A Five-wheel Wheelchair with an Active-caster Drive System

Yu Munakata, Aki Tanaka and Masayoshi Wada, *Member, IEEE*

Dept. of Mechanical Systems Engineering, Tokyo Univ. of Agriculture and Technology
2-24-16 Naka-cho, Koganei, Tokyo, 184-8588 Japan
mwada@cc.tuat.ac.jp

***Abstract*— A novel wheelchair system with an active-caster drive mechanism is presented in this paper. A manual (hand propelled) wheelchair with an external single-wheel drive system forms a five-wheel configuration. The active-caster mechanism is applied to a drive system to motorize a manual wheelchair. Two electric motors which drive a wheel axis and a steering axis of a drive wheel independently are equipped on the active-caster. A coordinated control of the two motors enables the velocity vector on the steering shaft to direct in an arbitrary direction with an arbitrary magnitude. The generated velocity vector allows a wheelchair to go straight and/or rotate completely in a same way as a standard electric wheelchair. Namely 2DOF of the wheelchair can be controlled independently by a single drive wheel without any constraint, such as the orientation of the drive wheel which is well known as a non-holonomic constraint. In addition to the 2DOF mobility, the proposed system enables wheelchair users to change drive modes, a rear drive and a front drive. The drive wheel on the back side of the wheelchair is vertically actuated by a linear motor to change the height of the drive wheel that can vary load distribution and the number of wheels contacting to the ground. The five-wheel-contact makes the wheelchair to move as the normal mode in which the center of rotation is located at the midpoint of the main wheels. Depressing the drive wheel results in lost contacts of the main wheels from the ground in which the center of rotation is jumped at the midpoint of the front wheels, namely it performs as a front drive wheelchair.**

In this paper, kinematic models of the wheelchair and that with an active-caster drive system are analyzed and a control method by using a 2DOF joystick is derived. Based on the kinematic model, a prototype mechanism of the active-caster is designed and mounted on a manual wheelchair to realize the five-wheel wheelchair. In the experiments, the independent 2DOF motion can be achieved by the control of the active-caster in which the wheelchair shows successful translation, rotation and compound motions which include flip motions of the active-caster mechanism.

Additionally, the two drive modes (front and rear) are tested by the prototype with a linear actuator.

I. INTRODUCTION

Electric wheelchairs are widely used by disabled, elderly or/and injured people all over the world. However, almost all of them are heavy and have rigid frames with small wheels and batteries with large capacity. Additionally, a wheelchair user has to determine a wheelchair configuration when he/she purchases an electric wheelchair. A front drive wheelchair is easy to maneuver in clouded areas, while a rear drive configuration is suitable in stable high speed drive. A normal electric wheelchair has either drive configuration, the front wheel drive or the rear wheel drive. However the configuration of an electric wheelchair cannot be varied by a user as long as he/she changes a whole wheelchair to another one. This configuration selection is only available for electric wheelchairs. For manual wheelchairs and motorized wheelchairs with add-on systems, large wheels (rear wheels) are driven.

In this paper, we propose a novel wheelchair system with a single wheel drive system called an active-caster [1]. By mounting the active-caster drive system on the back side of a manual wheelchair, a wheelchair can be used as an electric wheelchair. The wheelchair system has a unique configuration which has five wheels, four of them are passive equipped with a manual wheelchair and one is a drive wheel.

In the following sections, existing drive systems which can be attached to standard wheelchairs are shown in chapter II. The fundamental principle of the active-caster is briefly mentioned in chapter III before introducing the proposed system. The kinematics of the five-wheel wheelchair is analyzed in chapter IV. Based on the kinematics, a prototype is designed in chapter V. Experiments are performed to present the concept of the proposed system in chapter VI, the mobile capability with the active-caster and the function of driving mode changes. Concluding remarks are presented in chapter VII.

II. EXISTING WHEELCHAIR WITH AN EXTERNAL DRIVE

A simple solution for propelling a manual wheelchair is shown in Fig.1. In this system, a conventional orientable wheel whose wheel axis intersects to the steering axis is used (namely steering axis is crossing to the point of contact). This conventional orientable wheel involves non-holonomic constraint which gives a restriction to 2DOF of the wheelchair. This means that wheelchair motion is restricted such a way that 2DOF are not independently controlled.

