Fuzzy Control for Electric Power-Assisted Wheelchair Driving on Disturbance Roads

Hirokazu Seki, *Member, IEEE*, and Naoki Tanohata

***Abstract*—This paper describes a driving control scheme of electric power-assisted wheelchairs for assistive driving on various large disturbance roads. The "power-assisted wheelchair" that assists the driving force by electric motors is expected to be widely used as a mobility support system for elderly people and disabled people; however, there are lots of large disturbance roads such as uphill roads and rough roads and operators need to push hand-rims with larger power load in order to obtain enough driving distance and velocity. For example, wheelchairs might move backward on uphill roads due to the driving torque shortage. Therefore, this study proposes a fuzzy-algorithm-based torque control scheme in order to realize the assistive driving on large disturbance roads. The proposed fuzzy controller has a simple structure because high-performance CPUs and controllers are difficult to be carried on practical wheelchairs. The assisted torque after the operator releases hand-rims will be adjusted so that the enough velocity is kept even on large disturbance roads. Driving experimental results and evaluation results are provided to verify the effectiveness of the proposed control system.**

***Index Terms*—Assistive technology, driving control, fuzzy control, intelligent wheelchair, power-assisted wheelchair.**

Fig. 1. Photograph of an electric power-assisted wheelchair.

I. Introduction

The number of elderly people and disabled people who have difficulty in walking is increasing. As one of mobility support for them, the significance of "electric powered wheelchair" and "electric power-assisted wheelchair" which assist driving force using electric motors on both wheels and spread their areas of life has been recently enhanced [1].

Some types of powered wheelchairs can be defined according to interface devices and using forms. One is the joystick type of powered wheelchairs and operators can give the driving command such as the direction and velocity through joystick [2]–[7]. The other is the caregiver operation type of power-assisted wheelchairs, and it can be controlled by measuring or estimating the caregiver's operation force from the rear side [8], [9]. In addition, intelligent navigation wheelchairs have been also developed for navigating to the goal efficiently and safely without obstacle collisions [10]–[12].

Manuscript received November 24, 2011, revised May 11, 2012; accepted for publication July 27, 2012. Date of current version December 17, 2012. This paper was recommended by Associate Editor X. Guan.

H. Seki is with the Department of Electrical, Electronics and Computer Engineering, Chiba Institute of Technology, Chiba 275-0016, Japan (e-mail: seki.hirokazu@it-chiba.ac.jp).

N. Tanohata is with Nohmi Bosai Ltd., Saitama 341-0043, Japan (e-mail: tanohata@nohmi.co.jp).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSMCC.2012.2212008

This paper focuses on the rider operation type of power-assisted wheelchair and its advanced motion control system. The rider pushes right and left hand-rims and the assisted torque is generated according to human input torque. Fig. 1 shows an example of power-assisted wheelchair developed by Yamaha Co. called "JWII." Some advanced driving control schemes also have been presented [13]–[23], for example, basic driving control algorithm [13], safety front wheel raising control for climbing over steps without dangerous backward overturning [14], [15], stable and well-balanced straight and circular road driving control [16], [17], driving trajectory design based on jerk limitation [18], [19], tip-over prevention control [20], driving control system based on surface myoelectric signals of operator's hands [21], and regenerative braking control for energy efficiency [22], [23]. Multipurpose and high-performance control systems for power-assisted wheelchairs considering human's sense and driving environments must be further developed.

This paper focuses on "large disturbance roads" which give the large disturbance torque to wheelchairs through both wheels and cause the shortage of driving distance and velocity compared with flat and smooth surface roads. There are lots of large disturbance roads such as grass and gravel roads in practical driving environments. Uphill roads are also included in large disturbance roads. Fig. 2(a) and (b) shows examples of large disturbance roads. Human operators have to give larger torque if the controller generates constant assisted power. Wheelchairs might move backward on uphill roads due to the driving torque shortage. Thus, some ideas of the inertial assisted torque adjustment after human operators release hand-rims will be needed

Fig. 2. Examples of large disturbance roads. (a) Uphill road. (b) Rough terrain.

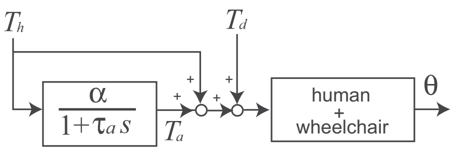


Fig. 3. Configuration of power assisting control system using LPF.

to reduce their physical power load. In addition, simpler algorithms and controllers are required because high-performance CPUs and controllers are difficult to be carried on practical wheelchairs.

Therefore, this study proposes a fuzzy controller to realize the assistive driving without operator's physical power load on large disturbance roads. The proposed fuzzy rules are designed from the integral value of human input torque and driving velocity and the assisted torque reduction rate is inferred by fuzzy algorithm. The assisted torque after operators release hand-rims will be adjusted so that the enough velocity is kept even on large disturbance roads. Driving experimental results and evaluation results will be provided to verify the effectiveness of the proposed control system. In addition, disturbance compensation control is also one of the possible solutions for disturbance road driving; therefore, driving experiment by disturbance observer control is conducted and compared with the proposed method.

II. Driving Control of Power-Assisted Wheelchair

Driving control systems for power-assisted wheelchairs can be classified into "position-control-based system" and "torque-control-based system" [16]. In position-control-based systems, the reference trajectory (or wheel angle) is generated from human input torque T_h. The wheel angle θ (or position x) is controlled by position controller. Then, the driving characteristics such as smoothness and stability largely depend on the reference trajectory generator.

