Cooperative Step-Climbing Method Using a Wheelchair and a Partner Robot

Hidetoshi Ikeda, Hikaru Kanda,
and Nobuyuki Yamashima,
Department of Mechanical Engineering
Toyama National College of Technology
Toyama-shi, Japan

Eiji Nakano
Research Institute
Chiba Institute of Technology
Narashino-shi, JAPAN

Abstract—This report discusses a method of cooperative step climbing for a wheelchair and a wheeled robot that has dual manipulators. In moving over a step, the wheelchair and the robot are linked together and the tilt of the vehicle climbing the step is controlled by the difference in speeds between the two vehicles. During this process, some of the manipulator joints are controlled passively and the upper-arm link is pressed against the front of the robot body to control the amount of passive rotation about the shoulder joint, and thus supports the motion of the wheelchair. Similarly, when the robot climbs a step, the upper-arm link is pressed against the rear of the wheelchair. We connected a teleoperation system for the robot through an intranet, and the experimental results show that this method is effective.

Keywords—step climbing, wheelchair, wheeled robot, coopera-tion

I. INTRODUCTION

In general, disabled people in wheelchairs can successfully move on flat ground. However, steps limit their movements because of driving wheel slippage or a body imbalance. Thus, without a human assistant, most wheelchair users need a wheelchair equipped with a step-climbing mechanism to enter an area with steps. Wheelchairs with such a special mechanism have been widely researched. For example, research programs to improve wheelchair mobility on steps has examined additional legs [1], multiple wheels and variable wheelbases [2]-[4], an adjustable center of gravity [5], a combination of an adjustable center of gravity and multiple wheels [6], special wheels [7], and tracked vehicles [8]. The research group of the present report has achieved cooperative step climbing and descending by a wheelchair connected to a wheeled robot through a passive link [9] and wheelchair step-climbing support by a wheeled robot equipped with manipulators [10]. This report presents the method of step climbing for a wheelchair and a partner robot having two manipulators.

Other reports of multiple vehicles cooperating for crossing irregular terrain include those of Asama *et al.* [11], who considered a forklift system, and Hirose *et al.* [12] and Yamawaki *et al.* [13], who described wheelchairs with tracked vehicles. The procedure described here differs from those in previous studies, which used passive links and joints, controlled moments, or speed differences between the two vehicles for climbing up and down steps. In another study employing speed differences between vehicles to cross irregular terrain, Deshpande and Luntz reported gap-crossing by using a tracked vehicle [14].

The wheelchair users considered in the present study were assumed to have difficulty walking due to an injury or other cause but to be capable of upper-body movement equivalent to that of an able-bodied person. Based on preliminary measurements of the friction coefficients of a robot in wet and dry conditions on asphalt, concrete, wood, and interior flooring, the ground surface considered in this research was assumed to have a friction coefficient in the range 0.6 to 0.9, which satisfies all of the above conditions. The heights of steps located at the entrances of typical buildings and other structures were measured, and the target step height was set at 120 [mm], which corresponded with more than 80% of the observed heights.

The paper is organized as follows. Section II describes the cooperative step-climbing system and Section III describes the process of climbing and descending a step. Section IV provides the theoretical analysis. Section V presents the experimental results, and Section VI is the conclusion.

II. WHEELED ROBOT AND WHEELCHAIR

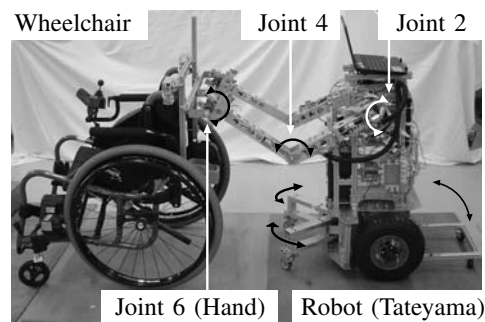The robot used in this research is the wheeled "Tateyama" developed in this laboratory (Fig. 1). TABLE I lists the

Figure 1. The wheelchair and the robot.

TABLE I   SPECIFICATIONS OF THE ROBOT.

Overall length	230 – 800 [mm]
Overall height	747 [mm]
Radius of front wheels (r_{Bf})	25 [mm]
Radius of middle wheels (R_B)	145 [mm]
Radius of rear wheels (r_{Br})	19 [mm]
Wheelbase (WB_f)	190 – 440 [mm]
Wheelbase (WB_r)	270 [mm]
Mass position from the rear axes (l_{rB})	93 [mm]
Height of the mass from the rear axes (h_{mB})	286 [mm]
Position of Joint 2 from the rear axes (l_{LB})	90 [mm]
Height of Joint 2 from the rear axes (h_{LB})	532 [mm]
Mass of the robot's body	55 [kg]
Mass of link 2 (from Joint 2 to 4)	2.55 ×2 [kg]
Mass of link 4 (form Joint 4 to hand)	0.8 ×2 [kg]
Length of link 2 (l_2)	330 [mm]
Length of link 4 (l_4)	300 [mm]
Length of the hand (l_6)	105 [mm]
Length from Joint 4 to the connecting position (l_{4c})	370 [mm]
Mass position of link 2 (L_2)	67 [mm]
Mass position of link 4 (L_4)	169 [mm]
Mass position of link 6 (hand mechanism) (L_6)	35 [mm]

TABLE II   SPECIFICATIONS OF THE MANUAL WHEELCHAIR.

