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Plural Wheels Control based on Slip Estimation

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Abstract **- In our current research, we are developing a holonomic mobile system which is capable of running over the step. This system realizes omni-directional motion on flat floor using special wheels and passes over non-flat ground in forward or backward direction using the passive suspension mechanism. In order to realize the high mobile performance during step climbing, it is required to reduce wheel slippage for maximizing wheel traction. This paper proposes a new plural wheel control method based on wheel slip estimation. Our key idea is estimation of wheel slippage comparing with the loads and rotation velocities of all actuated wheels, and using this result for wheel control of the vehicle for reducing wheel slippage. The controller can adjust control tractions of plural wheels when the wheel begins to slip and can improve the mobile performance of the vehicle. The performance of our proposed control scheme is experimented by computer simulations and experiments.**

Index Terms – wheel control, wheel slippage, traction control, passive linkages, step climbing.

I. INTRODUCTION

In recent years, mobile robots 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 vertical gaps made by two horizontal floors in such environments and it is difficult for general car-like vehicles to run around there.

Generally, the mobile robots are required to have quick and efficient mobile function for effective task execution. The omni-directional mobility is useful for the tasks, especially in narrow spaces, because there is no holonomic constraint on its motion [1][2]. Furthermore, the step overcoming function is necessary when the vehicle passes over the vertical gaps. Thus, in order to run around general environment, the vehicle needs to equip both of functions. In related works, various types of omni-directional mobile systems are proposed (legged robots, ball-shaped wheel robots, crawler robots, and so on). The legged robot [3][4] can move in all directions and passes over rough terrain. However, its energy efficiency is not so good because the mechanisms tend to be complicated and the robot needs to use its actuators in order to only maintain its posture. The robot with ball-shaped wheels can run in all directions [5], however, it cannot run on the rough grounds. The special crawler mechanism [6] is also proposed for the omni-directional mobile robot, however, which can climb over only small steps. Therefore, there is still a lack of well-adapted mobile system for both narrow spaces and step climbing operation.

Thus, we are developing a holonomic omni-directional vehicle with step-climbing ability. [7] Our prototype utilized new passive suspension system which is suitable for steps in the structured environment [8] and it has seven special wheels with actuators. In order to realize the high mobility during step climbing, our vehicle drives all wheels for increasing traction force. However, the wheel slippage occurs easily when the vehicle passes over the step. Wheel slippage reduces wheel traction force and disturbs the vehicle performance during step climbing. In general, it is difficult that these actions are reduced completely because of the physical characteristic, such as friction between the wheel and ground. However, it is important to reduce them for maximizing wheel traction.

In previous works, many wheel control methods are developed for reducing the wheel slippage. Several wheel traction control methods use slip estimation with the physical characteristic model between the wheel and ground. [9]-[11] However in general environment, the physical characteristic between the wheel and ground always changes and it is difficult to derive the constant physical model for these control methods. Furthermore, in many cases, these researches only consider to control the single wheel. Generally, the wheeled vehicle for rough terrain drives plural wheels in order to transmit maximum traction to the ground, therefore it is required to consider the relationship among them.

We propose a new plural wheels control scheme based on wheel slip estimation. Our proposed scheme realizes that the mobile performance of the vehicle increases by reducing the slippage of the wheels during the step climbing. Our key ideas are estimation of wheel slippage comparing with the loads and rotation velocities of all wheels, and using this result for wheel control of the vehicle. Usually, when the vehicle passes over the step, all wheels don't begin to slip at same time. The first, only wheel which is applied to the heaviest load begins to slip and this wheel cannot support the applied load. Then, this load is applied to other wheels and they begin to slip. Thus, comparing with the loads and rotation velocities of all wheels, the system can estimate the wheel slippage. We verify the performance of the proposed control method through the computer simulations and experiments.

This paper is organized as follows: we introduce the mechanical design and the controller of the vehicle in section 2; we discuss the new proposed control scheme in section 3; we show the results of computer simulations and experiments in section 4; section 5 is conclusion of this paper.