For instance, a wheelchair runs straight forward with the configuration shown in Fig.2 (a), where the drive wheel is directed forward of the wheelchair, but cannot rotate immediately from this configuration. To make the wheelchair to turn from this configuration, the drive wheel has to generate

Yu Munakata, Aki Tanaka and Masayoshi Wada are with the Department of Mechanical Systems Engineering, Tokyo Univ. of Agriculture and Technology, 2-24-16 Naka-cho Koganei-shi, Tokyo 184-8588 JAPAN (phone: +81-42-388-7096; fax: +81-42-388-7096; e-mail: mwada@ cc.tuat.ac.jp).

978-1-4673-6024-1/13/$31.00 ©2013 IEEE

sideways velocity. However it is impossible because of the non-holonomic constraint of the drive wheel. To turn the wheelchair, a wheelchair driver has to wait till the drive wheel changes its orientation to sideways as shown in Fig.2 (b). After changing the orientation of the drive wheel, the wheelchair can rotate about the midpoint of the left and right large wheels, as shown in Fig.2 (c). This kind of dead time is required between the rotation and translation motion as well, Fig.2(c)→(b)→(a). Thus the non-holonomic constraint makes the wheelchair maneuverability worse, especially in a crowded space where motion changing between translation and rotation is often needed.

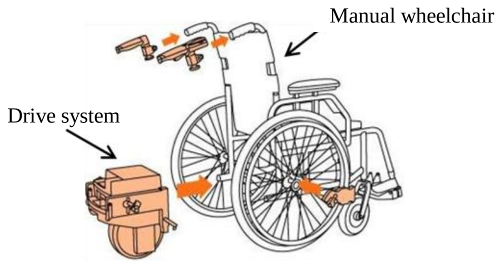


Fig.1 Single wheel type add-on unit [2]

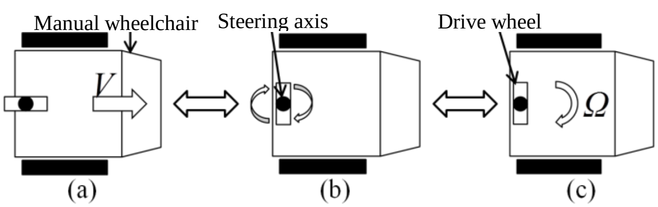


Fig. 2 Drive wheel configurations for wheelchair translation and rotation

To avoid the inconvenience and discomfort in the wheelchair maneuvering, a two-wheel-drive configuration shown in Fig.3 is chosen as the wheelchair drive systems. This differential drive configuration enables the wheelchair to move completely same as the movement of the manual wheelchair since the rotation of the left and right wheels in the same direction results in translational motion in back and forth and rotation of wheels in the opposite direction results in the turning of the wheelchair about the midpoint of the wheels. These 2DOF are independently controlled by the drive systems. However, in-wheel motor and a build-in reduction gear mounted on the left and right wheels are bulky since the motor torque has to be reduced with high ratio because the wheels have to be driven at low speeds with large torques. Addition to this, these in-wheel motor systems can only be attached to large wheels on a manual wheelchair. Thus a center of rotation is fixed to the midpoint of the large wheels. Therefore no other drive configuration can be realized such as the front drive.

Now, we propose a five-wheel wheelchair, similar to the Fig.1 and 2. To realize a 2DOF independent control of the wheelchair with a single wheel drive, we introduce the active-caster drive system for propelling a manual wheelchair. Furthermore, an active suspension system with a linear actuator realizes a drive mode change between a front drive and a rear drive by varying the height of the active-caster mechanism, without changing the configuration of the whole wheelchair.