Overall length	1060 [mm]
Overall height	985 [mm]
Radius of front wheels (r_A)	63 [mm]
Radius of rear wheels (R_A)	300 [mm]
Wheelbase (l_A)	430 [mm]
Handrim position (l_{LA})	250 [mm]
Mass position from the rear wheel axes (l_{rA})	149 [mm]
Height of mass from rear wheel axes (h_{mA})	371 [mm]
Mass (wheelchair + driver) (M_A)	92.7 [kg]

Figure 2.   Model of the wheelchair and robot.

Figure 3.   Push handle mechanism of the wheelchair.

specifications. When passing over a step, the wheelchair and robot are deployed in a forward-and-aft configuration (Fig. 2). This robot has three sets of wheels consisting of front, middle, and rear pairs on the left and right sides. The front and rear pairs are casters whose positions can be shifted and the middle pair are driving wheels. The robot has manipulators attached to the left and right sides of its upper half: the arm has 5 degrees of freedom (DOF) and the hand has 1 DOF for a total of 6 DOF. In step climbing of wheelchiar, Joints 1, 3, and 5 (Fig. 3) were fixed, and Joints 2 and 4 and the hand were movable, resulting in manipulators with 3 DOF on each side (see Fig. 1). In this study, the length from Joint 2 (shoulder) to Joint 4 (elbow) is called "Link 2" (length l_2), from Joint 4 to Joint 5 (wrist) is called "Link 4" (length l_4), and from Joint 5 to the tip of the hand is called "Link 6" (length l_6). The length from the elbow (Joint 4) to Joint 6 (the location of the connection between the wheelchair and the robot) is designated l_{4C}. The manipulator joint angles are -90 [deg] $\leq \phi_2 \leq$ +90 [deg] and 0 [deg] $\leq \phi_4 \leq$ +100 [deg]. The hands consist of two fingers that open and close in order to hold things (Fig. 3). The robot also has a stopper mounted on the front part of its body (Fig. 4 and Fig. 5 (a)). As described below, the stopper limits the passive rotational travel of the manipulators of the robot, and thus enables the robot to imitate the operation of a human pushing an object by limiting the passive rotation about the shoulder joint as the upper arm is pushed into the chest (Fig. 5 (b)).

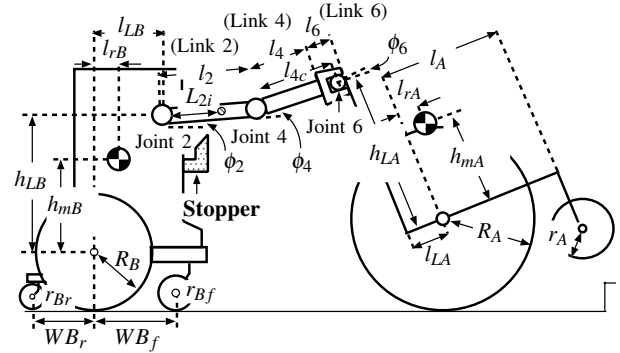The wheelchair (NOVA Integral-ME) has a shape typical of wheelchairs available in the market (Fig. 1). TABLE II provides the specifications. This is a manua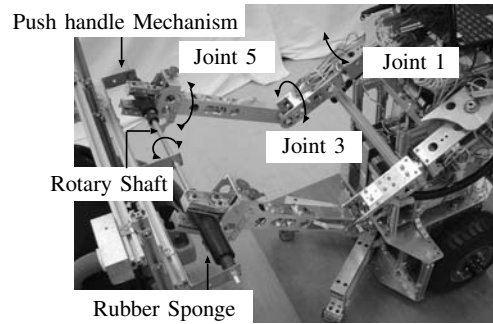lly operated chair to which an electric drive unit was added. In this study, the wheelchair is operated manually by the user, but also has a push handle mechanism on the back which is held by the robot hands (Fig. 3). The push handle mechanism is equipped with a rotary shaft that allows passive rotation of the handle with a rubber surface The hand mechanism grasps the handle to connect the two vehicles. The angle ϕ_6 is formed by the wheelchair with Link 4 (Fig. 2). The wheelchair has a stopper mounted on its rear side (Fig. 6 (a) and (b)). As described below, the stopper limits the passive rotational travel of the manipulators when the robot pushes (Fig. 6 (a)) and pulls (Fig. 6 (b)) the wheelchair while climbing a stair.

