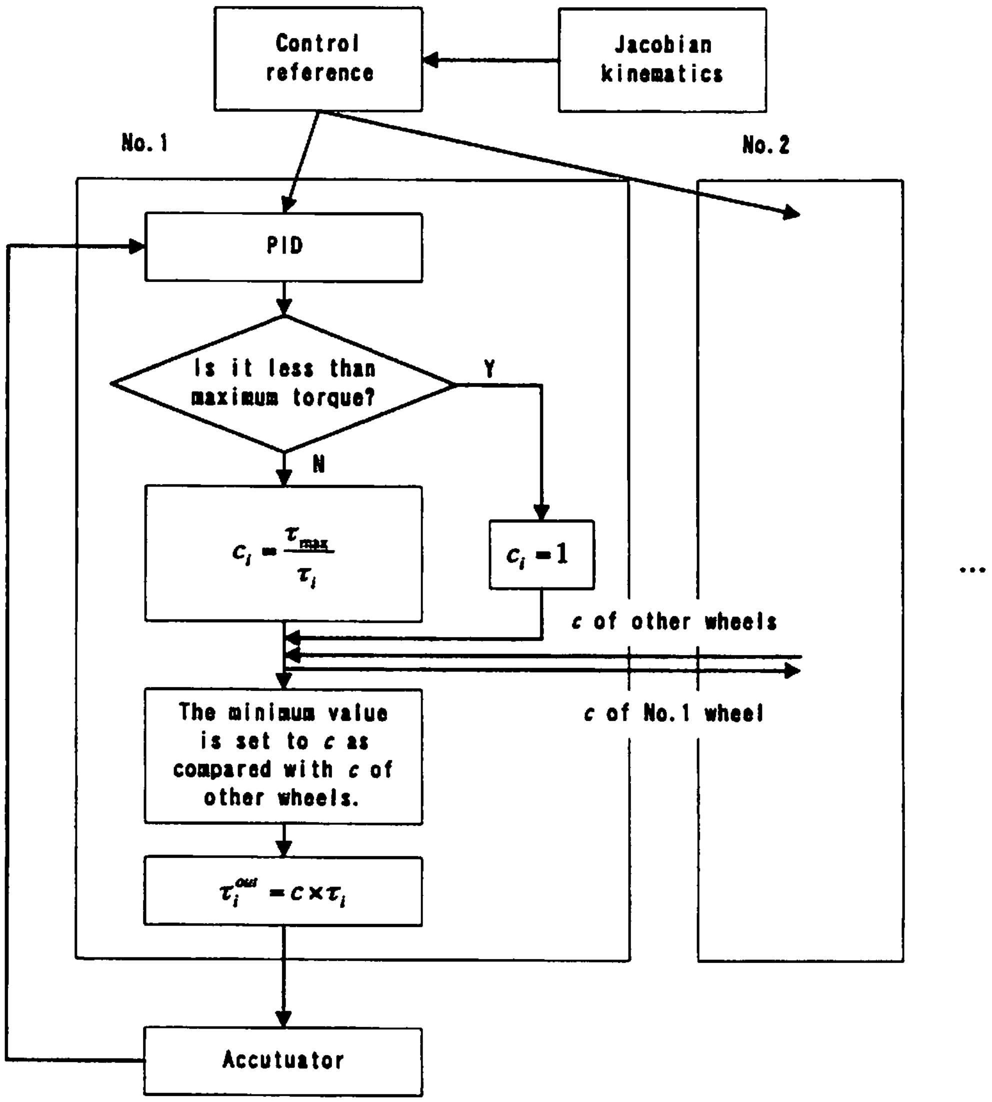


Figure 7. Flow chart of the control scheme.

- In order to fulfill the two criteria mentioned above, if the applied load exceeds the maximum torque, the system reduces the reference to the permissible value maintaining the rate of wheel rotation velocity. This is equivalent to distributing the extraordinary load by suppressing the whole output.

