DEVELOPMENT OF A STEP-CLIMBING OMNI-DIRECTIONAL MOBILE ROBOT

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Abstract: In this paper, we purpose a new holonomic omni-directional mobile robot that can move on not only flat floors but also uneven environment. A prototype robot can move in omni-direction, run on the uneven floors and slopes, and pass over large steps. The robot has seven universal wheels that have twelve cylindrical free rollers. We adopt a passive suspension system that enable the robot to change the shape of the robot body in proportion to ground states without using actuators and sensors. We construct the prototype robot and analyse the kinematics of the robot. The performance of the prototype robot is verified through experiments.

Keywords: Omni-Directional Mobile Robot, Holonomic Robot, Irregular Terrain, Passive Suspension

1 INTRODUCTION

Recently, it is expected that mobile robots undertake various tasks not only in the industrial fields as manufacturing plants, warehouses, construction sites, but also the environment we live in. The robots need transport heavy objects, guide us, and help house chores in these places.

A holonomic omni-directional robot that has high mobility is necessary, because it might become more important for mobile robots to accomplish diverse tasks in the various environments. The holonomic omni-directional mobile robots can move in all directions at any time. Therefore, these robots can complete complicated tasks in a narrow space and cooperative transportation of a large object with ease. The robot motion can be planned easily because there are no holonomic constraints (see [Campion et al., 1996]) of movable direction.

Almost all of previous omni-directional mobile robots are designed to move only on flat floors. However, the ability of running on uneven grounds, slopes and steps is necessary when mobile robots work in a place where we live and work.

In the outdoor environments where we make our living such as paved roads and the site of the residence, there exist the steps between the sidewalk and the roadway, gentle slopes, and the unevenness of road surfaces. In the indoor environments, there exist uneven places and little steps such as doors, codes for the power supply, and so on.

Accordingly, in this paper, we propose a holonomic omni-directional mobile robot that can move in the above-mentioned environments.

2 CONCEPT DESIGN OF A ROBOT

The mobile robots need the high ability of passing over unevenness and large steps when they move in the natural environment such as forestry, farmlands, and planet surfaces. These robots have a complex mechanism to improve the mobility.

We do not require complex mechanism to the robots for an artificial environment where we live. It is important to design the reasonable mechanism that has no excessive performance. Many mobile robots for savage conditions have been proposed until now. But an omni-directional mobile robot that works in our life range is not proposed.

In this paper, we propose to develop a new omni-directional mobile robot that can move in the uneven environment where we live.

2.1 Previous works

We mention about omni-directional mobile robots in this section and the running ability on irregular terrain in the next section.

Until now, various kinds of omni-directional mobile robots have been proposed: legged robots, ball wheel robots, crawler robots, normal wheeled robots, special wheeled robots, and so on.

The legged robots can move in all directions and can run in rugged and unlevelled fields. However, the mechanisms of the legged robots are very complicated and so are the control methods. The maximum speed of the legged robots is much slower than that of wheeled mobile robots.

There are many robots with ball wheels that can rotate in all directions (for example, [Wada and Asada, 1999]). As to the ball wheeled robots, a slide between ball wheels and the floor is larger. Moreover, the positioning is not accurate. The mechanism and the control are also complicated, and it is not so suitable for running on unlevelled grounds.

The omni-directional mobile robots that have special crawler mechanisms are also proposed [Hirose and Amano, 1993]. This kind of the robot has large payloads and is able to run fast. However, the crawler mechanism is very complicated. There exists a robot that improves a step-climbing ability [Mitsutake et al., 1998], but it is difficult to pass over large steps.

Many non-holonomic omni-directional mobile robots with normal wheels are proposed because of the simplicity of the mechanism. But the control of each wheel's speed becomes very difficult to be a holonomic mobile robot [Mori et al., 1999; Betourne and Campion, 1996].

