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Disturbance Road Adaptive Driving Control of Power-Assisted Wheelchair Using Fuzzy Inference

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Abstract— **This paper describes a novel driving control scheme of electric power-assisted wheelchairs for assistive driving on various large disturbance roads. The "electric power-assisted wheelchair" which 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 row the hand-rims with the larger power load on such roads in order to obtain the enough driving velocity. For example the wheelchair might move backward on uphill roads due to the driving torque shortage. Therefore this study proposes a fuzzy algorithm based adaptive control scheme in order to realize the assistive driving without the operator's power load on large disturbance roads. The proposed fuzzy rules are designed from the driving distance information and the control parameters are inferred by the fuzzy algorithm. The assisted torque can be adjusted so that the enough distance and velocity are kept even on large disturbance roads. Driving experimental results are provided to verify the effectiveness of the proposed control system.**

I. INTRODUCTION

Elderly people and disabled people who have difficulty in walking are 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 the interface devices and using forms. One is the joystick driving type of powered wheelchairs and the human operators can give the driving command such as the direction and velocity through the joystick [2]-[5]. 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 of the wheelchair [6][7]. In addition, intelligent navigation wheelchairs have been also developed for navigating to the goal efficiently and safely without the obstacle collisions [8][9].

This paper focuses on the rider operation type of "electric power-assisted wheelchair" and its advanced motion control system. The rider operates the right and left hand-rims for himself/herself and the assisted torque is generated according to the human input torque. Fig.1 shows an example of "electric power-assisted wheelchair" developed by YAMAHA Co. called "JWII". Some advanced driving control schemes also have been presented [10]-[17], for example, the basic driving control algorithm [10], the safety front wheel raising control for climbing over steps without the dangerous backward overturning [11][12], the stable and well-balanced straight and circular road driving control [13], the driving trajectory design based on jerk limitation [14], the tip-over prevention control [15], the driving control system based on the surface myoelectric signal of the operator's hand [16] and the regenerative braking control for the energy efficiency [17]. Multi purpose and high performance control systems for power-assisted wheelchairs considering the human's sense and the driving environments must be further developed.

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

This paper focuses on "large disturbance roads" which give the large disturbance torque to the wheelchair through the wheels and cause the shortage of driving distance and velocity compared to flat and smooth surface roads. There are lots of large disturbance roads such as grass and gravel roads in the practical driving environments. Uphill roads are also included in large disturbance roads. The human operators have to give larger rowing torque on large disturbance roads if the electric power-assisted wheelchair has only a simple control system generating the constant assisted power.

This study proposes a driving control system based on fuzzy algorithm and realizes the assistive driving on various large disturbance roads such as uphill roads and rough roads shown in Fig.2(a)(b). For example, the wheelchair might move backward on uphill roads due to the driving torque shortage and enough driving distance and velocity cannot be obtained on rough roads such as grass and gravel roads. Thus some ideas of the assisted torque adjustment after the wheelchair proceeds into large disturbance roads will be needed to reduce his/her physical power load.

Therefore this study proposes a fuzzy algorithm based assisted torque control scheme in order to realize the assistive driving without the operator's physical power load on large disturbance roads. The proposed fuzzy rules are designed from the driving distance information and the adaptive variations of the assisting control parameters are inferred by fuzzy

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(a) (b)

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

algorithm. The assisting control parameters 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.

II. DRIVING CONTROL OF POWER-ASSISTED WHEELCHAIR

The driving control systems for electric power-assisted wheelchairs can be classified into ”position control based system” and ”torque control based system” [13]. In the position control based systems, the reference trajectory (the wheel angle) is generated from the human input torque T_h. The wheel angle of the wheelchair θ (or the position x) is controlled by the position controller. Then the driving characteristics such as the smoothness and stability of power-assisted wheelchairs largely depends on the reference trajectory generator, that is, how to generate the reference position.

One of the torque control based systems using Low-Pass-Filter(LPF) shown in Fig.3 was proposed by the authors [13]. 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 the small value τ_f to the large value τ_s so that the inertial torque is generated also after the operator releases his/her hands from the 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 shows an example of the 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 the 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 rowing torque.