Our proposed control system is shown in Fig. 7. The control value is derived by the PID-based control system (10):

$$\tau_i = k_p e + k_i \int e \, dt + k_d \frac{de}{dt}, \tag{10}$$

where e is the error value of the motor rotation velocity and k_p is the proportional gain. k_i and k_d are the integral gain and the derivative gain for the PID controller, respectively.

The coefficient c_i is determined by:

$$c_i = \begin{cases} \frac{\tau_{max}}{\tau_i} & \text{if } \tau_i > \tau_{max} \\ 1 & \text{if } \tau_i \leqslant \tau_{max}, \end{cases} \quad (11)$$

where τ_{max} is the maximum torque of the motor and τ_i indicates the calculated torque value [i is the identifier of the actuator $(1 \dots 7)$].

The reference torque is determined by (12):

$$\tau_i^{out} = c \times \tau_i, \quad (12)$$

where $c = \min\{c_1, \dots, c_7\}$.

Using this method, the controller adjusts the control value for each actuator in the case when extraordinary loading occurs.

3.3. Computer simulation

Here, we verify the performance of our method by computer simulation. When the vehicle passes over rough terrain, the load is applied to each wheel independently. Thus, in this simulation, we confirm that our proposed controller maintains the synchronization among the wheels even if independent loads are applied to them randomly. As initial conditions, the multiple motors are rotating at the same rotation velocity (100 r.p.m.) and the load is applied to each wheel independently. In this simulation, we set three wheels which are referred to as wheels A, B and C and the loads which are applied to them are referred to as loads A, B and C, respectively. The load is expressed by a dumper model and it is adjustable by changing the dumper coefficient. In this simulation, we apply the load to the wheels as follows:

load A: 0.001 Nm/deg from 5.0 to 7.0 s and 0.003 Nm/deg from 37.0 to 60.0 s

load B: 0.004 Nm/deg from 14.0 to 52.0 s

load C: 0.008 Nm/deg from 22.0 to 57.0 s

In general, the maximum torque that the DC motor can generate changes in relation to its rotation velocity. In this case, we assume that the maximum torque of the wheel is decided by (13). This is based on the feature data of the motors which we used for the prototype:

$$\tau_{max} = -1.713v + 196.13, \quad (13)$$

where τ_{max} is the maximum torque (mNm) and v is the rotation velocity (r.p.m.).

The results of the simulation are shown in Fig. 8: (a)–(c) shows the rotation velocity of wheels A–C, respectively, and (d) shows the loads applied.

In the first, load A, 0.001 Nm/deg, is applied from 5.0 to 7.0 s. This load is smaller than the maximum torque of the motor and, thus, the rotation velocity is maintained.