Special wheeled robots that can move in all directions are proposed [Carisle, 1983]. The special wheel is called universal wheels and has free rollers. These robots have simplicity of mechanism same as the normal wheeled mechanism. Moreover, they can be controlled easily to realize holonomic movement. A smooth circular shape wheel is specially designed by devising the form of the free rollers (Figure 1) [Asama et al., 1995]. And an easy control method is proposed by arranging four universal wheels in every 90deg at its body. Therefore, high performance of omni-directional movement is realized.

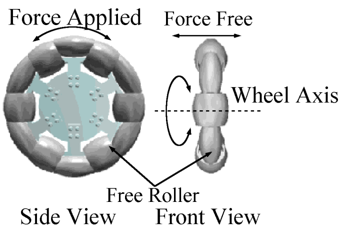


Figure 1. Universal wheel with free rollers

However, there is a fatal demerit that the robots with the universal wheels can nearly pass over the unevenness of a ground in the force free directions [Ferriere and Campion, 1996]. Therefore, a cooperative method by two robots for steps is proposed [Asama et al., 1996]. Nevertheless, it takes a lot of time to pass over steps. This cooperative technique is not realistic for the environment where many small steps and unevenness exist.

Namely, a holonomic omni-directional robot suitable for where we live has not been proposed until now.

2.2 Running ability on irregular terrain

The following factors are important for robots with wheels or crawlers to move on the uneven grounds and to improve the step-climbing ability.

(a) The driving torque of each wheel
(b) The radius of each wheel
(c) The nature (coefficient of friction and softness) of each wheel
(d) The load added to each wheel

As the size of the driving torque, the radius and a coefficient of friction between wheels and the ground are larger, the running ability on an irregular terrain is improved better. And if wheels are soft, they can fit the ground state by changing their shape. They can climb up little steps automatically. However, a robot cannot move fast with too soft wheels [Hirose et al., 1995].

Generally speaking, the step that the robot can pass over becomes higher in proportion to the radius of the wheel. However, if there is no contrivance on the robot body, it is impossible to climb up the step beyond 1/3 of the wheel diameter even when the driving torque is very large. This is because the load added to each wheel becomes small and the driving power is not conveyed to the ground in the middle of the step-climbing. It is not realistic to enlarge the wheel size to improve the ability, because the body becomes too large. It is important to change the robot shape like planetary rovers when they move on the irregular terrain and pass over steps. Even if a large wheel is not used, a robot can pass over large steps by changing the robot form adapted to the step [Uchida et al., 1999].

2.3 Demands for a mobile robot

The following performance will be necessary when mobile robots work in the general artificial environment. Some requirements to a robot that is developed in this paper are shown in the followings.

(1) Holonomic omni-directional robot

This means that a robot can move in all directions in every moment. Oppositely, when a non-holonomic omni-directional robot wants to move in all directions, it must face to the objective direction at first and then move. This property is very effective when robots transport a large object cooperatively and move in a narrow space.

(2) Uneven environment

We have to develop a robot that can move in the artificial environment where we usually live. In other words, the robot can move on pavements, sideways, and the site of residence. Generally, the unevenness of the artificial roads is within 5mm and the inclination of the slope is less than 10deg. In construction sites, it is sufficient that the robot can pass over steps of 20-30mm. The maximum height of steps that we assume is 100mm between a roadway and a sidewalk at pavements.

In this paper, a mobile robot need not have ability to go up stairs in all of cases, because it can go to the upper or lower floors using an elevator.

(3) Swiftness and compactness

This means that the robot can move at high speed. This property is important to carry out tasks rapidly. Simple mechanism and control method are preferable for fast movement.

It is desirable that the robot body is not large to move in narrow and complicated environments. It is necessary for robots to pass through doors. The door width of the elevators in the buildings and in the construction sites is often less than 900mm.

Therefore, it is desirable that a robot body is within the circle of 900mm diameters.