Fig. 7 is a diagram of the system configuration. In this study, the robot was operated by a caregiver (robot controller). The motors mounted on the robot are connected to Faulhaber
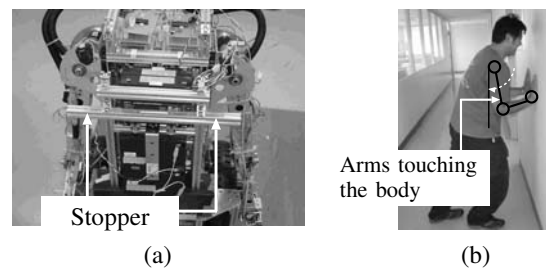

Figure 4.   Control of the rotary motions of the robot shoulder by using the body. (a) The front body of the robot. (b) A human pushing an object
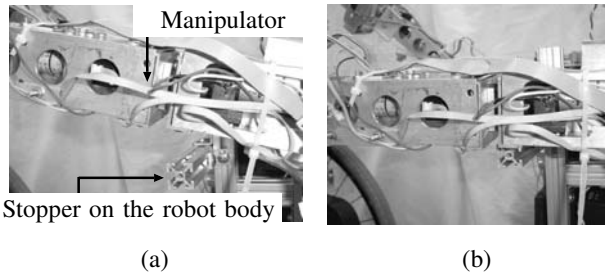
Figure 5. Detail of the stopper. (a) Pulling the wheelchair. (b) Pushing the wheelchair.
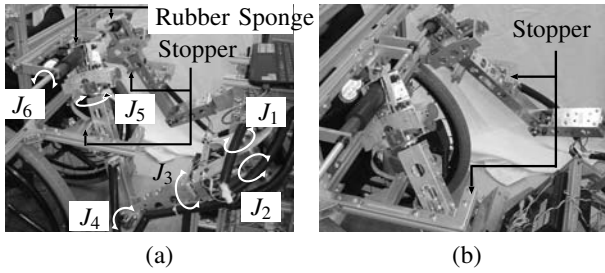

Figure 6. Action of the stopper. (a) Lifting the wheels of the robot. (b) Preventing the robot from falling down.

Figure 7. Diagram of the robot system.

motion controllers (Faulhaber MCDC3006-S, MCDC3003-S). In turn, these are connected to a notebook PC mounted on the robot. The motors are controlled via commands issued using the Faulhaber Motion Manager 4 software package. The robot employs a camera built into the PC, and the moving images from that camera and the Motion Manager 4 operating window are displayed on the notebook PC mounted on the robot. The screen on this notebook PC uses Real VNC software and is transmitted over the intranet as-is to the display of the PC used by the caregiver in a different location. The caregiver controls the robot by operating Motion Manager 4 from his PC. The keyboard commands for Motion Manager 4, which are issued using JoyToKey software, correspond to the manipulation by the caregiver (robot controller) for operating the robot. The caregiver and the wheelchair user both wear headsets and use the telecommunication software Skype to communicate verbally. The caregiver's headset is connected to the caregiver's PC, and the wheelchair user's headset is connected to the PC on the robot. In this study, the robot is operated at a constant speed (0.76 [km/h]).

III. PROCESS OF MOVING OVER A STEP

When encountering a step, the robot hands grasp the rotary shaft of the wheelchair push handle mechanism, thus linking the wheelchair and robot. The chair is then controlled to raise first its front wheels and then its back wheels onto the upper level of the step. In this study, stage 1 and stage 2 signify the processes in which the front and the back wheels of the wheelchair, respectively, ascend the step. Similarly, stage 3 and stage 4 signify the processes in which the front and the back wheels of the robot, respectively, ascend the step. The ascent process is described below. The states shown in Fig. 8
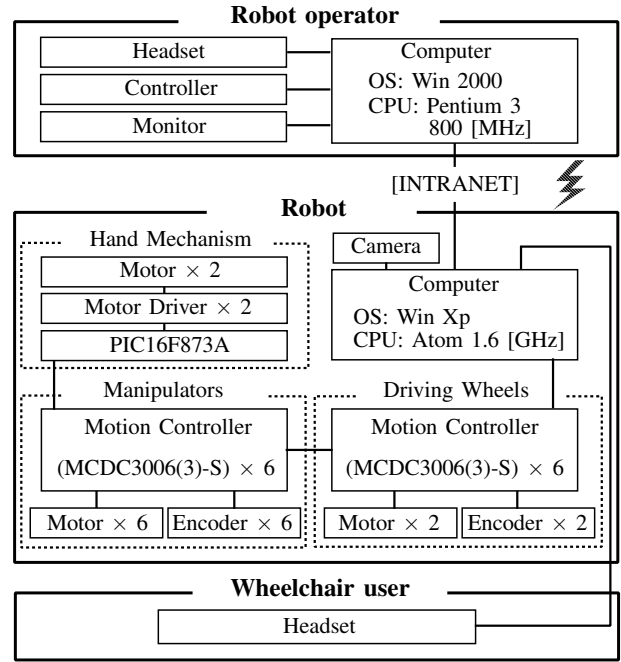
correspond to (1) – (8) below; "Forward" signifies the robot or the wheelchair motion ahead, and "Free" is the state in which the wheelchair user does not do anything.