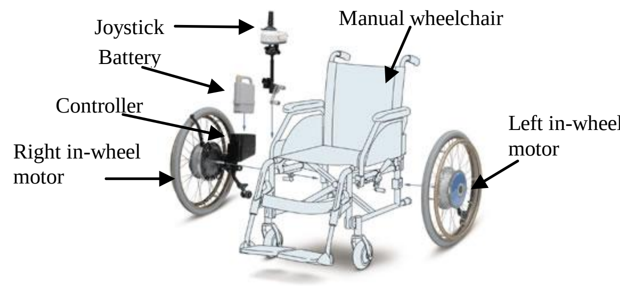


Fig. 3 Yamaha JW add-on system for manual wheelchairs[3]

III. ACTIVE-CASTER DRIVE SYSTEM

Figure 4 shows the top view of an original active-caster[1]. This mechanism has a single normal tire which is equipped off-centered position from a steering axis. This mechanism equips with two motors for actuating the wheel shaft and the steering shaft independently. For instance, only the wheel shaft is rotated by the former motor, the caster moves in forward direction which is denoted as V_w in Fig.4. When only the steering shaft is rotated by the latter motor, the mechanism rotates about the point of contact. By this rotational motion, the steering shaft moves in the velocity, V_s, along the tangential direction of the circle which center is at the point of contact with a radius s (caster-offset) which is shown in Fig.4.

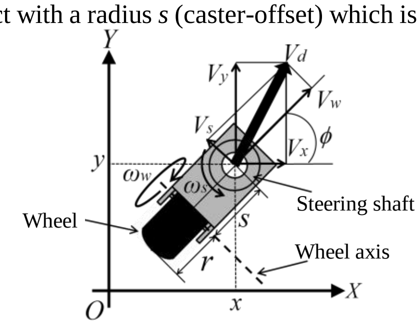


Fig. 4 Principle of an active-caster drive system

These velocity vectors are independently controlled and directing right angle to each other. Therefore, a velocity V_d, which direction and magnitude are arbitrary determined, is generated at the center of the steering shaft. The components of the velocity V_d are determined uniquely by the rotations of the wheel and the steering shaft, ω_w and ω_s, as,

$$\begin{bmatrix} V_w \\ V_s \end{bmatrix} = \begin{bmatrix} r & 0 \\ 0 & s \end{bmatrix} \begin{bmatrix} \omega_w \\ \omega_s \end{bmatrix} \tag{1}$$

These component vectors have to be precisely controlled for correct coordination. $[V_w\ V_s]^T$ can be represented by $[V_x\ V_y]^T$ by the coordinate transformation as shown in (2),

$$\begin{bmatrix} V_w \\ V_s \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} V_x \\ V_y \end{bmatrix} \tag{2}$$

From (1) and (2), we derive the kinematics of the active-caster as,

$$\begin{bmatrix}\omega_w \\ \omega_s\end{bmatrix} = \begin{bmatrix}\frac{1}{r}\cos\phi & \frac{1}{r}\sin\phi \\ -\frac{1}{s}\sin\phi & \frac{1}{s}\cos\phi\end{bmatrix}\begin{bmatrix}V_x \\ V_y\end{bmatrix} \tag{3}$$

Thus, to generate a velocity V_d, whose components are V_x and V_y in the coordinate system of the wheelchair, the wheel and steering rotations of the mechanism, ω_w and ω_s, can be derived by using the kinematics (3).

IV. Modeling of Motorized Wheelchair

A. Kinematics of the Standard Wheelchair

The objective of our system is to control a manual wheelchair with a single-wheel add-on system in the same manner as the standard electric wheelchair by a 2DOF joystick. Therefore, we first derive the relationship between joystick commands and wheelchair motions created by the left and right wheels. Figure 5 shows the top view of an electric wheelchair whose wheels are driven by electric motors. The inclination of joystick in back and forth direction is regarded as the command for translation motion along X_w axis, V, while a joystick operation in the left and right direction is regarded as the command for the rotation Ω about the center of O_w, the origin of the wheelchair coordinate frame, as shown in Fig.5.

Therefore, V and Ω are represented by the velocities of left and right wheels of the wheelchair, V_L and V_R, as,

$$\begin{bmatrix}V \\ \Omega\end{bmatrix} = \frac{1}{2}\begin{bmatrix}1 & 1 \\ -1/W & 1/W\end{bmatrix}\begin{bmatrix}V_L \\ V_R\end{bmatrix} \tag{4}$$

As shown above, wheel velocities are determined by the wheelchair motion and the joystick operation uniquely.

