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# Holonomic Omni-Directional Vehicle with New Omni-Wheel Mechanism

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***Abstract :*** *In this paper, we focus on the "Vuton-II", a new omni-directional vehicle developed as a transport vehicle to operate within factories, hospitals, and warehouses. This vehicle is composed of three or more "Omni-Discs." The Omni-Disc mechanism ensures that individual wheels of the Omni-Disc assembly are always aligned in the same direction, and can always roll freely. The Vuton-II was based on the Vuton-I, an earlier omni-directional vehicle with similar targeted use and controls characteristics. The Vuton-II is designed to be low in cost, short in stature, and reasonably high in payload.*

***KeyWords :*** *Omni-directional vehicle, Omni-Disc*

## 1. Introduction

Transport vehicles for factories, hospitals and warehouses need to possess high mobility to enable correct orientation to target locations while moving freely on narrow floor surfaces and to avoid repetitively switching drives and ensure smooth turning in any desired direction.

The authors have previously developed an omni-directional vehicle, the "Vuton-I", that fits the description above. Building off the Vuton-I, the authors have developed a new omni-directional vehicle, "The Vuton-II", which also fits the description above. This new vehicle is designed to be low in cost, short in stature, and reasonably high in payload. This paper will provide an introduction to the mechanisms of the vehicle and the principles of its actuator, as well as present the results of driving experiments.

## 2. Prior Omni-Directional Vehicles

Automobiles need to switch drives often when engaged in tasks such as parallel parking. The drive performance of ordinary automobiles, which includes neither rotating in place nor maneuvering in a sideways fashion, cannot be considered satisfactory for confined operational environments. For this reason, numerous efforts have been made to develop omni-directional vehicles with two independent translational degrees of freedom and one rotational degree of freedom, for a total of three degrees of motion freedom on a flat surface.

One potential solution is to install an independent steering mechanism in each wheel. The Nakano group has conducted leading research in this approach [1]. However, with this method, the turning motion cannot always be performed continuously. For example, when such a vehicle attempts a turn of 90 degrees, it must first stop and turn its wheels 90 degrees as a preparatory action.

To realize an instantaneous change in motion with three degrees of freedom on a flat surface requires holonomic motion characteristics. Holonomic motion characteristics are thus indispensable for omni-directional vehicles.

There have been attempts to produce this kind of omni-directional vehicle by using wheels on which many free rollers are arranged [2][3]. The basic form of such a wheel is shown in Figure 1. Omni-directional and holonomic motion can be achieved if three or more of these wheels are arranged in differing directions. However, this kind of mechanism raises the center of gravity of the chassis, and decreases the stability of the vehicle's motions.

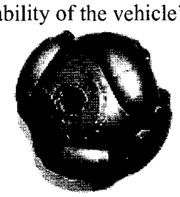


Fig.1 Example of free roller wheels for holonomic omni-directional vehicles

Other than these specialized wheels, omni-directional vehicles with crawler tracks, as shown in Figure 2, have also been proposed [4]. The crawler track is a system in which multiple spheres are supported along the crawler belts, and the spheres that touch the ground are simultaneously in contact with two rods located inside the crawler belts. Because the crawler has this kind of mechanical configuration, it generates ordinary forward motion in the direction of the belts by rotating the belts, and it generates sideways motion by rotating the pair of rods and driving the spheres sideways. In this mechanism, multiple spheres rotate at the same time, and translational omni-directional motion can be produced without slippage. However, attempts at rotational motions with sufficiently small rotational radii inevitably leads to slipping, decreased mobile efficiency, and potential floor surface damage.

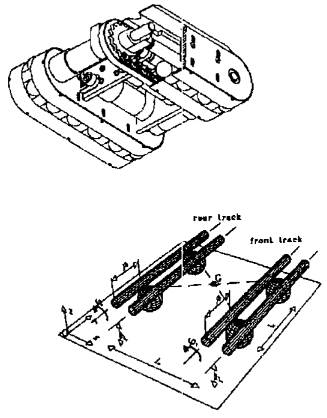


Fig.2 Omnitrack with balls along crawler

# 3. The Vuton Crawler

## 3.1 Mechanism of the Vuton Crawler

In order to resolve the problems associated with the conventional omni-directional mobile mechanisms described in Section 2, a novel type of crawler, called the "Vuton crawler", has been developed and is shown in Figure 3 [5]. The free rollers of the Vuton crawler are supported by square frame members with rotational motion independence, and the square frame members are connected to the chains at diagonal points separated by a horizontal distance t. The pair of chains is also offset with a distance t, and the chains are driven simultaneously. With this arrangement of shifted support, the Vuton crawler always maintains its free rollers in a horizontal posture.