2.4 Our approach to design a robot

When we design a mobile robot, there are two approaches to improve the step-climbing ability of the robot. One is to improve the step-climbing ability in all the directions equally, and the other is to improve the maximum ability to pass over steps in a fixed direction. If the robot has a holonomic and omni-directional movable ability, it can change its direction in front of steep steps. The active range of a robot spreads out to adopt rather the latter approach than the former approach, because the robot in the latter approach can reach for the steps that the robot in the former approach cannot reach.

We design the holonomic omni-directional robot based on the latter approach and on the requirement mentioned in section 2.3.

3 DESIGN OF A ROBOT MECHANISM

As mentioned above, it is necessary that the mechanism and the control of a robot are easy and that a robot can move at high speed for a holonomic omni-directional mobile robot. Accordingly, the universal wheel with free rollers is adopted.

Proper wheel arrangement to the robot body is necessary to make up for the fault of poor running ability of the universal wheels on uneven ground. Also, it is desirable that the shape of the robot changes to fit a ground state. It takes a long time for a robot to pass over on uneven grounds or to climb steps if the robot changes the form and then moves after sensing the environmental information (the condition of the ground and the height of the step). In this case, the mechanism is also complicated because there need external sensors and actuators that changes the robot shape.

We develop the mechanism that realizes step-climbing without using sensors and actuators for the body deformation. We adopt a passive suspension system that the body shape can be transformed automatically when the wheels touch a step.

3.1 Wheel mechanism of a robot

The universal wheel (Figure 1) is adopted to realize high speed and holonomic omni-directional movement. This wheel can rotate freely in the direction which is vertical to the driving direction. The omni-directional movement can be realized not to arrange three and more universal wheels parallel on a robot body, because parallel wheels cannot convey the driving force to the ground in the force free direction (Figure 1). The free rollers of the universal wheels are made of rubber and have many studs to improve the grip to the ground.

Furthermore, it is important that all wheels have the driving power to improve a step-climbing ability. Accordingly, one actuator is carried on each wheel. A spring suspension is installed in each wheel unit, and the unit can move up and down. A little unevenness can be pass over with this suspension unit (Figure 2).

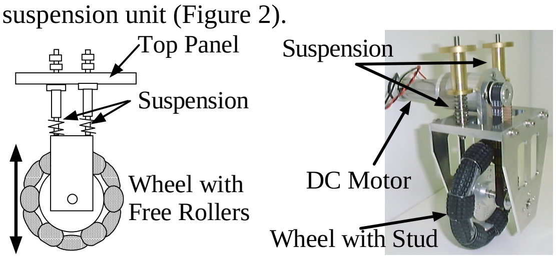


Figure 2. Developed wheel unit

3.2 Body mechanism of a robot

We arrange the above wheel units on the robot body to realize a holonomic omni-directional moving ability, and improve the step-climbing ability by devising the structure of the robot body.

In previous works, the universal wheels are arranged in every 120deg or every 90deg on the robot body because the step-climbing ability is not taken into consideration. But these types of robots, which have simple suspension system, cannot move on the uneven grounds because and wheels can easily apart from the ground and the driving power cannt be conveyed to the ground. In this paper, we develop the mechanism that wheels do not float when there are unevenness and steps on a floor.

Accordingly, the universal wheels are arranged regarding the followings.

- The number of wheels is reduced.
- The control that realizes the objective motion can be done easily.
- The robot form can be easily transformed in accordance with the floor condition.

In case of designing planetary rovers, at least six wheels are necessary to pass over large steps. And it is desirable that wheels are arranged in parallel or vertical to simplify the control. We propose the robot which has seven universal wheels (Figure 3).

