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Development of a Control System of an Omni-directional Vehicle with a Step Climbing Ability

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Abstract. We proposed a new holonomic mobile mechanism which is capable of running over the step. This mechanism realizes omni-directional motion on flat floor and passes over non-flat ground in forward or backward direction. The vehicle equips seven omni-directional wheels with cylindrical free rollers and two passive body axis that provide to change the shape of the body on the rough terrain. This paper presents a method to control the wheels for passing over rough terrain with the stable posture. Our vehicle is required to keep synchronization among its wheels for climbing the step without slipping and blocking. Therefore, in this paper, an algorithm of synchronization among all wheels is proposed. The performance of our system is experimented by means of computer simulations and experiments using our prototype vehicle.

1 Introduction

In recent years, mobile robots are expected to perform various task in general environment such as nuclear power plants, large factories, welfare care facilities and hospitals. However, there are a lot of narrow spaces with steps and slopes in such environments, and it is difficult for general car-like vehicles to run around.

Generally for effective task execution, it is required to realize quick and efficient mobile function. The omni-directional mobile capability is useful for the tasks in narrow spaces, because there is no holonomic constraint on its motion [1]. On the other hand, it is required to run over the irregular terrain. Both of these capabilities are required to compose high mobility system for field and service robots.

In related works, various types of omni-directional mobile robots are proposed: legged robots, ball-shaped wheel robots, crawler robots, and so on. The legged robots [2] can move in all directions and pass over rough terrain. However, its mechanism and control system tend to be complicated and energy efficiency is generally not so high. The robot with ball-shaped wheels can run in all directions [3], however, it cannot run on the rough grounds. The special crawler mechanism [?] is also proposed

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for the omni-directional mobile robot. It can move on the rough terrain, but it cannot climb over large steps.

For realization of running in narrow spaces and on irregular terrain, we developed a new holonomic omni-directional vehicle with step-climbing ability. [5] Our prototype utilized the rocker-bogie suspension system and also has the redundant actuators, and it is important to keep synchronization among the wheels. However, during the vehicle is climbing steps, it is difficult to synchronize the wheels without slipping and blocking.

For wheel control, we utilized the traction control. Several traction control methods for mobile robots to pass over the rough terrain were already proposed [6,7]. These methods consider to control only single wheel and do not address the problem related to synchronization among plural wheels.

Our proposed method realizes that the mobile robot passes over the irregular terrain with synchronization among the wheel rotations. The key idea of our method is that not only the single wheel state but also the plural wheel states are utilized as feedback value. We verify the performance of the proposed control method through the computer simulations and experiments.

This paper is organized as follows: we discuss the mechanical design, the kinematic model of the robot in section 2; the new control method is proposed in section 3; we show the implementation and experimental results in section 4; section 5 is conclusion of this paper.

2 System Configuration

2.1 Mechanical Design

We already developed a prototype mobile mechanism [5] and also an advanced prototype vehicle system (Figure 1 and 2). The vehicle has seven wheels with DC motors. The size of the vehicle is 750mm(L) x 540mm(W) x 520mm(H) and the total weight is approximately 22 [kg] with the batteries.

The mobile mechanism consists of seven special wheels with free rollers and a rocker-bogie suspension system. The special wheels consist of twelve cylindrical free rollers (Figure 2) [8] and realize to generate the omni-directional motion. Generally, on the viewpoint of energy efficiency of running on the structured terrain [9], the wheeled mobile system is better than the other type of mobile systems (e.g., legged or crawler type). Thus, our mobile mechanism realizes the omni-directional function and high-energy efficiency, compatibly.

Our mechanism utilizes the rocker-bogie suspension system, which consists of passive links, and it can adapt itself to rough terrain. [6,10]. No sensors and no additional actuators are equipped to pass over irregular terrain. In general environment, it is not easy task to estimate terrain condition precisely. Our system realizes such estimate function only using passive body axis.