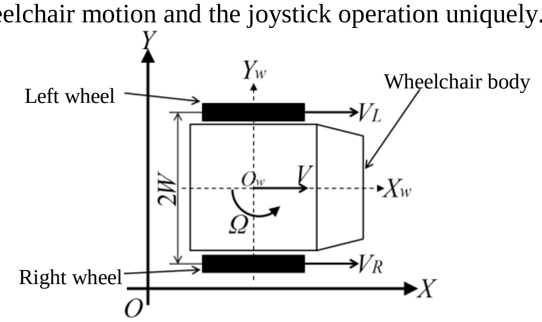


Fig. 5 A conventional manual wheelchair

B. Kinematics of Manual Wheelchair with Active-caster

To motorize a manual wheelchair, an active-caster drive unit is put on the wheelchair as shown in Fig.6. A wheelchair coordinate system is set at the midpoint of large wheels of the manual wheelchair whose X_w-axis directing to the forward direction of the wheelchair. The location of the steering shaft of the active-caster is indicated as (x, y) on the wheelchair coordinate system. In the proposed design, the active-caster drive unit is mounted on the back side position along the center line of the wheelchair. However, the location of the drive unit is generalized in the modeling process in this paper.

The velocity components generated by the active-caster, V_x and V_y are represented by the linear velocity V and the rotation velocity Ω of the wheelchair motion as,

$$\begin{bmatrix}V_x \\ V_y\end{bmatrix} = \begin{bmatrix}1 & -y \\ 0 & x\end{bmatrix}\begin{bmatrix}V \\ \Omega\end{bmatrix} \tag{5}$$

Suppose the operation of the wheelchair is commanded by using a 2DOF joystick, an inclination in back and forth direction is regarded as a command for the linear velocity V, while an inclination in sideways direction is regarded as a command for rotation Ω respectively. Therefore by using (3) and (5), the rotation of the wheel axis and the steering axis of the active-caster are represented by V and Ω as,

$$\begin{bmatrix}\omega_w \\ \omega_s\end{bmatrix} = \begin{bmatrix}\frac{1}{r}\cos\phi & \frac{1}{r}(-y\cos\phi + x\sin\phi) \\ -\frac{1}{s}\sin\phi & \frac{1}{s}(y\sin\phi + x\cos\phi)\end{bmatrix}\begin{bmatrix}V \\ \Omega\end{bmatrix} = \mathbf{H}\begin{bmatrix}V \\ \Omega\end{bmatrix} \tag{6}$$

Where,

$$\mathbf{H} = \begin{bmatrix}\frac{1}{r}\cos\phi & \frac{1}{r}(-y\cos\phi + x\sin\phi) \\ -\frac{1}{s}\sin\phi & \frac{1}{s}(y\sin\phi + x\cos\phi)\end{bmatrix} \tag{7}$$

Here, **H** is an inverse Jacobian which is used for determining the motor movements from the command $[V\ \Omega]^T$. The inverse matrix of **H**, namely Jacobian, indicates the controllability of the system. When $\mathbf{H}^{-1}$ does not exist, the motion of the mechanism cannot be determined by the active-caster motions. A determinant of **H** is represented as,

$$\det\mathbf{H} = \frac{1}{rs}\left\{\cos\phi(y\sin\phi + x\cos\phi) + \sin\phi(-y\cos\phi + x\sin\phi)\right\} = \frac{x}{rs} \tag{8}$$

Therefore if x=0, the wheelchair motion cannot be controlled by the drive mechanism which is known as a singular configuration. In the configuration, the velocity component V_y is generated in the sideways direction of the large wheels and conflicts to the non-holonomic constraint of the large wheels (they cannot move in sideways directly).

Thus, if the condition ($x \neq 0$) is satisfied, the motion of the active-caster is determined by the wheelchair motion, V and Ω uniquely.