[stage 1]

(1) The robot hand grasps the wheelchair push handle to link the two vehicles. Joints 2, 4, and 6 are allowed to rotate passively until the ascent of the wheelchair has been completed. (2) The robot controller stops the robot. The wheelchair user manipulates the handrims as if to move forward, lifting the front wheels. (3) If the location of the center of mass of the wheelchair shifts behind the contact point between the back wheels of the wheelchair and the ground as the wheelchair tilt increases, the chair exerts forces on the manipulators, causing passive rotation about Joint 2 (Fig. 5 (b)). In this case, the bottom part of the manipulator upper-arm link comes into contact with the stopper and limits the extent of the rotation (Fig. 5 (b)). Thus, the robot supports the wheelchair from behind to prevent the wheelchair from tipping over backward. (4) The robot moves forward and the wheelchair user manipulates the handrims to adjust the difference between the speeds of the two vehicles, so that the front wheels of the wheelchair are placed on the upper level of the step. After completion of stage 1, the wheelchair user does not do any operations until the end of stage 2.

[stage 2]

(5) The robot continues to move forward while pushing the wheelchair from behind. (6) The back wheels of the wheelchair come into contact with the step. (7) The robot continues to push on the wheelchair so that the rear wheels of the wheelchair climb up onto the step. The robot supports the wheelchair during this process to prevent the wheelchair from
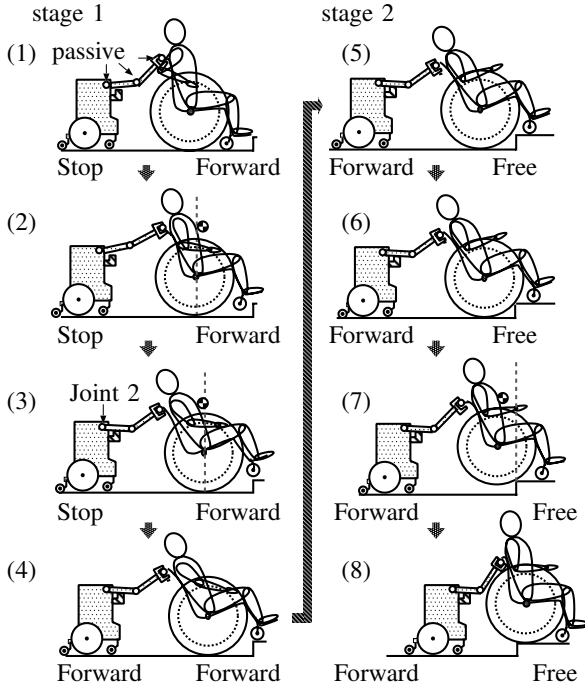
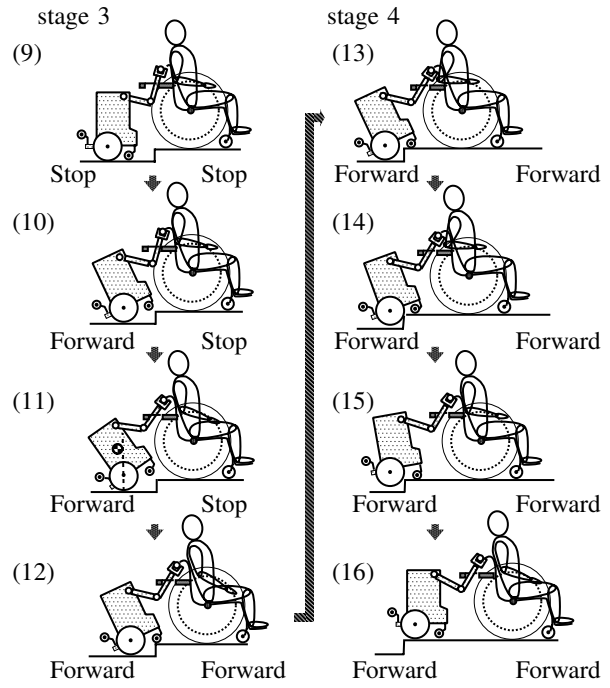Figure 8.   Step-climbing process of the wheelchair (stages 1, 2).

Figure 9.   Step-climbing process of the robot (stages 3, 4).

tipping over backward. (8) Once the wheelchair rear wheels have reached the upper level of the step, the robot stops.

[stage 3]

(9) After stage 2, the rear wheels of the robot are folded upward. The sides of the robot are opened, and the two manipulators are inseted of the stopper (Fig. 6 (a)). The wheelchair user holds the handrims and maintains the position of the wheelchair. The robot moves forward, the manipulator forearm link comes into contact with the stopper of the wheelchair (Fig. 6 (a)). (10) The robot continues to push on the wheelchair and the front wheels of the robot are lifted. (11) If the location of the center of mass of the robot shifts behind the contact point between the middle wheels of the robot and the ground as the robot tilt increases, the robot begins to tip over backward, but the part of the manipulator forearm link comes into contact with the stopper of the wheelchair, limiting the extent of rotation (Fig. 6 (b)). Thus, the wheelchair supports the robot and prevents the robot from tipping over backward. (12) The robot moves forward and the wheelchair user manipulates the handrims, thereby adjusting the difference between the speeds of the two vehicles, so that the front wheels of the robot are placed on the upper level of the step.

