

Paper:

Development of Holonomic Omnidirectional Vehicle "Vuton-II" with Omni-Discs

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In this paper, we focus on a new omni-directional vehicle "The Vuton-II" that was developed for use as a transport vehicle to operate within factories, hospitals and warehouses. This vehicle is composed of using three or more "Omni-Discs". Its mechanism ensures that individual wheels of the assembly are always aligned in the same direction, and can always roll freely. The Vuton-II is designed to be low in cost, short in stature, and to bear a reasonably high payload.

Keywords: omnidirectional vehicle, Omni-Disc,

1. Introduction

Transport vehicles for factories, hospitals, and warehouses must have high operational performance, being able to move freely in narrow spaces and to reach desired points precisely without complicated switchover.

We developed an omnidirectional vehicle, Vuton-II, that shows high operational performance on a flat surface, together with an "Omni-Disc" used with Vuton-II. We describe the drive principles, mechanisms, and features of Vuton-II and the Omni-Disc.

2. Study on Conventional Omnidirectional Vehicles

A driver of an automobile, for example, must steer right and left to park in a parking space. Ordinary cars that do not rotate at a certain spot or move laterally are not suitable to narrow work areas. Efforts were made to develop omnidirectional vehicles move with 3 degrees of freedom (DOF) on a flat surface, i.e., 2 DOF for translational motions and 1 DOF for rotation. One contemplated omnidirectional vehicle has independent steering for each wheel, on which Nakano et al. studied¹⁾. This vehicle has the disadvantage that when it turns at an angle of, say, 90 deg, it must prepare to turn its wheels 90 deg. It cannot make a continuous omnidirectional movement. A vehicle that instantly realizes 3 DOF movement on a flat surface from any direction is known as being holonomic. Such holonomic features are required to realize high operational performance. The sections that follow detail a ve-

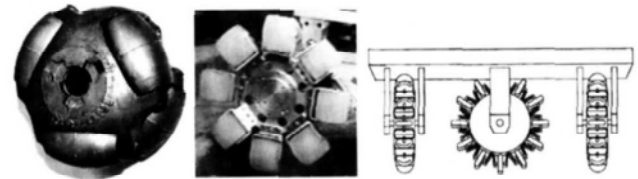


Fig. 1. Example of free roller wheels for holonomic omnidirectional vehicles.

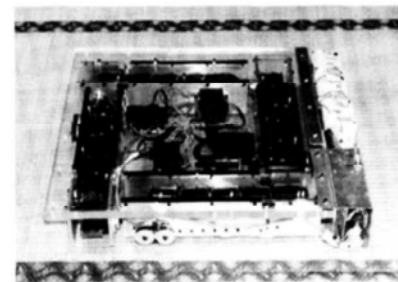


Fig. 2. Appearance of the Vuton-I.

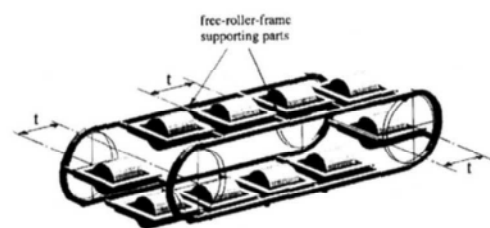


Fig. 3. Mechanism of the Vuton crawler.

hicle with holonomic omnidirectional features.

To realize an omnidirectional vehicle, omni α wheels²⁻⁴⁾ and a Mechnum wheel⁵⁾, each with over one free roller, were experimentally developed. Fig. 1. shows basic examples. With 3 or more wheels arranged in different directions, a vehicle can make holonomic omnidirectional movements, but may become too high due to its large wheels. The lower a mobile platform, the better. Before study on the Vuton-II, we developed Vuton-I⁶⁾ (Fig. 2), which weighs 29.5 kg. (exclusive of battery), is, 560 mm long, 560 mm wide, and 135 mm high, and bears over 200 kg on tatami mats. Vuton-I has 3 or more crawlers,

known as a Vuton crawler, in which free rollers installed in a square frame were built in a row between a pair of catapillar chain.(Fig.3).