III. FUZZY ALGORITHM BASED ASSISTED TORQUE CONTROL

A. Adaptive driving control system

The control parameters α and τ_s described in the last chapter are the important values to determine the assisted torque. The assistance ratio α mainly determines the total assisted torque and inertial time constant τ_s mainly determines the continuity of the assisted torque after the operator releases the hand-rims. Therefore the enough driving distance and velocity can be realized by changing these parameters. This study proposes an adaptive control system to sequentially adjust these parameters based on the driving results at the last rowing action.

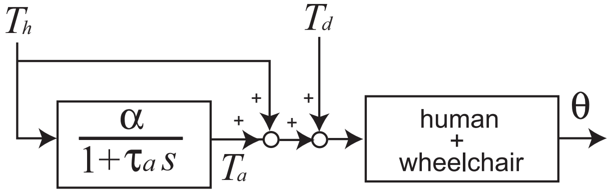


Fig. 3. Configuration of power assisting control system using Low-Pass-Filter.

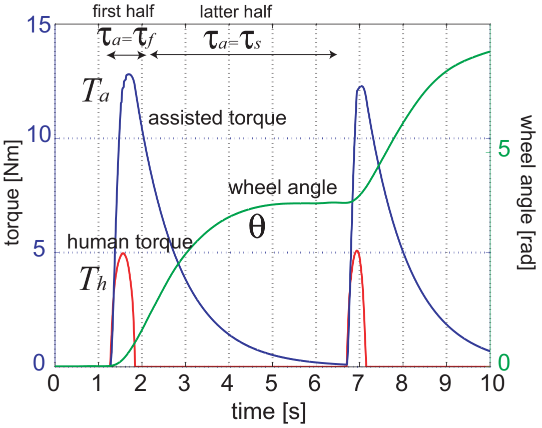


Fig. 4. Example of the driving experimental result.

The assistance ratio $\alpha[k]$ and inertial time constant $\tau_s[k]$ at the kth rowing action can be shown as the following equations.

$$\alpha[k] = \alpha[k-1] + \Delta\alpha[k] \tag{2}$$

$$\tau_s[k] = \tau_s[k-1] + \Delta\tau[k] \tag{3}$$

$\Delta\alpha[k]$ and $\Delta\tau[k]$ are the variation of α and τ_s respectively and these will be inferred by fuzzy algorithm.

Two important values are applied to the fuzzy inference input. One is the driving distance D at the last rowing action. This value will be decreased on large disturbance roads. The other is the driving distance proportion of the first half and latter half at the last rowing action. Fig.5 shows examples of the distance proportion on a small disturbance road, 4 degree inclined road and artificial grass road. The proportion R of the latter half decreases especially on inclined roads due to the shortage of the inertial torque.

The proposed fuzzy system will infer the variation of the control parameters α and τ_s based on the driving distance information D and R.

B. Fuzzy inference for parameter adjustment

Some simpler control systems without modeling of the human-wheelchair system will be required because the system variation including the human’s weight and the road

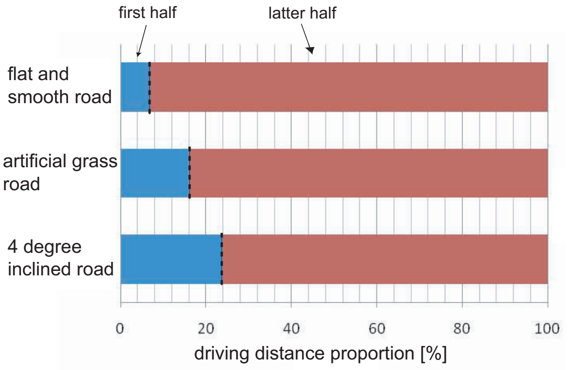


Fig. 5. Example of the driving distance proportion.

