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A 4WD Omnidirectional Mobile Platform and its Application to Wheelchairs

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1. Introduction

The aging of society in general and the declining birth rate have become serious social issues world wide, especially in Japan and some European countries. It is reported in Japan that the number of people over 65 years old would reach 30,000,000 in 2012 and increase to over 30% of total population by 2025 (estimated and reported in 2006 by the National Institute of Population and Security Research, Japan). Wheelchairs are currently provided mainly for handicapped persons however, such rapid growth in the elderly population suggests that the numbers of electric wheelchair users will soon increase dramatically.

Currently, reconstruction of facilities to make them barrier-free environments is a common method. Such reconstruction of existing facilities is limited mainly to large cities because large amounts of money can be invested in facilities used by large numbers of people. However, it would be economically inefficient and therefore quite difficult to reconstruct facilities in small towns occupying small populations. Moreover, the aging problem is more serious in such small towns in local regions because of the concurrent decline in the number of young in rural areas where the towns are dispersed and not centralized. Thus, economic and time limitations make the reconstruction of existing facilities to accommodate wheelchair users unfeasible.

One solution to this problem would be to improve wheelchair mobility to adapt to existing environments. Electric wheelchairs, personal mobiles, and scooters are currently commercially available not only for handicapped persons but also for the elderly. However, those mobile systems do not have enough functionalities and capabilities for moving around existing environments including steps, rough terrain, slopes, gaps, floor irregularities as well as insufficient traction powers and maneuberabilities in crowded areas. By the insufficient capabilities of the mobile system, independency of users is inhibited. For example, wheelchair users in Japan must call station staff for help for both getting on and off train cars, because large gaps and height differences exist between station platforms and train cars. To alleviate these difficulties, station staff place a metal or aluminum ramp between the platform and the train. This elaborate process may make an easy outing difficult and cause mental stress.

Addition to this, electric wheelchairs are difficult to maneuver especially for elderly people who have little experience using a joystick to operate a driven wheel system. Current wheelchairs need a complex series of movements resembling parallel automobile parking when he or she wants to move sideways. The difficulties in moving reduce their activities of daily living in their homes and offices.

From this viewpoint, the most important requirements for wheelchairs are maneuverability in crowded areas indoors and high mobility in rough terrain outdoors. Current wheelchair designs meet one or the other of these requirements but not both. To ensure both maneuverability and mobility, we propose an omnidirectional mobile system with a 4WD mechanism.

In this chapter, we discuss the development of the omnidirectional mechanism and control for the 4WD. After analyzing basic 4WD kinematics and statics, basic studies are presented using a small robotic vehicle to demonstrate the advantages on the 4WD over conventional drive systems, such as rear drive (RD) or front drive (FD). Based on the experimental data, a real-scale wheelchair prototype was designed and built. To demonstrate the feasibility of the proposed system, including omnidirectional mobility and high mobility, the result of prototype test drives are presented.

2. Existing Wheelchair Drive Mechanisms

2.1 Differential Drives
The differential drives used by most conventional wheelchairs, both hand-propelled and electrically driven, have two independent drive wheels on the left and right sides, enabling the chair to move back and force with or without rotation and to turn in place. Casters on the front or back or both ends keep the chair level (Fig.1) [Alcare], [Meiko]. This drive maneuver in complex environments because it rotates about the chair's center in a small radius.

The differential drive's drawback is that it cannot move sideways. Getting a wheelchair to move sideways involves a complex series of movements resembling parallel automobile parking. The small-diameter casters most commonly used also limit the wheelchair's ability to negotiate steps.
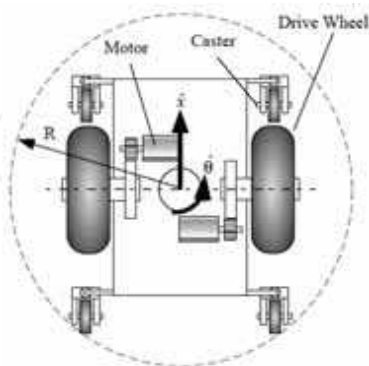

Fig. 1. Differential drive wheelchair with four casters front and back

2.2 Differential 4WD Drives

The 4WD drive was invented in 1989 [Farnam, 1989] (Fig. 2(a)) and was recently applied to a product [Kanto] to enhancing differential drive traction and step negotiation (Fig. 2(b)). The 4WD drive has a pair of omniwheels on the front and a pair of normal wheels on the back. The omniwheel and normal wheel on the same side of the chair are connected by a transmission and driven by a common motor to ensure the same speed in the direction of movement, so all four wheels of the 4WD provide traction. Motors on the left and right drive normal/omniwheel pairs via synchronous-drive transmissions to allow differential driving by the 4WD.

The 4WD controlled in differential drive mode has the center of rotation at the mid-point of the normal back wheels, meaning that spinning in a turn requires more space than for the original differential drive (dotted curve, Fig. 3), limiting indoor maneuverability.
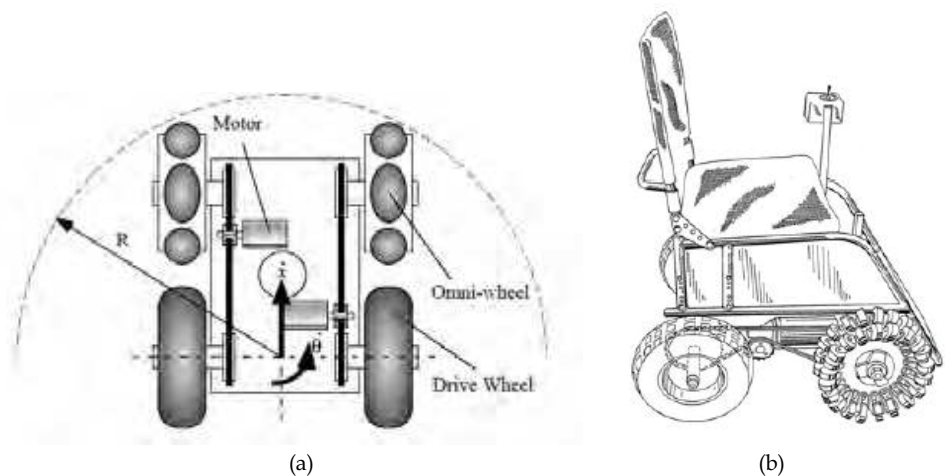

| (a) | (b) |

Fig. 2. 4WDdrive (a) and a wheelchair with 4WD [Farnam, 1989](b)

2.3 Omnidirectional Drive

Omnidirectional drives used on electric wheelchairs [Fujian], [Wada, 1999] were developed to enhance standard wheelchair maneuverability by enabling them to move sideways without changing chair orientation. Examples include the Universal and Mechanum wheels.

In Fig. 3, an omnidirectional vehicle with Mechanum wheels uses rollers on the large wheel's rim inclining the direction of passive rolling 45 degrees from the main wheel shaft and enabling the wheel to slide in the direction of rolling. The standard four-Mechanum-wheel configuration assumes a car-like layout.