Each roller of the crawler, which rotates freely, is supported in a square frame. Each of the frame has two connectors at its edges at opposite corners on diagonal line. The square frame is fixed on the chains of caterpillar ring with the connectors. Since two connectors are not located on same side of square frame but on diagonal line, the positions of connectors are different by "t", depth of square frame. To maintain the free rollers always horizontally stable, that is to keep square frames horizontally stable, the connectors are fixed on the chain at the positions which are shifted by a distance "t", for different caterpillar ring as seen in Fig. 3. To realize such arrangement, a chain ring of caterpillar is shifted by "t" against the other so that square frames are maintained horizontally always regardless movements of the crawler.

Our original objective was to make vehicles as low as possible. We developed an omnidirectional vehicle lighter than its early version "Vuton-I" by tilting the large wheel.

3. New Omnidirectional Vehicle and Omni-Disc

3.1. Omni-Disc Principles and Features

We developed a light omnidirectional vehicle, "Vuton-II", in which new "Omni-Discs" are used. Principles and features are described below.

To develop Vuton-II, we employed first large wheels with free rollers (Fig.1) inclining on the flat surface (Fig.4). In this mechanism, however, frictional forces prevent the motion of the chassis, when two small free rollers are not being aligned parallel to the direction of velocity of the chassis(Fig.5). To solve this problem, we developed a three dimensional parallel link mechanism in order to maintain these free rollers in a certain direction.

Figure 6 illustrate mechanism of free roller unit developed for Vuton II. The first shaft supporting a small wheel that rotates freely is bound to the first rotary frame. The first shaft is connected to a eccentric shaft, the second supporting shaft, center line of which is shifted to the center line of first supporting shaft. The second shaft is put into the hole in the second rotary frame so the small wheel is held in a certain direction(Fig.7). The first and second rotary frames are fixed after being shifted vertically. A certain eccentricity quantitatively equivalent to eccentricity x of the first and second supporting shafts of small rollers is given to the central axes of these frames (Fig.8), supporting shafts of small wheels are installed between the upper and lower rotary frames so they rotate freely. The solid parallel link thus made is useful for keeping small wheels in a certain direction. The whole Omni-Disc mechanism realize 4 Degree of Freedom with respect to its supporting plate. so only 1 or 2 small rollers at the end of wheel mechanism contact the floor simultaneously. The omnidirectional wheel thus turns smoothly

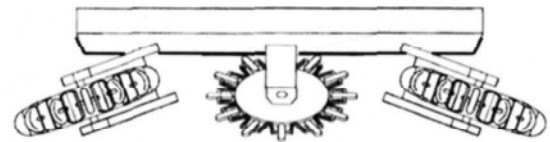


Fig. 4. Inclining the large wheels on which many free wheels are arranged to decrease height of the mechanism.

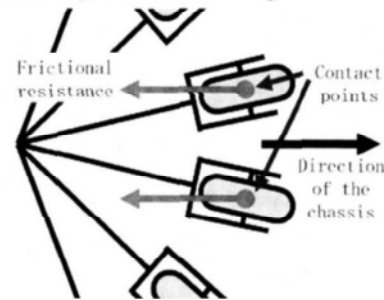


Fig. 5. Two free rollers with contact points.

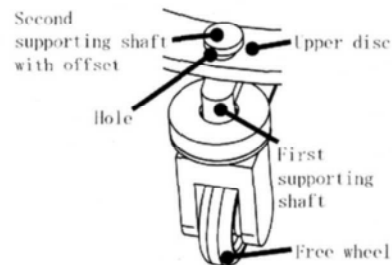


Fig. 6. Hole to hold vertical shaft of free wheel.

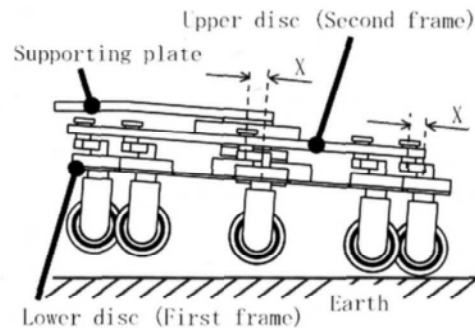


Fig. 7. Side view of the Omni-Disc.