Figure 4 shows a prototype Vuton crawler. One of the chains (2) is directly driven by a geared motor (1), and the other chain (3) is synchronously driven by transmitting the rotation of the motor (1) via a timing belt (4) to an axis offset from the geared motor by a distance t. The diagonal connecting sections (6) of the square frame (5) are linked into the chains via axle receiving units that substitute for chain units. The square frame (5) moves so as to contact the support rollers (7), which are arranged on the lower part of the crawler frame. This configuration transfers the support forces applied to the free rollers to the crawler frame. (8) is a wedge type mechanism which regulates the chain sprocket distance.

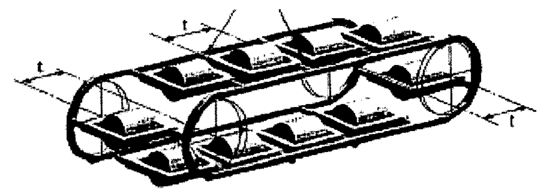



Fig.3 The mechanism of the Vuton crawler

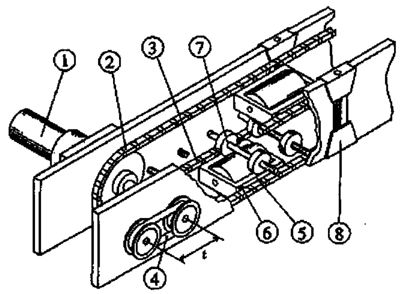


Fig.4 The driving mechanism of the Vuton crawler

## 3.2 Control of the Vuton Crawler

A vehicle equipped with three or more Vuton crawlers in mutually differing directions can realize omni-directional and holonomic mobility. The steering control is also very simple. When translational and rotational motion velocities are commanded to the vehicle, these instructions can be directly translated to the forward velocity of each crawler.

For example, consider the steering control of the omni-directional vehicle provided with four Vuton crawlers (shown in Figure 5). The velocity command values $v_i$ (i=1-4) to the four crawlers may be calculated from the velocity command values $(v_x, v_y)$ and the rotational angular velocity ( $\omega$ ) around the point of origin, all defined in the mobile body coordinate system (x,y):

$$\begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & r_0 \\ -1 & 0 & r_0 \\ 0 & -1 & r_0 \\ 1 & 0 & r_0 \end{bmatrix} \cdot \begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} \tag{1}$$

Here, $r_0$ is the distance from the vehicle center point to each crawler, and the counter-clockwise rotation is assumed positive. The 4x3 matrix is the Jacobian matrix of the control of the omni-directional vehicle.

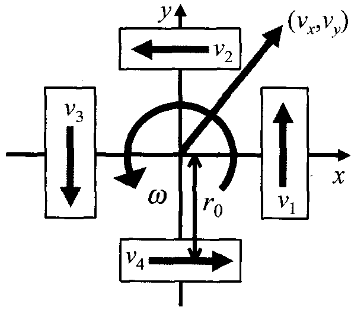



Fig.5 Control of the omni-directional vehicle

### 3.3 The Prototype Machine and Driving Tests

The Vuton-I was manufactured by arranging four Vuton crawlers, as shown in Figure 6. Its specifications are: it has a mass of 29.5 kg (without the battery); it has dimensions of 560 mm x 560 mm x 135 mm. It can be manually driven by a joystick, or automatically driven by a computer. The joystick produces velocity commands to the motors of each crawler by generating the relationships outlined in Equation (1) with an analog circuit.

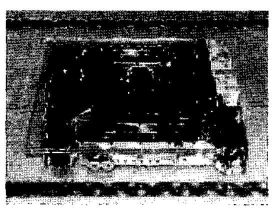


Fig.6 Photograph of the Vuton-I

## 4. The Omni-Disc

### 4.1 The principle and features of the Omni-Disc

In addition to the Vuton crawler mechanism and associated omni-directional vehicle Vuton-I, at this time the authors have also developed a new type of omni-directional wheel named the Omni-Disc and associated vehicle Vuton-II. This new vehicle is designed to be lower in cost and shorter in stature than the Vuton-I, but still maintain a reasonably high payload capacity.