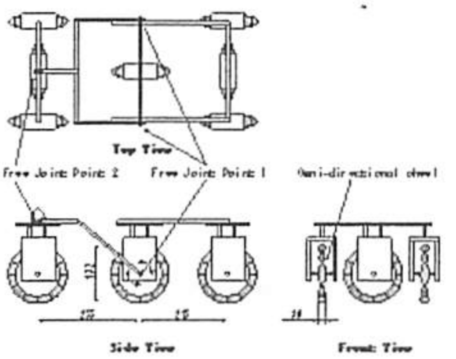


Fig. 1. Overview of the mechanism

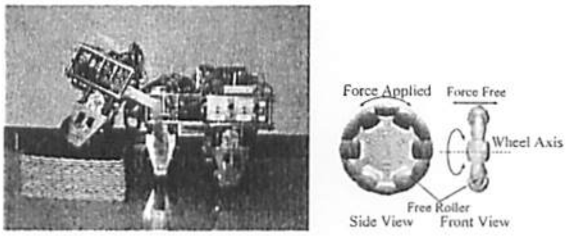


Fig. 2. Prototype Vehicle and Special wheel

2.2 Kinematics

The vehicle's configuration, position and attitude are defined by the body parameters: R1, R2 and wheel rotation velocity values $(\omega_1, \ldots, \omega_7)$, in Figure 3.

Here, equation(1) indicates the wheel rotation velocity.

$$\omega_i = kV_i (i = 1, \ldots, 7) \tag{1}$$

where,

r : radius of the wheel [mm]
ω_i :rotation velocity of the wheel i [rad/s]
V_i :rotation velocity of the actuator i [rad/s]
k : gear ratio between the actuator and the wheel

Now, $\dot{X} = \ \dot{x}\ \dot{y}\ \dot{\theta}\ ^{T}$ and $V = \ V_1 \cdots V_7\ ^{T}$ express the motion velocity vector of the vehicle and the rotation velocity vector of the actuators, respectively. V is also derived by using $\dot{X}$ in equation (2).

$$V = J^{+} \cdot \dot{X}, \tag{2}$$

where J^+ is pseudo inverse of Jacobian matrix;

$$J^+ = \left(J^T J\right)^{-1} J^T = \frac{1}{kr} \cdot \begin{bmatrix} 1 & 0 & R_2 \\ 0 & -1 & R_1 \\ -1 & 0 & R_2 \\ 1 & 0 & 0 \\ 1 & 0 & R_2 \\ 0 & 1 & R_1 \\ -1 & 0 & R_2 \end{bmatrix} \tag{3}$$

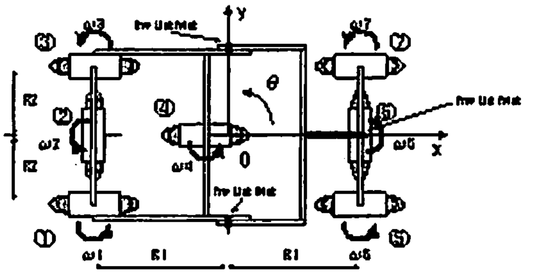


Fig. 3. Coordination and parameters

2.3 Problem Specification

The developed vehicle has redundant actuation system using seven wheels. Thus, our system has to synchronize the wheels with following each control reference, which is calculated by equation (2) using Jacobian. However, during the robot passes over the irregular terrain, the load distribution to each wheel is complex problem. Therefore, it is difficult to synchronize among the wheel. If the system fails to take the synchronization among the wheels, the vehicle will lose the balance of the body posture as shown in Figure 4.

Thus, each wheel has to synchronize with the others when the vehicle runs on the rough terrain. In related works, some traction control methods for single wheel are already proposed. However, they do not discuss synchronization of the wheels for running on rough terrain. For our system, we must consider the synchronization among the wheels. We explain our proposed method in next section.

3 Control System

3.1 Proposed method

In order to synchronize the wheels rotation during the vehicle passes over the step, calculated torque reference value should not over the maximum torque of the

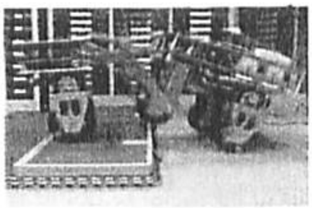


Fig. 4. The vehicle losing the balance

motor. If extraordinary load applies on the wheel(s) or the torque reference exceeds maximum torque of the motor, the system cannot control the wheels, properly.