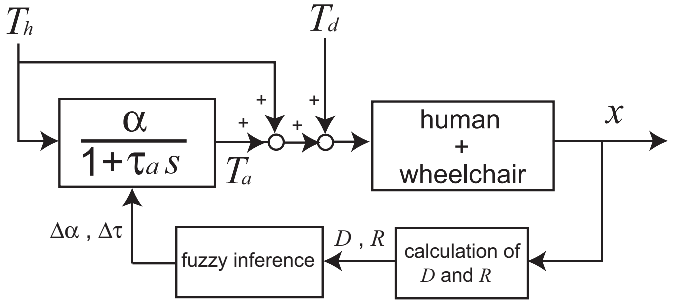


Fig. 6. Proposed fuzzy adaptive driving control system.

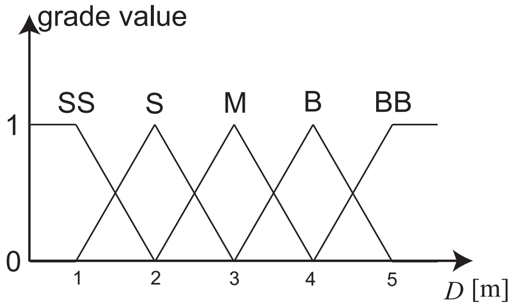


Fig. 7. Triangular fuzzy variable of D.

conditions makes the modeling difficult. Therefore this study applies the fuzzy inference based on the driving distance information. The idea of the fuzzy algorithm is very close to the human's thinking and doesn't need the modeling of the human-wheelchair system. Fig.6 shows the proposed fuzzy adaptive control system for assistive driving on large disturbance roads.

C. Design of fuzzy algorithm

Fig.7 and Fig.8 show the fuzzy variables of D and R respectively and the vertical axis shows the grade value from 0 to 1. In Fig.7 and Fig.8, 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 variation $\Delta\alpha$ and $\Delta\tau$ is designed by IF-THEN rules. Fig.9 and Fig.10 show the proposed fuzzy IF-THEN control rules. For example, when both D and R are "SS", that is, the driving distance is short and the proportion of latter half is small, the assisted torque should be increased so much, therefore, the fuzzy rules to determine $\Delta\alpha$ and $\Delta\tau$ are designed as "PB".

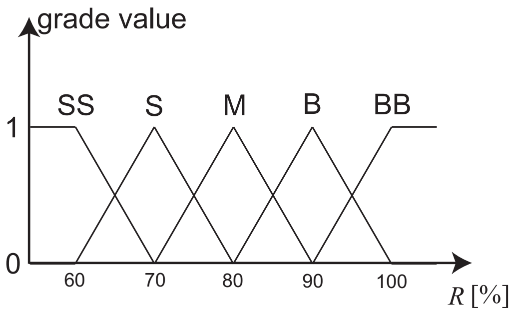


Fig. 8. Triangular fuzzy variable of R.

R \ D	SS	S	M	B	BB
SS	PB	PB	PS	ZO	
S	PB	PB	PS	ZO	ZO
M	PB	PB	PS	ZO	ZO
B	PS	PS	ZO	ZO	NS
BB		ZO	ZO	NS	NS

Fig. 9. Fuzzy IF-THEN control rules of $\Delta\alpha$.

R \ D	SS	S	M	B	BB
SS	PB	PB	PB	PS	
S	PB	PB	PB	PS	ZO
M	PS	PS	PS	ZO	ZO
B	ZO	ZO	ZO	ZO	NS
BB		ZO	ZO	NS	NS

Fig. 10. Fuzzy IF-THEN control rules of $\Delta\tau$.

The proposed fuzzy control system applies "Min-Max" method [18]. The symbols NS, ZO, PS and PB show Negative-Small, Zero, Positive-Small and Positive-Big respectively. There are twenty three rules as shown in Fig.9 and Fig.10 respectively and the smaller grade values are selected in each rule by "Min" method. Thus four grade values, NS, ZO, PS and PB are respectively determined by selecting the maximum grade values based on "Max" method.