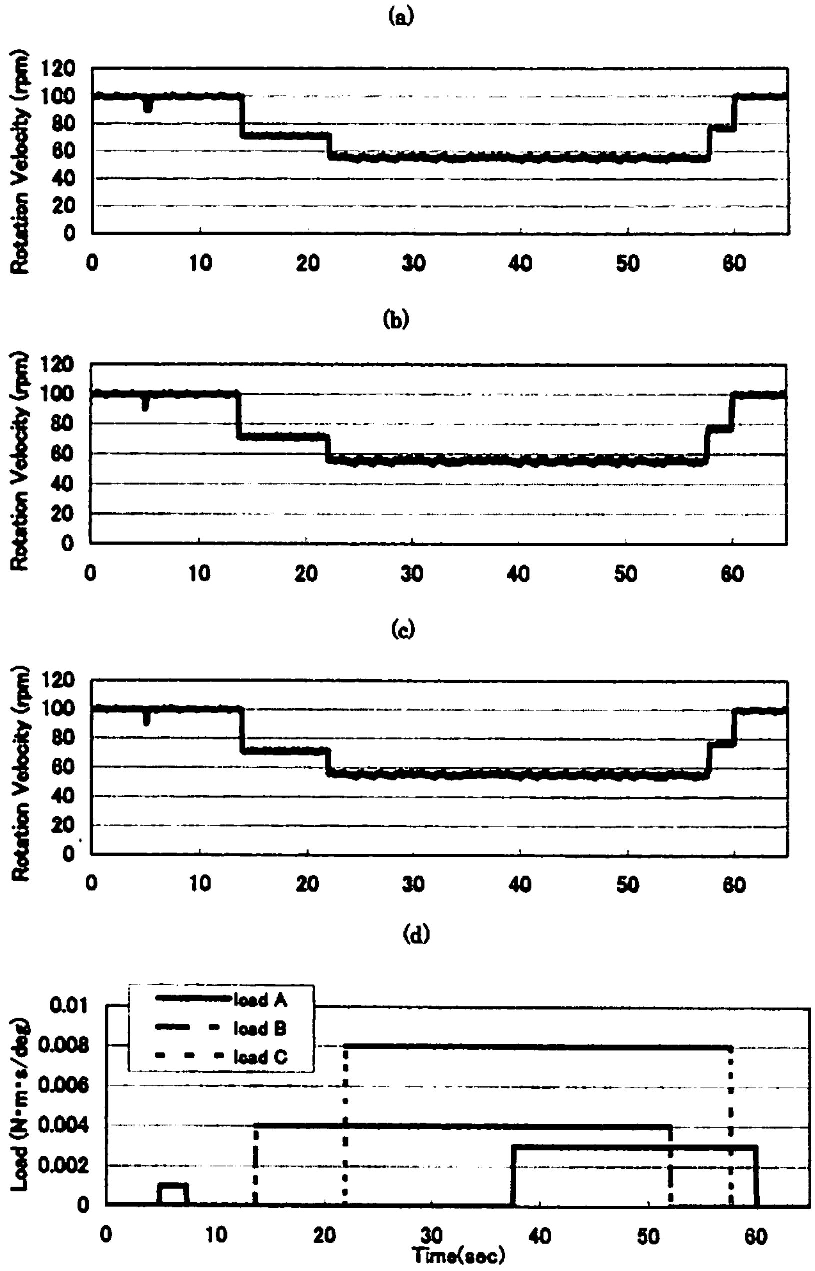
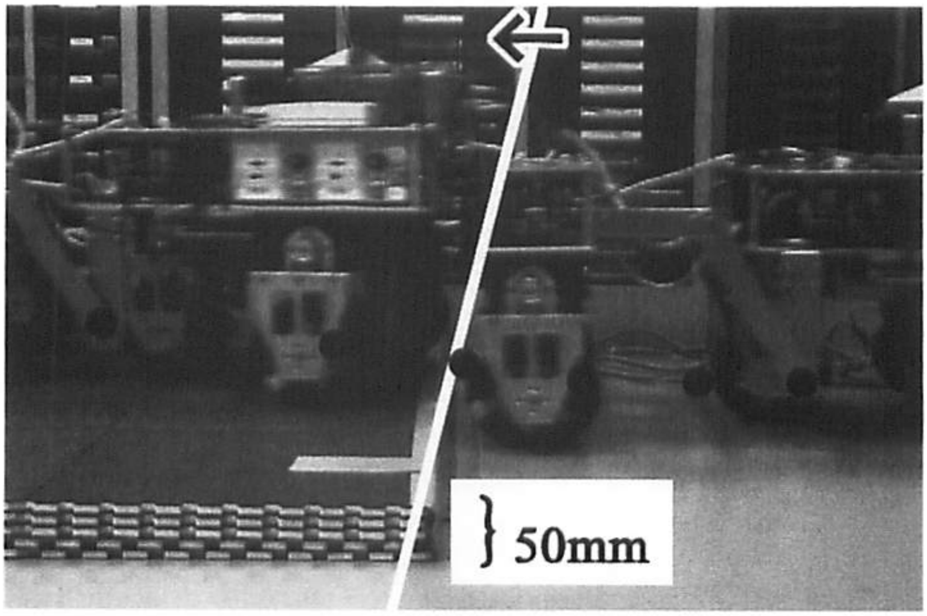


Figure 8. Simulation result. Wheel A (a), B (b), C (c) and applied loads (d).