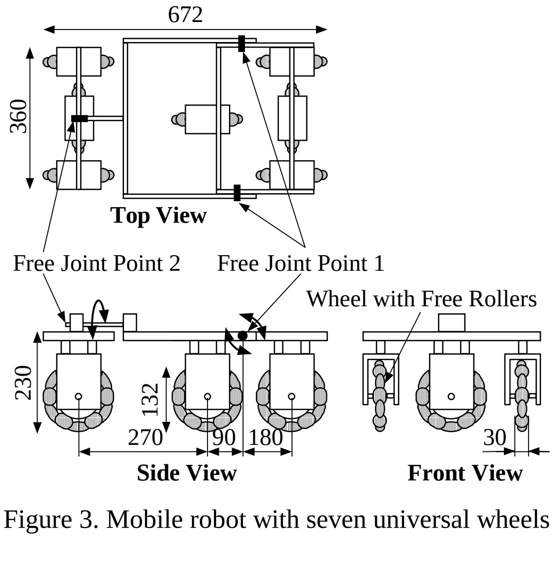


Figure 3. Mobile robot with seven universal wheels

The rotational joints are adopted so that the body form might be transformed freely. By adopting the joints, the shape of the robot can be easily transformed when a force is added to the robot body or the wheels. In other words, it can be transformed more flexibly according to the floor condition.

The universal wheels are connected to the links and they are connected at two rotational joint points shown in Figure 4. It is possible that all wheels can touch the ground at any situations by automatic rotation of the joints.

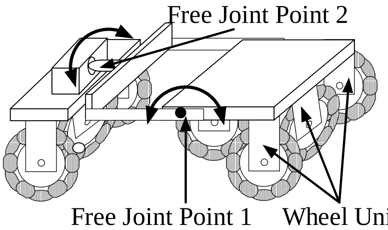


Figure 4. Passive suspension system of a robot

The change of the robot body when it climbs up a large step is shown in Figure 5. At first, the robot changes its direction in front of the step to face the step-climbing axis. If the wheel contacts the step, the free joint point 1 can rotate autonomatically and change the pose to fit the shape of the step. In this way, the robot can climb up and down the step smootly. And the robot can pass over the step from forward side and back side. The free joint point 2 helps the robot to balance the difference of height between the right and left wheels.

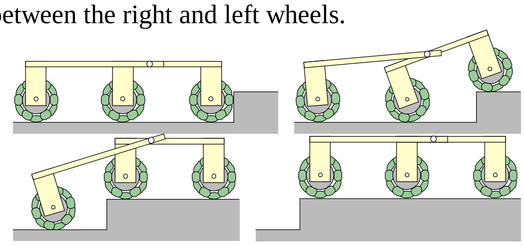


Figure 5. Process of climbing up a large step

3.3 The kinematics of a robot

The kinematics of the developed robot is mentioned in this section. The coordinates Σ_r, the length of each links, and the rotate speed of each wheel when the robot is on the flat floor are shown in Figure 6.

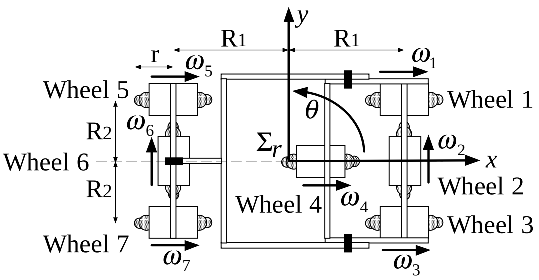


Figure 6. Coordinates of a robot

Each variable is as the following:

r: the radius of the wheels (mm)

ω_i : the rotate speed of the wheel i (rad/s)

V_i: the rotate speed of the actuator i (rad/s)

k : the gear ratio between the actuators and the wheels

Here, let $[{}^r\dot{x} \quad {}^r\dot{y} \quad {}^r\dot{\theta}]^T$ be the velocity of the robot in the robot coordinate.