One of torque-control-based systems using low-pass filter (LPF) shown in Fig. 3 was proposed by the authors [17]. The symbol α is the assistance ratio, T_a is the assisted torque, and T_d is the disturbance torque. The time constant τ_a is switched from small value τ_1 to large value τ_2 so that the inertial torque is generated also after the operator releases his/her hands from hand-rims. The assisted torque is generated as the following equations using transfer function representation:

$$T_a = \frac{\alpha}{1 + \tau_a s} T_h. \tag{1}$$

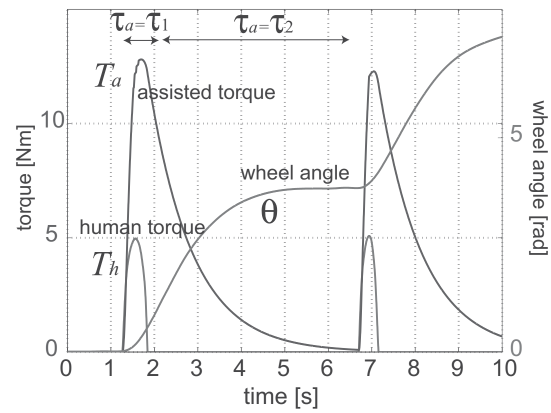


Fig. 4. Example of the driving experimental result.

Fig. 4 shows an example of driving experimental results by the torque-control-based system. The human input torque T_h is always intermittent, as shown in Fig. 4, because the human operator necessarily releases hand-rims after imposing the torque and grasps them again. Therefore, the suitable assisted torque must be generated also after the human operator decreases his/her pushing torque. Particularly, on large disturbance roads, the driving distance will be shortened unless larger assisted torque is generated.

III. Fuzzy-Algorithm-Based Assisted Torque Control

A. Driving Control Mode Switching

This study applies a simple LPF-based control system shown in Fig. 3, while human operators are imposing the torque and applies a fuzzy-algorithm-based torque control described in this section after they release hand-rims. Therefore, the proposed control system has two different driving modes during pushing driving and repeats the mode switching.

This study defines two driving modes as "LPF mode" and "Fuzzy mode," and the mode is switched from "LPF mode" to "Fuzzy mode" when the human operator releases hand-rims. In "LPF mode," the assisted torque is increased according to the human input torque and the wheelchair will accelerate. In "Fuzzy mode," the assisted torque is suitably reduced by the proposed fuzzy algorithm. The mode switching timing can be determined based on the human input torque information. In this study, the mode is switched when the human input torque decreases by some specific value from the maximum value.

Then, from "LPF mode" to "fuzzy mode," the continuity of the calculated assisted torque T_a can be kept because the reduction value will be adjusted in "fuzzy mode." On the other hand, from "fuzzy mode" to "LPF mode," the assisted torque will be discontinuous if (1) is simply applied because the initial output of (1) is zero. In order to avoid this problem, the final value of T_a in "fuzzy mode" is kept also at the beginning of "LPF mode" until the output value of (1) becomes larger than that value.

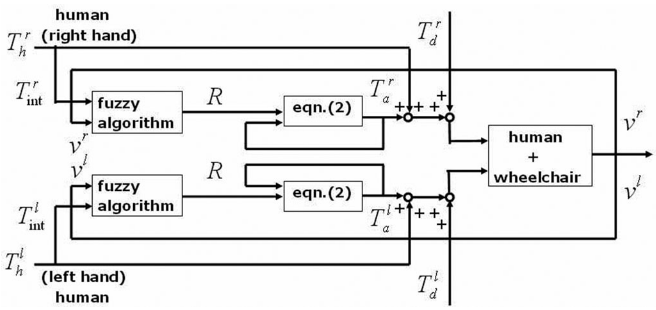


Fig. 5. Proposed fuzzy-algorithm-based driving control system.

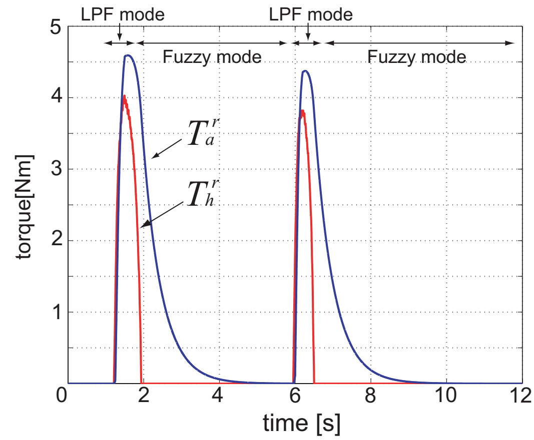


Fig. 6. Example of the driving experimental results with the proposed driving control scheme.

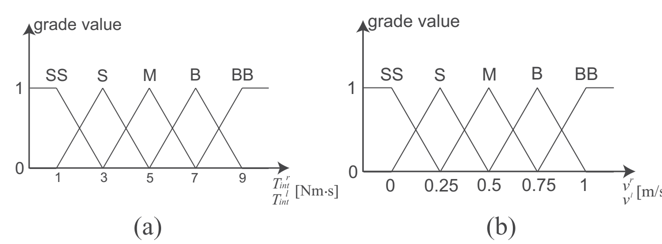


Fig. 7. Triangular fuzzy variable.

$T_{int}^{r,l}$ \ $v^{r,l}$	SS	S	M	B	BB
SS	S	M	B	BB	BB
S	SS	S	M	B	BB
M	SS	S	M	B	BB
B	SS	S	S	M	B
BB	SS	SS	S	M	M

Fig. 8. Fuzzy IF–THEN control rules.

B. Fuzzy Inference for Assisted Torque Adjustment

Some simpler control systems without modeling of the human–wheelchair system will be required because the parameter variation such as human's weight and road conditions makes modeling difficult. Therefore, this study applies fuzzy inference based on two important signals, the integral value of human input torque, and the driving velocity. The idea of fuzzy algorithm is very close to the human's thinking and does not need the modeling of human–wheelchair system. It has been often used for the estimation and motion control [24], [25]. Fig. 5 shows the proposed fuzzy control system for assisted power compensatory driving on large disturbance roads.

The symbols T_h^r, T_h^l are the human input torque of right and left wheels, respectively; $T_{\rm int}^r, T_{\rm int}^l$ are the integral values of human input torque of right and left wheels during LPF mode, respectively; T_d^r, T_d^l are the disturbance torque of right and left wheels, respectively; T_a^r, T_a^l are the assisted torque of right and left wheels, respectively, calculated by the proposed fuzzy control system; and v^r, v^l are the velocity of right and left wheels, respectively.