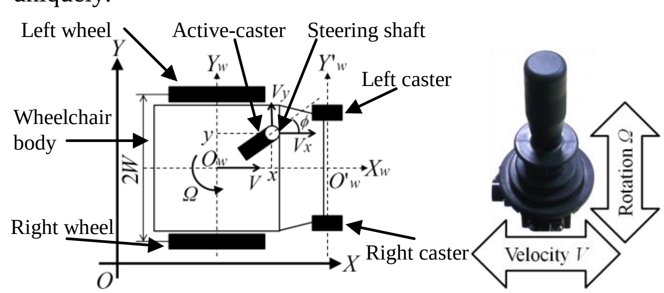


Fig. 6 Wheelchair with an active-caster drive system and a joystick

Thus, for the rear drive mode, the active-caster is controlled based on the kinematics derived in the X_w-Y_w coordinate system. In the front drive mode, both large wheels on the left and right of the wheelchair lose contact with the ground and front casters are locked to orient in the forward direction. To change the control method for the front drive mode, the coordinate system has to be defined in such a way that an origin is located at the midpoint of the front wheels which indicated as O'_w in Fig. 6. Therefore the Y axis is re-defined as Y'_w as seen in Fig. 6. However, the kinematics (6) can be used for the control law of the wheelchair by changing the parameter about the location of the active-caster, x. Thus, the wheelchair user can change two drive modes without changing the whole wheelchair.

V. Prototype Design

The active-caster drive mechanism is shown in Fig.7. This mechanism was originally designed for mobile robots [4]. The 200W AC motors are used for the actuators. The drive powers are transmitted to the wheel and steering shafts via gear boxes and gear trains. To detect the orientation of the wheel, an 8bit absolute encoder is installed in the center of the steering shaft. The radius of the wheel is 65mm and the caster-offset is 40mm.

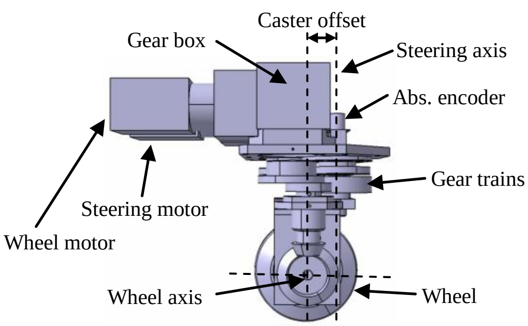


Fig. 7 Active-caster drive mechanism

The active-caster drive mechanism used for this prototype was designed for mobile robot application as mentioned previously. Therefore size, weight and gear ratio are not optimized for a wheelchair application. However, it equips two motors both of which are 200W and the maximum speed of the mechanism is approx. 6km/h. These specs are acceptable for a wheelchair drive to validate the principle of the proposed control system.

For the motorized wheelchair prototype, the active-caster drive mechanism is pivotally supported on the wheelchair frame as shown in Fig. 8. The other side of the active-caster is actuated by a linear motor to change the height of the drive wheel. The location of the steering shaft of the active-caster mechanism is set along the center line, x=-0.26m and y=0m.

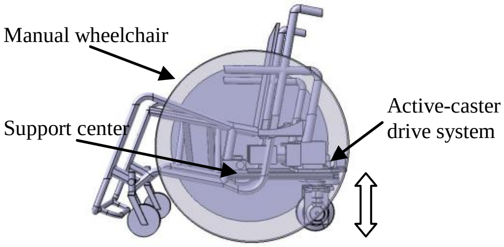


Fig. 8 The active-caster on a wheelchair

Fig. 9 shows an overview of the prototype. A manual wheelchair “NEO” made in OX engineering, Co, Ltd., is used for the platform of the prototype. The active-caster mechanism, motor drivers, a joystick, a battery, a personal computer is mounted on the wheelchair. The block diagram of the control systems is shown in Fig. 10. The command of the joystick, V and Ω, is determined and the PC calculates motor rotations depended on wheelchair kinematics (6) and the steering angle of the wheel is detected by an abs. encoder.