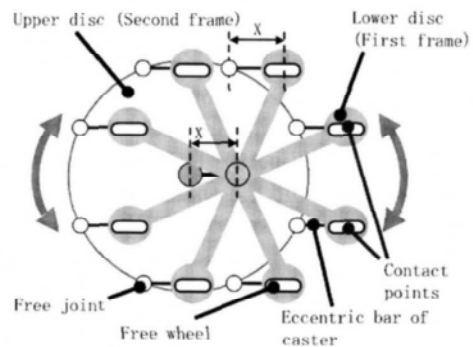


Fig. 8. Principle of the Omni-Disc.

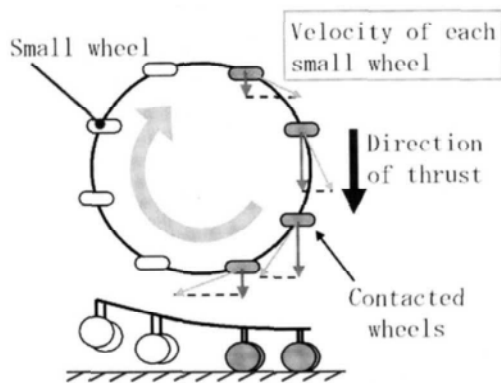


Fig. 9. Compliance and incination of the lower disc.

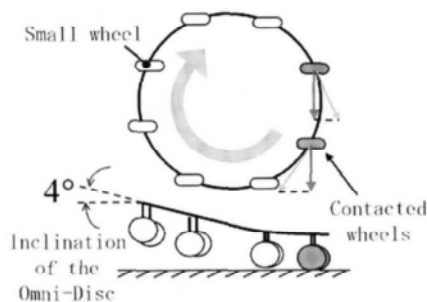


Fig. 10. Desirable compliance and incination for smooth motion.

in any direction.

3.2. Design of Omni-Disc

The Omni-Disc is designed as follows:

With an increase in the number of small wheels for use in the Omni-Disc, small wheels touch the floor more smoothly. Too many small wheels, however, may generate mutual interference mechanically or make the mechanism heavier than intended. We thus introduced 8 small wheels.

The compliance and inclination of the rotary frame made of a leaf spring at the lower part of the Omni-Disc must ensure smooth rotation for the Omni-Disc. When compliance is smaller than anticipated, the lower rotary frame deflects greatly (Fig.9) and the area of the small wheel that contacts the floor increases. When this area is too large, some small wheels at the back of the contact area of the omnidirectional wheel cannot move fast enough in relation to the chassis, slowing the chassis. When the compliance of the lower rotary frame is suitable, the contact area of small wheels is restricted to the end of the Omni-Disc (Fig.10). The difference in velocity between small wheels and the chassis decreases and chassis movement becomes smoother. We decided to use stainless-steel SUS304 for the lower rotary frame and to set the angle of inclination of the wheel to 4 deg. for preventing 3 or more small wheels from contacting the floor simultaneously.

The compliance of the lower rotary frame is related to a different effect. When a single caster or 2 casters are provided at the top of the mechanism, the positional dif

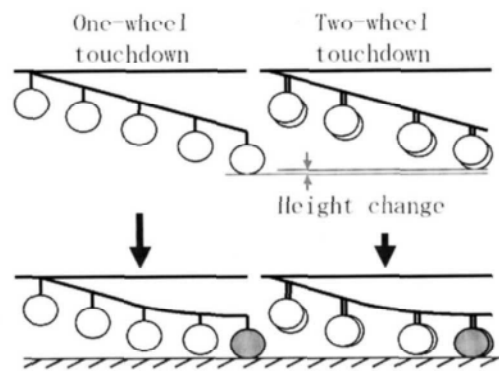


Fig. 11. Effect of the compliance.