Fig.11 and Fig.12 show the single-ton type fuzzy reasoning system. The output of the fuzzy control system, parameter variations $\Delta\alpha$ and $\Delta\tau$, can be obtained by calculating the center of gravity as shown in Fig.11 and Fig.12 and the

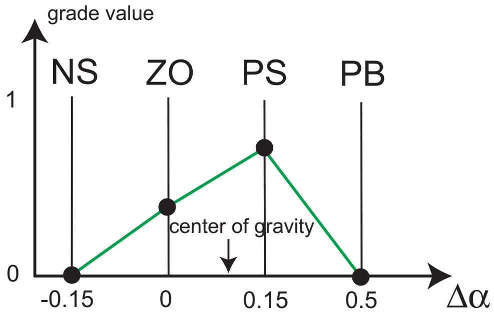


Fig. 11. Singleton-type fuzzy reasoning of $\Delta\alpha$.

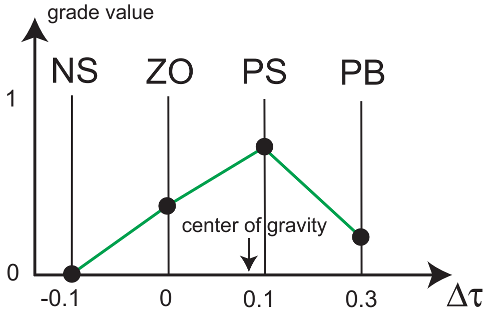


Fig. 12. Singleton-type fuzzy reasoning of $\Delta\tau$.

following equations.

$$\Delta\alpha = \frac{-0.15 \times NS + 0 \times ZO + 0.15 \times PS + 0.5 \times PB}{NS + ZO + PS + PB} \quad (4)$$

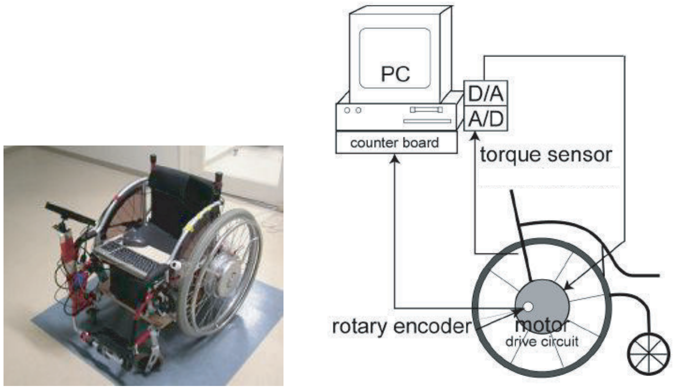
$$\Delta\tau = \frac{-0.1 \times NS + 0 \times ZO + 0.1 \times PS + 0.3 \times PB}{NS + ZO + PS + PB} \quad (5)$$

IV. DRIVING EXPERIMENTS

A. Experimental Setup

The effectiveness of the proposed fuzzy algorithm based control system for electric power-assisted wheelchairs will be verified through some basic driving experiments on an uphill road with 4 degree inclined angle and a rough road. Fig.13(a) shows the experimental setup of the electric power-assisted wheelchair and Fig.13(b) shows the configuration of the experimental setup. Two torque sensors, two rotary encoders and the motor drive circuit are installed. The wheelchair's velocity can be calculated by subtracting the encoder information. The wheelchair is controlled by the PC with real-time OS, called ART-Linux, as shown in Fig.13(b). The control period is 1[ms].

In the following experiments, the initial assistance ratio is set as $\alpha = 1.2$, the initial inertial time constant is set as $\tau_s = 0.5$[s] and the rising time constant is set as $\tau_f = 0.05$[s]. 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 becomes almost the same for the straight road driving. Four subjects (A, B, C and D) will try the wheelchair driving. They are physically unimpaired men.



(a) (b)

Fig. 13. Experimental setup of power-assisted wheelchair. (a) Photograph. (b) Configuration.

Fig. 14. Photograph of the uphill road driving experiment.

B. Uphill Road Driving

First experiment is tried on an uphill road with 4 inclined angle as shown in Fig.14.