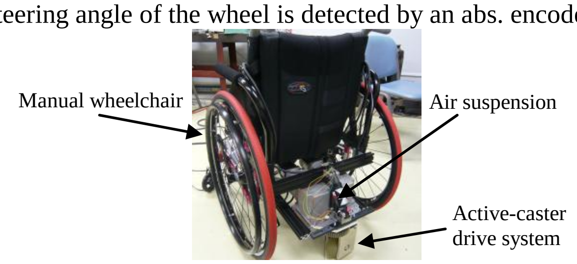


Fig. 9 Manual wheelchair with the active-caster drive system

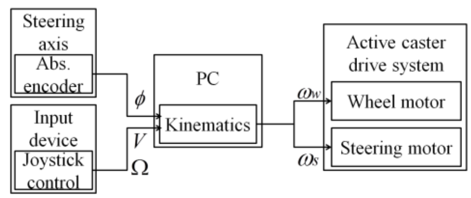


Fig. 10 Control system for the motorized wheelchair prototype

VI. Experiments

To verify the availability of the proposed drive system, we tested fundamental wheelchair motions created by the active-caster drive system, a linear translation and a pivot turn. These motions are compared with simulation results to verify kinematic model (6). After these experiments, we also tested the drive mode change function, the front and the rear drive modes.

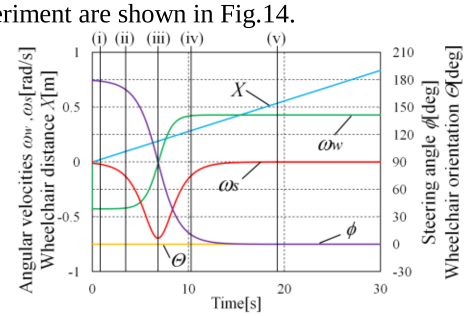
In the test of a translation motion, a constant velocity along the forward direction was commanded to the controller, while a constant rotation about the midpoint of two large wheels was commanded in a pivot turn test. In each test, the wheelchair motions were measured by potentiometers for detecting wheel rotations of the manual wheelchair as shown in Fig.11. The motion of the active-caster drive system can be detected by angular velocities of the wheel and the steering axis, ω_w and ω_s, and wheel orientation ϕ detected by the abs. encoder.

Fig. 11 Potentiometer for measuring wheelchair motion

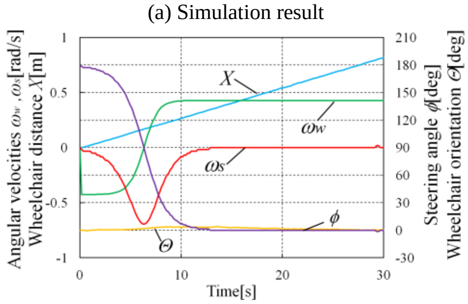
Figure 12(a) and (b) show one of simulation results and experimental results about forward direction of the wheelchair. The drive wheel was directing almost 180degs (back of the wheelchair) at the initial condition. As shown in Fig. 12 (a), the wheelchair started to move from the initial configuration in constant velocity V. At first, the drive wheel angular velocity

ω_w of the active-caster was negative. The direction of rotation changes gradually from negative to positive with changing the steering angle ϕ. This is a coordinated control of the active-caster. During this coordinated motion, the wheelchair was driven in forward direction where the distance of the wheelchair X increases linearly while the orientation of the wheelchair Θ remains zero. About 7sec of the experiment, the flip motion of the active-caster is observed and the angular velocity ω_w of the wheel rotation changes from negative to positive. At this moment, the steering angle ϕ crosses 90degs and the angular velocity ω_s shows the maximum value. Some configurations for understanding of the motion are illustrated in Fig.13. In Fig.13(a)-(e) show the schematics of the wheelchair with the active-caster at each moment of the simulation, indicated as (i)-(v) in Fig.12 (a).

Figure 12(b) shows the experimental result. The wheelchair moved in the constant velocity and the flip motion of the active-caster can be observed. Some of the continuous shots of the experiment are shown in Fig.14.