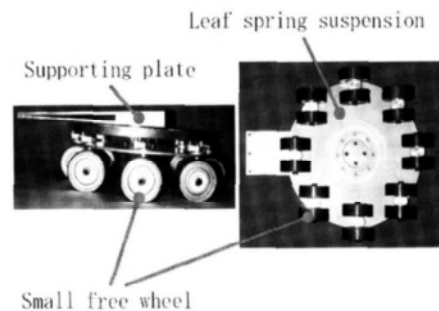


Fig. 12. Passive Omni-Disc as a free caster.

ference between wheels vertical after touching is decreased by deflection of the spring, i.e., the number of omnidirectional wheels supporting the chassis is taken as n . As shown at left in Fig.11, a caster with 1 wheel is at the top of the mechanism. The distance between the caster and the bottom of the chassis increases. As $1/n$ of the weight of the chassis is supported by 1 caster, the deflection of the spring attached to the caster also increases. As shown at right in Fig.11, a caster with 2 wheels is located at the top of the mechanism. The distance between the caster and the bottom of the chassis decreases. As $1/2n$ of the weight of the chassis is supported by 1 caster, the deflection of the spring attached to the caster also decreases. The difference between the distance from the bottom of the chassis (described in the two cases above) is relieved by deflection of the spring, enabling casters to contact the floor more smoothly.

3.3 Passive Omni-Disc

An Omni-Disc without power is an excellent passive wheel. When a vehicle changes direction, for example, the conventional free caster tends to shift to where vehicle movement cannot be easily predicted due to force at the wheel contact by rotation around the caster's rotation supporting shaft of the caster.

Omni-Disc wheels are kept in a certain direction so friction generated even when a vehicle changes direction is small and vehicle movement is unhindered. Fig.12 shows an Omni-Disc used as a passive wheel. Fig.13 shows a graph of the static frictional coefficient on floors of the passive Omni-Disc. Fig.14 shows a graph of the

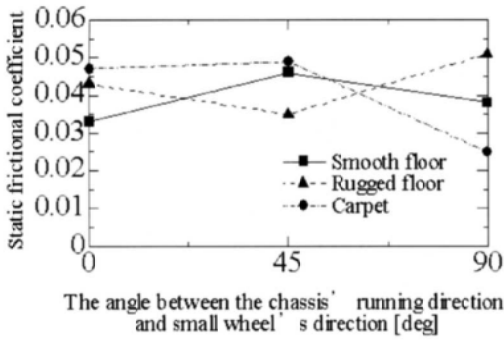


Fig. 13. Static frictional coefficient on various floors.

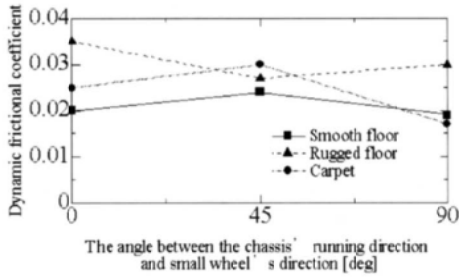


Fig. 14. Dynamic frictional coefficient on various floors.

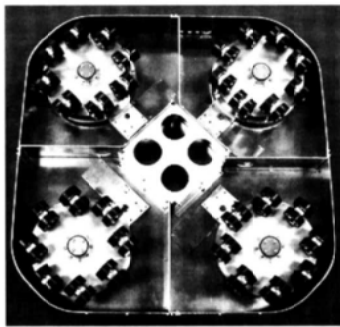


Fig. 15. Passive cart with Omni-Disc.

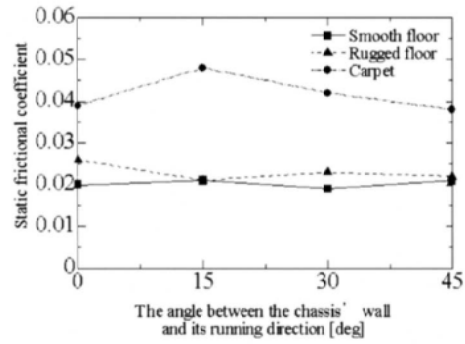


Fig. 16. Static frictional coefficient of a cart with Omni-Disc on various floors.