Our proposed control system is shown in Figure 5. The control reference is calculated by PID-based control system (equation (4)).

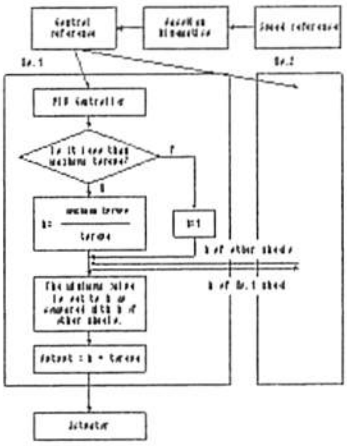


Fig. 5. Flow chart of the control system

The torque reference of i-motor is calculated by equation (4).

$$\tau_i = k_p e + k_i \int e\,dt + k_d \frac{de}{dt}, \tag{4}$$

where

e :Error value of the motor rotation velocity
k_p :Proportional gain for PID controller
k_i :Integral gain for PID controller
k_d :Derivative gain for PID controller

The coefficient k_i is calculated as:

$$k_i = \begin{cases} \frac{\tau_{\max}}{\tau_i} & if \quad \tau_i > \tau_{\max}, \\ 1 \quad if & \tau_i \leq \tau_{\max}, \end{cases} \tag{5}$$

where

$\tau_{\max}$:Maximum torque of the motor
τ_i :Calculated torque value
i : 1 ... 7(number of an actuator)

The reference torque is determined by equation (6):

$$\tau_i^{out} = k \times \tau_i, \tag{6}$$

where $k = \min \{k_1, \cdots, k_7\}$.

The controller adjusts the synchronization among the wheel in the case of extraordinary load occurring.

3.2 Simulation

We verify the performance of our method by computer simulations. As initial conditions, three motors are rotating at same fixed velocity speed 100[deg/s] and the load applies to each motor independently. The load is approximated by a dumper model and the dumper coefficients are applied to each wheel as follows.

load A : 0.001[Nm/deg] from 37 to 60[sec]
load B : 0.004[Nm/deg] from 14 to 52[sec]
load C : 0.005[Nm/deg] from 22 to 57[sec]

In this case, we assume that the maximum torque of the motor is 30[N].

The results of the simulation are shown in Figure 6. During the load applied to the wheel (from 14 to 60[sec]), rotation velocity of the motor is reduced. Using proposed method, each controller adjusts control command to the wheel and recovers synchronization among the wheel.

3.3 Method of Sensing the Step

We utilized PID based control system, however it is difficult to determine the parameters of the controller when the control target has complex dynamics. Thus, we switch two parameter sets according to the situations. The vehicle has the accurate control mode for the flat floor and the posture stability control mode for the rough terrain. The stability mode utilizes the proposed traction control method, too.

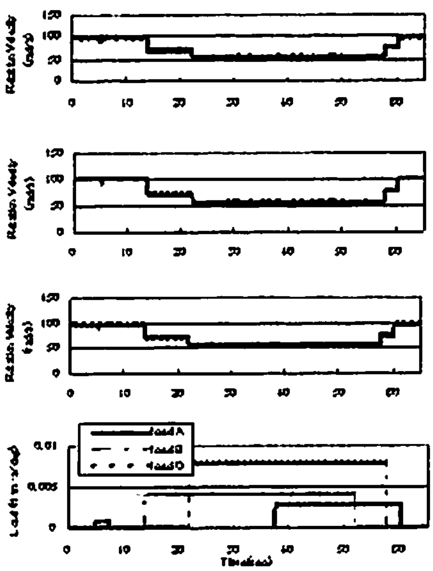


Fig. 6. Simulation result

In order to switch two parameter sets, the terrain estimation function is required. Thus, we proposed the estimation method using the body axes. The angle of two axes of the body is changed passively by the ground surface. The terrain can be measured by using the body kinematics information. Two potentiometers measure the angle of the axes (Figure 7). By this information, the controller can switch two parameter sets according to the terrain condition.