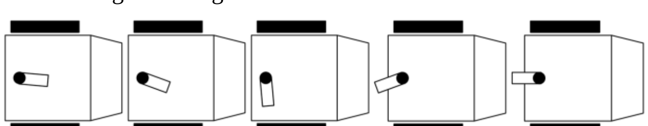


(a) Simulation result



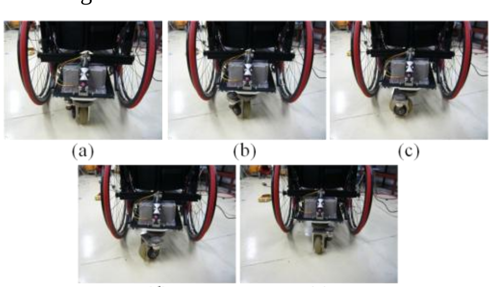
(b) Experimental result

Fig. 12 Straight run of the motorized wheelchair



(a):i (b):ii (c):iii (d):iv (e):v

Fig. 13 Schematic of translational motion

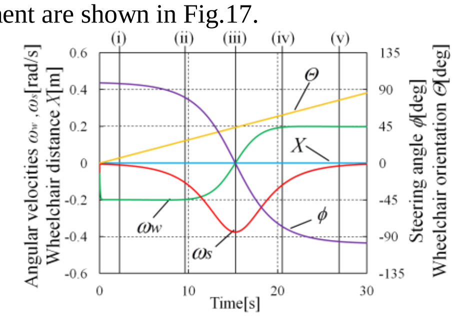


(a) (b) (c) (d) (e)

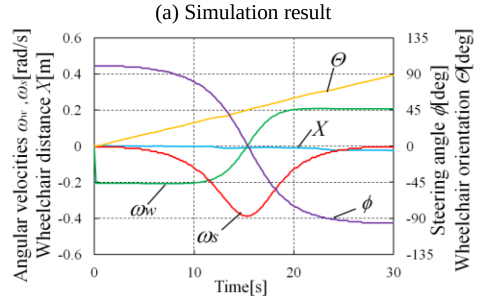
Fig. 14 Straight motion of the wheelchair propelled by the active-caster drive system

Figure 15(a) and (b) show a simulation result and an experimental result of the pivot turn. The drive wheel directs almost 90degs (sideways of the wheelchair) at the initial condition. In Fig. 15(a), the wheelchair started to rotate in a constant angular velocity, Ω. At the initial of the motion, the drive wheel angular velocity ω_w of the active-caster rotates gradually in the negative direction to positive with changing its orientation as same as previous experiment. During the cooperative active-caster motion, the orientation of the wheelchair Θ linearly increases, while the direction of the wheelchair X remains zero, as shown in the figure. About 15sec of the experiment, the flip motion of the active-caster is seen in which the angular velocity ω_w of the wheel rotation changes from negative to positive. At this moment, the steering angle ϕ crosses 0deg and the angular velocity ω_s shows the maximum value. For understanding the pivot turn, some schematics are illustrated in Fig.16. In Fig.16(a)-(e) show the configuration of each moment of the simulation separated from the top figure, indicated as (i)-(v) in Fig.15(a).

The experimental behavior of the prototype about the flip motion of the active-caster is observed as shown in Fig.15(b). The experimental result of the rotation motion is also the same as the simulation. Some of the continuous shots of the experiment are shown in Fig.17.

