

Paper:

Mechanical Design of VmaxCarrier2: Omnidirectional Mobile Robot with Function of Step-Climbing

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“VmaxCarrier2” is an omnidirectional mobile robot with step-climbing capability, usable as a compact, quiet, durable transport vehicle in cluttered, cramped environments. We have developed several kinds of omnidirectional mobile robots for situations where movement must be possible in any direction, such as “VUTON [1]” and “VmaxCarrier [2,3]”. To construct an omnidirectional mobile robot with a greatly improved capability to climb steps, we developed the Omni-Disc2, a Bent Pneumatic Actuator, and a pneumatic system. These novel components were constructed into a prototype, and through evaluation experiments we have confirmed improved step climbing capability of VmaxCarrier2.

Keywords: Omni-Disc, omnidirectional mobile robot, VmaxCarrier, Bent Pneumatic Actuator, step-climbing

1. Introduction

Transport vehicles for factories, hospitals, and warehouses must have high operational performance, be able to move freely in narrow spaces, and reach desired points precisely without complicated switchover. Many kinds of omnidirectional mobile robots have been developed to attain these goals. We developed an omnidirectional mobile robot called “VmaxCarrier” (Figs.1 and 3). By providing a unique mechanism called an “Omni-Disc,” shown in Fig.2, “VmaxCarrier” has a high operational performance on a smooth surface such as a floor.

Many everyday environments such as the home or office may have an abundance of small but still significant obstacles such as bumps and steps. For an omnidirectional robot to operate successfully in such common real environments, it must have a sufficient ability to climb steps. In previous studies about omnidirectional mobile robots able to operate off-road [4] and step climb steps [5], but these robots do not remain a horizontal posture of the main body when climbing steps such as HELIOS



Fig. 1. Overview of VmaxCarrier.

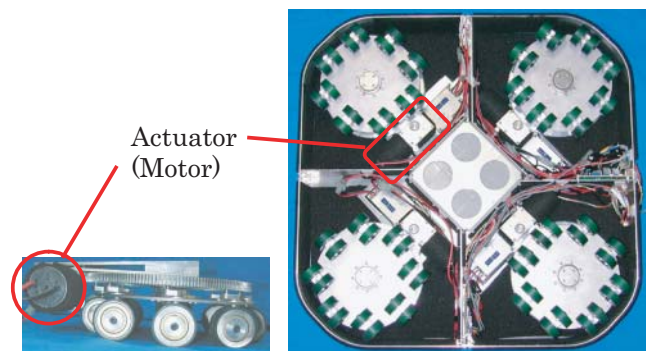


Fig. 2. Side view of Omni-Disc.

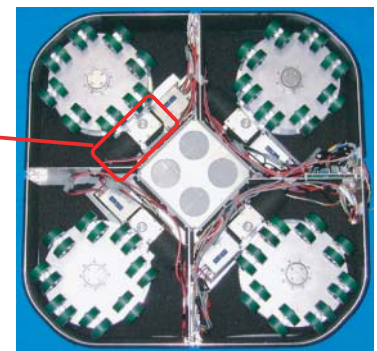


Fig. 3. Bottom view of VmaxCarrier.

[6], which are undesirable for heavy or delicate payloads. In this paper, we propose a “variable inclination angle mechanism,” able to keep the main body horizontal as the robot ascends. We used this mechanism to construct the “VmaxCarrier2 [7],” and confirmed the realization of that function.

2. Previous Model, “VmaxCarrier”

In this section, we explain the previous model “VmaxCarrier”, focusing on that driving mechanism, the “Omni-

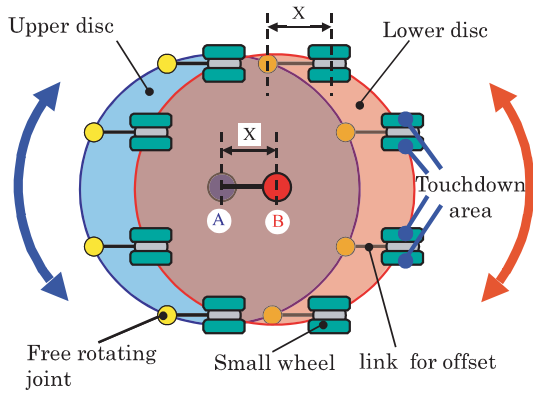


Fig. 4. Mechanism of Omni-Disc (Bottom view).

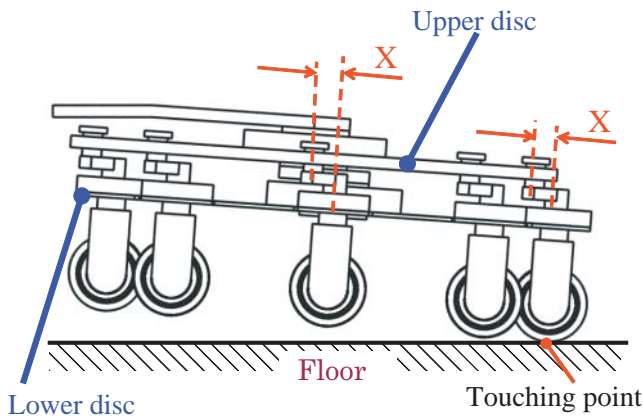


Fig. 5. Mechanism of Omni-Disc (Side view).

Disc". And after that we give some examples of problems of previous model.

2.1. Basic Mechanism of Omni-Disc

The mechanism of the Omni-Disc consists of small wheel modules mounted on two offset discs (Fig.4). Each small wheel module is always kept fixed in one direction. The whole mechanism is mounted on the main body in an inclined posture (Fig.5). So at any given time, only part of the Omni-Disc touches the floor, and creates a propelling force just in one direction, but in perpendicular to the direction of movement, only a small passive wheel rotates, while the disc itself does not propelling.