The free roller wheel as shown in Figure 1 raises the center of gravity of the chassis, which may make its motion unstable. We first considered inclining the large wheel (9) on which many free rollers (10) are arranged (as shown in

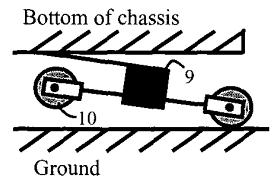



Fig.7 Inclined free roller wheel

Figure 7) to bring the chassis closer to the ground. But, in this mechanism, frictional forces prevent the motion of the chassis when two small free rollers not aligned to the chassis' movement direction touch the ground simultaneously, as shown in Figure 8.

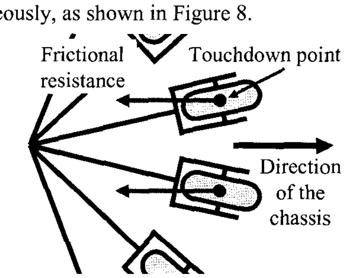



Fig.8 Two free rollers with touchdown points

In order to avoid this problem, we designed a new mechanism that keeps the direction of the free wheels always constant, as shown in Figure 9.

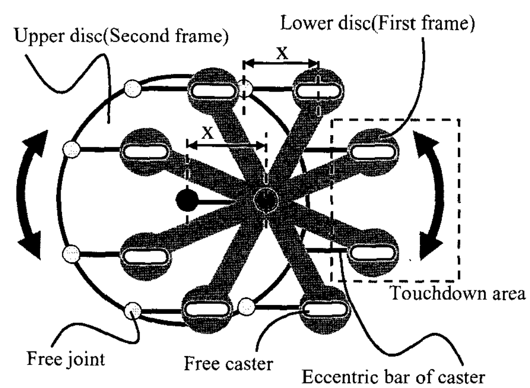



Fig.9 Principle of the Omni-Disc

As shown in Figure 9 and Figure 10, the two rotating discs in the Omni-Disc lie in separate planes, and are eccentrically fixed. The vertical shafts that support the multiple small free wheels are installed in the lower disc so that they can rotate freely. The tips of the vertical shafts of the free wheels, which have the same eccentricities as the two rotating shafts of the discs, are inserted in the holes in the upper disc as shown in Figure 11. This ensures that individual wheels of the assembly are always aligned in the same direction, and that the Omni-Disc casters can always roll freely in that direction; this resolves the problem shown in Figure 8. The two discs and multiple free wheels of the Omni-Disc constitute a kind of parallel mechanism. The whole Omni-Disc mechanism is inclined 4 degrees with respect to its supporting plate (11), so only one or two casters at the tip of the Omni-Disc touch the ground simultaneously.

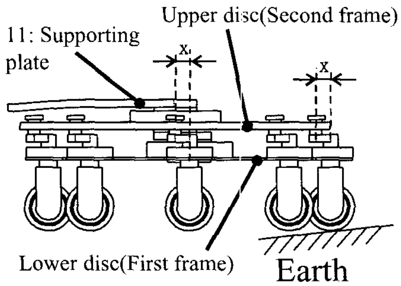



Fig.10 Side view of the Omni-Disc

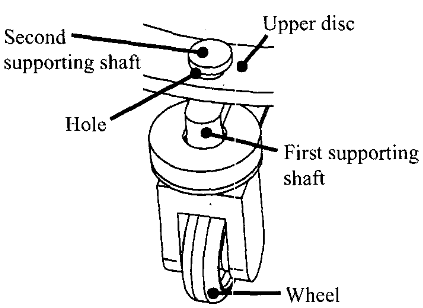



Fig.11 Hole to hold vertical shaft of wheel

The Lower disc of the Omni-Disc is a leaf spring that allows casters to touch the floor continuously. If only one wheel of the Omni-Disc touches the ground, the leaf spring suffers a displacement corresponding to 1/n of the weight of the vehicle (n is the number of Omni-Discs that support the load). When two wheels of the Omni-Disc touch the ground simultaneously, the distance between the wheels and center of the bottom of the chassis is shorter, and the displacement of the springs (one for each wheel) is also smaller, because each spring supports only 1/2n of the weight of the vehicle. This reduces the height variations associated with different touchdown combinations, and so the rotation of the disc is very smooth, as shown in Figure 12.