The inclination of rollers on the Mechanum wheel causes the contact point relative to the main wheel to vary, resulting in energy loss due to conflicts among the four motors. Because four-point contact is essential, a suspension mechanism is needed to ensure 3-degree-of-freedom (3DOF) movement.
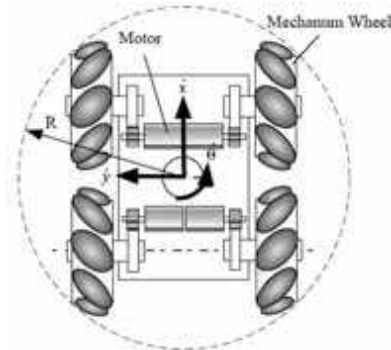
Fig. 3. Four-wheel omnidirectional wheelchair

2.4 Summary

Maneuverability and mobility are essential to barrier-free environments. As discussed above, existing wheelchair designs fulfill one requirement or the other but not both. Omnidirectional wheelchairs are highly maneuverable indoors but dynamically unwieldy outdoors, while 4WD wheelchairs, although highly mobile outdoors, require a 4WD mechanism that prevents them from changing their orientation independently. The maneuverability of the original 4WD must thus be improved to move in complex environments.

To meet these requirements in a single wheelchair design, we propose a new omnidirectional 4WD in the sections below. Although invented in 1989, the kinematics and statics of the original 4WD configuration has not been discussed in depth. In basic studies enabling 4WD to be applied to an omnidirectional mobile base, we analyze 4WD statics and kinematics before discussing the wheelchair's omnidirectional mechanism and control algorithm.

3. Static Analysis for Wheel-and-step

Figure 4 shows a vehicle with a 4WD configuration in which the motor torque is distributed and transmitted to both front and rear wheels. In this configuration, the front and the rear wheels are actively driven in the same speed.

Before bumping a step edge, both the front and the rear wheel provide respective traction forces, F_f and F_r, in the horizontal direction to propel the vehicle forward. However, right after a wheel touches a step edge, the traction force distributed to the front wheel, F_f, changes its direction and applies the moment to flip up the center of the front wheel that has contacted the step edge. The applied force from the rear wheel, F_r, is still directed horizontally after the bump. Figure 5 shows statics of the front wheel in a 4WD system contacting a step edge. In this case, the condition to surmount the step is derived as,

$$F_f + F_r \cos\theta \geq W_f \sin\theta \qquad (1)$$

When the vehicle weight and motor torque are equally distributed to the front and rear wheel, namely $W_f=W_r$, $F_f=F_r=F/2$. Equation (1) would be,

$$F \geq W \frac{2\sin\theta}{1+\cos\theta} \tag{2}$$

Equation (2) gives the required minimum motor power for overcoming the specific step height. Next, we have to consider the limitation of the traction forces which are restricted by the friction coefficient between the wheel and the ground or step edge.

Let μ be the friction coefficient at the contact point on the wheel. The traction force at each wheel is restricted as,

$$\begin{aligned} F_f &\leq \mu W_e \\ F_r &\leq \mu W_r \end{aligned} \tag{3}$$

where W_e is a force component directing along the line O-B in the figure which is represented as,

$$W_e = W_f \cos\theta + F_r \sin\theta \tag{4}$$

From Eq. (3) and Eq. (4) we get,

$$W_f \sin\theta \leq \mu^2 W_r \sin\theta + \mu(W_f + W_r)\cos\theta \tag{5}$$

Again we suppose that the vehicle weight is equally distributed and motor torque is transmitted in the same ratio to the front and the rear wheels, the slip condition for 4WD is given by following relationships from Eq. (5).

$$\mu \leq \frac{1-\cos\theta}{\sin\theta} \quad (if \ \sin\theta \neq 0) \tag{6}$$

Theoretical load curves derived by Eq. (2) and Eq. (6) are shown together with the experimental results in Section 6.
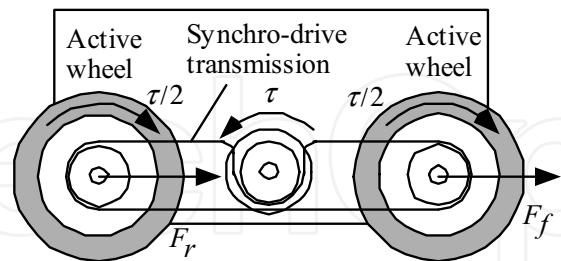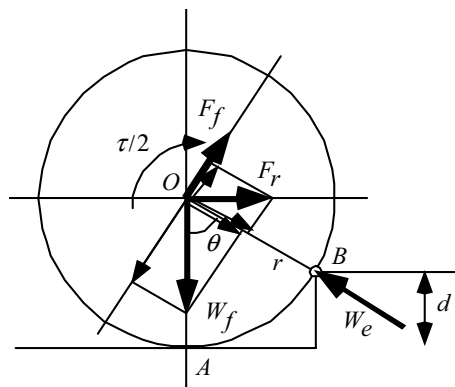
Fig. 4. 4WD drive transmission

Fig. 5. Statics of the 4WD front wheel contacting a step edge

4. Kinematics of 4WD Drive Mechanism

In this chapter, we analyze the motions of the front omniwheels driven by synchro-drive transmissions for deriving the kinematic condition for non-slip drive.

Figure 6 is a schematic top view of a 4WD mechanism. When the two rear wheels are driven by independent motors to travel in velocities v_R and v_L on the ground with no slips, the wheels allow the vehicle to rotate about the point on the ground indicated O_r (Instantaneous Center of Rotation, ICR) in Fig. 6. It is well known that the vehicle's forward velocity and rotation are represented by the wheel velocities as follows,

$$\dot{x}_v = \frac{v_R + v_L}{2}$$

$$\dot{\phi}_v = \frac{v_R - v_L}{W} \tag{7}$$

where W is a tread of the mobile base (displacement of the two parallel wheels). Now considering a velocity vector on a specific point p on the 4WD mechanism which location is (x_p, y_p) as shown in the figure. The components of vector v_p along the X- and Y-directions of the vehicle coordinate system, indicated as v_{px} and v_{py} , are represented as,

$$v_{px} = \dot{x}_v - \ell \dot{\phi}_v \sin \theta_p$$
$$v_{py} = \ell \dot{\phi}_v \cos \theta_p \tag{8}$$

Note that $\ell \sin \theta_p = y_p$ and $\ell \cos \theta_p = x_p$, and the following relations are derived.

$$v_{px} = \left(\frac{1}{2} - \frac{y_p}{W} \right) v_R + \left(\frac{1}{2} + \frac{y_p}{W} \right) v_L$$