2.2. Control of VmaxCarrier

A vehicle equipped with three or more Omni-Discs in mutually differing directions move omnidirectionally and holonomically. The steering control is also very simple. When translational and rotation velocities are commanded to the vehicle, these instructions are directly translated to the forward velocity of each Omni-Disc. For example, consider the steering control of an omnidirectional vehicle provided with four Omni-Discs (Fig.6). Ve-

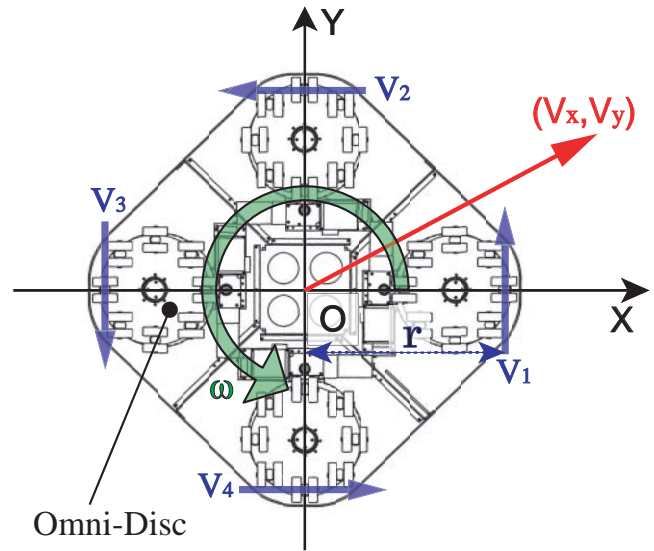


Fig. 6. Control of VmaxCarrier.

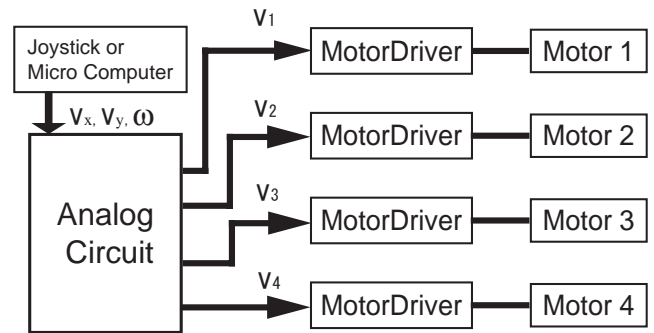


Fig. 7. Control system of VmaxCarrier.

locity commands v_i ($i=1-4$) to the four crawlers are calculated from velocity commands (V_x, V_y) and rotational angular velocity ω around the point of origin, all defined in the mobile body coordinate system (x, y) :

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & r \\ -1 & 0 & r \\ 0 & -1 & r \\ 1 & 0 & r \end{bmatrix} \cdot \begin{bmatrix} V_x \\ V_y \\ \omega \end{bmatrix} \dots (1)$$

Here, r is the distance from the vehicle center to the touchdown point of each Omni-Disc, and the counterclockwise rotation is assumed positive. The 4×3 matrix is the Jacobian matrix of the control of the omnidirectional vehicle.

And the control system of VmaxCarrier is shown in Fig.7.

2.3. Problems of Previous Model

The previous Omni-Disc (Fig.2), successfully functioned as a drive component for an omnidirectional mobile robot, but it still had several shortcomings:

- **Bulkiness:** the actuator was installed outside of the disc mechanism and made the robot bigger.

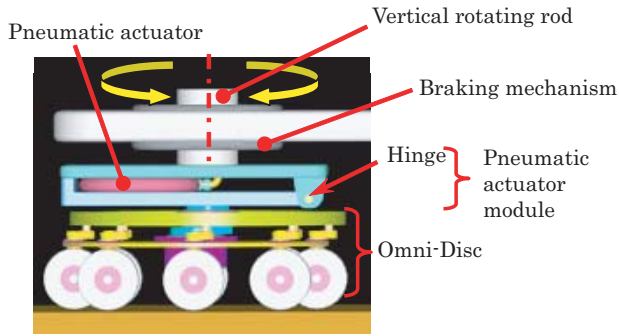


Fig. 8. Side view of the mechanism to change the inclining angle of Omni-Disc.

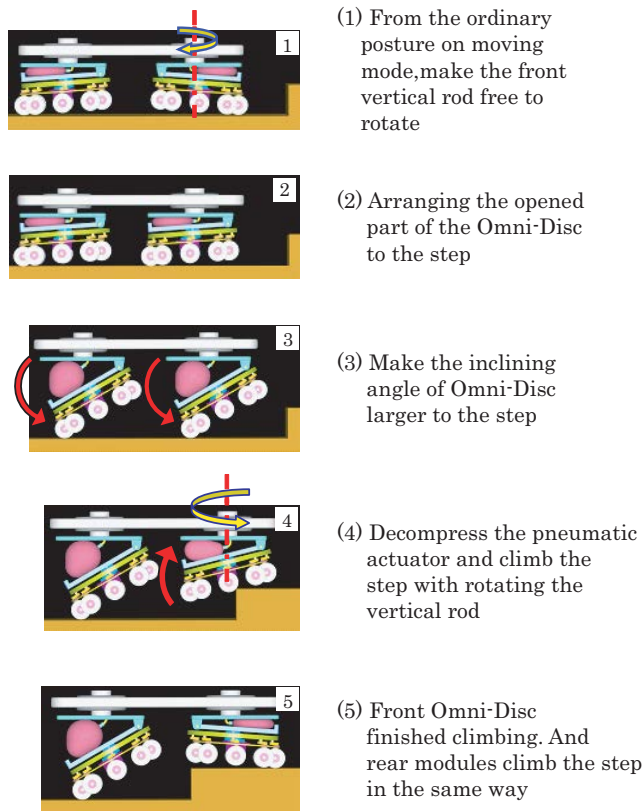


Fig. 9. Motion of climbing step.