The relations between the speed of each wheel and the speed of each actuator are calculated in Equation (1).

$$\omega_i = kV_i \quad (i = 1...7) \tag{1}$$

When we consider the arrangement of wheels, the relations between the velocity of the robot body and the rotation speed of each wheel are gained. The speed of the wheel 5 must be equal to the speed of the wheel 1, because the wheel 1 and the wheel 5 is on the same straight line [Hirose and Amano, 1993]. The speed of the wheel 7 is equal to the speed of the wheel 3, too. After all, Equation (2) – (5) are calculated as follows.

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

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

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

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

After substituting Equation (1) for Equation (2) – (5), we can get the Equation (6) that indicates the relation between the velocity of the robot and the rotate speed of each actuator.

$$\begin{bmatrix} {}^r\dot{x} \\ {}^r\dot{y} \\ {}^r\dot{\theta} \end{bmatrix} = J \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_7 \end{bmatrix} \tag{6}$$

$$J = \begin{bmatrix} \frac{kr}{5} & 0 & \frac{kr}{5} & \frac{kr}{5} & \frac{kr}{5} & 0 & \frac{kr}{5} \\ 0 & \frac{kr}{2} & 0 & 0 & 0 & \frac{kr}{2} & 0 \\ -\frac{kr}{6R_2} & \frac{kr}{6R_1} & \frac{kr}{6R_2} & 0 & -\frac{kr}{6R_2} & -\frac{kr}{6R_1} & \frac{kr}{6R_2} \end{bmatrix}$$

Where J is the Jacobi matrix with respect to Σ_r.

Therefore, the order value of each actuator to realize the objective speed can be calculated as the following:

$$V_1 = V_5 = \frac{1}{kr}({}^r\dot{x} - R_2\,{}^r\dot{\theta}) \quad (7)$$

$$V_2 = \frac{1}{kr}({}^r\dot{y} + R_1\,{}^r\dot{\theta}) \quad (8)$$

$$V_3 = V_7 = \frac{1}{kr}({}^r\dot{x} + R_2\,{}^r\dot{\theta}) \quad (9)$$

$$V_4 = \frac{1}{kr}{}^r\dot{x} \quad (10)$$

$$V_6 = \frac{1}{kr}({}^r\dot{y} - R_1\,{}^r\dot{\theta}) \quad (11)$$

By using Equation (7) – (11), we can control the velocity of the robot by controlling the rotating speed of each wheel.

3.4 Design of control devices

A control device and a power supply are carried on the robot itself to construct the autonomous mobile robot system. The AT compatible PC is on the robot, and control all the behavior of the robot. Small motor drivers control each actuator on each wheel. The size of this motor driver is 47.0 mm (L) x 60.0mm (W) x 30.0mm (H) and the weight is 90g. The order to each motor driver is generated by the multi-functional input and output boards connected to the ISA bus of the AT compatible.

Four 12V batteries are used for the power supply. Two batteries are used for motor drive and the rest batteries supply the power to the computer.

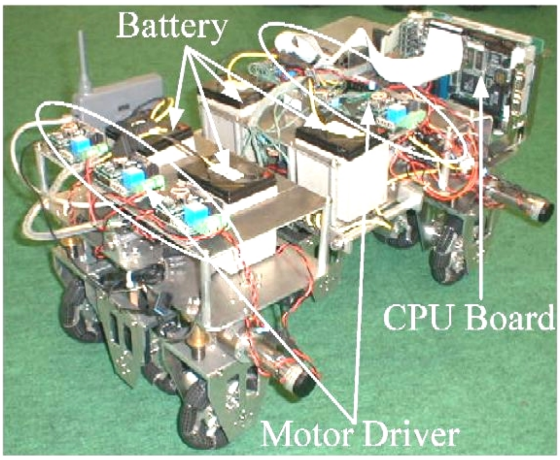


Figure 7. A prototype mobile robot

3.5 A prototype robot

The overview of the developed holonomic omni-directional mobile robot is shown in Figure 7. The size of the robot is 672mm (L) x 360mm (W) x 450mm (H). The weight of body frame is about 14.0kg and the weight of the control devices is about 4.5kg. The total weight is about 26.0kg when the robot is loaded with four batteries.