The human input torque becomes intermittent as mentioned previously. Then, the integral values during LPF mode $T_{\rm int}^r, T_{\rm int}^l$ are calculated once at the mode switching timing and they are reset as zero at the next LPF mode.

First, the integral value of human input torque $T_{\rm int}^r, T_{\rm int}^l$ of right and left wheels and the velocity v^r, v^l are applied to the input variables of fuzzy control and the torque reduction rate R is determined. The assisted torque at $k+1$th control period can be shown as the following equation using discrete-time representation:

$$T_a[k+1] = (1-R)T_a[k]. \tag{2}$$

The simple control shown in Fig. 3 generates the assisted torque regardless of the actual driving velocity and distance, and the driving velocity and distance will be reduced on large disturbance roads. Longer inertial driving torque is required to obtain the longer driving distance on large disturbance roads; therefore, the torque reduction rate R should be made smaller if the velocity is low even though large human torque is imposed. The proposed fuzzy rules will be designed based on such theory.

As described previously, the rising torque is generated by the torque-control-based system, as shown in Fig. 3, while the operator inputs the torque and the inertial assisted torque is generated by the proposed fuzzy control system, as shown in Fig. 6, after the operator begins to decrease the input torque. The proposed fuzzy algorithm is applied to right and left wheels, respectively, as shown in Fig. 5.

C. Design of Fuzzy Algorithm

Fig. 7(a) and (b) shows the fuzzy variables of $T_{\rm int}^r$ (or $T_{\rm int}^l$) and v^r (or v^l), respectively, and the vertical axis shows the grade value from 0 to 1. In Fig. 7, the symbols SS, S, M, B, and BB show Small–Small, Small, Middle, Big, and Big–Big, respectively.

The fuzzy control system to determine the torque reduction rate R is designed by IF–THEN rules. Fig. 8 shows the proposed fuzzy IF–THEN control rules for the power compensatory driving for large disturbance roads. For example, when $T_{\rm int}^r$ (or $T_{\rm int}^l$) is "B" and v^r (or v^l) is "M," that is, the human input torque is large and driving velocity is small, the assisted torque should

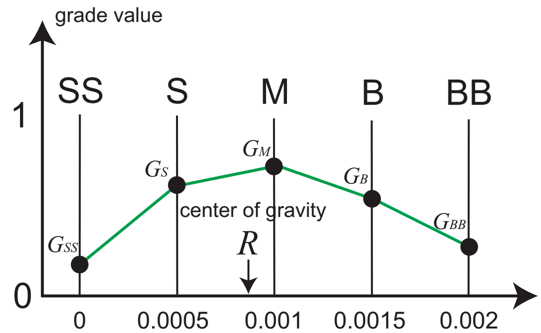
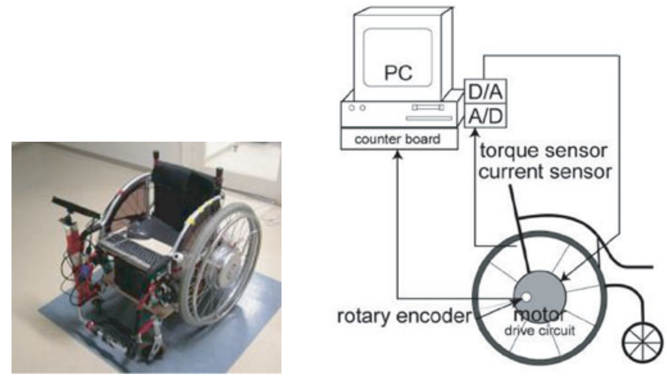


Fig. 9. Singleton-type fuzzy reasoning of R.



(a) (b)

Fig. 10. Experimental setup of power-assisted wheelchair. (a) Photograph. (b) Configuration.

not be reduced so much; therefore, the fuzzy rule to determine R is designed as "S."

The proposed fuzzy control system applies the "Min-Max" method [26]. There are 25 different rules, as shown in Fig. 8, and the smaller grade values are selected in each rule by the "Min" method. Thus, five grade values, i.e., $G_{\mathrm{SS}}, G_{\mathrm{S}}, G_{\mathrm{M}}, G_{\mathrm{B}}$ and G_{BB}, are, respectively, determined by selecting the maximum grade values based on the "Max" method.

Fig. 9 shows the singleton-type fuzzy reasoning system. The output of fuzzy control system, i.e., the torque reduction rate R, can be obtained by calculating the center of gravity, as shown in Fig. 9, and the following equation:

$$R = \frac{0 \times G_{\mathrm{SS}} + 0.0005 G_{\mathrm{S}} + 0.001 G_{\mathrm{M}} + 0.0015 G_{\mathrm{B}} + 0.002 G_{\mathrm{BB}}}{G_{\mathrm{SS}} + G_{\mathrm{S}} + G_{\mathrm{M}} + G_{\mathrm{B}} + G_{\mathrm{BB}}}. \tag{3}$$

This value is applied to (2), and the suitable right and left assisted torque can be determined.

Parameters in Figs. 7 and 9 were designed based on some driving experiment results on a flat and smooth road in order to realize the assistive driving on large disturbance roads. The fuzzy rules are independent of the types of disturbance roads, and the same algorithm can be used for any disturbance roads. Fig. 8 shows an example of the possible solutions.

IV. Driving Experiments

A. Experimental Setup

The effectiveness of the proposed fuzzy-algorithm-based control system for power-assisted wheelchairs will be verified through some basic driving experiments on a flat and smooth road, uphill roads with 4° and 6° inclined angle and a rough road. Fig. 10(a) shows the experimental setup of power-assisted wheelchair, and Fig. 10(b) shows the configuration of experimental setup. Two torque sensors, two rotary encoders, and motor drive circuit are installed. The wheelchair's velocity can be calculated by subtracting the encoder information. The wheelchair is controlled by PC with real-time OS, called ART-Linux, as shown in Fig. 10(b). The control period is 1 ms.