In the second, load B, 0.004 Nm/deg, is applied at 14.0 s. This load is larger than its marginal value and, thus, the rotation velocity of wheel B falls to the velocity which the motor can keep with the maximum torque. The rotation velocities of wheels A and C converge to the velocity of wheel B.



(a)

Figure 9. Passing over the step with the proposed controller (a) and with a general controller (b).

Load C, 0.008 Nm/deg, is applied at 22.0 s. Therefore, the velocity of motor C slows down from the velocity before the load is applied to the velocity which motor C can rotate at, and the velocities of wheel A and B converge on the velocity of wheel C, thus maintaining synchronization.

Load A, 0.003 Nm/deg, is applied at 37.0 s. However, at this time, load B is the biggest and their velocities do not change. At 57.0 s, load B stops and at this time load A is the biggest. Therefore, the velocities of the three wheels converge on the velocity which motor A can cope with the marginal torque.

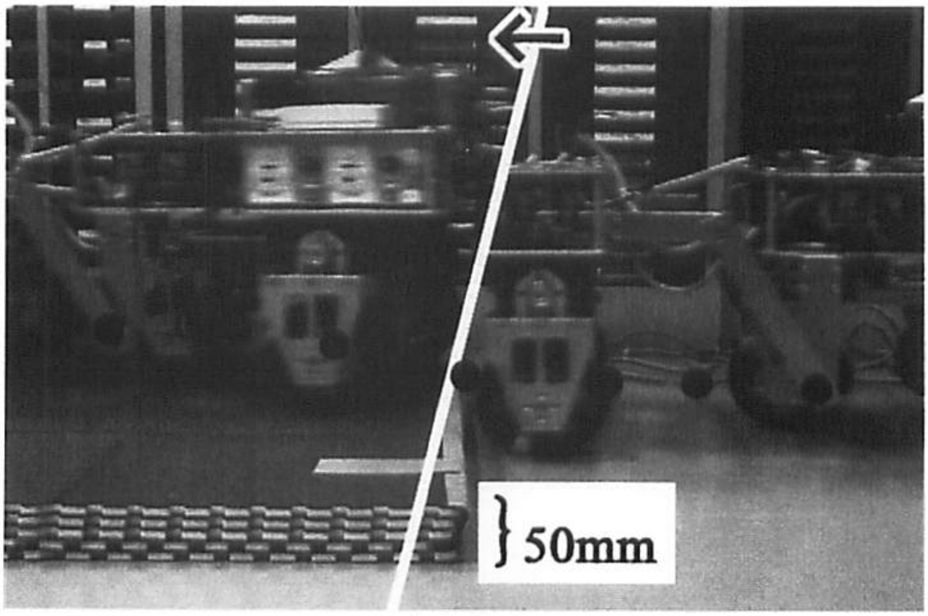
As mentioned above, using the proposed method, each controller adjusts the control command to the wheel and recovers synchronization among the wheel.

4. EXPERIMENTAL RESULT

Here, we show the experiment. The vehicle moves forward at 0.3 m/s and passes over the 5 cm high step. Furthermore, we compare our proposed controller with the general PID controller.

As a result of this experiment, the vehicle can climb up the step more smoothly by our method (Fig. 9). The white points indicate the trajectory of the joint point on the middle wheel and they are plotted at every 0.3 s.