[stage 4]

(13) Both vehicles move forward. (14) The middle wheels of the robot come into contact with the step. The wheelchair pulls the robot, and the value of the normal reaction from the step, which affects the robot's middle wheels (driving wheels), is increased, Consequently, the robot is able to avoid falling down by the force of the manipulators. The middle wheels of the robot start to climb the step. (15) Both vehicles continue to

move forward. (16) The center wheels of the robot are able to climb the step. Once the robot's middle wheels have reached the upper level of the step, both vehicles are stopped.

IV. THEORETICAL ANALYSIS

The analysis needs to satisfy the following three conditions. When the system achieves these conditions, the vehicles are able to climb a step.

- No part of the manipulator (such as a link) contacts the wheelchair except the robot hands.
- The push handle is within the range reachable by the hands.
- The driving wheels of both vehicles do not slip. For example, at $\phi_2 + \phi_4 + \phi_6 = 0$, $\mu > |f_{5x}|/f_{6z}$ and $\mu > |f_{1x}|/f_{2z}$. At $\phi_2 + \phi_4 + \phi_6 = 24.54$ [deg], $\mu > |f_{5x}|/f_{6z}$ and $\mu > |f_{1x}|/f_{2z}$.

Here, 24.54 [deg] is the maximum incline of the wheelchair when the wheelchair operator climbs a step, and the height between the lowest point on the front wheel tread surface and the ground surface below the step is $h_t = 200$ [mm]. (It was observed that people tend to raise the front wheels higher than the step they will traverse when actually operating a wheelchair, so h_t was measured for 5 participants.)

Fig. 10 shows the state in stage 1 in which the wheelchair center of mass is forward of the contact point between the rear wheels and the ground. At this time point, the robot is stopped, the wheelchair is propelled, and the robot exerts a backward force by pulling on the wheelchair.

Fig. 11 shows the state when the tilt of the wheelchair is increasing, and the wheelchair center of mass is behind the
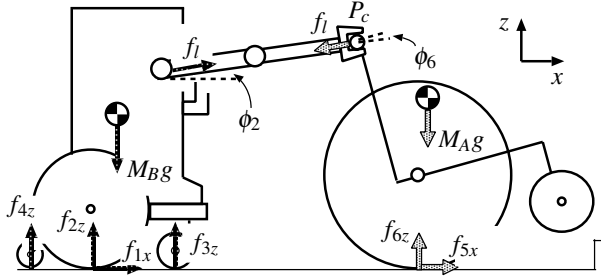
4

Figure 10. The step-climbing system using the wheelchair and the wheeled robot.

contact point between the rear wheel and the ground. When the situation shown in Fig. 10 changes to that shown in Fig. 11, the manipulators rotate passively. In this procedure, the stoppers limit the amount of passive rotation about the robot's shoulder joint (Fig. 5(b)).

Σ_B is the basic coordinate system for the robot, where contact point B is between the robot's middle (driving) wheels and the ground is the origin (Fig. 11). Joints 2 (shoulder), 4 (elbow), and 6 (location where the hands holds the push handle) are the joints that are controlled passively. The position vectors for these joints in system Σ_B are expressed as ${}^B\boldsymbol{p}_{2i} = [x_{2i}\ z_{2i}]^T$ ($i = 1 \sim 3$). These are ${}^B\boldsymbol{p}_2 = [x_2\ z_2]^T = [l_{LB}\quad R_B + h_{LB}]^T$, ${}^B\boldsymbol{p}_4 = [x_4\ z_4]^T = [l_{LB} + l_2\cos\phi_2\quad R_B + h_{LB} + l_2\sin\phi_2]^T$, and ${}^B\boldsymbol{p}_6 = [x_6\ z_6]^T = [l_{LB} + l_2\cos\phi_2 + l_{4c}\cos(\phi_2 + \phi_4)\quad R_B + h_{LB} + l_2\sin\phi_2 + l_{4c}\sin(\phi_2 + \phi_4)]^T$ (Fig. 2).