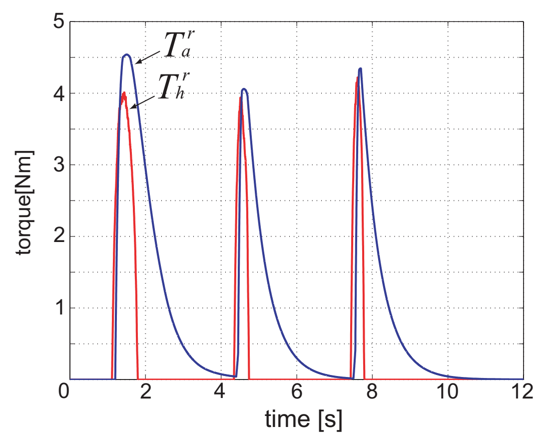


Fig. 11. Driving experimental results with the proposed control.

In the following experiments, the assistance ratio is set as $\alpha = 1.2$ and the time constant is set as $\tau_1 = 0.05$ s in LPF mode. Only right wheel data of the human input torque and assisted torque will be shown in the following figures because the right and left data necessarily become almost the same in case of the straight road driving. All experiments in this section are conducted by the same unimpaired rider.

B. Flat and Smooth Road Driving (Small Disturbance Road)

First, the driving performance with the proposed fuzzy control on a flat and smooth road with small disturbance is confirmed. Fig. 11 shows the straight road driving experimental results with the proposed fuzzy control system. The assisted torque was suitably decreased after the operator released hand-rims. The proposed fuzzy control system can be applied also as a basic assisting control system on flat and smooth roads.

C. Uphill Road Driving

Next experiments are tried on uphill roads with 4° and 6° inclined angle, as shown in Fig. 12. Most of typical uphill roads have less than 10° inclined angle.

Fig. 12. Photograph of the uphill road driving experiment.

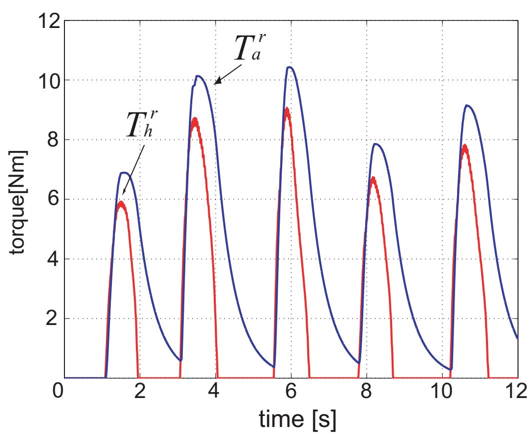


Fig. 13. Driving experimental results on a 4° inclined road without the proposed control.

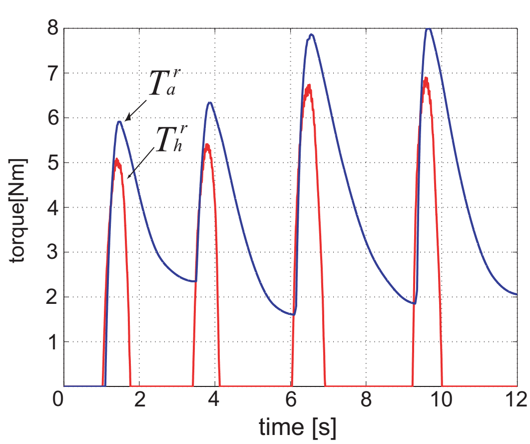


Fig. 14. Driving experimental results on a 4° inclined road with the proposed control.

Figs. 13 and 14 show the driving experimental results on a 4° inclined road without and with the proposed fuzzy control system, respectively. "Without the proposed control" means that only the simple control system shown in Fig. 3 is applied at all times and the time constant in (1) is set as $\tau_1 = 0.05$ s and $\tau_2 = 0.5$ s. These parameters are effective for the flat and smooth road driving.

The assisted torque decrement of Fig. 14 is smaller than that of Fig. 13, although the human input torque is almost the same.

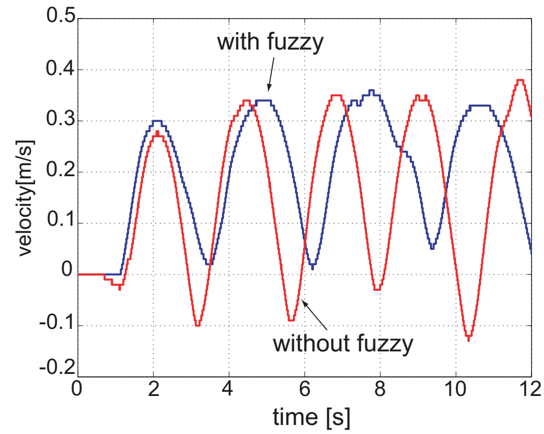


Fig. 15. Velocity comparison results on a 4° inclined road with and without the proposed control.

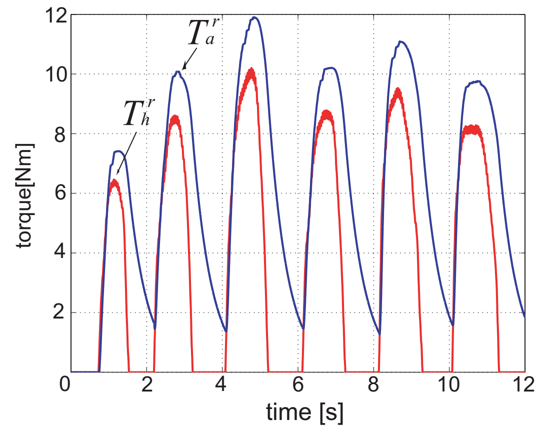


Fig. 16. Driving experimental results on a 6° inclined road without the proposed control.