II. Mobile Platform

A. *Mobile Mechanism*

Fig. 1 shows our prototype vehicle system. [8] The vehicle has seven wheels and each wheel is connected to a single DC motor. The size of prototype vehicle is 750[mm](Length) x 540[mm](Width) x 520[mm](Height) and its weight is 22[kg].

The mobile mechanism consists of seven special wheels with free rollers and a passive linkage system. The special wheel equips twelve cylindrical free rollers (Fig. 2) and realizes to generate the omni-directional motion using plural wheels arranged in the different direction and suitable wheel control. [12]

Our mechanism utilizes the passive linkage mechanism consists of two or plural body linkages which are connected with free joints. The wheels are attached with articulated linkage and actuated independently. Therefore, the passive linkage mechanism does not require sensors and additional actuators for terrain adaptation. Our passive linkage mechanism is more suitable for the step than general rocker-bogie suspensions as shown in Fig. 3. [13][14]

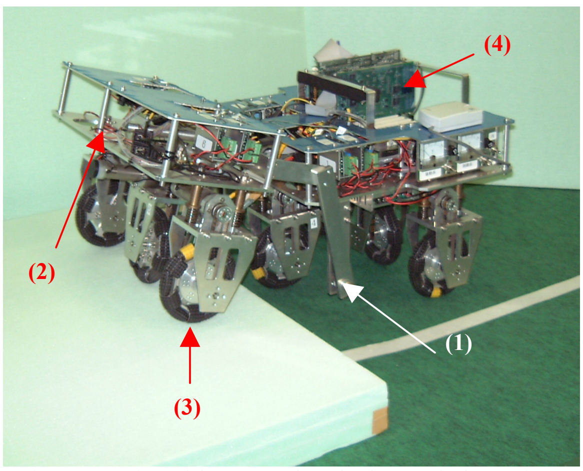


Fig. 1 Overview of the proposed mechanism. (1) is the passive joint 1 (pitch angle), (2) is the passive joint 2 (roll angle), (3) is the special wheel and (4) is the control computer system (CPU and I/O card).

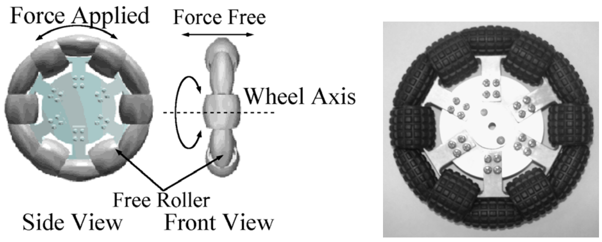


Fig. 2 Special wheels

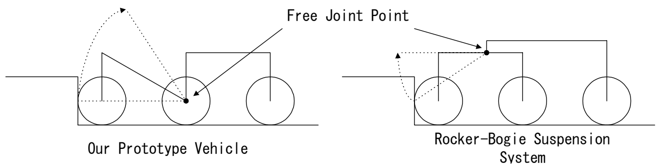


Fig. 3 Our new passive linkage mechanism

B. *Controller*

The control system is shown in Fig. 4. The developed vehicle has seven motor drivers, two potentiometers each joint for the configuration angle and two tilt meters for the inclination of the vehicle body. Our vehicle has redundant actuation system using seven wheels and PID-based control system [8] coordinates the wheel rotation based on control reference, which is calculated according to the body configuration as shown in next paragraph.

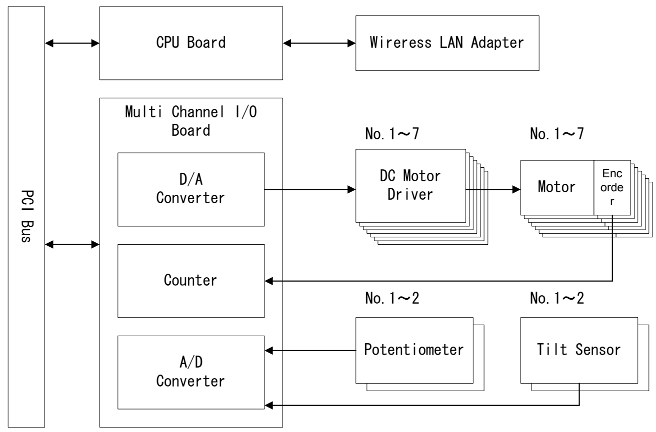


Fig.4 Overview of the vehicle's control system

C. *Kinematics*

Our prototype vehicle drives all wheels and has redundant actuations. Therefore, the vehicle system calculates from its reference speed to the actuator velocity commands based on its kinematic model. [15] However, the passive linkage mechanism changes its body shape and it is required to modify its kinematic model. If the system does not modify the vehicle's kinematic model, the actuator velocity commands are unsuitable to an actual situation because of the difference between an actual body configuration and assumed configuration of the model which is used for calculation.