Figures 10 and 11 show the disturbed ratio, i.e. the error ratio of the rotation velocity (a), the slip ratio (b) [14] and the rotation velocity of each wheel (c). The disturbed ratio of wheel rotation and the slip ratio of it are defined by (14) and (15),



(b)

Figure 9. (Continued).

respectively:

$$\hat{d} = \frac{\omega_{\text{ref}} - \omega}{\omega}, \tag{14}$$

$$\hat{s} = \frac{r\omega - v_{\omega}}{r\omega}, \tag{15}$$

where ω is the rotation speed of the actuator, ω_{ref} is the reference value of rotation velocity, and r and v_{ω} indicate the radius of the wheel and the vehicle speed, respectively.

Figures 10 and 11 show only three parameters (front, middle and rear wheel) because our vehicle is symmetric and it passes over the step in forward and backward directions.

5. CONCLUSION

In this paper we discuss the control system for an omni-directional mobile vehicle with step-climbing ability. We designed a new control method that utilizes the state of all the wheels as a feedback value and holds down the torque reference to the maximum torque of the motor. Using this control method, our proposed control system realizes synchronization among the wheels when the vehicle passes over rough terrain. We implemented the system and verified its effectiveness

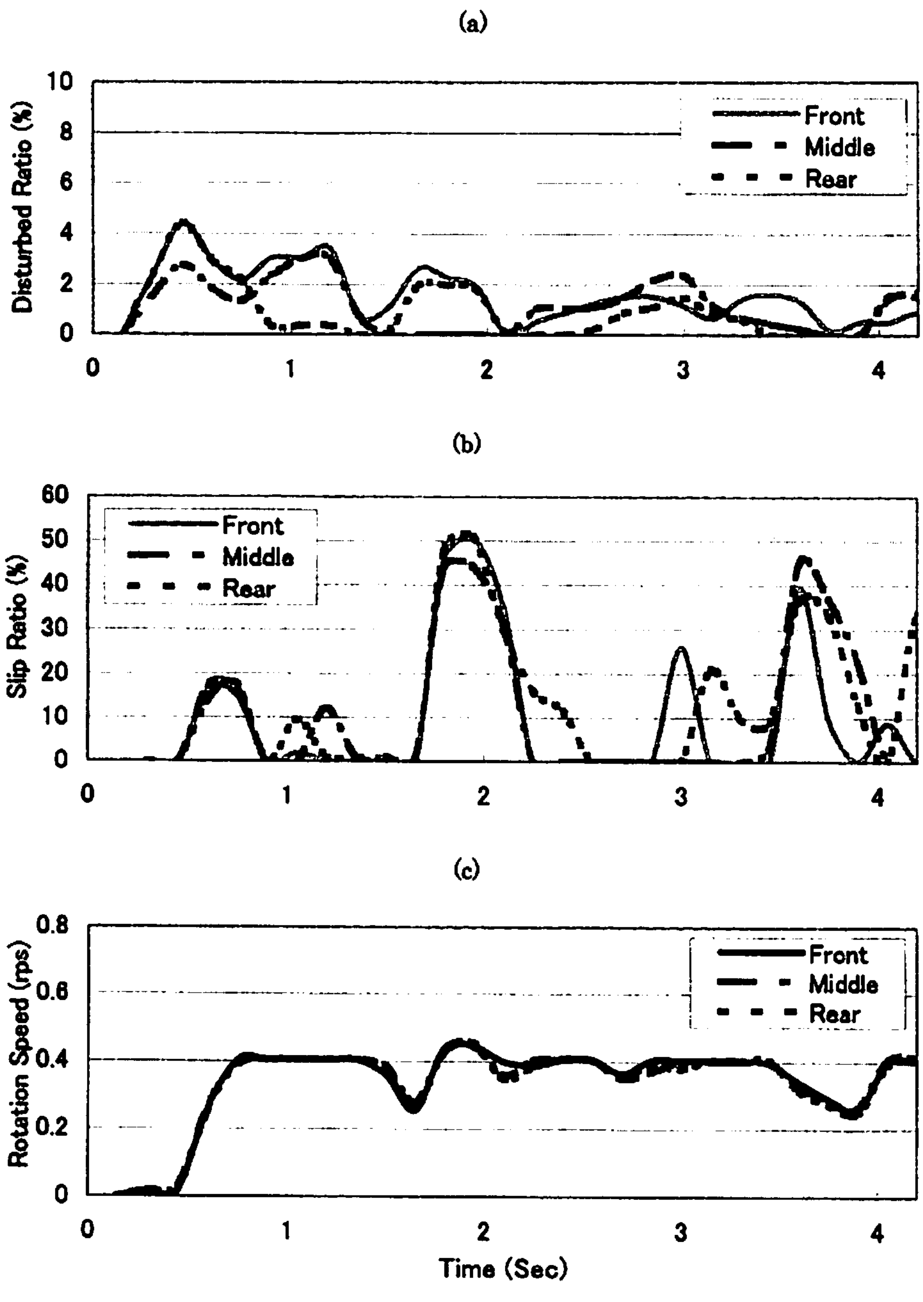


Figure 10. Experimental result of the proposed method. Disturbed ratio of wheel rotation (a), slip ratio of each wheel (b) and rotation velocity of wheel (c).

by simulation and experiment. The error of synchronization decreases, and the disturbed ratio of wheel rotation and the slip ratio are reduced. For future works, we will consider a motion planning method based on environmental information.