Fig. 15 shows the driving velocity comparison results. The driving velocity without the proposed system decreased soon and became negative at every pushing actions. On the other hand, the driving velocity with the proposed control system slowly decreased and never became negative due to the enough inertial assisted torque.

Figs. 16 and 17 show the driving experimental results on a 6° inclined road without and with the proposed fuzzy control system, respectively. Fig. 18 shows the velocity comparison results. The driving performance could be improved by the proposed control system in the same way as the last experiments, although the driving velocity became negative.

D. Rough Road Driving

The rough terrain driving performance by the proposed fuzzy control system is examined. Fig. 19 shows the test course of rough road driving experiments. This experiment applies artificial grass as an example of rough roads.

Figs. 20 and 21 show the driving experimental results without and with the proposed fuzzy control system, respectively, and Fig. 22 shows the driving velocity comparison results. These figures indicate the wheelchair could drive on the rough road

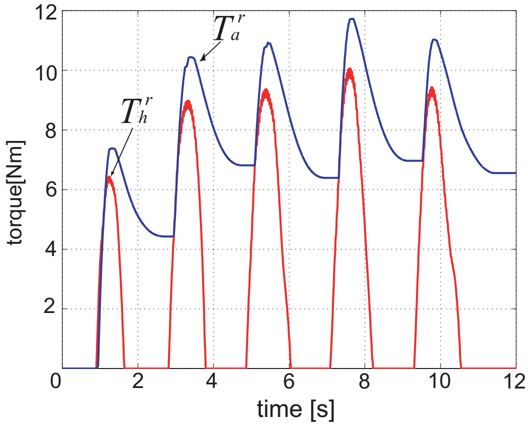


Fig. 17. Driving experimental results on a 6° inclined road with the proposed control.

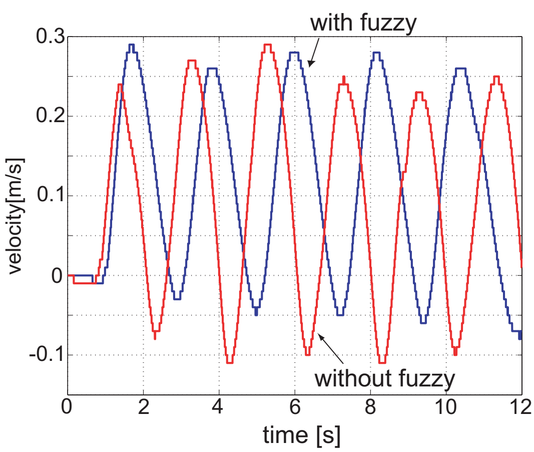


Fig. 18. Velocity comparison results on a 6° inclined road with and without the proposed control.

Fig. 19. Photograph of the rough road driving experiment.

with the enough velocity by the proposed control system because the driving power after the operator released hand-rims was sufficiently compensated by large inertial assisted torque.

E. Driving Efficiency Evaluation

In order to evaluate the proposed control system quantitatively, this study defines a new evaluation value "driving effi-

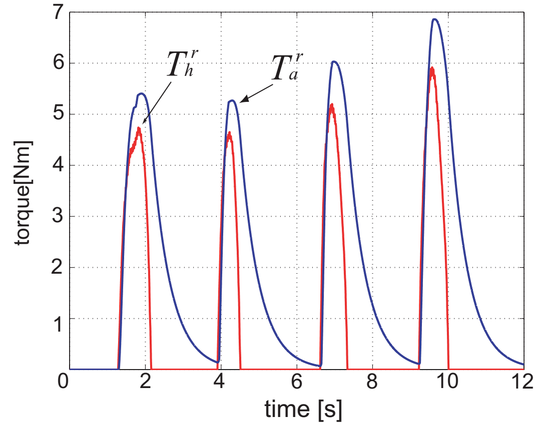


Fig. 20. Driving experimental results on a rough road without the proposed control.

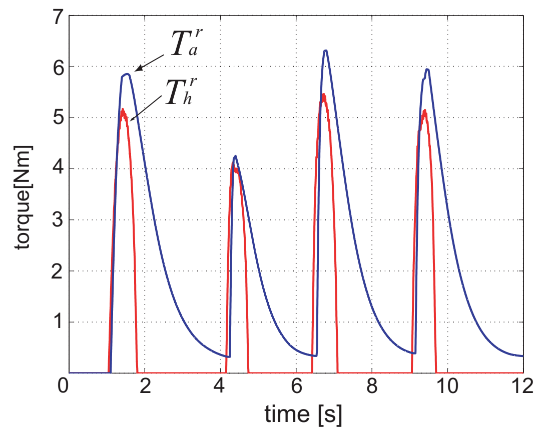


Fig. 21. Driving experimental results on a rough road with the proposed control.

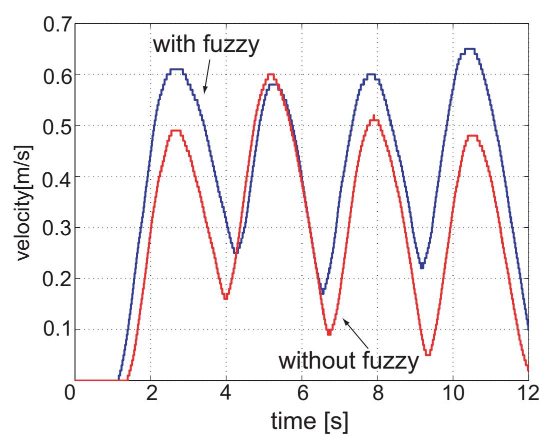


Fig. 22. Velocity comparison results on a rough road with and without the proposed control.

ciency" (DE) shown in the following equation:

$$\mathrm{DE} = \frac{\frac{1}{2}(x_f^r + x_f^l)}{\frac{1}{2}\left(\int_0^{t_f} T_h^r dt + \int_0^{t_f} T_h^l dt\right)}. \tag{4}$$