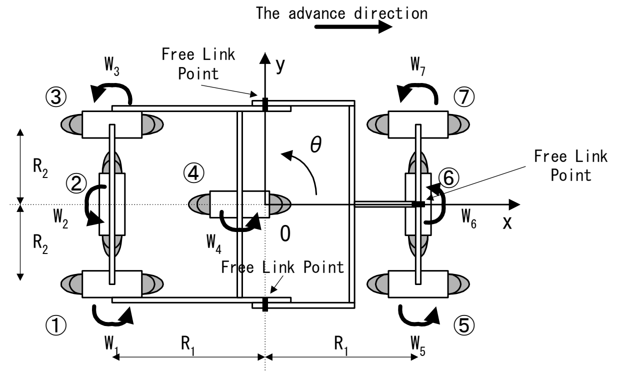


Fig. 5 Wheel coordination and parameters

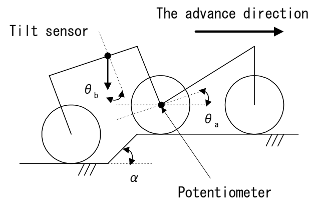


Fig. 6 Body configuration during step climbing

Thus, our prototype derives its wheel control reference using kinematic modification method. [16] Fig. 5 shows the arrangement of the wheels (We display as wheel i: $i = 1 \cdots 7$) and the definition of the coordinates, the length of each links, and the rotate speed of each wheel, respectively. R_1 and R_2 indicate the length of each links. When the vehicle passes over the step at an incline of α [deg] and the body configuration is shown in Fig. 6, the control reference value of each actuator can be calculated by (1).

$$V = J^{+}(\theta_a, \theta_b) \cdot \dot{X} \tag{1}$$

$V = \begin{bmatrix} v_1^{ref} & \cdots & v_7^{ref} \end{bmatrix}^T$ is rotation velocity reference vector of each wheel, $\dot{X} = \begin{bmatrix} \dot{x} & \dot{y} & \dot{\theta} \end{bmatrix}^T$ is the velocity vector of vehicle motion and $J^{+}(\theta_a, \theta_b)$ is pseudo inverse of Jacobian matrix based on its body configuration. r is radius of the wheel and k is gear ratio on the actuator.

$$J^{+}(\theta_a, \theta_b) = \left(J^T J\right)^{-1} J^T$$
$$= \frac{1}{kr} \cdot \begin{bmatrix} \cos\theta_b / \cos(\alpha - \theta_b) & 0 & R_2 \\ 0 & -1 & R_1 \\ -\cos\theta_b / \cos(\alpha - \theta_b) & 0 & R_2 \\ 1 & 0 & 0 \\ \cos\{\alpha - (\theta_a + \theta_b)\} / \cos(\theta_a + \theta_b) & 0 & R_2 \\ 0 & 1 & R_1 \\ -\cos\{\alpha - (\theta_a + \theta_b)\} / \cos(\theta_a + \theta_b) & 0 & R_2 \end{bmatrix} \tag{2}$$

III. Control System

A. Problem Specification

In order to have high mobile performance on step climbing, the vehicle has to transmit enough traction force to the ground. Therefore, our prototype vehicle drives all wheels to generate maximum traction force.

When the vehicle passes over the step, too heavy load is applied to one wheel which contacts the step. If the load is heavier than the friction force between the wheel and ground, the wheel will begin to slip and it cannot transmit its traction force to the ground. If one wheel slips, the other wheels cannot generate traction force even if the other wheels don't slip because unstable posture in Fig. 7. As a result, the vehicle will fail to pass over the step. Therefore, it is important to reduce wheel slippage with distributing the load to all wheels.