4 EXPERIMENTS

A running experiment was done to verify the performance of developed holonomic omni-directional mobile robot.

On the flat floor, the prototype robot can move forward, back, right and left. And it can realize pivot turn, too. The holomic and omni-directional ability is verified by these experiments.

As the result of the step-climbing (Figure 8), the robot can climb up and down steps very smoothly. The maximum difference in level that the robot can climb is 100mm.

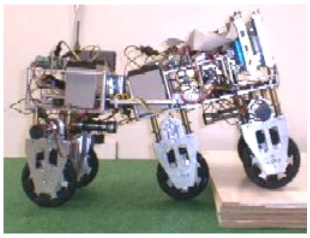
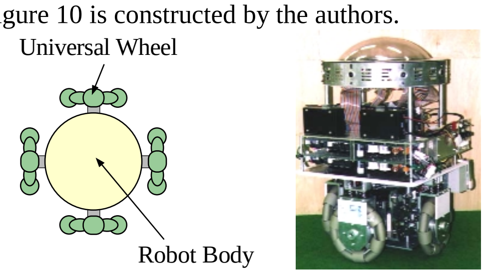


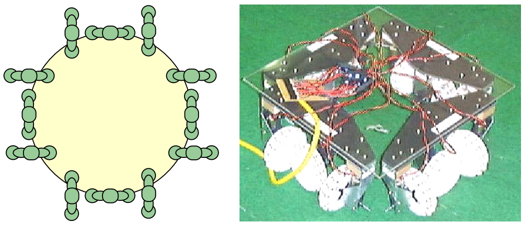
Figure 8. Experimental view of step climbing

To investigate the performance of step-climbing ability, we compare the prototype robot with previous robots that have the universal wheels. Four wheel robot shown in Figure 9 is developed in [Asama et al., 1995] and twelve wheel robot shown in Figure 10 is constructed by the authors.



(a) A top view (b) Overview of a robot

Figure 9. A robot ZEN [Asama et al., 1995]



(a) A top view (b) Overview of a robot

Figure 10. A robot with twelve wheels

Because the size of each robot is different, we normalized the step-climbing ability with the radius of the wheel and the size of robot body. And the comparison is done. We define the step-climbing ability E_{rad} and E_{size} as follows. Let h mm be the maximum height that the robots can pass over, let r mm be the radius of the wheel, and let S mm^2 be the area of robot that is seen from the top.

$$E_{rad} = \frac{h}{r} \quad (12)$$

$$E_{size} = \frac{h}{\sqrt{S}} \qquad (13)$$

The calculated value of E_{rad} and E_{size} are shown in Table 1.

Table 1. The calculated value of E_{rad} and E_{size}

	4 wheel (Figure 9)	12 wheel (Figure 10)	7 wheel (Our robot)
E_{rad}	0.110	0.620	1.515
E_{size}	0.026	0.078	0.203

When we compare the value of E_{rad}, the step-climbing ability of our proposed robot (seven wheel type robot) is 13.8 times of four wheel type robot (Figure 9), and 2.4 times of twelve wheel type robot (Figure 10). About E_{size}, the ability of proposed robot is 7.9 times of four wheel type robot, and 2.6 times of twelve wheel type robot.

This result shows that our proposed robot have high ability of step-climbing.

5 CONCLUSIONS

In this paper, we propose a new holonomic omni-directional mobile robot that can move on the unevenness and pass over steps. We adopt the universal wheels with free rollers for holonomic movement. And we connect the parts of the robot body by the link mechanism to change the form adapted to the uneven grounds.

We constructed a prototype robot and evaluated the robot's performance with experiments. It is proved that the robot have high ability of step-climbing compared with previous omni-directional robots. And the requirement for the robot was satisfied as experimental results.

For future works, we must put the external sensors on the robot to detect the step. And a motion planning technique based on the information about environment must be built.

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