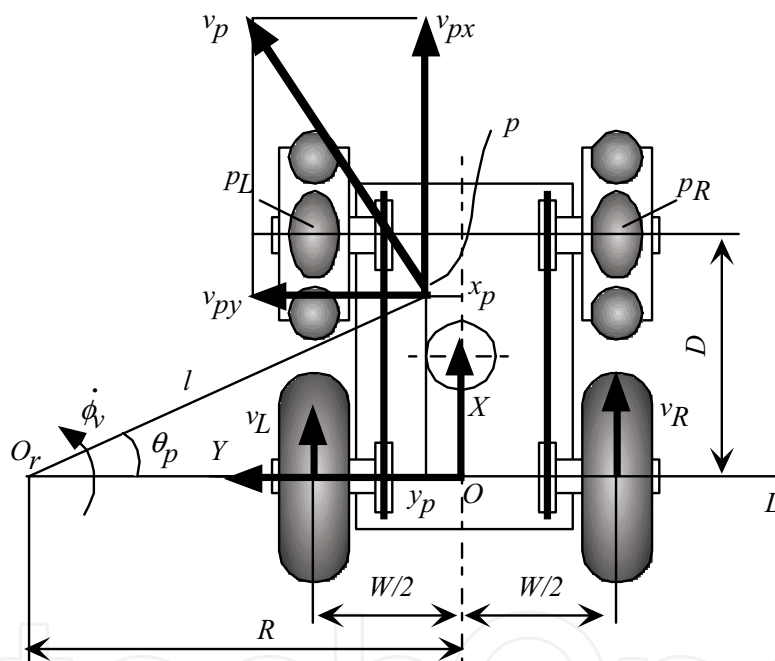$$v_{py} = \frac{x_p}{W} \left(v_R - v_L \right) \tag{9}$$

Fig. 6. 4WD kinematics

The location of the contact point of the front left omniwheel is defined as $(x_p, y_p)=(D, W/2)$ on the vehicle coordinate system. From Eq. (9), the velocity components at left omniwheel are represented as,

$$v_{px} = v_L$$
$$v_{py} = \frac{D}{W} \left(v_R - v_L \right) \tag{10}$$

Thus only when $y_p = W/2$, velocity component in the X-direction of the left omniwheel becomes completely identical to the rear wheel velocity and is independent from the right wheel motion. The velocity component in the Y-direction is generated as a passive motion by free rollers on the omniwheel. The velocity components of right side omniwheel can be derived in the same manner as,

$$v_{px} = v_R$$
$$v_{py} = \frac{D}{W}(v_R - v_L)$$

(11)

From these analyses, it is clear that omniwheels can follow the rear wheel motion with no slip or conflict as long as the contact point of the omniwheel is located completely on the line which is passing through the contact point of the rear wheel with directing the wheel rolling direction. Thus, omni and normal wheel pairs on the same side of the 4WD mechanism can be driven by a synchro-drive transmission with a common motor.

5. Powered-Caster Control System

5.1 Powered-caster Control for Twin Caster Configuration

The powered-caster drive systems were developed by the authors group [Wada, 1996], [Wada, 2000]. The drive system enables holonomic and omnidirectional motions with the use of normal wheels rather than a class of omniwheels.

Two types of caster configurations are available for the powered-caster drive system including the single-caster type (a normal wheel with a steering shaft supporting the wheel with a caster offset) and the twin-caster type (two parallel normal wheels supported by a steering shaft with a caster offset). To apply the powered-caster control, the configuration of a wheel mechanism has to have a caster offset between drive wheel(s) and a steering axis.

Figure 7 illustrates an omnidirectional vehicle design for AGV (Automated Guided Vehicle) with a drive unit which forms a twin caster configuration [Wada, 2000]. Two drive wheels and a steering mechanism are mounted on the drive unit where each wheel or a steering is driven by a respective motor. The displacement between the midpoint of the two wheels and the center of the steering shaft, called caster offset, s, and the displacement between two wheels, called vehicle tread, W, are respectively indicated in Fig. 7. Thus, the wheels and the steering shaft form a twin-caster configuration. Coordination of these three motors allows the vehicle body to move in an arbitrary direction with arbitrary magnitude of velocity from any configuration of the drive unit.

Relationships between wheel velocities and the motion of the drive unit, which is defined as the velocity and the rotation at the center of the steering axis are derived as (see [Wada, 2000] for details),
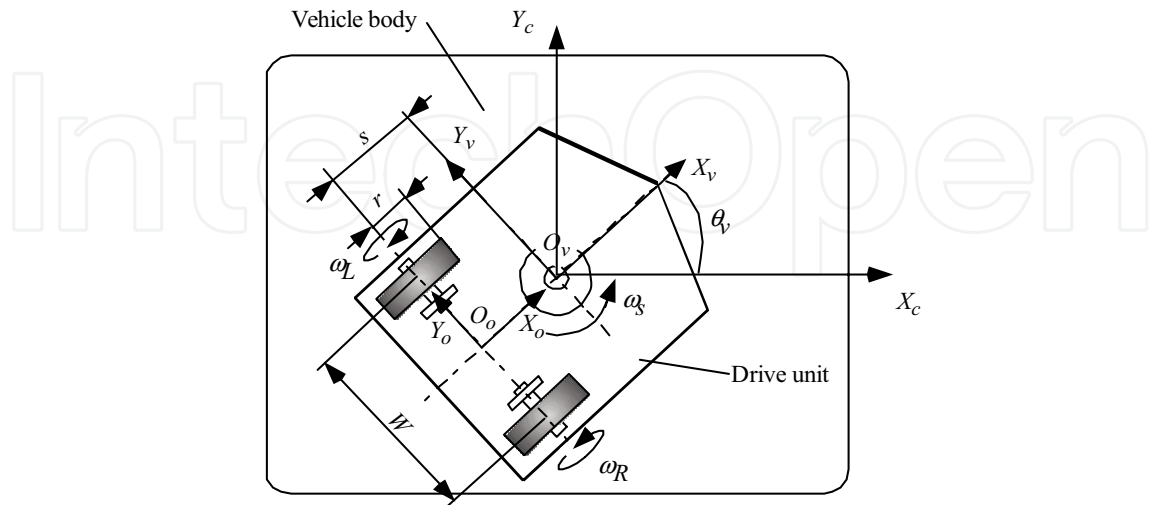
Fig. 7. Omnidirectional AGV with a twin-caster drive

$$\begin{pmatrix} \dot{x}_v \\ \dot{y}_v \\ \dot{\theta}_v \end{pmatrix} = \begin{pmatrix} r/2 & r/2 \\ rs/W & -rs/W \\ r/W & -r/W \end{pmatrix} \begin{pmatrix} \omega_R \\ \omega_L \end{pmatrix} \tag{12}$$

where r is the wheel radius. Note here that the rotation of the drive unit, $\dot{\theta}_v$, in Eq. (12) is not independent from the translation velocity, $\dot{x}_v$ and $\dot{y}_v$, the third motor is required to compensate for the rotation of the drive unit and directing the vehicle body to the desired direction. In the wheelchair applications, desired motion is given along the vehicle body coordinate system since a joystick is fixed and moves together with the chair. Considering these effects, Eq. (12) can be resultantly united with the rotation of the vehicle body as shown below.