In the same way, the position vectors for the contact points between the robot's front and rear wheels and the ground are expressed as ${}^B\boldsymbol{p}_{fwb} = [WB_f\ 0]^T$ and ${}^B\boldsymbol{p}_{rwb} = [-WB_r\ 0]^T$, respectively. The body of the robot, neglecting the manipulators, is Link 0 with mass m_0. If the centers of mass of the robot body and each manipulator link (Links 2, 4, and 6) are denoted by ${}^B\boldsymbol{p}_{gj} = [x_{g2j}\ z_{g2j}]^T$ (where j = 0–3), then the center of mass of the entire robot ${}^B\boldsymbol{p}_{GB} = [x_{GB}\ z_{GB}]^T$ is given by ${}^B\boldsymbol{p}_{GB} = (\Sigma_{j=0}^3 m_{2j}^B \boldsymbol{p}_{g2j})/\Sigma_{j=0}^3 m_{2j}$. The driving force vector for the robot middle wheels is $\boldsymbol{f}_1 = [f_{1x}\ 0]^T$, and the resistance force from the ground surface is $\boldsymbol{f}_2 = [0\ f_{2z}]^T$. Also, the resistance force at the robot front wheels is $\boldsymbol{f}_3 = [0\ f_{3z}]^T$, and that at the rear wheels is $\boldsymbol{f}_4 = [0\ f_{4z}]^T$. The reaction force from the linked wheelchair is given by $\boldsymbol{f}_L = [f_l\cos(\phi_2 + \phi_4)\quad f_l\sin(\phi_2 + \phi_4)]^T$.

Σ_A for the wheelchair is the coordinate system fixed at the point of contact between the wheelchair rear wheels and the ground, A. In Σ_A, the wheelchair center of mass is located at ${}^A\boldsymbol{p}_{GA} = [x_{GA}\ z_{GA}]^T = [l_r\cos(\phi_2 + \phi_4 + \phi_6) - h_m\sin(\phi_2 + \phi_4 + \phi_6)\quad l_r\sin(\phi_2 + \phi_4 + \phi_6) + h_m\cos(\phi_2 + \phi_4 + \phi_6) + R_A]^T$, and the push handle location (where it is held by the robot hand) P_c is ${}^A\boldsymbol{p}_c = [x_c\ z_c]^T = [-l_{LA}\cos(\phi_2 + \phi_4 + \phi_6) - h_{LA}\sin(\phi_2 + \phi_4 + \phi_6)\quad -l_{LA}\sin(\phi_2 + \phi_4 + \phi_6) + h_{LA}\cos(\phi_2 + \phi_4 + \phi_6) + R_A]^T$.

The driving force at the wheelchair rear wheels is $\boldsymbol{f}_5 = [f_{5x}\ 0]^T$, and the resistance force felt at the ground surface is $\boldsymbol{f}_6 = [0\ f_{6z}]^T$. Also, the reaction force from the linked robot is given by $\boldsymbol{f}'_L = [-f_l\cos(\phi_2 + \phi_4)\quad -f_l\sin(\phi_2 + \phi_4)]^T$.

Summing the total forces on the wheelchair exerted by the ground surface (resistance) and by the linked robot for $\boldsymbol{f}_{\Sigma A} \in \boldsymbol{R}^2$, we find that $\boldsymbol{f}_{\Sigma A} = [f_{5x} - f_l\cos(\phi_2 + \phi_4)\quad f_{6z} - f_l\sin(\phi_2 + \phi_4)]^T$. When the linked vehicles are moving together in static
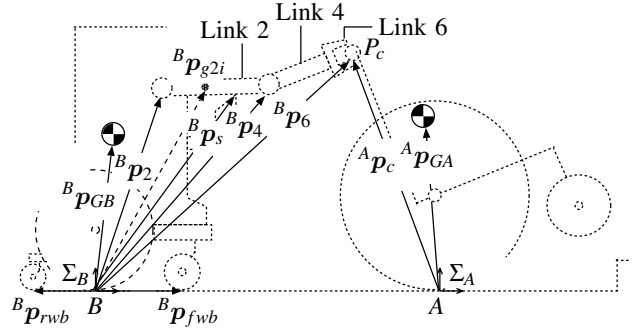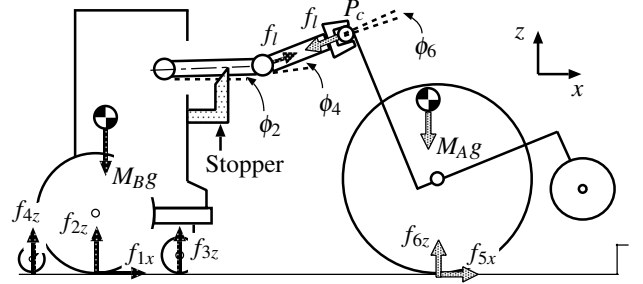

Figure 11. Step-climbing system using the wheelchair and the wheeled robot.

equilibrium, the equilibrium in both the x and z axes yields (1), while the equilibrium of moments about the point of contact between the wheelchair rear wheels and the ground yields (2). Here, $\boldsymbol{g} = [0\ -g]^T$ is gravitational acceleration.

$$\boldsymbol{f}_{\Sigma A} + \mathrm{M}_A\boldsymbol{g} = 0 \tag{1}$$

$$^A\boldsymbol{p}_{GA} \times \mathrm{M}_A\boldsymbol{g} + {}^A\boldsymbol{p}_c \times \boldsymbol{f}'_L = 0 \tag{2}$$