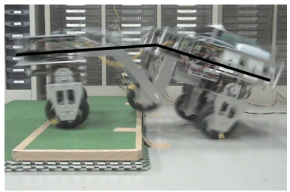


Fig. 7 Off balance situation during step climbing

For reducing wheel slippage, it is required to estimate it. In related works, traction control methods with slip estimation for single wheel have already been proposed. [9]-[11] However, their control methods are not suitable for practical use, because these require the accurate movement information with external world sensor, or the physical characteristic model between wheel and ground. Furthermore, they do not discuss the load disturbing between plural wheels.

Thus, we propose new wheel control scheme based on wheel slip estimation which is derived from only relationship among plural wheels, without the accurate movement information and the physical characteristic model.

B. Proposed scheme

The control traction value of the wheel is derived by PID-based controller. [8] Our novel control scheme adjusts the control traction value for reducing the wheel slippage.

- In general, all wheels don't begin to slip at the same time. The first, only wheel which is applied to the heavy load begins to slip and this wheel cannot support the heavy load. Then, this load applies to the other wheels and they begin to slip. Thus, the system can estimate the wheel slippage comparing with the action of plural wheels.
- If the wheel slips, its rotation velocity will become faster than velocities of other wheels. The rotation velocities of each wheel are derived by the kinematic relationship between them. Therefore, comparing with velocity error value e_i of each wheel in (3), the system can estimate wheel slippage when (4) is satisfied. (Condition 1)

$$e_i = v_i^{ref} - v_i \tag{3}$$

v_i^{ref} is control velocity reference derived from (1) and v_i is actual rotation velocity.

$$e_i > \frac{\sum_{j=1}^{7} e_j - e_i}{6} \tag{4}$$

- However, there is a possibility that the control system will misjudge the non-slippage wheel to be slipping when other wheels are stuck, using only the previous condition. Because comparing with the velocity of the stuck wheel, the velocity of the other wheel will be faster even if the wheel doesn't slip.
- Therefore, we set second condition. When the wheel slips, it cannot transmit its traction force to the ground and its output traction will reduce. Thus, comparing with the output tractions τ_i of the other wheels, the system can estimate wheel slippage when (5) is satisfied. (Condition 2)

$$\tau_i > \frac{\sum_{j=1}^{7} \tau_j - \tau_i}{6} \tag{5}$$

- Using both conditions, the system can estimate the slippage of each wheel. The controller reduces traction output of the wheel which slips largest, because we can judge that this wheel is applied to the heaviest load. Furthermore, the traction output of the other wheels is reduced at same rate for keeping the coordination among each wheel.
- Therefore, we set the coefficient c_i for measuring the extent of wheel slippage in (6). Comparing with these coefficients, the controller can judge that the wheel slips largest when the value of c_i is smallest. The controller coordinates the traction output τ_i^{out} in (7).

$$c_i = \begin{cases} \dfrac{6\tau_i}{\sum_{j=1}^{7} \tau_j - \tau_i} & if \quad e_i > \dfrac{\sum_{j=1}^{7} e_j - e_i}{6} \quad and \quad \tau_i > \dfrac{\sum_{j=1}^{7} \tau_j - \tau_i}{6} \\ 1 & if \quad e_i \le \dfrac{\sum_{j=1}^{7} e_j - e_i}{6} \quad or \quad \tau_i \le \dfrac{\sum_{j=1}^{7} \tau_j - \tau_i}{6} \end{cases} \tag{6}$$

$$\tau_i^{out} = c \cdot \tau_i \tag{7}$$

where $c = \min\{c_1, \cdots, c_7\}$

- Therefore, proposed control system can distribute the load and reduce the wheel slippage with coordination among drive tractions of all wheels.

The flow chart of our proposed scheme is shown in Fig. 8.

IV. Experiment

A. Computer simulation

We verify the performance of our proposed scheme by computer simulations. Here, we discuss the vehicle motion in the direction of the X-axis in Fig. 5, because our vehicle passes over the step in its forward and backward direction. As initial conditions, simulation parameters are chosen from the prototype model. The parameters are shown in Table 1.