- Noise: the torque driver produced a distracting whir.
- Durability: It was not strong enough for climbing steps.

Another purpose of this study was to improve upon the Omni-Disc to facilitate step climbing. Details of the new version, called “Omni-Disc2”, are discussed in section 3.



Fig. 10. Approximation of Omni-Disc as a large wheel.

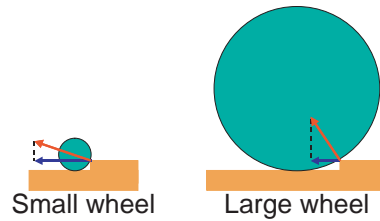


Fig. 11. Scale effect as wheel.

3. Concept of “Variable Inclination Angle Mechanism” of VmaxCarrier2

3.1. Module Mechanism

For the function to climb steps, we propose a mechanism to change the inclination angle of the Omni-Discs that compose the omnidirectional mobile robot (**Fig.8**).

3.2. Motion of Step Climbing

As an actuator to change the inclination angle of Omni-Disc to climb steps, we recommend a pneumatic actuator because of its high ratio of power to size, or power to weight [8, 9]. As for the characteristic of air, it may work as a damper or the structure with some compliance [10], so it is expected to be able to climb steps easily using this feature. The mechanism of the pneumatic actuator module consists of two plates connected by a hinge with a balloon-type pneumatic actuator between plates. When the pneumatic actuator expands, the angle between plates increases. On the contrary, the pneumatic actuator contracts, and the angle between plates decreases. The Omni-Disc is installed on the lower of these two plates, which is how the Omni-Disc changes its installation angle.

There is a vertical rod with a braking mechanism on top of the pneumatic actuator module. The rod is able to change the mode whether it is locked by the braking mechanism or free to rotate. When the rod is locked, the Omni-Disc drives ordinarily to make the platform move. On the other hand, when the rod is free to rotate and the Omni-Disc drives, the whole Omni-Disc module rotates along the yaw axis. The Omni-Disc thus changes the direction of its opened part to bumps by shifting these two modes of the rod. An omnidirectional mobile robot with these modules climbs as (1) to (5) (**Fig.9**). The important point is that the main body of vehicle is kept horizontal as it moves. This is advantageous for a mobile robot to transport heavy or delicate payloads. And we can assume the effect that if the entire device is approximated as a single large wheel, its arc length is greater for smaller incline angles (**Figs.10, 11**). In section 7, we confirm this effect through a step-climbing experiment.

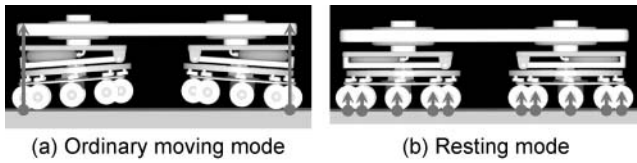


Fig. 12. Changing the two modes.

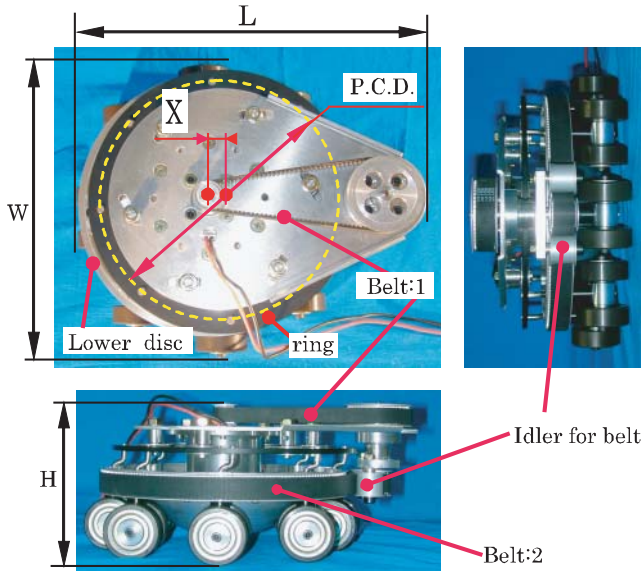


Fig. 13. Overview of Omni-Disc2 from 3 directions.

3.3. Other Functions

The mechanism to change the installation degree of the Omni-Disc can change from normal moving mode to resting mode. In resting mode, the degrees of the Omni-Disc are kept flat, so all small wheels touch the ground in this posture, and the whole weight of the mobile platform is distributed to each small wheels, so each wheel is kept in a stable condition (Fig.12).

To construct the robot, we first developed its components, the Omni-Disc2, the Bent Pneumatic Actuator (BPA), and Pneumatic System, and Direction changing mechanism “Lock-Pin” in the chapters that follow.

4. “Omni-Disc2”: Omni-Disc for Step-Climbing

We developed the new Omni-Disc for step climbing as shown in Figs.13, 14.