We obtain (3) and (4) from (1).

$$f_{5x} = f_l\cos(\phi_2 + \phi_4) \tag{3}$$

$$f_{6z} = \mathrm{M}_A g + f_l\sin(\phi_2 + \phi_4) \tag{4}$$

Then, from (2), we find

$$f_l = \frac{x_{GA}\mathrm{M}_A g}{z_c\cos(\phi_2 + \phi_4) - x_c\sin(\phi_2 + \phi_4)} \ . \tag{5}$$

Next, from the z-coordinate of ${}^B\boldsymbol{p}_6$ and ${}^A\boldsymbol{p}_c$, we obtain

$$h_{LA} = \frac{z_6 + l_{LA}\sin(\phi_2 + \phi_4 + \phi_6) - R_A}{\cos(\phi_2 + \phi_4 + \phi_6)} \ , \tag{6}$$

where $z_6 = R_B + h_{LB} + l_2\sin\phi_2 + l_{4c}\sin(\phi_2 + \phi_4))$.

When the robot acts statically in stage 1, the equilibrium in the x and z axes gives us

$$\boldsymbol{f}_{\Sigma B} + M_B\boldsymbol{g} = 0. \tag{7}$$

Here, $\boldsymbol{f}_{\Sigma B} \in \boldsymbol{R}^2$ is the sum of forces on the robot due to resistance from the ground surface and from the linked wheelchair, and $\boldsymbol{f}_{\Sigma B} = [f_{1x} + f_l\cos(\phi_2 + \phi_4)\quad \Sigma_{k=2}^4 f_{kz} + f_l\sin(\phi_2 + \phi_4)]^T$.

From (7), we obtain (8) and (9).

$$f_{1x} = -f_l\cos(\phi_2 + \phi_4) \tag{8}$$

$$f_{2z} = M_B g - f_l\sin(\phi_2 + \phi_4) - f_{3z} - f_{4z} \tag{9}$$

5

While the manipulators are pulling the wheelchair (Fig. 10), the manipulators and stoppers do not come into contact, as shown in (10).

$$^B\boldsymbol{p}_{GB} \times \mathrm{M}_B \boldsymbol{g} + {}^B\boldsymbol{p}_2 \times \boldsymbol{f_L} + {}^B\boldsymbol{p}_{fwB} \times \boldsymbol{f}_3 + {}^B\boldsymbol{p}_{rwB} \times \boldsymbol{f}_4 = 0 \quad (10)$$

When the robot is supporting the wheelchair from behind (Fig. 11), passive rotation about Joint 2 (shoulder) is limited by the stopper, as shown in (11).

$$^B\boldsymbol{p}_{GB} \times \mathrm{M}_B \boldsymbol{g} + {}^B\boldsymbol{p}_4 \times \boldsymbol{f_L} + {}^B\boldsymbol{p}_{fwB} \times \boldsymbol{f}_3 + {}^B\boldsymbol{p}_{rwB} \times \boldsymbol{f}_4 = 0 \quad (11)$$

We obtain f_{3z} and f_{4z} from (10) and (11). In addition, $\mu > |f_{1x}|/f_{2z}$ or $\mu > |f_{5x}|/f_{6z}$ can be calculated from (3)–(6), (8), and (9).

V. EXPERIMENT

An experiment was carried out using this system under an environment with a step 120 [mm] high and a friction coefficient $\mu = 0.72$ (Fig. 14). The wheelchair user and robot operator were both able-bodied adult males.

The robot operator performed his task over the intranet while observing the situation via camera and communicating with the wheelchair user over a voice link. The operator was on the third floor of the main building of Toyama National College of Technology Department of Mechanical Engineering, and the user was on the second floor of the same building. The operator was successful in moving the wheelchair over the step. The robot speed was constant (0.76 [km/h]).
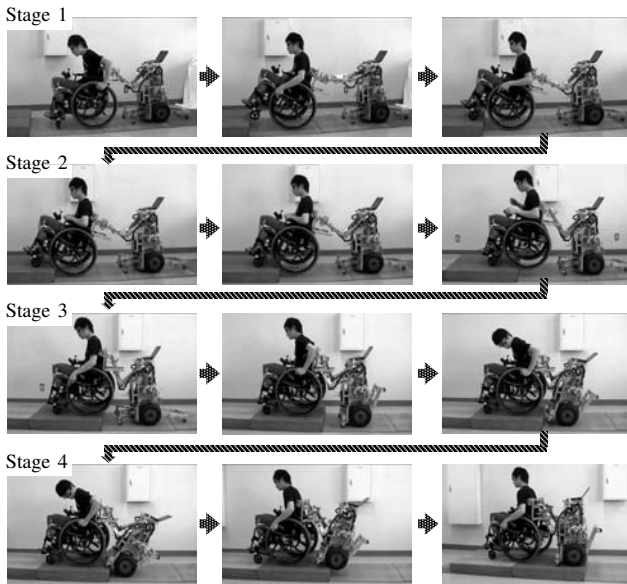

Figure 14.   Experiment.