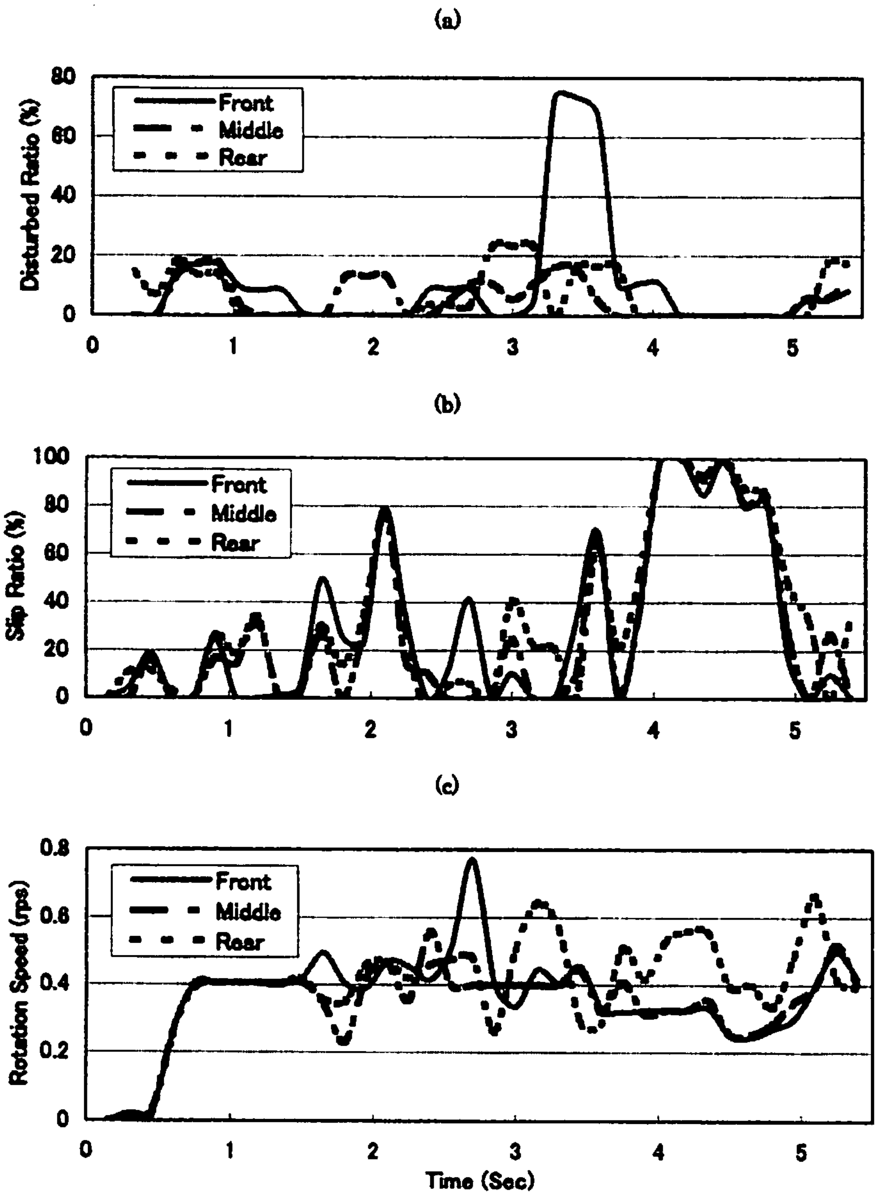


Figure 11. Experimental result of the general method. Disturbed ratio of wheel rotation (a), slip ratio of each wheel (b) and rotation velocity of wheel (c).

REFERENCES

1. G. Campion, G. Bastin and B. D. Andrea-Novel, Structural properties and classification of kinematic and dynamic models of wheeled mobile robots, *IEEE Trans. Robotics Automat.* **12**, 47–62 (1996).
2. M. Ichikawa, Wheel arrangements for wheeled vehicle, *J. Robotics Soc. Jpn.* **13**, 107–112 (1995).

3. G. Endo and S. Hirose, Study on roller-walker: system integration and basic experiments, in: *Proc. IEEE Int. Conf. on Robotics and Automation*, Detroit, MI, pp. 2032–2037 (1999).
4. T. McGeer, Passive dynamic walking, *Int. J. Robotics Res.* **9**, 62–82 (1990).
5. M. Wada and H. Asada, Design and control of a variable footpoint mechanism for holonomic omnidirectional vehicles and its application to wheelchairs, *IEEE Trans. Robotics Automat.* **15**, 978–989 (1999).
6. S. Hirose and S. Amano, The VUTON: high payload, high efficiency holonomic omnidirectional vehicle, in: *Proc. 6th Int. Symp. on Robotics Research*, Hidden Valley, PA, pp. 253–260 (1993).
7. A. Yamashita, H. Asama, H. Kaetsu, I. Endo and T. Arai, Development of a step-climbing omnidirectional mobile robot, in: *Proc. Int. Conf. on Field and Service Robotics*, Helsinki, pp. 327–332 (2001).
8. D. Chugo, K. Kawabata, H. Kaetsu, H. Asama and T. Mishima, Development of omni-directional vehicle with step-climbing ability, in: *IEEE Int. Conf. on Robotics and Automation*, Taipei, pp. 3849–3854 (2003).