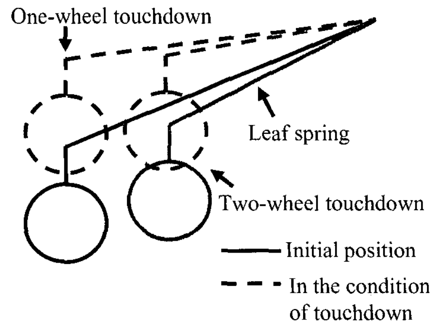



Fig.12 Two types of touchdowns

In Fig.13, if we define the tip of the Omni-Disc's touchdown area as the front and consider merely the rotational direction of the casters, it is acceptable for casters in the entire front half of the Omni-Disc mechanism to touch the ground. However, if the casters of the Omni-Disc touch the ground over a wide range, the casters at the edges of this range can't move at sufficiently high velocities toward the chassis, and they will produce a relative deceleration rather than an acceleration effect on the chassis.

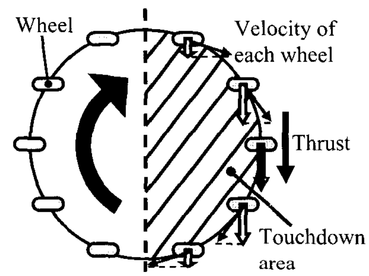



Fig.13 Touchdown area of Omni-Disc

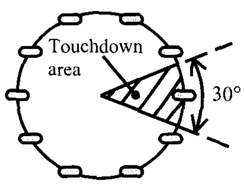



Fig.14 Desirable touchdown area

So, it is desirable that the casters only ground in a range of 30 degrees around the center of Omni-Disc's touchdown area, as shown in Figure 14. That's why the Omni-Disc mechanism is angled downwards by 4 degrees.

The Omni-Disc is much cheaper than the Vuton crawler because it is composed of many commercial instead of customized components.

### 4.2 Passive Omni-Disc

The passive Omni-Disc, as a free caster, has an advantage over commercial free casters. An ordinary commercial caster can rotate freely around its vertical shaft, but generates frictional forces that might prevent straight motion of the chassis when the caster experiences large changes in its movement direction. In the case of the Omni-Disc, even though the wheel at the tip of the mechanism, which is touching the ground rotates around the center of the Omni-Disc, its alignment is kept constant by the parallel mechanism. Thus, when the direction of the chassis changes suddenly, the frictional forces generated by the Omni-Disc are much smaller, and do not impede the motion of the chassis. The overall view of the passive Omni-Disc as a free caster is shown in Figure 15.

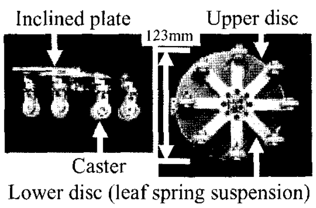
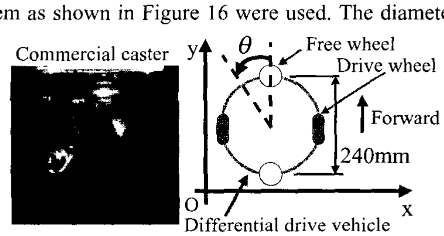



Fig.15 Passive Omni-Disc as free caster

Experiments measuring the motions of a differential drive vehicle ( shown in Figure 16) outfitted with the Omni-Disc and a type of ordinary commercial free caster were carried out to compare the passive Omni-Disc with ordinary casters. In the experiment, commercial casters and the coordinate system as shown in Figure 16 were used. The diameter of the drive wheel is 50 mm and the power of the geared motor that actuates one drive wheel is 4.5 watts. During testing, the chassis was driven forward 0.8 m and backwards 0.8 m in the same posture and at a speed of $1.23\times10^{-1}$ [m/s]. Comparing the average slippage distance from the initial position showed that the slippage of the chassis with the passive Omni-Disc was very small; the excellence the Omni-Disc's running performance was confirmed.

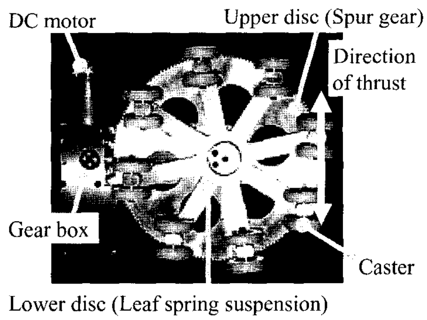



| Slippage | $\lvert\Delta x\rvert$[mm] | $\lvert\Delta y\rvert$[mm] | $\lvert\Delta\theta\rvert$[deg] |
|---|---|---|---|
| Commercial caster | 308 | 181 | 37.6 |
| Omni-Disc | 2.4 | 0.8 | 0.5 |

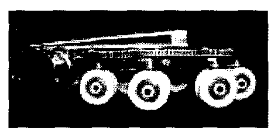
Fig.16 Comparison of Omni-Disc and Commercial Free Caster

### 4.3 Active Omni-Disc

By driving the upper disc as a spur gear with a gear system, it is possible to obtain thrust in the direction perpendicular to the small casters' rotating direction, and a new type of omni-directional vehicle can be created. One actuator unit of the omni-directional vehicle "The Vuton-II" is shown in Figure 17, and the gear system that drives the wheel is shown in Figure 18.