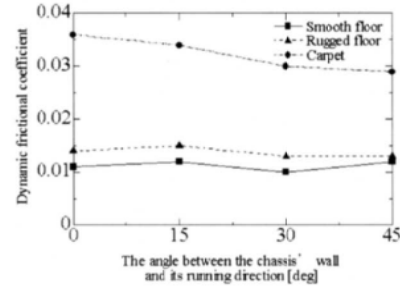


Fig. 17. Dynamic frictional coefficient of a cart with Omni-Disc on various floors.

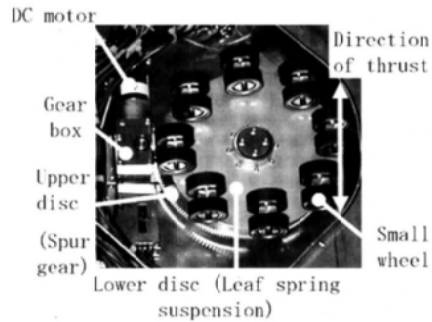


Fig. 18. Bottom view of the active Omni-Disc.

dynamic frictional coefficient. The value at each point of measurement represents the average measured value obtained from 15 run performance experiments. The abscissa in each graph represents the angle between the advance of the chassis and the direction of rotation of small wheels of the Omni-Disc. When this angle is 0 deg., the chassis and small wheels advance in parallel; small wheels only rotate. When it is 90 deg., the advance of the chassis and wheels is vertical; small wheels do not rotate, while the Omni-Disc rotates as a single wheel. When it is 0 deg., 45 deg., or 90 deg., the frictional coefficient is small and makes no substantial difference to other cases, proving that the Omni-Disc is an excellent omnidirectional chassis.

4 passive Omni-Discs spaced at an angle of 90 deg. each (Fig.15) are arranged on a chassis. The static (Fig.16) and dynamic (Fig.17) frictional coefficients are obtained when the chassis is moved in different directions. Each point of measurement represents the average of measurements obtained for 15 run performance experi-

ments. The abscissa in each graph represents the angle between the wall of the chassis and the advancing direction of the chassis. By taking symmetry between Omni-Discs on the chassis mechanism into consideration, run performance of the chassis is tested from 0 deg. to 45 deg. Data in this range is plotted. At angles in this range, the frictional coefficient is small and almost identical. The passive chassis with passive Omni-Discs is excellent as a passive chassis.

3.4. Active Omni-Disc

Using a spur gear instead of the upper second rotary frame of the passive Omni-Disc in the previous section and by rotating it actively by a geared motor (Fig. 18), active thrust is generated perpendicularly to the direction of rotation of each small wheel (against the flat surface) while power for free rotation is generated in the direction (i.e., the rotation of each small wheel) that intersects at right angles to it, forming an active omnidirectional

Dimensions	568mm × 568mm × 92mm
Total mass	16.2 kg (without battery)
Portable load	130kg
Velocity	400 mm/s
Actuator	12 V DC motor × 4
Battery	12 V /3.2 Ah Lead acid battery
Degree of freedom	3



Fig. 19. The Vuton-II.



Fig. 20. Overall view the Vuton-II with a chair.

wheel. Using this wheel, we developed an omnidirectional vehicle, Vuton-II.

4. Omnidirectional Vehicle Vuton-II

4.1. Control of Active Omni-Disc

A vehicle having 3 or more Omni-Discs in different directions (Fig.19) realizes omnidirectional, holonomic movement. Fig.19 shows the particulars of Vuton-II that is with 4 active Omni-Discs. It is operated continuously for 2 hours per charge. Fig.20 shows a new comfortable-to-sit-on model of Vuton-II formed by mounting a chair on the Vuton-II in Fig.19.