4.1. Mechanism

Rotation is transmitted as follows: Through belt 1, the upper axis of the motor rotates the upper pulley, and the lower pulley synchronously rotates the lower disc. At the bottom of the lower disc are mounted eight small wheel modules. The center of the ring and the center of the lower

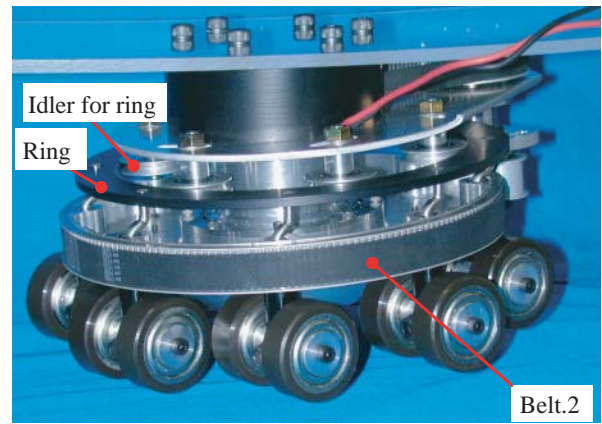


Fig. 14. Overview of Omni-Disc2.

Table 1. Specification of Omni-Disc2.

Radius of the small wheel	40mm
Length	256.4mm
Width	228mm
Height	115mm
P.C.D.	172mm
Weight	3.5kg
actuator	80W DC Motor × 1

disc are offset by a length X. Each bent rod is also offset by length X.

4.2. Points Differing from Previous Version

Some different points between the new and old Omni-Disc differ as follows:

- The position of the mounted motor is changed to the center of the Omni-Disc, making it much more compact.
- We use the timing belt as the devices to transmit torque to reduce noise.
- Previously, two discs composed the Omni-Disc, so the mechanism needed complex parts. The new Omni-Disc consists of one disc and one offset ring (Fig.15), much less expensive.
- The wheel module has a long pipe configuration, so for the offset rod, it is stronger and can bear more weight. Omni-Disc2 specifications are shown in Table 1.

5. Pneumatic Actuator as Inclining Mechanism

5.1. Mechanism

First, we developed the Unit-type Pneumatic Actuator (UPA) with the simple configuration (Fig.16). For the material of the pneumatic actuator, we selected fire hose,

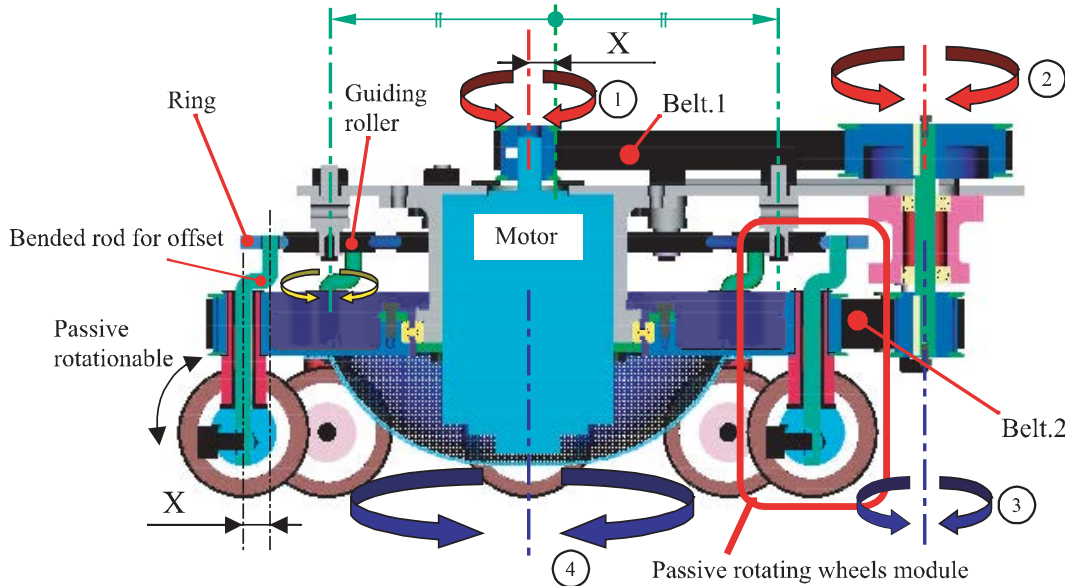


Fig. 15. Structure of Omni-Disc2 (Section view).

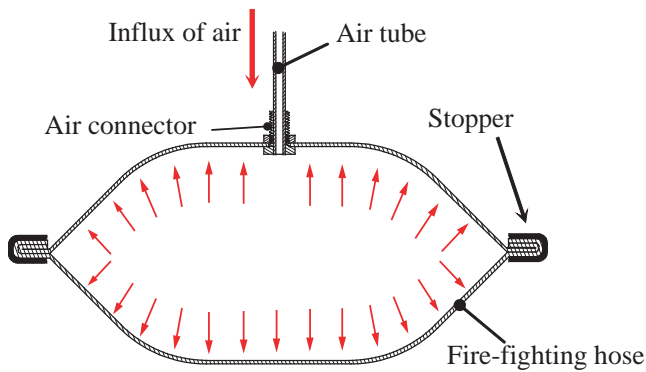


Fig. 16. Section view of uni-pneumatic actuator.

which generally quite tough and able to bear pressure, exceeding 10MPa. Both sides of the fire hose are bent and fixed by bent aluminum plates acting as a stopper. A screw connector at the center of the pneumatic actuator prevents air leakage. The actuator is 101×150×9.6mm and weighs 9.6g.

We applied 0.1 and 0.2MPa to the UPA, which expanded as shown in Fig.17. We define “stroke” as the difference between the heights before and after the actuator expands (i.e., $stroke = h_{after} - h_{before}$).

The shape of the graph is aligned (Fig.18). Considering the actual usage of this UPA as an actuator to change the inclination angle of Omni-Disc, it is difficult to make the angle large enough to climb steps with just one UPA. So, we propose another type of novel pneumatic actuator.

5.2. Bent Pneumatic Actuator

The new type of actuator is also made of fire hose. The most characteristic point of this pneumatic actuator is its bend along the hinge that connects the two plates (Fig.19).