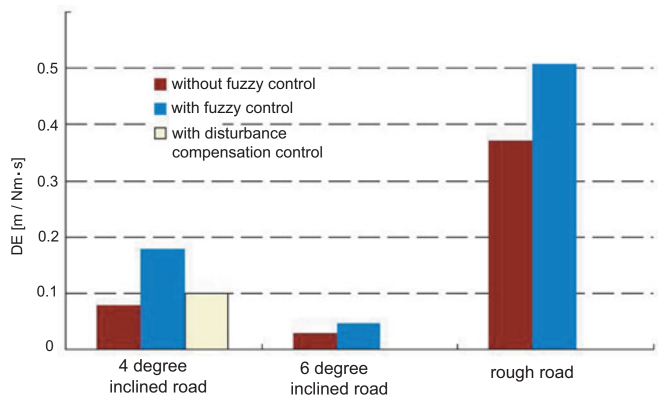


Fig. 23. Results of driving efficiency DE.

The symbols x_f^r and x_f^l show the driving distance of right and left wheels, respectively, and t_f is the total driving time. The numerator means the driving distance and the denominator means the average of right and left input torque. DE is calculated by dividing the driving distance by the human input power and is similar to the fuel efficiency of automobiles.

Fig. 23 shows the driving efficiency results of 4° and 6° inclined road driving and rough road driving. These results show that the driving efficiency can be improved by the proposed fuzzy control system.

V. Evaluation

A. Summary of Practical Test

The driving experimental results shown in the last section are just examples by a specific rider; therefore, the proposed control system is evaluated using many trial subjects in this section. Ten trial subjects (S1–S10) including two women (S1 and S2) and eight men (S3–S10) drive the power-assisted wheelchair, and all of them are physically unimpaired people. They drive on a 4° inclined road shown in Fig. 25 with and without the proposed control system, and the content of the driving control system is hidden from the subjects.

The proposed control system will be evaluated from two aspects: One is the quantitative evaluation using DE value shown in (4) and the other is the subjective evaluation using five scales rating.

B. Quantitative Evaluation

The driving efficiency of ten subjects is quantitatively evaluated using DE value shown in (4). Fig. 24 shows the results of DE. The proposed control system realized the higher driving efficiency for all subjects, although there is some individual difference due to the manners of pushing.

C. Subjective Evaluation

The subjects rate on a scale of one to five as to the power assistance and mobility. Fig. 25 shows the results. Seven subjects relatively valued the proposed system and the following comments were obtained.

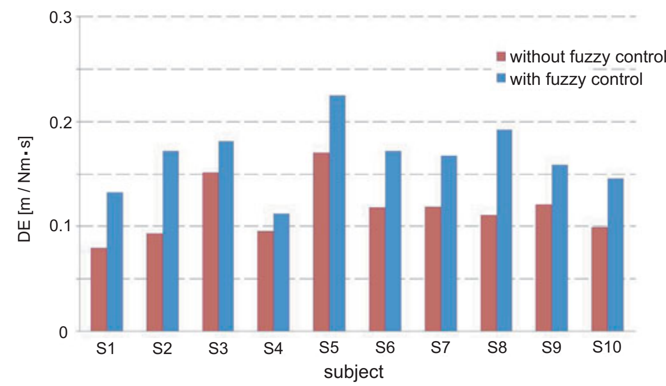


Fig. 24. Results of driving efficiency DE.

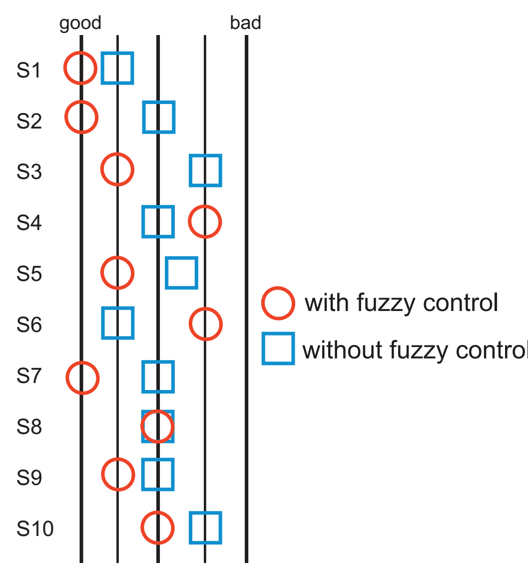


Fig. 25. Subjective evaluation results.

1) A feeling of safety was provided because the wheelchair rarely moved backward on inclined roads.
2) It was easier because the frequency of pushing hand-rims was reduced.
3) There was a feeling someone was pushing the wheelchair from behind.

A few subjects expressed the opposite views, for example, one of them said the driving was unsteady because of much assistance power than imagination. However, the proposed control system received good reports from subjects as a whole.

VI. Discussion

This study realized the assisted torque control of power-assisted wheelchairs for large disturbance road driving with consideration of practical use such as simplicity, ride quality, and control design without model identification. The proposed control system could reduce the burden on wheelchair's riders as the quantitative and subjective evaluation results show. The proposed system using fuzzy controller has the following advantages.

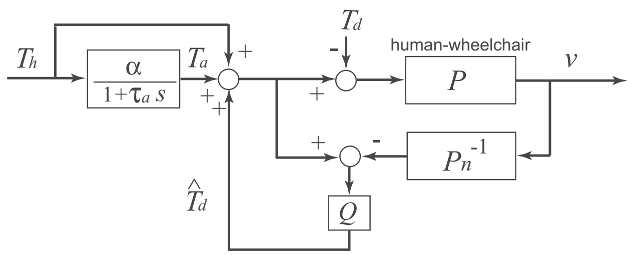


Fig. 26. Construction of disturbance compensation control.