Steering this vehicle is simple. If velocities for trans

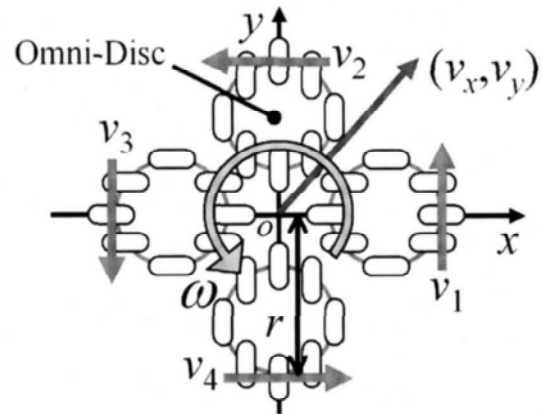


Fig. 21. Control of Vuton-II.

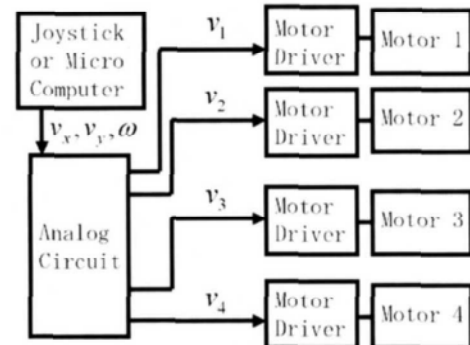


Fig. 22. Control system of the Vuton-II.

lational and rotational movements are specified, all procedures to take are to induce the velocity of each Omni-Disc advancing and to give command velocity to the Omni-Disc. In steering control (Fig.21), the velocity command value $v_i (i=1-4)$ to the 4 Omni-Discs is shown in equation (1) based on velocity command values (v_x, v_y) in each direction of vehicle coordinates (x, y) and turning angle command value ω at the origin,

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

where r is the distance between the origin of the vehicle and the contact of each Omni-Disc, and each Omni-Disc turns clockwise in positive rotation. The first matrix at right is a Jacobian matrix used for controlling Vuton-II. Fig.22 shows control of Vuton-II used in our study. This is operated manually with a 3 DOF joystick or automatically with a basic stamp-II microcomputer. The joystick generates velocity command values (v_x, v_y) and turning angle command value ω by analog voltage signals and to transmit the velocity command to the driving motor of each Omni-Disc through the analog circuit composing the Jacobian matrix shown in equation (1). Part of joystick functions may be transferred to the basic stamp-II microcomputer, PWM signals (v_x, v_y, ω) from the microcomputer smoothed by a low-pass filter, and signals smoothed to be transmitted to the analog circuit for controlling

Vuton-II.

4.2. Experiments on Run Performance of Vuton-II

Vuton-II set to manual operation was exhibited at RoboFesta Kanagawa 2001 and put to test-operation. Vuton-II can easily be steered by those without special skills for omnidirectional holonomic movement.

To study features of translational movement of Vuton-II, a series of experiments was conducted with a micro-computer set to automatic operation. Vuton-II was steered either in the x-direction with 2 Omni-Discs or in the x-y 45-deg direction with 4 Omni-Discs. Positional targets were set with a spacing of 0.5m from 0.5m to 2.5m for PTP position control, and positional and orientational errors at each target were measured (Figs. 23 and 24). Each measurement represents the average of measurements obtained after 3 run trials. Based on these results, the error in the distance of translational movement within 2.5m is less than 35mm, proving relatively satisfactory accuracy. For comparison between the translational movement of Vuton-II in the x-direction with 2 Omni-Discs and that in the oblique x-y 45-deg direction with 4 Omni-Discs, the former is larger in the scatter of positional and orientational errors than the latter, mainly due to wheel slippage and transmission backlash. When 4 Omni-Discs on the left and right rotate, errors are offset by disc interaction. When only 2 Omni-Discs rotate, errors cannot be offset easily and scatter increases.

To study features in Vuton-II rotation, z-axis clockwise rotational movement experiments were conducted by rotating 4 Omni-Discs counterclockwise. Rotational angle targets were set at 360 deg from 360 deg to 2160 deg for PTP position control, and the orientational error at each target was measured (Fig.25). Each measurement represents the average of measurements obtained after 3 run trials. Results made it clear that rotational running has an error of about 1% against a rotational angle within 2160deg. Errors in moving distance and rotational angle of Vuton-II are thus negative and targets are beyond attainment. The main cause of errors is wheel slippage.