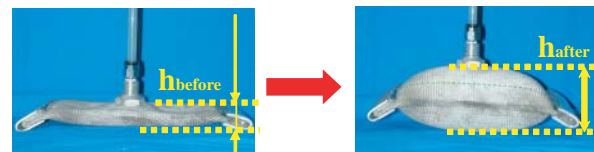


Fig. 17. Pneumatic actuator.

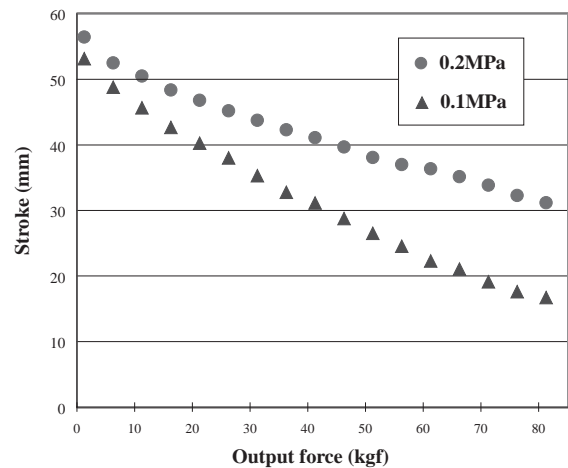


Fig. 18. Result of experiment of one unit type pneumatic actuator.

We call this actuator the Bent Pneumatic Actuator (BPA). The expanding motion of the BPA is shown in Fig.20.

To control the actuator’s angle and torque and so on, we have to recognize the performance of the BPA. The experimental apparatus to analyze the correlation between output torque and output angle is shown in Fig.22. The device consists of a partial pulley to produce a constant torque.

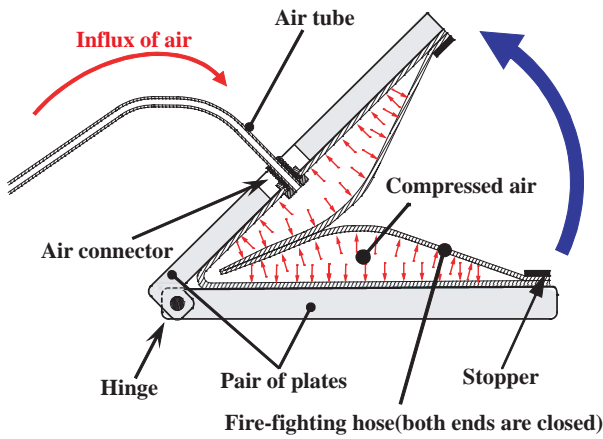


Fig. 19. Section view of Bent Pneumatic Actuator.

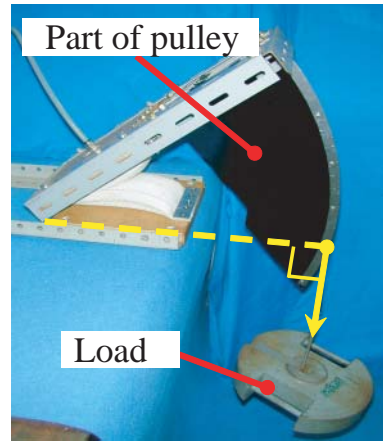


Fig. 22. Experimental devices.

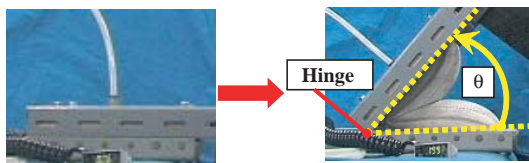


Fig. 20. Bent Pneumatic Actuator.

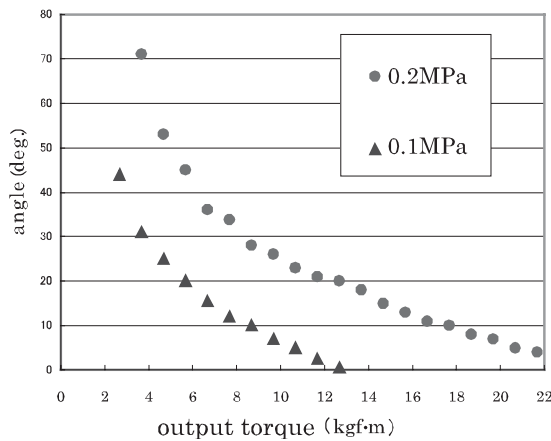


Fig. 21. Result of the experiment of Bent Pneumatic Actuator.

Result are shown in Fig.21. At 0.1MPa, when output torque is less than 3, and at 0.2MPa, when it is less than 4, the angle of the actuator increased to over 90°.

5.3. Comparison Between UPA and BPA

To compare the performance between the two UPAs and one BPA, we consider the two-UPA type as shown in Fig.23. L equals the pulley radius (Fig.22).

The two-UPAs type and the theoretical value are also added in the graph. The two-UPAs type cannot produce enough torque when the angle exceeds approximately 40° because it cannot cover the area of the theoretical value.

$$\Theta = 2 \tan^{-1}(S/L) \dots \dots \dots (2)$$

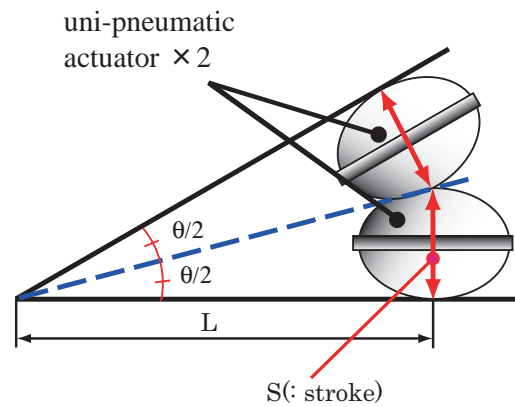


Fig. 23. Two UPAs for angle motion.

$$T = F \times L \dots \dots \dots (3)$$

Combining (2) and (3) yields

$$\Theta = 2 \tan^{-1}(S \cdot F/T) \dots \dots \dots (4)$$

which is the approximation from two uni-pneumatic actuators as angular motion.