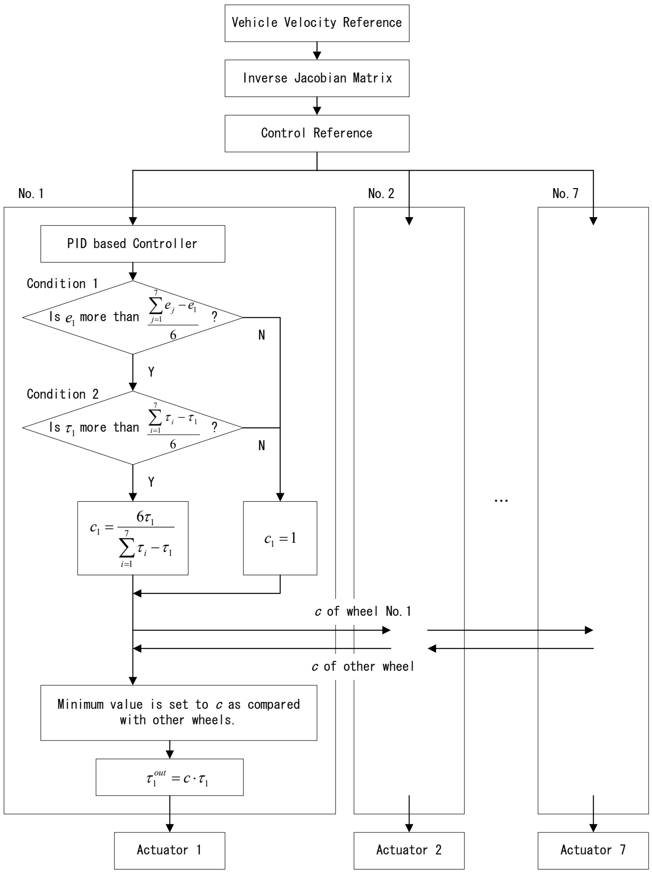


Fig. 8 Flow chart of proposed control scheme

TABLE I
VEHICLE PARAMETERS

Length	Front 195[mm] Rear 400[mm]
Body Weight	Front 7.8[kg] Rear 13.8[kg]
Wheel diameter	132[mm]
Distance between wheels	Front 255[mm] Rear 215[mm]
Center of Gravity	Front: on the front wheel
	Rear: 105[mm] from middle to rear wheel
Friction coefficient	Static 0.4 Dynamic 0.3
Running speed	0.25[m/sec]

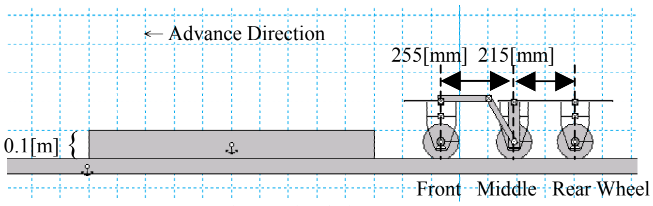
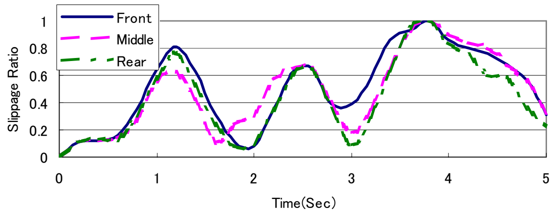


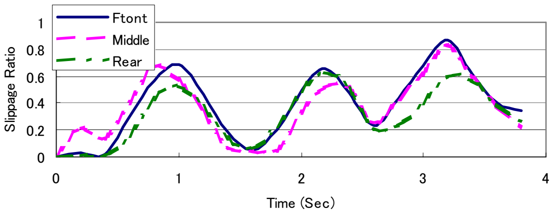
Fig. 9 Simulation Setup

In this simulation, the vehicle passes over the step as shown in Fig. 9. The height of slope is 0.1[m] and the length is 1[m]. In order to verify that proposed system is effective, we compare the result by our proposed control scheme with the result utilizing standard PID controller, which doesn't estimate wheel slippage.