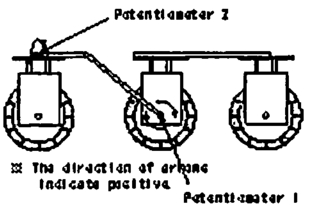


Fig. 7. Two Potentiometers

4 Experiment

Here, we have the following two experiments.

4.1 Measuring the Step

In first experiment, we verify the sensing ability of the vehicle when it passes over the rough ground. The vehicle climbs the step with 30[cm] depth and 1[cm] height.

The experimental result is shown in Figure 8 and it indicates that the height of the step is 0.9[cm] and the depth is 32.5[cm]. Our vehicle need to change the control mode when the step is more than 3[cm] [7], it is enough step detection capability.

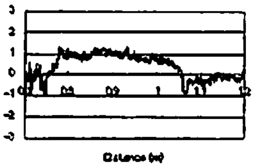


Fig. 8. The result of measuring the step

4.2 Passing Over the Step

Second experiment is for passing over the steps. The vehicle moves forward at 0.3[m/s] and passes over the 5[cm] height step. Furthermore, we compare the result by our proposed method with the one by general PID method.

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

Figure 10 and 11 show the disturbed ratio which means the error ratio of the rotation velocity (a), the slip ratio (b) [11] and the rotation velocity of each wheel (c). The disturbed rotation ratio and the slip ratio are defined by the equation (5) and the equation (6), respectively.

$$\hat{d} = \frac{\omega_{ref} - \omega}{\omega} \tag{7}$$

$$\hat{s} = \frac{r\omega - v_{\omega}}{r\omega} \tag{8}$$

ω :Rotation speed of the actuator.
ω_{ref} :Reference of rotation speed.
r : The radius of the wheel.
v_{ω} :The vehicle speed.

As the result, the rotation velocity of the wheels is synchronized with the proposed control method. Furthermore, the disturbed rotation ratio and the slip ratio are reduced. Thus, this control method is efficiency for step climbing.

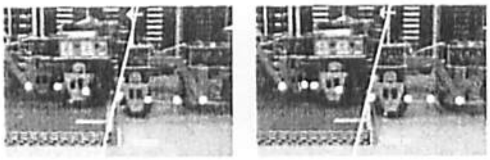
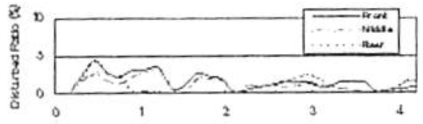
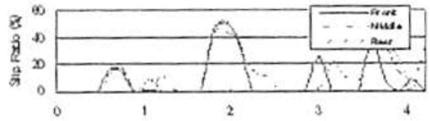


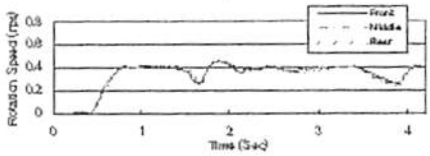
Fig. 9. Step climbing with proposed controlling and general controlling



(a)The disturbed rotation ratio

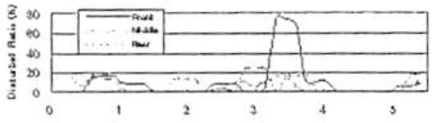


(b)The slip ratio

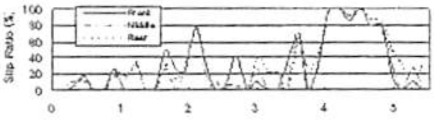


(c)The rotation speed

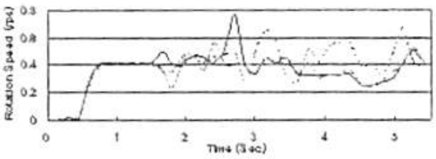
Fig. 10. Experimental Result of proposed method



(a)The disturbed rotation ratio



(b)The slip ratio



(c)The rotation speed

Fig. 11. Experimental Result of old method

5 Conclusions

In this paper, we discuss the control method for omni-directional mobile vehicle with step-climbing ability and the terrain estimation method using its body. We also designed new control system which realized the synchronization among the wheels when the vehicle passed over rough terrain.

We implemented the system and verified its effectiveness by the simulations and experiments. For future works, we will consider the motion planning method based on the environment information.

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