5.4. Endurance Test

To be sure, BPA has a bent point. This begs the question, how strong is this part, and how much can it endure? So, we conducted a strength and endurance test. The result is that the BPA had no air leakage after 20,000 times repeated drive, so we concluded that the BPA is durable enough for practical use.

5.5. Pneumatic Systems

To drive the pneumatic actuator, small lightweight pneumatic power producing system is needed. So we developed small lightweight pneumatic power producing system, shown in Fig.25. The overview of the piston compressor and the tank are shown in Fig.26. The dimensions of the piston motor are 65×105×135mm. The whole pneumatic circuit excluding the BPA weighs 1.95kg.

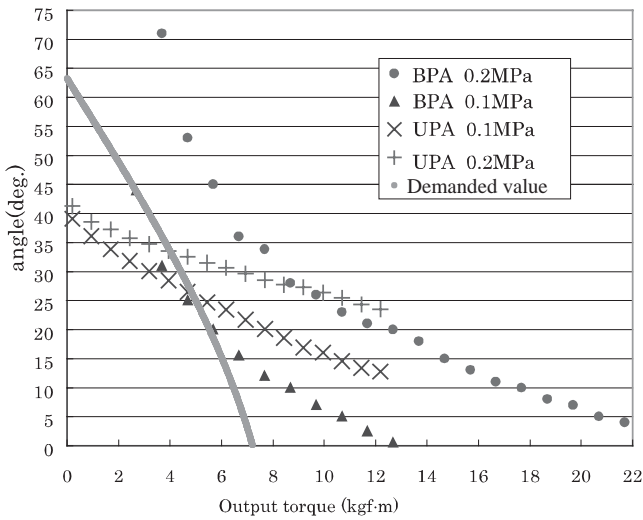


Fig. 24. Result of the experiment of Bent Pneumatic Actuator.

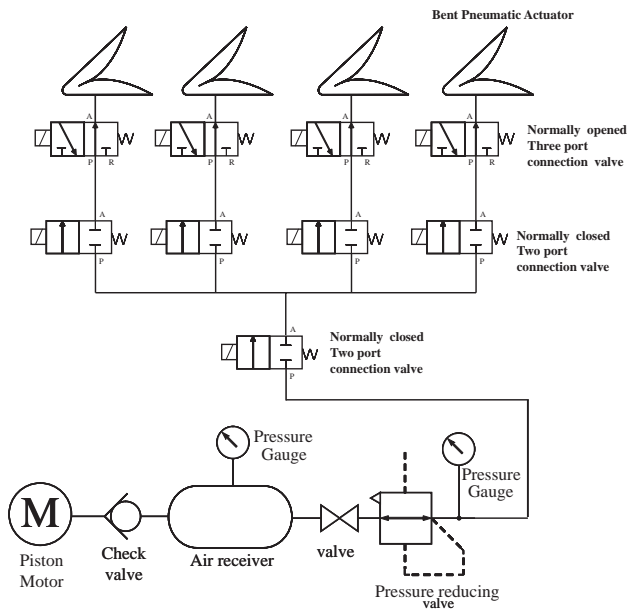


Fig. 25. Pneumatic circuit.

The tank consists of a P.E.T. bottle with a cubic capacity of 1.5L. We confirmed the tank, which is configured in the same way, could bear 0.824MPa. It takes 2.5 minutes to fill the tank with compressed air. This compressed air can drive the BPA four or five times when the pneumatic actuator’s angle range is 45° and the pressure is set to 0.2MPa. It has enough ability to drive the BPA, and is strong and lightweight enough for practical use.

6. Direction Changing Mechanism “Lock-Pin Mechanism”

For an omnidirectional mobile robot, it is desirable to have the step-climbing ability in any direction. We there-

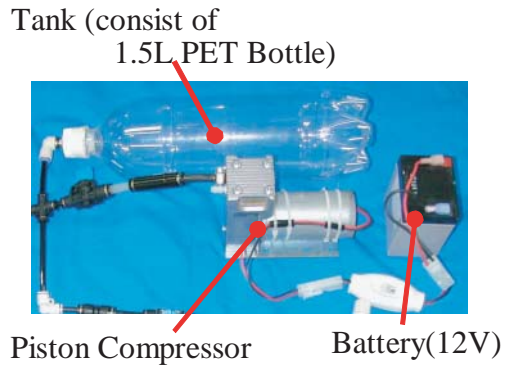


Fig. 26. Overview of compressor and tank.

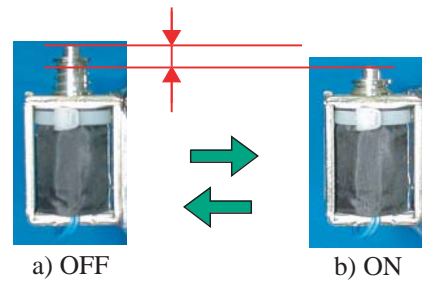


Fig. 27. Solenoid for Rock-Pin mechanism.