$$\begin{pmatrix} \dot{x}_c \\ \dot{y}_c \\ \dot{\theta}_c \end{pmatrix} = \begin{pmatrix} J_{11} & J_{12} & 0 \\ J_{21} & J_{22} & 0 \\ r/W & -r/W & 1 \end{pmatrix} \begin{pmatrix} \omega_R \\ \omega_L \\ \omega_S \end{pmatrix} \tag{13}$$

where,

$$
\begin{aligned}
J_{11} &= \frac{r\cos\theta_v}{2} - \frac{rs\sin\theta_v}{W} \\
J_{12} &= \frac{r\cos\theta_v}{2} + \frac{rs\sin\theta_v}{W} \\
J_{21} &= \frac{r\sin\theta_v}{2} + \frac{rs\cos\theta_v}{W} \\
J_{22} &= \frac{r\sin\theta_v}{2} - \frac{rs\cos\theta_v}{W}
\end{aligned}
\qquad (14)
$$

Note that θ_v is rotation of the vehicle body relative to the drive unit, namely rotation created by the third motor. A 3x3 matrix in the right side of the Eq. (13), called a Jacobian, is a function of the orientation of the drive unit relative to the vehicle body, θ_v. All elements in the Jacobian can always be calculated, and determinant of the Jacobian may not be zero for any θ_v. Therefore there is no singular point on the mechanism and an inverse Jacobian always exists. 3D motion commands, $\dot{x}_c$, $\dot{y}_c$ and $\dot{\theta}_c$, are translated into three motor references by the inverse of Eq. (13), i.e. inverse kinematics. The three motors are controlled to provide the reference angular velocities by independent speed controllers for omnidirectional movements. Thus, holonomic 3DOF motion can be realized by the proposed mechanism.

This class of omnidirectional mobility, so called "holonomic mobility", is very effective to realize the high maneuverability of a wheelchair by an easy and simple operation.

5.2 Powered-caster Control for 4WD Mechanism

Now we refer back to control of the 4WD mechanism. As mentioned in Section 2.2, for applying 4WD to a wheelchair design, there must be an offset between the rear wheels and the center of the chair to allow enough room on the front side for mounting the omniwheels. When the wheelchair is controlled in a differential drive manner, the offset distance makes the maneuverability of the wheelchair worse, as mentioned previously. However, that offset allows us to apply the powered-caster control for the 4WD mechanism with a third motor. Therefore, by adding the third motor to the original 4WD mechanism for rotating a chair, coordinated control of three motors enables the wheelchair to realize independent 3DOF omnidirectional motion.

For wheelchair applications, a 4WD drive unit can be held level since omniwheels are installed in the front end of the drive unit. Therefore, no caster is required to support a chair base or the drive unit. Figure 8 illustrates a schematic of an omnidirectional mobile base with a 4WD mechanism.
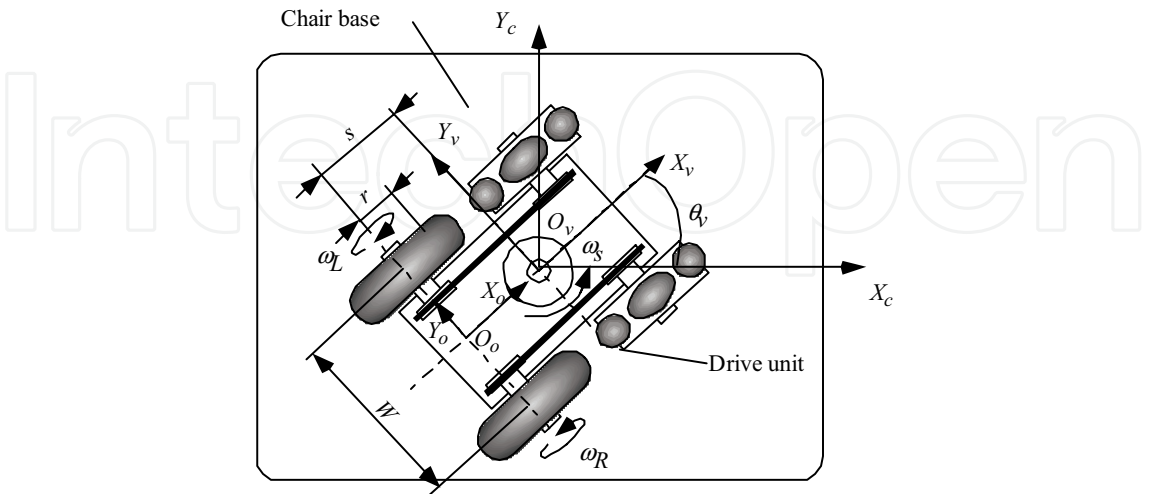
Fig. 8. Omnidirectional mobile base with 4WD

6. Basic Experiments Using a Small Robot

Figure 9 shows an overview of a small vehicle designed for experiments for fundamental studies. The vehicle is equipped with four wheels, where the front two wheels are omniwheels and rear two are normal rubber tires. A servo motor is installed on each side of the vehicle to drive the right or left wheel(s) independently. The servo motor for driving wheels is located at the midpoint between the front and rear wheels, as shown in the figure. Each motor torque is distributed to the front and rear wheel shafts by pulley-belt synchro-drive transmission(s). The dimension of the prototype is approx. 450 mm in width and 350 mm in length. The vehicle body is made of aluminum on which four wheels and two motors are mounted. All four wheels are 100 mm in diameter. The wheelbase is 200 mm and the tread is 430 mm. The capacity of the motors is 100 W.

Fig. 9. Omnidirectional mobile platform with 4WD for experiments

6.1 Step Climb Capability

To test the step climb capability for the 4WD system, a series of experiments was performed using the small vehicle. The following three configurations were tested,

1) 4WD configuration with 4 normal wheels

The front omniwheels shown in Fig. 9 are changed to normal wheels to avoid the wheel mechanically seizing the step edge. This configuration allows both front and rear wheels to make pure touching contacts with floor and the step.

2) Rear drive configuration

The transmission belts for the front wheels are removed from the 4WD configuration with four normal wheels. Therefore, only rear wheels provide traction forces. This configuration is tested to clarify the advantage of the 4WD system over the conventional drive system.

3) 4WD configuration with two omniwheels in front and two normal wheel in the rear. The surface of the omniwheel is not continuously smooth. Mechanical gaps between the free rollers are found on the surface that can make mechanical seizing contact between a step edge and the wheel. This contact is different from pure point contact by which traction force is not independent from the friction coefficient. Through the mechanical seizing contact, motors can provide larger torque which allows the vehicle to surmount the higher step than the 4WD configuration with four normal wheels. This configuration is for finding the difference between the contact condition between front wheels and a step edge.

On each test, the vehicle runs towards the step at a very slow speed to avoid the dynamic effects. A step made of wood plates which can be re-configured from 2.5 mm to 50 mm in height. The velocities of the right and left wheel motors are controlled by respective motor controllers with PD feedback loops to which the identical velocity command is given by analog voltage provided form a potentiometer operated by a human.