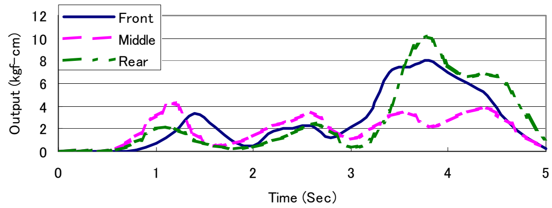
B. *Simulation Result*



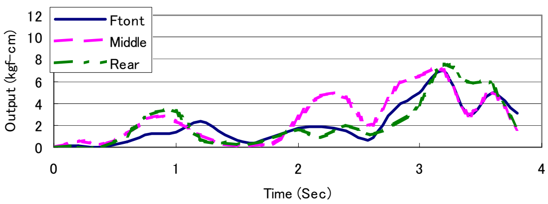
(a) The slip ratio with standard controller



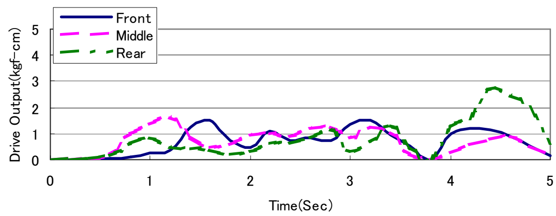
(b) The slip ratio with proposed controller



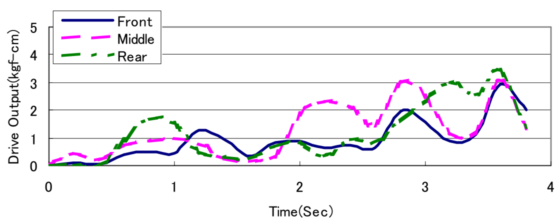
(c) The output traction with standard controller



(d) The output traction with proposed controller



(e) The drive traction with standard controller



(f) The drive traction with proposed controller

Fig. 10 Simulation results

Fig. 10 and Table 2 shows the simulation results. The slip ratio [9] and the force transmit ratio of the wheel are calculated by (8) and (9), respectively. The force transmit ratio means that how much force is transmitted to the ground among the power which the wheel outputs.

$$\hat{s}_i = \frac{r_i\omega_i - v_i}{r_i\omega_i} \tag{8}$$

$$\hat{t}_i = \frac{\tau_i^{out} - \tau_i^{trs}}{\tau_i^{out}} \tag{9}$$

ω_i is the rotation speed of the actuator and ω_i^{ref} is the reference value of wheel rotation velocity derived from (2). r_i and v_i indicate the radius of the wheel and the vehicle speed, respectively. τ_i^{trs} is the drive force which is transmitted from the wheel to the ground.

TABLE II
SIMULATION RESULTS

	Scheme	Front Wheel	Middle Wheel	Rear Wheel	Average
Slip	Standard	26.7	25.9	24.4	25.7
	Proposed	12.9	12.0	10.4	11.7
Trans	Standard	49.6	52.4	56.7	52.9
mit	Proposed	79.8	83.3	89.5	84.2

By these simulations, we verified the proposed control scheme improves the performance of the step overcoming. The slip ratio of the wheel decreases 54.5[%] on the average. And the force transmit ratio of the wheel increases 37.2[%]. Furthermore, output force with standard controller is larger than one of proposed scheme as shown in Fig. 10 (c) and (d), however, drive force with proposed scheme is larger than one of standard scheme as shown in Fig. 10 (e) and (f). It means our proposed control scheme transmit the drive force to ground more efficiently than the standard controller.

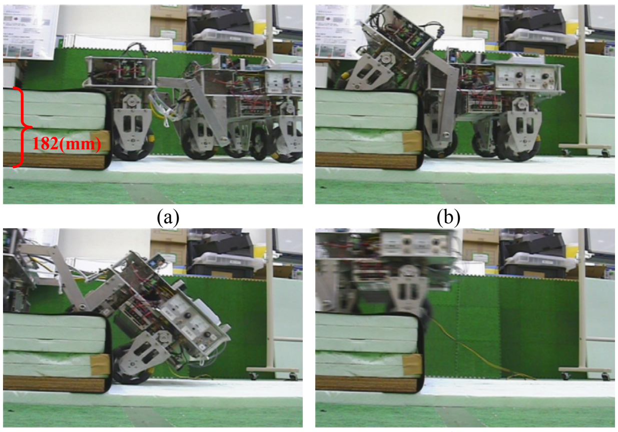
As the result, the performance of our proposed scheme is better than one of the standard PID controller for passing over the step.