9. K. Iagnemma, R. Burn, E. Wilhelm and S. Dubowsky, Experimental validation of physics-based planning and control algrithms for planetary robotic rovers, in: *Proc. 6th Int. Symp. on Experimental Robotics*, Sydney, pp. 319–328 (1999).
10. K. Yoshida and H. Hamano, Motion dynamic of a rover with slip-based traction model, in: *Proc. IEEE Int. Conf. on Robotics and Automation*, Washington, DC, pp. 3155–3160 (2001).
11. H. Asama, M. Sato, L. Bogoni, H. Kaetsu, A. Matsumoto and I. Endo, Development of an omnidirectional mobile robot with 3 DOF decoupling drive mechanism, in: *Proc. IEEE Int. Conf. on Robotics and Automation*, Nagoya, pp. 1925–1930 (1995).
12. T. Estier, Y. Cravsaz, B. Merminod, M. Lauria, R. Pignet and R. Siegwart, An innovative space rover with extended climbing abilities, in: *Proc. Video Proc. of Space and Robotics 2000*, Albuquerque, NM (2000).
13. B. Bickler, A new family of JPL planetary surface vehicles, in: *Proc. Missions, Technologies, and Design of Planetary Mobile Vehicle*, Toulouse, pp. 301–306 (1992).
14. H. W. Stone, Mars Pathfinder microrover: a low-cost, low-power spacecraft, in: *Proc. AIAA Forum on Advanced Developments in Space Robotics*, Madison, WI (1996).
15. P. Lamon and R. Siegwart, 3D-odometry for rough terrain — towards real 3D navigation, in: *Proc. IEEE Int. Conf. on Robotics and Automation*, Taipei, pp. 440–445 (2003).
16. B. Carlisle, An omni-directional mobile robot, in: *Development in Robotics*, B. Rooks (Ed.), pp. 74–87. IFS, Kempston (1983).