In the experiments, motor torques on the right and left are measured throughout each trial run. Figure 10 shows one of the test results which includes detected motor torques. When a wheel successfully climbs to the top of a step, a peak appears in the torque profile. When both the front and the rear wheels climb the step, two peaks can be measured. By reading the torque at the top of the peak from the torque profile, the required torques for the step climbing for front wheel and rear wheel can be derived after noise reduction, as shown in the figure.

The dashed line in the lower part of Fig. 11 shows the required torques vs. step height that are theoretically calculated by Eq. (2) for the 4WD configuration that wheel diameter, D=100 mm, vehicle weight, M=7 kg, and friction coefficient μ =0.7. To clarify the advantage of the 4WD system over the conventional rear drive system (RD), required torque for the RD configuration is also plotted by a dashed line at the top of the figure. The emphasized thick parts in the continuous curves indicate that slip conditions are satisfied in the areas for RD and 4WD. Equation (6) gives the slip condition for the 4WD mechanism.

The experimental results are also shown in the same figure by triangles, circles and squares which indicate that the small vehicle successfully surmounted a step, h in height with motor peak torque τ. The maximum motor torque that can be provided by a 100 W motor,

0.95 Nm, is also illustrated by a dashed line in the figure. It is clear that the limitation of the step height is restricted by slip conditions but not by the insufficient motor power.

In the experiments, the RD vehicle could surmount a step 10 mm in height (triangles show experimental data) while theoretical results suggests approx. 8 mm is the limitation for satisfying the slip condition. On the other side, the 4WD vehicle with four normal wheels could surmount a step 35 mm in height (circles), which is more than three times the RD, while 32.5 mm is the limit in step height suggested by the theoretical slip condition, Eq. (6). A series of the required torques for each step height shows good agreement with the theoretical results. As the step height increases, the required motor torque for RD increases dramatically compared with the one for 4WD. For instance, for the RD vehicle to overcome a step 300 mm in height, the motor must provide approx. τ =1 Nm which exceeds the current maximum motor torque with the friction coefficient τ =2.3 which is not achieved by a normal tire.

The 4WD vehicle equipped with omniwheels in front overcame a 50mm step (squares) which is same dimension as its radius. Even in this case, the required motor torque calculated by Eq. (2) agreed with the experimental results while limitation given by the slip condition was broken by the mechanical seizing contacts between the wheels and the step edge.

These experiments verified that the analysis well estimated the required torque and the limitation of the maximum step heights for the vehicle with flat surface tires. This value can be regarded as a guaranteed step height which should be considered the maximum step climb capability in a design process.

Thus, the fundamental static models of wheel-and-step for 4WD are derived which provide a useful model for designing the 4WD large-scale vehicle. Moreover, the improved mobility and the step climb up capability of the 4WD system are clarified through theory and experiments.
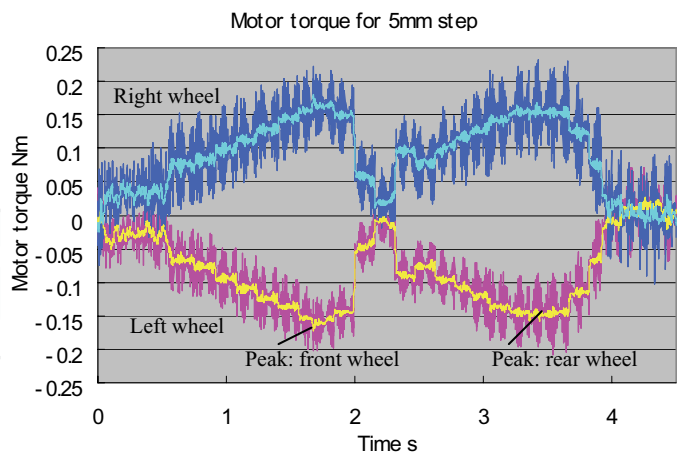

Fig. 10. Motor torques measured by experiment: Noisy plots (pink and blue) at negative and positive area are detected motor torques for left and right motors. Light plots (yellow and light blue) around the center of noisy signals are motor torques with noise reduced for measuring peaks for climbing the step
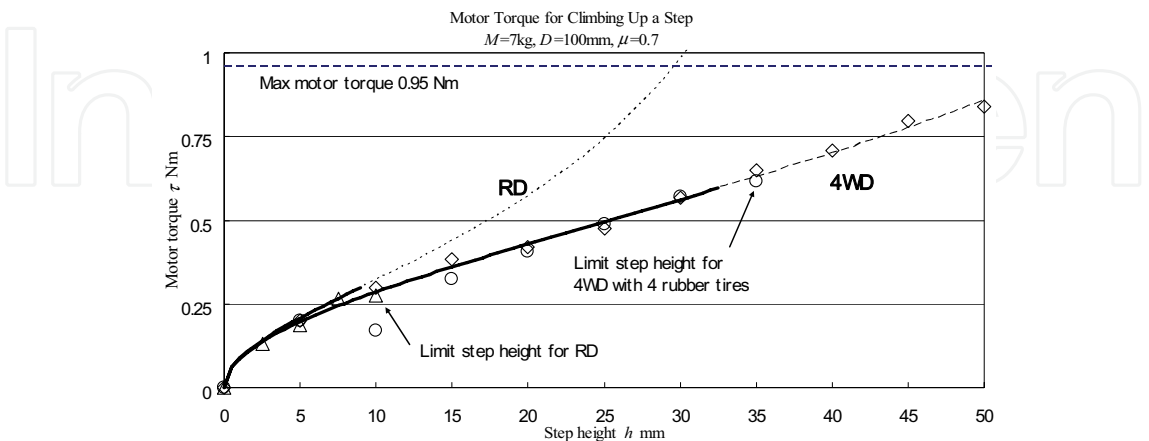
Fig. 11. Required motor torque vs. surmountable step height:
Lines 1) lower: 4WD, 2) upper: RD, dashed lines denote theoretical motor torque
while thick lines represent surmountable parts that meet slip conditions. Triangles
are experimental results of the RD configuration, circles represent a 4WD which has
four normal rubber tires, and squares represent a 4WD having omniwheels in front
and normal wheels in the rear

6.2 Omnidirectional Mobility

To verify the omnidirectional control of a 4WD mechanism, the proposed algorithm is
installed on the control system for the vehicle prototype. Each of the three motors is
controlled by the velocity controller.

The operator can control the vehicle trough a 3D joystick which provides individual 3D
motion command to the vehicle controller. Two motors for the wheel drive are coordinated
to translate the center of the vehicle body to the desired direction. The rotation and
orientation of the 4WD base can be calculated by the dead-reckoning algorithm by using
shaft encoders installed on those motors. Based on the result of the dead-reckoning, the
angler velocity of the vehicle body is controlled by the third motor to compensate for the
rotation of the 4WD mechanism and to direct the body in the desired direction. To achieve
this control, the reference motor velocity commands are given by the inverse of Eq. (13).