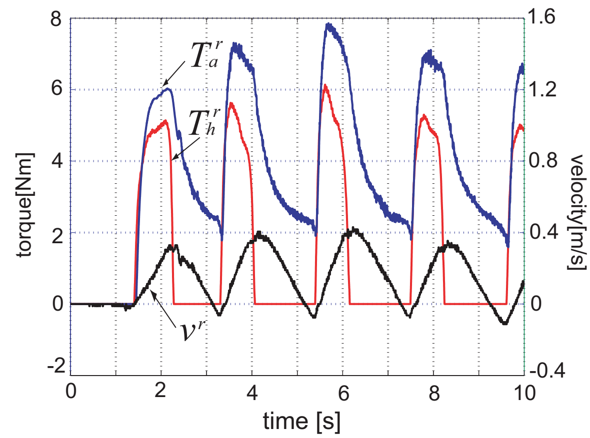


Fig. 27. Driving experimental results on a 4° inclined road with disturbance compensation control.

1) The structure of fuzzy controller is simple and easy to implement on practical wheelchairs and never provides the input torque pulsation leading to the ride quality deterioration because the fuzzy rules determine the torque reduction rate. In addition, it never needs any external sensors.
2) The control rules shown in Fig. 8 can be easily designed based on the human's thinking and experience. In addition, the whole system works well even if a few parts of the rules are improper.
3) The control purpose can be realized without the modeling of human and wheelchair system if the environmental disturbance and rider's weight variation are in the average range, for example, the designed parameters in this study showed enough performance on inclined roads with less than 6° angle.

Some experimental results and practical evaluation results were provided to verify the effectiveness of the proposed system, but it still has the following important future problems.

1) This study examined only the straight road driving performance. The same efficiency will be obtained also on circular roads by the proposed control system, and its performance will have to be tested.
2) Driving experiments were conducted with constant parameters in this study; however, the automatic parameter adjustment according to users and driving situations should be developed in order to obtain better driving performance. The fuzzy parameters were adjusted for riders with average weight and for practical range of environmental disturbance roads in this study, but they will have to be readjusted in other cases.
3) The ride quality and safeness will have to be examined by many kinds of human operators and disturbance roads.

For large disturbance road driving, robust control [27] is also one of the possible solutions. It can be applied to the wheelchair's control system design [8], [16], [20], [28]. Fig. 26 shows the block diagram of the driving control with disturbance observer and compensation. Q is an LPF. This control system requires the difficult model identification of P_n taking into account the reference flat road driving characteristics and rider's weight. Fig. 27 shows the driving experimental results on a 4° inclined road with disturbance compensation control. The velocity waveform shows that it produces a certain level of effect on large disturbance road driving compared with the simple control system ("without fuzzy" in Fig. 15). Fig. 23 shows that DE value can be improved by the disturbance compensation control.

It is certain that the disturbance compensation control is one of the possible solutions; it has some demerits from a practical application standpoint. Specifically, the plant model identification is very difficult because of the reference flat road driving characteristics analysis, rider's weight variation, air pressure variation of tires, and other nonlinear factors. The identification error might induce an overcompensation which could contribute to accidents. On the other hand, the proposed fuzzy control never needs the model identification, and the same fuzzy rules can be applied to all users and roads. In addition, it never provides the input torque pulsation leading to the ride quality deterioration unlike disturbance compensation control because the proposed fuzzy control determines the torque reduction rate. Therefore, the proposed control system has an advantage from a practical application standpoint.

VII. Conclusion

This paper proposed a driving control scheme of power-assisted wheelchairs based on the fuzzy algorithm. The proposed system could improve the driving performance on large disturbance roads and has some advantages from a practical application standpoint, although a classical fuzzy algorithm was applied. Some basic driving experiment results and evaluation results were provided to verify the effectiveness of the proposed control system. Our future work will solve some important problems described in the previous section.

References

[1] D. Ding and R. A. Cooper, "Electric powered wheelchairs," *IEEE Control Syst. Mag.*, vol. 25, no. 2, pp. 22–34, Apr. 2005.
[2] R. A. Cooper, L. M. Widman, D. K. Jones, R. N. Robertson, and J. F. Ster, "Force sensing control for electric powered wheelchairs," *IEEE Trans. Control Syst. Technol.*, vol. 8, no. 1, pp. 112–117, Jan. 2000.
[3] R. A. Cooper, D. K. Jones, S. Fitzgerald, M. L. Boninger, and S. J. Albright, "Analysis of position and isometric joysticks for powered wheelchair driving," *IEEE Trans. Biomed. Eng.*, vol. 47, no. 7, pp. 902–910, Jul. 2000.
[4] R-X. Chen, L-G. Chen, and L. Chen, "System design consideration for digital wheelchair controller," *IEEE Trans. Ind. Electron.*, vol. 47, no. 4, pp. 898–907, Aug. 2000.