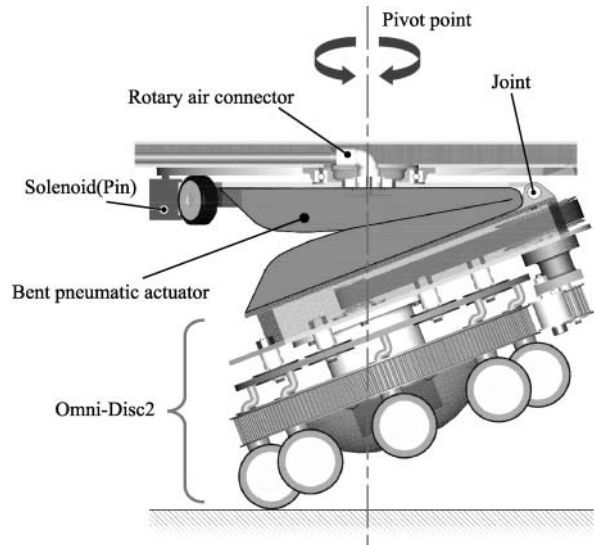


Fig. 28. Integrated module.

fore designed the whole module, which consists of an Omni-Disc2 and a BPA both above and below, to be able to change its own direction.

Specifically, a solenoid (Fig.27) installed on the integrated module is shown in Fig.28. There are some holes in dividing equally on the basement. The up-down motion of pin of the solenoid makes the two modes, “lock” and “free” on the yaw axis. When the pin of the solenoid is in the hole, the integrated module is locked on the yaw axis, on the other hand, when the pin of the solenoid is not in

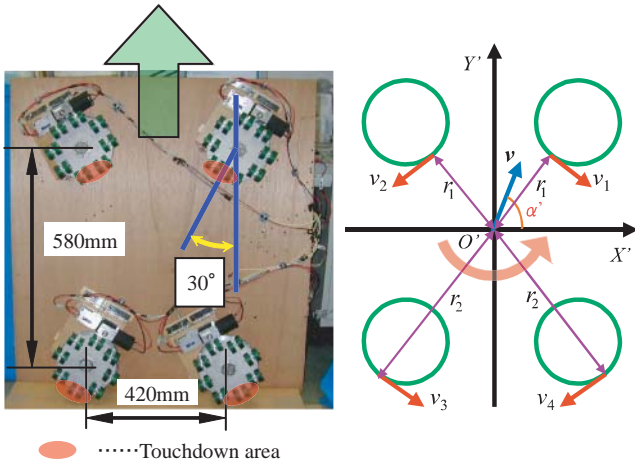


Fig. 29. Bottom view of prototype vehicle.

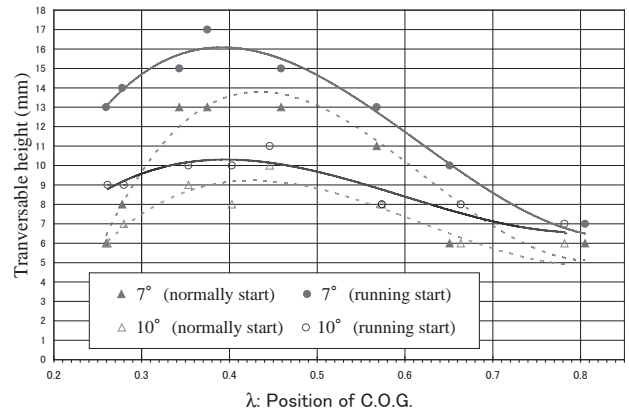


Fig. 31. Experimental result of step-climbing.

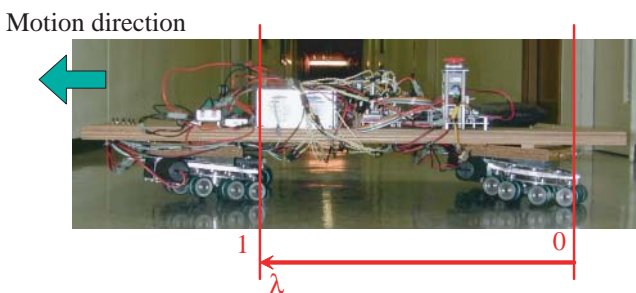


Fig. 30. Side view of the prototype vehicle.

the hole, the integrated module is free to change its own direction.

7. Basic Step-Climbing Experiment Using Previous Model

7.1. Prototype Vehicle for Step Climbing Experiment

First, we investigated the climbing ability of the previous Omni-Disc. We rearranged the configuration angle of each of the four Omni-Discs (Fig.29). The contact areas are changed from the previous vehicle (Fig.3) so that the direction of the open part of each Omni-Disc faces obstacles. We set the inclination angle of Omni-Disc to either 7° or 10°. We also considered the effects of positioning the center of gravity x_{COG} of the robot by the formula

$$x_{COG} = (1 - \lambda)x_{front} + \lambda x_{rear} \dots \dots \dots (5)$$

where x_{front} and x_{rear} are the axial positions in the front and rear, and λ ranges from 0 to 1 (Fig.30).

The velocity commands to each of the four Omni-Discs are shown in eqs.(6) to (9).

$$v_1 = |v|\cos\left(\alpha' + \frac{\pi}{6}\right) - r_1\omega \dots \dots \dots (6)$$

$$v_2 = |v|\cos\left(\alpha' - \frac{\pi}{6}\right) + r_1\omega \dots \dots \dots (7)$$

$$v_3 = |v|\cos\left(\alpha' + \frac{\pi}{6}\right) + r_2\omega \dots \dots \dots (8)$$

$$v_4 = |v|\cos\left(\alpha' - \frac{\pi}{6}\right) - r_2\omega \dots \dots \dots (9)$$

The control system of this prototype vehicle uses a serial I/O called “TITech Wire”.

7.2. Experimental Results

The result of the step climbing experiment is shown in Fig.31. In “running start” mode, the prototype vehicle has velocity of 40cm/s in front of the step. On the other hand, in “normally start” mode, the prototype vehicle start from just in front of the step.