ABOUT THE AUTHORS

Daisuke Chugo received the BE and ME degrees in Mechanical Engineering from Tokyo University of Science in 2000 and 2002, respectively. He is PhD Candidate Student in the Department of Information and Mathematical Sciences of Saitama University. He is a student member of the RSJ and IEEE.

Kuniaki Kawabata received the BE, ME and PhD degrees in Electrical Engineering from Hosei University in 1992, 1994 and 1997, respectively. He joined the Biochemical Systems Laboratory at RIKEN (Institute of Physical and Chemical Research) as a Special Postdoctoral Researcher from 1997 to 2000. In 2000, he joined Advanced Engineering Center at RIKEN as a Research Scientist. In 2002, he joined to Distributed Adaptive Robotics Research Unit, RIKEN. His research interests cover distributed autonomous robotic systems, emergent systems and adaptive mechanisms. He is a member of the RSJ, SICE, IEEJ, JSAI and IEEE.

Hayato Kaetsu joined the Radioisotope Technology Division at RIKEN (Institute of Physical and Chemical Research, Japan) in 1971. He worked at the Biochemical Systems Laboratory at RIKEN from 1986 to 2002. From 2002, he joined the Distributed Adaptive Robotics Research Unit at RIKEN as a Senior Engineer. His research interests cover the separation of radioisotopes and distributed autonomous robotic systems. He is a member of the JSME and JSPE.

Hajime Asama received the MS and DS degrees in Engineering from the Department of Precision Machinery Engineering, University of Tokyo, in 1984 and 1989, respectively. He worked at RIKEN (Institute of Physical and Chemical Research, Japan) as a Research Associate, Research Scientist, Senior Research Scientist and Senior Scientist from 1986 to 2002, and became the Professor of RACE (Research into Artifacts, Center for Engineering), University of Tokyo in 2002. He received the JSME Robotics and Mechatronics Division Robotics and Mechatronics Award in 1995, the JSME Robotics and Mechatronics Division Robotics and Mechatronics Academic Achievement Award in 2000, the JIDPO Good Design Award in New Frontier Design Category in 2002, etc. He also received the RoboCup-97 Engineering Challenge Award and the RoboCup-98 Japan Open JSAI award as a member of UTTORI United Team. He was an Editor of *Distributed Autonomous Robotics Systems*, for its second and fifth volumes, which were published by Springer-Verlag, Tokyo in 1994, 1996 and 2002 respectively. He is a member of the IEEE, RSJ, JSME, SICE, New York Academy of Science, etc. His main interests are distributed autonomous robotic systems, cooperation of multiple autonomous mobile robots, emergent robotic systems intelligent data carrier systems and service engineering.

Taketoshi Mishima received the PhD degree from Meiji University in 1973. He worked at the Ministry of International Trade and Industry (MITI) as a Research Scientist and a Senior Research Scientist from 1974 to 1992. In 1992, he became Professor of Josai International University and, in 1993, he became the Professor of Saitama University. His main interest is security system integration. He is a member of the IEICE and IEEE.