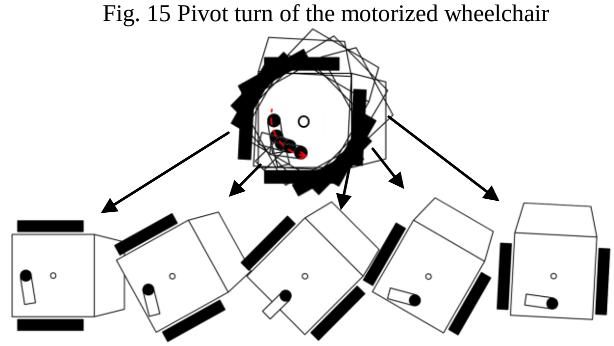


(a) Simulation result



(b) Experimental result

Fig. 15 Pivot turn of the motorized wheelchair



(a):i (b):ii (c):iii (d):iv (e):v

Fig. 16 Schematic of each moment in pivot turn

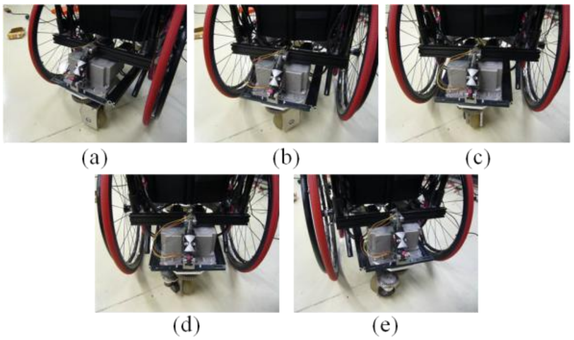


Fig. 17 Rotation motion of the wheelchair propelled by the active-caster drive system

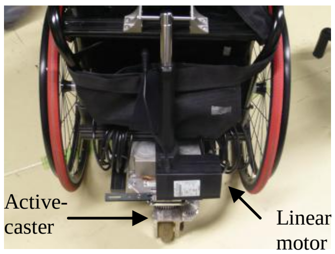


Fig. 18 A linear motor for actuating the active-caster

Figure 18 shows a linear motor equipped on the back side of the wheelchair to actuate the active-caster mechanism vertically. When the five wheels in contact with the ground, the wheelchair performs as a normal motorized wheelchair whose center of rotation is located at the midpoint of large wheels as shown in Fig. 19. By depressing the active-caster down so as to make the large wheels lose contact with the ground, the wheelchair contacts with the ground by front casters and the active-caster.

In this configuration, the non-holonomic constraint of the large wheels is not available and the center of rotation moves to the midpoint to the front casters. As this configuration, the wheelchair changes in front drive mode as shown in Fig. 20.

VII. Conclusions

A five-wheel wheelchair with an add-on single wheel drive system was presented in this paper. To realize independent 2DOF control of the wheelchair, we proposed an active-caster external drive mechanism which equips two motors to generate velocity vectors in an arbitrary direction with an arbitrary magnitude. By changing the height of the drive system, the wheelchair can change mode from the rear drive to the front drive. This function of the proposed system is unique and could not be seen in other wheelchairs.

First, the kinematics of the proposed active-caster mechanism was analyzed and a mechanical condition for avoiding singular configurations was derived. The kinematic model enables us to control the active-caster drive system by using a conventional 2DOF joystick.

To verify the availability of the proposed five-wheel wheelchair, we designed a prototype. The active-caster drive system was mounted on the standard manual wheelchair. In the experiments using the prototype, the wheelchair showed successful independent 2DOF motions. Additionally, the drive mode change function was also tested. In the front drive mode, the active-caster was actuated vertically by the linear actuator then the large wheels of the manual wheelchair lost contact with the ground. The three-point contact configuration by the two front casters and the drive wheel performs as a front drive wheelchair, while five-wheel-contact configuration realizes the normal rear drive mode. The fundamental concept to control the motion of a manual wheelchair was verified through these experiments.

Acknowledgments

This project was partly supported by Research Institute of Science and Technology for Society (RISTEX), Japan Science and Technology Agency (JST).

References

[1] M.Wada et al," Holonomic and Omnidirectional Vehicle with Conventional Tires," Proc. of the Inter. Conf. on Robotics and Automation, pp3671-3676, 1996.
[2] Ulrich Alber GmbH,http://www.alber.de/en/home.html
[3] Yamaha motor Corp. JW. http://www.yamaha-motor.jp/wheelchair/
[4] M.Wada et al, "Caster Drive Mechanisms for Holonomic and Omnidirectional Mobile Platforms with no Over Constraint," Proc. of the Inter. Conf. on Robotics and Automation, pp1531 -1538, 2000.


(a) (b) (c) (d) (e)

Fig. 19 Normal drive (rear drive) mode (five wheels contact to the ground)


(a) (b) (c) (d) (e)

Fig. 20 Front drive mode (large wheels floating from ground)