C. *Experiment using the prototype*

Here, we verify the performance of our control scheme by the experiment using our prototype. In this experiment, the prototype vehicle passes over the step from forward direction and we verify about two topics. One topic is the height of the step which the vehicle can climb up. The other topic is the slippage of the wheels when the vehicle passes over 125[mm] height step. We compare the result by our proposed scheme with the result utilizing standard PID controller, which doesn't consider the body shape.

As the result of the experiment, the vehicle can pass over the 182[mm] height step with our proposed method as shown in Fig. 11. The diameter of wheel is 132[mm] and the vehicle passes over the step which height is 1.5 times higher than wheel diameter. With standard PID controller, the vehicle can pass over the only 125[mm] height step.

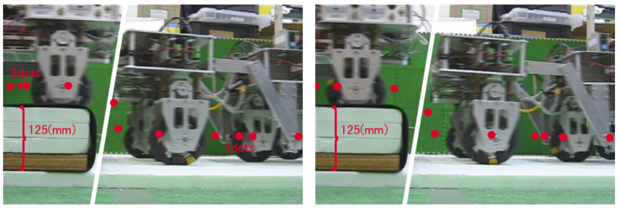
Fig. 12 (a) and (b) show the tracks of the vehicle during 125[mm] height step with standard scheme and proposed scheme, respectively. Using proposed control scheme, the vehicle can passes over the step more smoothly.



(a) (b)

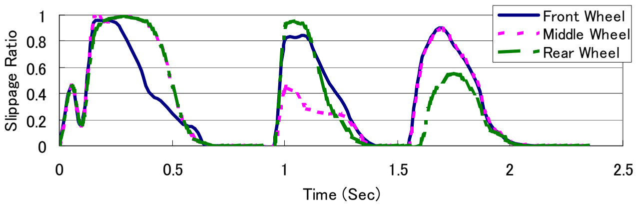
(c) (d)

Fig. 11 Passing over 182[mm] height step

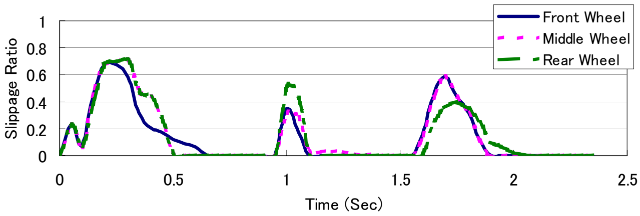


(a) With standard scheme (b) With proposed scheme

Fig. 12 Tracks during passing over 125[mm] height step
Red points are plotted at every 0.3[sec].



(a) With standard controller



(b) With proposed controller

Fig.13 Slip ratio during passing over 125[mm] height step

Fig. 13 (a) and (b) show the slip ratio by standard PID controller and proposed control scheme, respectively. When the vehicle passes over the 125[mm] height step, the slip ratio reduces with our proposed scheme. Furthermore, with our proposed scheme, difference of slip ration between front, middle and rear wheels are reduces.

From these results, our proposed scheme reduces the slippage of the wheels and disturbs heavy load to all wheel. Furthermore, our scheme improves the vehicle's performance of the step overcoming. Therefore, our proposed control scheme is effective for passing over the step.

V. Conclusion

In this paper, we propose new plural wheels control scheme based on wheel slip estimation for step climbing wheeled vehicle, which has plural actuated wheels. We discuss the estimation of wheel slippage comparing with the loads and rotation velocities of all actuated wheels. Using our proposed scheme, the controller can adjust plural wheel control tractions for reducing wheel slippage and can increase the mobile performance of the vehicle on rough terrain.

We verified the effectiveness of our proposed scheme by the computer simulations and experiments. Utilizing our proposed scheme, the slip ratio of the wheel reduces and its step overcoming performance is improved.

As our future works, we will consider the motion planning method based on the environment information.

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