Control in experiments was an open loop, so errors above are considered acceptable. We can thus reduce errors by improving mechanisms, introducing proper feedback control, and developing digital Omni-Disc velocity control.

5. Conclusion

We proposed an omnidirectional wheel, the Omni-Disc, for use in omnidirectional vehicles and developed the omnidirectional vehicle Vuton-II. Vuton-II realizes slip-free translational rotation with high mobile efficiency. Vuton-II offsets certain irregularities on the floor with its suspension. It is highly practical and efficient. We are planning further improvement of part shape and quality so Vuton-II will be widely used for wheel chairs, in entertainment, in factories and warehouses, etc. Production of the new model started in Okazaki Industries,

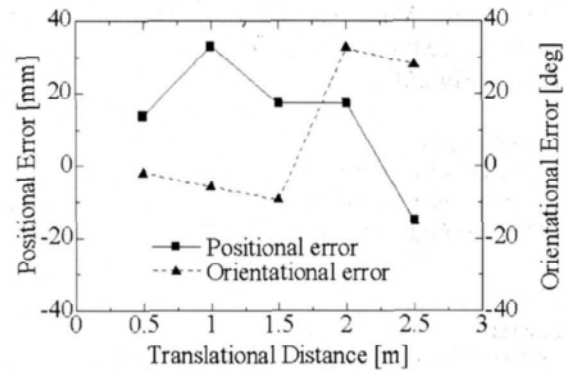


Fig. 23. Error in translational motion along x-axis.

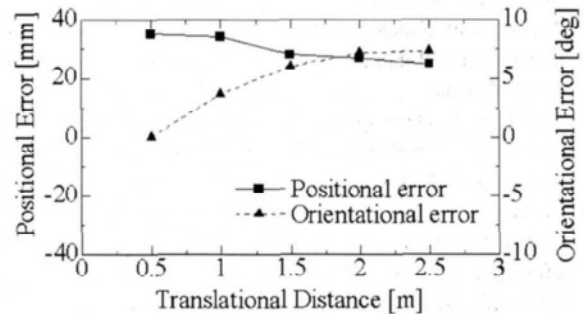


Fig. 24. Error in translational motion along x-y-axis.

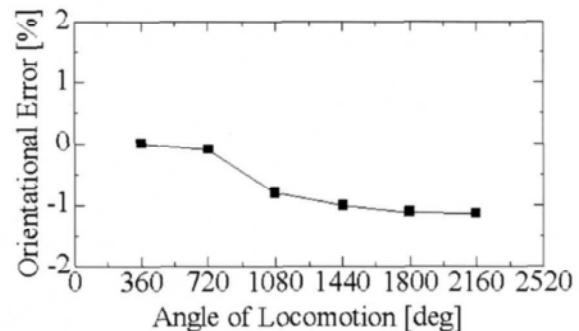


Fig. 25. Error in translational motion about z-axis.



Fig. 26. Demonstration of the Vuton-II

Co., Ltd. as the Vmax Carrier and 5 experimental vehicles were offered to RoboFesta Kanagawa 2001 for demonstration (Fig.26).

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References:

- 1) Nakano, Eiji and Koyachi N., An Advanced Mechanism of the Omni-Directional Vehicle (ODV) and its Application to the Working Wheelchair for Disabled, Proc. '83 Int. Conf. Advanced Robotics, pp.277-284, 1983.
- 2) Catalog of Fuji Mfg. Co.
- 3) Asama, et al. Kinema 3-DOF independent Driving Omni-directional Mobile Robotics, Proc. 12th Annual Meeting, Robotic Society of Japan
- 4) Maeda et al., Development of a Omni-directional Power Assist Cart, Proc. of the 18th Annual Meeting of Robotic Society of Japan, pp.1155-1156.
- 5) Catalog of Mitsui-Miike Mfg.
- 6) Hirose, S. and Amano, S., The VUTON: High Payload, High Efficiency Holonomic Omni-Directional Vehicle, Proc. 6th Int. Symp. On Robotics Research, 1993.



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