(a) Bottom view of the active Omni-Disc



(b) Side view of the active Omni-Disc

Fig.17 Active Omni-Disc

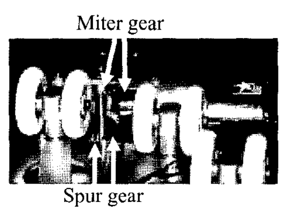
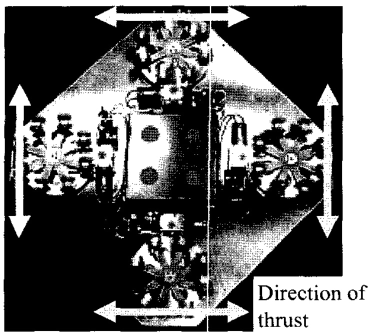


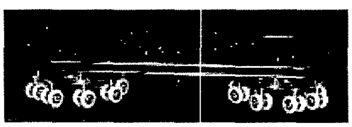

Fig.18 The gear system of the Omni-Disc

## 5. The Prototype of "The Vuton-II" with Active Omni-Discs

The overall view of the first prototype of the new Omni-directional vehicle "Vuton-II" is shown in Figure 19. The vehicle is equipped with four active Omni-Discs, so the positions of the actuators and the control method of this vehicle are identical to those described in Section 3.2 for the Vuton-I. Vuton-II's specifications are: it has a mass of 11.4 kg (without the battery); it has dimensions of 622 mm x 622 mm x 90 mm; and it has a carrying load capacity of 45 kg. The basic running experiment of this vehicle have been performed, as shown in Fig.20, and Vuton-II exhibited quite good performance, just like the Vuton-I.




(a) Bottom view of the Vuton-II



(b) Side view of the Vuton-II

Fig.19 Overall view of the Vuton-II

Fig.20 Manual control experiment of the Vuton-II

## 6. Conclusions

In this paper, after outlining the challenges facing conventional omni-directional vehicles, we proposed the Vuton crawler and the Omni-Disc as potential actuators for omni-directional transport vehicles. Then, we discussed the design, control, and testing of two omni-directional vehicles, one using four Vuton crawlers and one utilizing four Omni-Discs.

The new omni-directional vehicle described in this paper, the Vuton-II, uses Omni-Disc mechanisms that support multiple free casters horizontally. In principle, it can realize translational and rotational motion without slippage, and so it can be highly effective for practical applications that demand:

1) High mobility.
2) Smooth response to slight irregularities in the floor surface.

The development of the second prototype of the Vuton-II with improved Omni-Disc mechanism and much higher payload capacity will be carried out in near future.

## Acknowledgments

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## References

[1] E. Nakano, N. Koyachi, "An Advanced Mechanism of the Omni-Directional Vehicle (ODV) and Its Application of the Working Wheel chair for the Disabled," in Proc. of Int. Conf. of Advanced Robotics, pp.277-284 (1983).

[2] H. Asama, M. Sato, L. Bogoni, H. Kaetsu, A. Matsumoto, and I. Endo, "Development of an omni-directional mobile robot with 3 dof decoupling drive mechanism," in Proc. of IEEE Int. Conf. on Robotics and Automation, pp.1925-1930 (1995).

[3] N. Keiji, T. Satoshi, S. Makoto, T. Yutaka, "Improvement of Odometry for Omnidirectional Vehicle Using Optical Flow Information," in Proc. of IEEE/RSJ IROS, Takamatsu, Japan, pp.468-473 (2000)

[4] M. West and H. Asada, "Design of a Holonomic Omnidirectional Vehicle," in Proc. of IEEE Int. Conf. on Robotics and Automation, pp.97-103 (1992)

[5] S. Hirose and S. Amano, "The VUTON: High Payload, High Efficiency Holonomic Omni-Directional Vehicle," in Proc. of 6th Int. Symp. on Robotics Research, pp.253-260 (1993).