When the inclination angle of the Omni-Disc is set to 7°, the robot climbs steps higher than one with an inclination angle set to 10°, i.e.. This is explained by the fact that if the device is approximated as a single large wheel, its arc length is greater for smaller incline angles (Figs.10, 11).

We also found that the best position of the center of gravity to optimize the step climbing capability is about $\lambda = 0.4$, or two-fifths the distance between the rear and front axial positions. Combining these results, we confirmed that this characteristic of the large wheel effect is effective for step climbing.

Now, we considered about the effect of step-climbing ability of VmaxCarrier2, from this point of view, assuming that the C.O.G. does not change between ordinary moving mode and step-climbing mode, so, the C.O.G. in step-climbing mode, λ exceeds than 0.5 in this experiment. For this reason, the step-climbing ability of Vmax-Carrier2 is not optimum position to use this effect.

It is one of the solutions to put devices to change the of C.O.G. for the vehicle to use this effect.

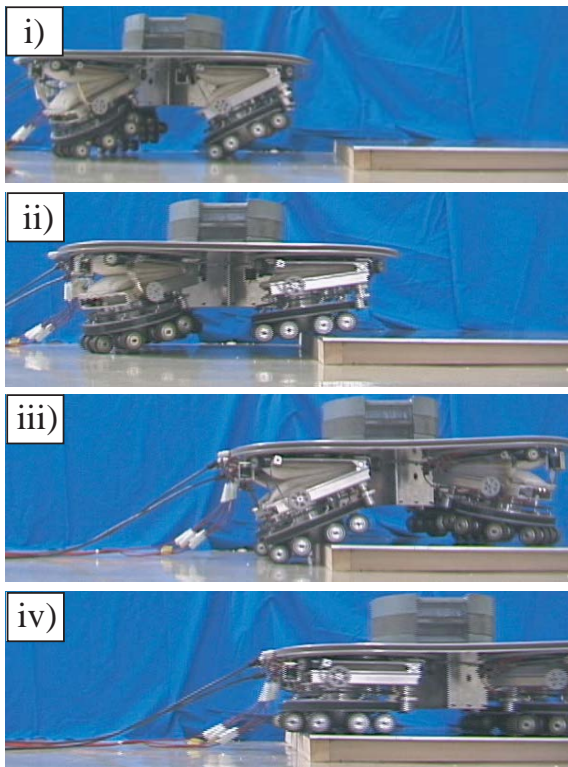


Fig. 32. Motion of climbing step by prototype robot.

8. Fundamental Performance of “VmaxCarrier2”

In this section, we show the functions of “VmaxCarrier2” as a step-climbing omnidirectional robot for (1) climbing steps and (2) imposing a friction in resting mode.

8.1. Step-Climbing

After constructing the vehicle from these components, a step-climbing experiment was done (Fig.32). The height of each step was 45mm high, and the load on the prototype vehicle was 30kg. We confirmed the basic step-climbing function of VmaxCarreir2 through this experiment.

8.2. Enhancement of the Frictional Force on the Floor

By changing the inclination angle of the Omni-Disc, we can add another feature to the vehicle. When the inclination angle of the Omni-Disc is horizontal, all small wheels touch the floor (Fig.12), so the load is distributed to all wheels. In resting mode, the vehicle stays very stable, and friction becomes stronger than in ordinary moving mode.

In this section, we discuss the experiment of function of friction. The experiment procedure is to pull a pin attached to the center of the main body, and measure the force needed to make it slip. The result of the experiment is shown in Fig.33. The “0°” in this graph indicates the

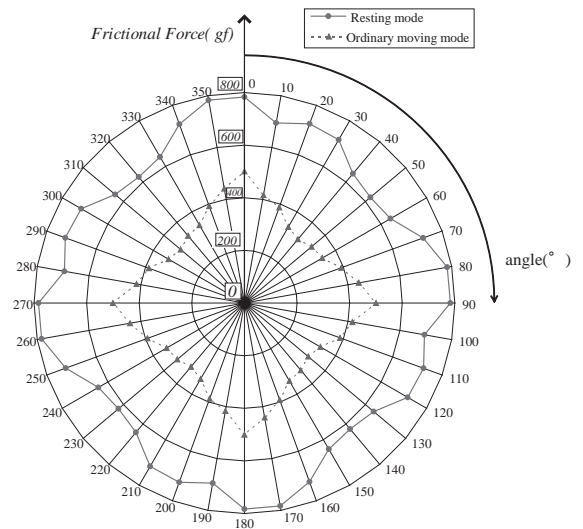


Fig. 33. Frictional force in each direction in two different mode (ordinary moving mode and resting mode).

frontal direction, which faces up in Fig.3. The prototype robot weighs 27.45kgf.

The graph below shows that the frictional force in the resting mode (706gf: average value) is stronger than in ordinary moving mode (388gf: average value), so we confirmed that changing the inclination angle properly enhances the frictional force. This feature of improved strength of stability in resting mode is not provided by any other omnidirectional mobile robot, to our knowledge, this enhancement is effectively applied to existing mobile robots.

9. Conclusion and Future Work

In this paper, we have discussed an omnidirectional mobile robot with step climbing capability and proposed the principle of changing the inclination angle. To construct the robot, we first developed its components, i.e., Omni-Disc2, BPA, and pneumatic system, and direction changing mechanism “Lock-Pin”. From the evaluation experiment using the prototype robot, we confirmed the step climbing capability and enhancement of friction force in resting mode.

We anticipate adding other sequential motions of step-climbing to the “VmaxCarrier2”, and to determine the optimum sequential motion from the view of efficiency, stability, time, and so on. After we evaluate the motions to recognize which is the best in each point of view, we will complete the omnidirectional mobile robot with step climbing capability as a finished product.

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