The velocity-based control system is useful for the wheelchair application because the
power is provided intermittently to the motors. When the wheelchair user does not touch a
joystick for a pre-specified time, power to the motors is cut off to preserve the battery
charge. If the motors are controlled by the position controller, large torques may sometimes
be provided to the motor when wheels are passively rotated and large position errors are
accumulated during the no-power period. To avoid this kind of dangerous situation, motors
used to power wheelchairs should be driven by velocity controllers.

Figure 12 shows a set of screen shots of the video in which the vehicle motion in the
experiment was recorded. The steering shaft is located on the center of the 4WD mechanism.
Initially, the vehicle is located in the center of the picture frame (a). Then it starts to move to

the right side of the frame (b)-(e), where the center of the vehicle moving in right direction with the orientation of the vehicle body (octagon plate) are constant. After stopping at the right side, it moves back toward the left (f)-(k). The vehicle body changes its orientation from right to left around the center in frames (h), (i) and (j), which is called a "flipping" motion by powered-caster control. After reaching the left side of the frame (k), the vehicle returns to the initial position. From a set of snapshots, it is shown that typical holonomic motion was successfully presented by the prototype vehicle with a 4WD mechanism.
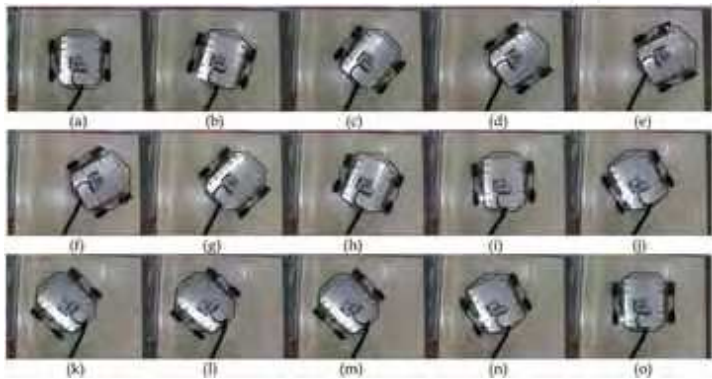

Fig. 12 Snapshots of the mobile robot in the experiment: The robot moved from center of the picture frame to the right side then went to the left and back to original position. During the motion, robot body (the octagon shaped transparent acryl plate) keeps constant orientation

7. Design of a Wheelchair Prototype

In the prototype design, the static model discussed in Section 3 was used for the fundamental design calculation. The wheelbase and tread of the 4WD mechanism are 400 mm and 535 mm, respectively. Those dimensions are determined to satisfy the limitation for a wheelchair that is 600 mm in width and 700 mm in length, as shown below. The required step height which can be surmounted by the wheelchair is approx. 100 mm. The maximum running speed for a continuous drive is 6 km/h which is same as conventional wheelchairs in Japan.

```
                    ** Wheelchair Specifications**
         Dimension
                 Width            600 mm
                 Length           700 mm
                 Height           450 mm
         Weight
                 Total            180 kg (human + wheelchair)
                 Wheelchair       80 kg (including batteries)
         Speed                    6 km/h
         Surmountable step height 100 mm
```

To satisfy these specifications for the 4WD mobile system, the load curves derived by Eq. (2) and Eq. (6) are used for the design process shown in Fig. 13. For determining the wheel diameter of the 4WD, several combinations of wheel diameters and gear ratios were calculated and compared as wheelchair specifications by load curves. First, to maintain the rated driving velocity, 6 km/h, gear ratio between motor shaft and the wheel shaft are determined by the wheel diameter, since the rated rotation of the nominated motors are both 3000 rpm. Then load curves can be plotted by substituting a determined parameter, weight, gear ratio and friction coefficient, into Eqs. (2) and (6) for each case. In the figure, the maximum torque from a 300 W motor is plotted by dashed line. For the 100 mm step, a 200 W motor may be too small and a 400 W motor is over the specification. From Fig. 13 again, it is obvious that the D=250 mm case does not meet the requirement for sufficient motor torque and friction condition to overcome the 100 mm step. In the case of D=350 mm or over, the step climb capability is increased, however, the dimension of the mobile platform would need to be larger, especially in the longitudinal direction. Therefore D=300 mm is acceptable from an overall standpoint in terms of dimension, speed, motor power and step climb capability.

By the analysis, it is expected that the prototype wheelchair can step over a 100 mm step when the friction coefficient is kept to μ=0.7 or over.

Based on the design process described above, a prototype wheelchair was designed and built.

Figure 14(a) shows an overview of the wheelchair prototype. The vehicle is equipped with four wheels, where the two front wheels are omniwheels and the two rear are normal rubber tires. Figure 14(b) shows right side of the drive mechanism in which a front omniwheel and rear normal tire are shown. Both wheel shaft rotations are synchronized by belt pulley transmissions which are not shown but illustrated in the figure. The configuration of the omniwheel used in the front wheels is also shown in the figure which enables continuous changes of the contact point between passive rollers. The wheel has inner and outer rollers which are arranged to keep the contact points on the center of the wheel width, thus resulting in small gaps and continuous contact changes between the rollers.

A 300 W servo motor is installed and connected to the drive shaft via a gear unit which translates the direction of the motor rotation at a right angle for driving the wheel shafts via the synchro-drive transmission (the gear units are seen in bottom view in Fig. 15).

In the design process, the wheelchair weight was estimated to be less than 80 kg including batteries however, actual prototype weights approx. 100 kg. Therefore, maximum total weight, 180 kg, gives a limitation of 80 kg for the wheelchair user.

A tablet PC is used for the controller of the wheelchair, in which calculations of the kinematics, inverse kinematics, motor feedback control and dead-reckoning, are executed together with the I/O and wireless communication process. The proposed omnidirectional control algorithm is also programmed on the control system of the prototype.

8. Experiments

8.1 Omnidirectional Motion

Figure 16 shows a series of snapshots of the experiment in which the prototype wheelchair presented the omnidirectional motion. In this experiment, the wheelchair was programmed

to track the reference trajectories automatically without joystick operation. The wheelchair moved in a lateral direction while maintaining the chair orientation, causing the drive unit orientation to vary. The location of center of the chair was controlled by two wheel motors located on the reference straight line facing the lateral direction at all times. Figure 17 also shows another omnidirectional motion to translate in backward. At the initial configuration, the drive unit orientation had almost agreed with the chair, it moved backward, changed the direction of motion and directed the moving direction. This series of motion is called "caster flip" which is unique for proposed omnidirectional control systems.

8.2 Step climb capability

As shown in the experiments of omnidirectional motions, the 4WD drive unit directs the moving direction spontaneously after the small travel. Therefore, step climb capability is limited by the large wheel diameter and not by the small diameter of the free rollers.

Figure 18 shows an experiment where the prototype attempted to climb a 90 mm step with no load on the chair. In the experiment, the front wheels successfully climbed the step, but the rear wheels failed and both front and rear wheels slipped. In Section 3, a design calculation was discussed under the assumption that the total weight of the wheelchair was equally distributed to the front and rear wheels. When the rear wheels bump the step edge, this assumption can not be satisfied because of the upward inclination of the chair.