When the wheelchair was too close to the step in stage 1 (lifting the wheelchair front wheels), the front wheels bumped into the vertical riser of the step, but the robot controller followed instructions from the wheelchair user to back up the two linked vehicles together and re-start the ascent. It was then possible for the front wheels of the wheelchair to climb the step with ease. Subsequently, during stage 2 (lifting the

wheelchair rear wheels over the step), the user never needed to push the wheels: it was possible to lift the chair onto the upper level of the step by following the procedure proposed here and using only the forward operation of the robot. Stages 3 and 4 were executed similarly.

VI. CONCLUSIONS

This report describes the procedure of cooperative step climbing using a wheelchair and a robot, which imitates the motion of the upper arms of a human pushing against the chest when pushing a heavy object. We constructed the robot system and an experiment was carried out incorporating teleoperation of the robot over an intranet, and this procedure was demonstrated to be effective.

In the future, an autonomous control system to assist the wheelchair user and robot operator will be built.

REFERENCES

[1] V. Kumar and V. Krovi, "Optimal traction control in a wheelchair with legs and wheels," Proc. of 4th national Applied Mechanisms and Robotics Conference, December 95, pp. 95-030-01–95-030-07, 1995.

[2] N. Yanagihara, F. Sugasawa, Suzuki, T. Ikeda, and Y. Kanaumi, "Mechanical analysis of a stair-climbing wheelchair using rotary cross arm with wheels," Proc. 17th Annual Conference of the Robotics Society of Japan, Kanagawa, pp. 1143–1144, 1999.

[3] M. Lawn and T. Ishimatsu, "Modeling of a stair-climbing wheelchair mechanism with high single step capability," IEEE Trans. on Neural Systems and Engineering, vol. 11, no. 3, pp. 323–332, 2003.

[4] A. Gonzalez, E. Ottaviano, and M. Ceccarelli, "On the kinematic functionality of a four-bar based mechanism for guiding wheels in climbing steps and obstacles," Mechanism and Machine Theory, vol. 44, pp. 1507–1523, 2009.

[5] Y. Takahashi, S. Ogawa, and S. Machida, "Human assist robot (1st report: Prototype of wheelchair which can fly up and run)," Proc. JSME ROBOMEC'99, Tokyo, pp. 1A1-75-106, 1999.

[6] Independence Technology, L.L.C., iBOT, http://www.ibotnow.com/, 2008.

[7] K. Taguchi and T. Emoto, "A study of the wheel-feet mechanism for stair climbing," Proc. 10th Annual Conference of the Robotics Society of Japan, Kanazawa, pp. 111–112, 1992.

[8] K. Sugiyama, T. Ishimatsu, T. Shigechi, and M. Kurihara, "Development of stair-climbing machines at Nagasaki," Proc. of 3rd IWAN, pp.214–217, 1999.

[9] H. Ikeda, Y. Katsumata, M. Shoji, T. Takahashi, and E. Nakano, "Cooperative strategy for a wheelchair and a robot to climb and descend a step," Advanced Robotics, vol. 22, pp. 1439–1460, 2008.

[10] H. Ikeda, N. Yamanaka, T. Kurose, S. Nagai, S. Haruta, K. Sato, and E. Nakano, "Step climbing of a wheelchair using a wheeled robot with passive joint manipulators," Journal of Robotics Society of Japan, vol. 28, no. 7, pp. 802–810, 2010.

[11] H. Asama, M. Sato, N. Goto, H. Kaetsu, A. Matsumoto, and I. Endo, "Mutual transportation of cooperative mobile robots using forklift mechanisms," Proc. 1996 IEEE International Conference on Robotics and Automation, pp. 1754–1759, 1996.

[12] S. Hirose, T. Shirasu, and E. Fukushima, "A proposal for cooperative robot 'Gunryu' composed of autonomous segments," Proc. IROS'94, pp. 1532–1538, 1994.

[13] T. Yamawaki, O. Mori, and T. Omata, "4R and 5R parallel mechanism mobile robot," Journal of Robotics Society of Japan, vol. 23, no. 2, pp. 213–219, 2005.

[14] A. Deshpande and J. Luntz, "Behaviors for physical cooperation between robots for mobility improvement," Autonomous Robot, vol. 23, no. 4, pp. 259–274, 2007.

[15] H. Ikeda, Z. Wang, T. Takahashi, and E. Nakano, "Step climbing strategy using two wheelchair robots connected by a semi-passive link," Interdisciplinary Information Sciences, vol. 7, no. 2, pp. 209–217, 2001.

[16] H. Ikeda, Z. Wang, T. Takahashi, and E. Nakano, "Step climbing and descending method by tandem wheelchairs and analysis of the influence of changes of the operator's posture," Journal of Society of Biomechanism Japan, vol. 27, no. 3, pp. 134–143, 2003.