[5] S. Katsura and K. Ohnishi, "Semiautonomous wheelchair based on quarry of environmental information," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1373–1382, Apr. 2006.
[6] A. Mihailidis, P. Elinas, J. Boger, and J. Hoey, "An intelligent powered wheelchair to enable mobility of cognitively impaired older adults: An anticollision system," *IEEE Trans. Neural. Syst. Rehab. Eng.*, vol. 15, no. 1, pp. 136–143, Mar. 2007.
[7] B. E. Dicianno, D. M. Spaeth, R. A. Cooper, S. G. Fitzgerald, M. L. Boninger, and K. W. Brown, "Force control strategies while driving electric powered wheelchairs with isometric and movement-sensing joysticks," *IEEE Trans. Neural. Syst. Rehab. Eng.*, vol. 15, no. 1, pp. 144–150, Mar. 2007.
[8] S. Katsura and K. Ohnishi, "Human cooperative wheelchair for haptic interaction based on dual compliance control," *IEEE Trans. Ind. Electron.*, vol. 51, no. 1, pp. 221–228, Jan. 2004.
[9] S. Tashiro and T. Murakami, "Step passage control of a power-assisted wheelchair for a caregiver," *IEEE Trans. Ind. Electron.*, vol. 55, no. 4, pp. 1715–1721, Apr. 2008.
[10] L. Montesano, M. Diaz, S. Bhaskar, and J. Minguez, "Towards an intelligent wheelchair system for users with cerebral palsy," *IEEE Trans. Neural. Syst. Rehab. Eng.*, vol. 18, no. 2, pp. 193–202, Apr. 2010.
[11] C. Urdiales, B. Fernandez-Espejo, R. Annicchiaricco, F. Sandoval, and C. Caltagirone, "Biometrically modulated collaborative control for an assistive wheelchair," *IEEE Trans. Neural. Syst. Rehab. Eng.*, vol. 18, no. 4, pp. 398–408, Aug. 2010.
[12] T. N. Nguyen, S. W. Su, and H. T. Nguyen, "Robust neuro-sliding mode multivariable control strategy for powered wheelchairs," *IEEE Trans. Neural. Syst. Rehab. Eng.*, vol. 19, no. 1, pp. 105–111, Feb. 2011.
[13] R. A. Cooper, T. A. Corfman, S. G. Fitzgerald, M. L. Boninger, D. M. Spaeth, W. Ammer, and J. Arva, "Performance assessment of a pushrim-activated power-assisted wheelchair control system," *IEEE Trans. Control Syst. Technol.*, vol. 10, no. 1, pp. 121–126, Jan. 2002.
[14] Y. Takahashi, S. Ogawa, and S. Machida, "Front wheel raising and inverse pendulum control of power assist wheel chair robot," in *Proc. Annu. Conf. IEEE Ind. Electron. Soc.*, 1999, pp. 668–673.
[15] H. Seki, T. Iijima, H. Minakata, and S. Tadakuma, "Novel step climbing control for power assisted wheelchair based on driving mode switching," in *Proc. Annu. Conf. IEEE Ind. Electron. Soc.*, Nov. 2006, pp. 3827–3832.
[16] H. Seki, T. Sugimoto, and S. Tadakuma, "Novel straight road driving control of power assisted wheelchair based on disturbance estimation and minimum jerk control," in *Proc. IEEE Int. Conf. Ind. Appl. Soc.*, Oct. 2005, pp. 1711–1717.
[17] H. Seki and S. Tadakuma, "Straight and circular road driving control for power assisted wheelchair based on fuzzy algorithm," in *Proc. Annu. Conf. IEEE Ind. Electron. Soc.*, Nov. 2006, pp. 3898–3903.
[18] H. Seki, T. Sugimoto, and S. Tadakuma, "Driving control of power assisted wheelchair based on minimum jerk trajectory," in *Proc. Int. Power Electron. Conf.*, Apr. 2005, pp. 1682–1687.
[19] H. Seki and S. Tadakuma, "Velocity pattern generation for power assisted wheelchair based on jerk and acceleration limitation," in *Proc. Annu. Conf. IEEE Ind. Electron. Soc.*, Nov. 2005, pp. 457–462.
[20] S. Oh, N. Hata, and Y. Hori, "Integrated motion control of a wheelchair in the longitudinal, lateral, and pitch directions," *IEEE Trans. Ind. Electron.*, vol. 55, no. 4, pp. 1855–1862, Apr. 2008.
[21] Y. Oonishi, S. Oh, and Y. Hori, "A new control method for power-assisted wheelchair based on the surface myoelectric signal," *IEEE Trans. Ind. Electron.*, vol. 57, no. 9, pp. 3191–3196, Sep. 2010.
[22] H. Seki, K. Ishihara, and S. Tadakuma, "Novel regenerative braking control of electric power assisted wheelchair for safety downhill road driving," *IEEE Trans. Ind. Electron.*, vol. 56, no. 5, pp. 1393–1400, May 2009.
[23] H. Seki and Y. Takahashi, "Downward slope driving control for electric powered wheelchair based on capacitor regenerative brake," in *Proc. Annu. Conf. IEEE Ind. Electron. Soc.*, Nov. 2009, pp. 2237–2242.
[24] C. W. Tao, J. Taur, J. H. Chang, and S.-F. Su, "Adaptive fuzzy switched swing-up and sliding control for the double-pendulum-and-cart system," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 40, no. 1, pp. 241–252, Feb. 2010.
[25] T-H. S. Li, Y-T. Su, S-W. Lai, and J-J. Hu, "Walking motion generation, synthesis, and control for biped robot by using PGRL, LPI, and fuzzy logic," *IEEE Trans. Syst., Man, Cybern. B, Cybern.*, vol. 41, no. 3, pp. 736–748, Jun. 2011.
[26] E. H. Mamdani, "Advances in the linguistic synthesis of fuzzy controller," *Int. J. Man-Mach. Stud.*, vol. 8, no. 6, pp. 669–679, 1976.
[27] T. Umeno and Y. Hori, "Robust speed control of DC servomotors using modern two degrees-of-freedom controller design," *IEEE Trans. Ind. Electron.*, vol. 38, no. 5, pp. 363–368, Oct. 1991.
[28] C. Ou, C. Chen, and T. Chen, "Modelling and design a power assisted wheelchair used torque observer," in *Proc. Int. Symp. Comput. Commun., Control Autom.*, vol. 2, 2010, pp. 63–66.

Hirokazu Seki (M'04) received the B.S. degree in system engineering from Osaka University, Osaka, Japan, in 1998, and the M.S. and Ph.D. degrees in electrical engineering from the University of Tokyo, Tokyo, Japan, in 2000 and 2003, respectively.

He joined the Department of Electrical, Electronics and Computer Engineering, Chiba Institute of Technology, Chiba, Japan, as a Research Associate in 2003. He later became an Associate Professor in 2008. His research fields are measurement and control engineering and its application to human support welfare systems.

Dr. Seki is a member of the Institute of Electrical Engineers of Japan and the Society of Instrument and Control Engineers of Japan.

Naoki Tanohata received the B.S. degree in electrical engineering and the M.S. degree in electrical, electronics, and computer engineering from the Chiba Institute of Technology, Chiba, Japan, in 2009 and 2011, respectively.

He joined Nohmi Bosai Ltd., Saitama, Japan, in 2011.