In the next experiment, the extra 40 kg weight was mounted on the front side of the chair, as shown in Fig. 19, to reduce the change of the load distribution ratio between front and rear. In this case, the prototype could surmount the 90 mm step, even though the total weight increased 40 kg from the first experiment. From these experiments, it is clear that the prototype wheelchair has enough power and capability to climb a 90 mm step, but needs to improve the load distribution of the wheelchair between the front and the rear wheels.
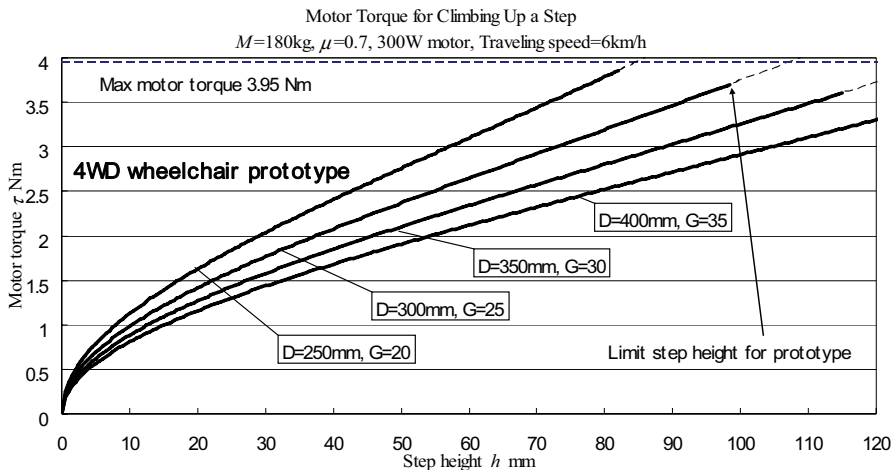

Fig. 13. Surmountable step height vs. required motor torques and friction condition satisfied area for 4WD wheelchair prototype design for wheel diameters D=250, 300, 350 and 400 mm
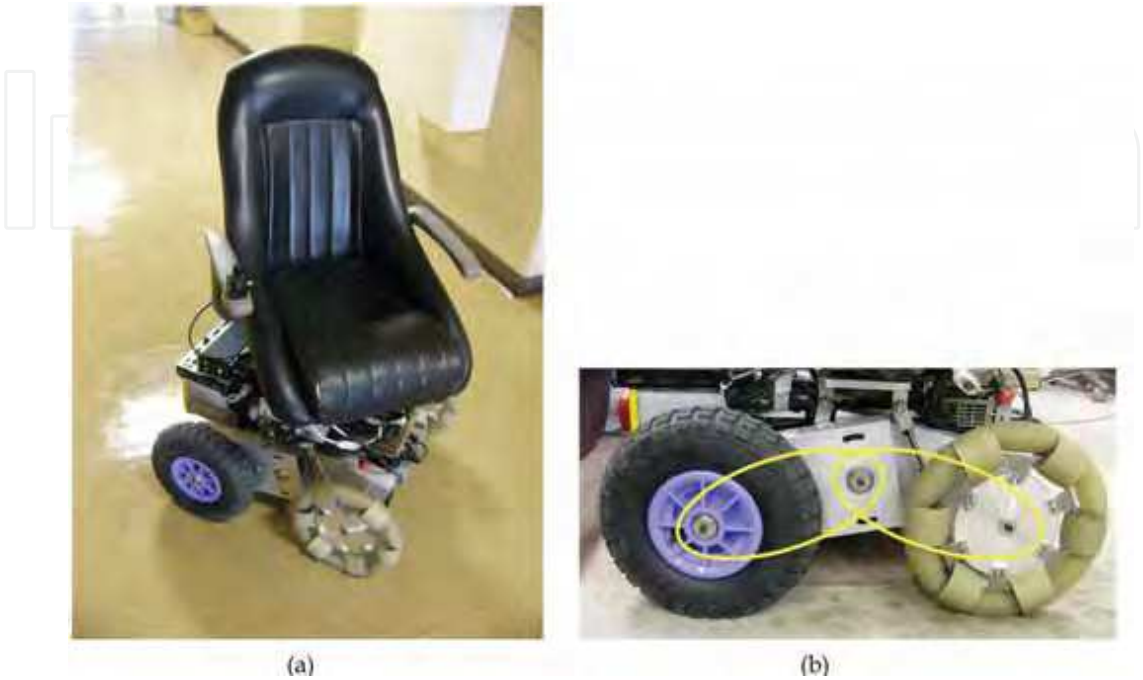
Fig. 14. 4WD omnidirectional wheelchair prototype, overview (a) and synchronized 4WD
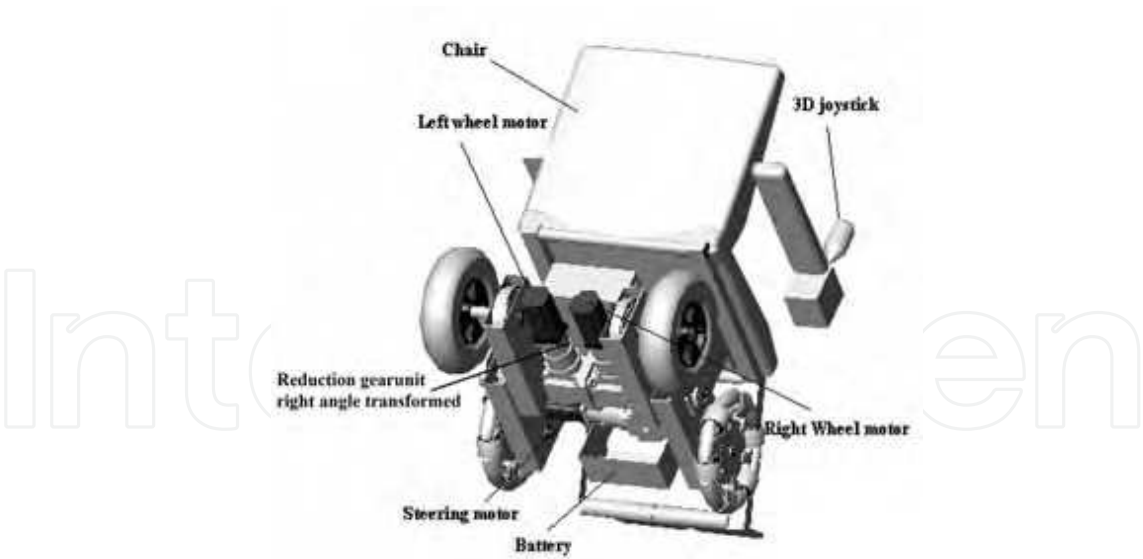transmission (b)

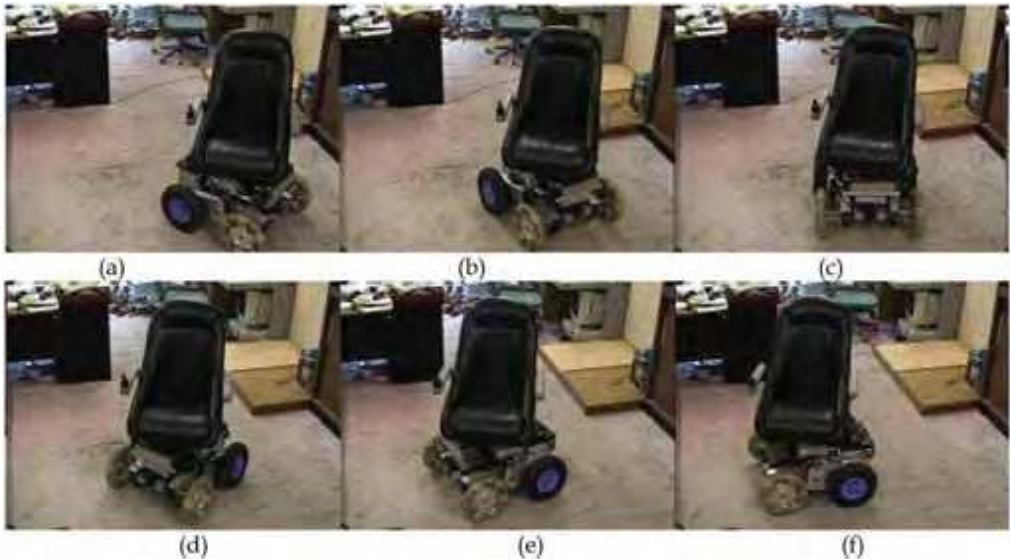Fig. 15. Prototype bottom view by 3D CAD

Fig. 16. Lateral motion of the wheelchair prototype; it moves in sideways while maintaining the chair orientation from the right side to the left of the picture frames
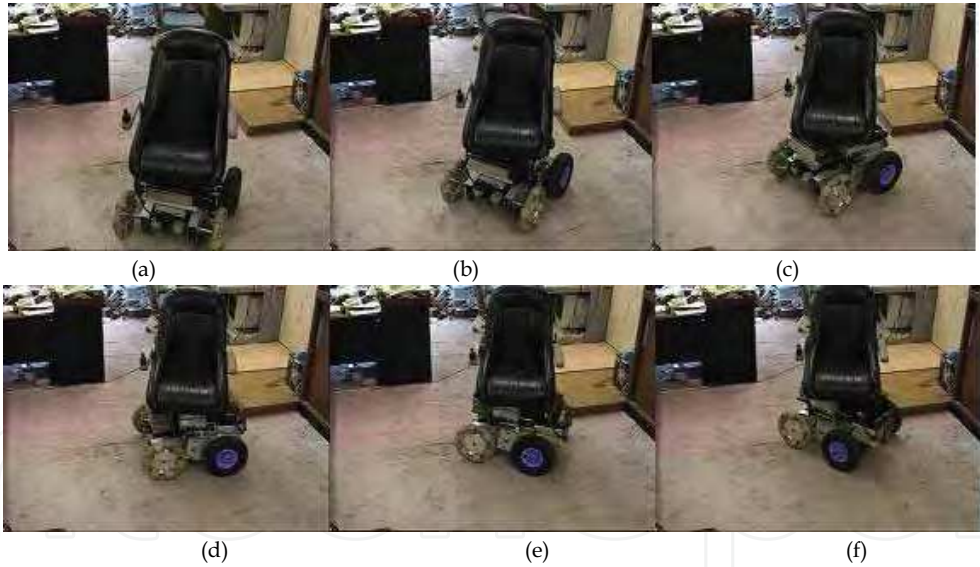

Fig. 17. The prototype moving in backward; it moves in backward while maintaining the chair orientation

<div align="center">(a)   (b)   (c)</div>

Fig. 18. Snapshots of the wheelchair in experiment: Climbing up a 90 mm step. Rear wheels failed to step up and all wheels slipped

<div align="center">(a)   (b)   (c)</div>

Fig. 19. Snapshots of the wheelchair in experiment: Climbing up a 90 mm step with carrying 40 kg weight on the chair

9. Conclusion

Conventional electric wheelchairs can not meet requirements for both maneuverability and high mobility in rough terrain in a single design. Enhancing their mobility could facilitate the use of wheelchairs and other electric mobile machines and promote barrier-free environments without re-constructing existing facilities.

To improve wheelchair step-climbing and maneuverability, we introduced a 4WD with a pair of normal wheels in back and a pair of omniwheels in front. A normal wheel and an omniwheel are connected by a transmission and driven by a common motor to make them rotate in unison. To apply the 4WD to a wheelchair platform, we conducted basic analyses on the ability to climb steps.

After analyzing the original 4WD statics and kinematics and determining theoretical mechanical conditions for non-slip omniwheel driving, we derived the required motor torque and slip conditions for step-climbing.

We discussed powered-caster control for the 4WD where control was applied to coordinate velocity provided by two rear wheels. Powered-caster control enables the center of the vehicle to move arbitrarily with an arbitrary configuration of the 4WD. Orientation of the vehicle is controlled separately from movement by the third motor on the 4WD.

Theoretical results and omnidirectional control were verified in experiments using a small vehicle configured selectively for RD, FD, and 4WD. In experiments, step-climbing and

required motor torque were measured for a variety of step heights. The results agreed quite well with theoretical results. In experiments, a 4WD transmission enabled the vehicle to climb a step three times higher than a vehicle with an RD transmission without changing motor specifications or wheel diameter. The derived wheel-and-step model is useful for designing and estimating the mobility of wheeled robots.

For omnidirectional control of the 4WD, velocity-based coordinated control of three motors on the robot was verified through experiments in which omnidirectional movement was successfully achieved.

To verify the availability of the proposed omnidirectional 4WD system for wheelchair applications, a prototype was designed and built. The prototype wheelchair presented holonomic and omnidirectional motions for advanced maneuvering and easy operation using a 3D joystick. It also showed a basic step climb capability which can go over a 90 mm step. Improvement in the load distribution would be the next subject of this project, together with the development of a stability control mechanism which keeps static stability of a chair by an active tilting system.

10. Acknowledgements

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Climbing and Walking Robots: towards New Applications

Edited by Houxiang Zhang

With the advancement of technology, new exciting approaches enable us to render mobile robotic systems more versatile, robust and cost-efficient. Some researchers combine climbing and walking techniques with a modular approach, a reconfigurable approach, or a swarm approach to realize novel prototypes as flexible mobile robotic platforms featuring all necessary locomotion capabilities. The purpose of this book is to provide an overview of the latest wide-range achievements in climbing and walking robotic technology to researchers, scientists, and engineers throughout the world. Different aspects including control simulation, locomotion realization, methodology, and system integration are presented from the scientific and from the technical point of view. This book consists of two main parts, one dealing with walking robots, the second with climbing robots. The content is also grouped by theoretical research and applicative realization. Every chapter offers a considerable amount of interesting and useful information.

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