Fig.15 and Fig.16 show the driving experimental results of subject A on a 4 degree inclined road with the proposed fuzzy control. They show that the assisted torque could be gradually increased after the second rowing action and also the driving velocity could be increased. In addition, Fig.16 show the control parameters α and τ_s and they almost converged at fifth rowing action.

C. Rough Road Driving

The rough terrain driving performance by the proposed fuzzy control system is examined. Fig.17 shows the test course for the rough road driving experiments. This experiment applies the artificial grass as an example of rough roads.

Fig.18 and Fig.19 show the driving experimental results of subject D on an artificial grass road with the proposed fuzzy control. They show that the assisted torque could be gradually increased after the second rowing action and also the driving velocity could be increased. In addition, Fig.19 show the control parameters α and τ_s and they almost converged at fourth rowing action.

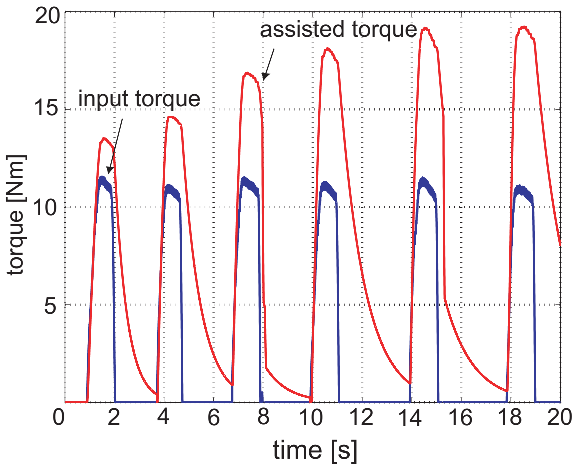


Fig. 15. Driving experimental results on a 4 degree inclined road with the proposed control (human input torque and assisted torque).

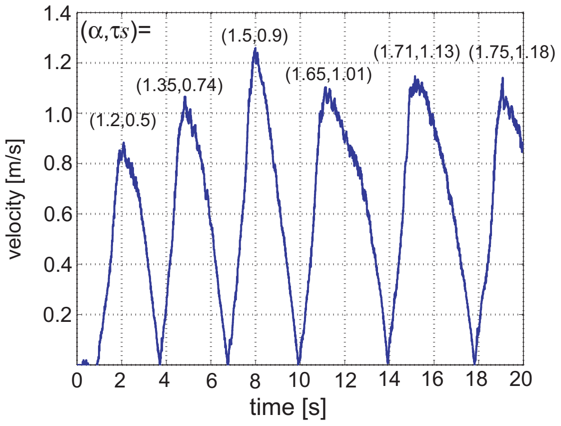


Fig. 16. Driving experimental results on a 4 degree inclined road with the proposed control (driving velocity).

Fig. 17. Photograph of the rough road driving experiment.

D. Driving Efficiency Evaluation

In order to evaluate the proposed control system quantitatively, this study defines "Driving Efficiency" DE shown in the following equation.

$$DE = \frac{D}{\frac{1}{2}(\int T_h^r dt + \int T_h^l dt)} \qquad (6)$$

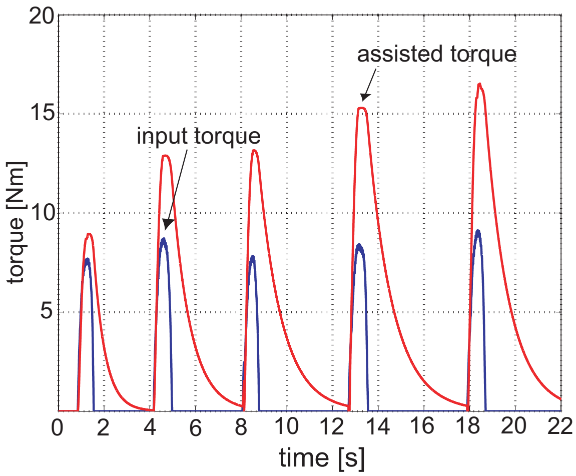


Fig. 18. Driving experimental results on an artificial grass road with the proposed control (human input torque and assisted torque).

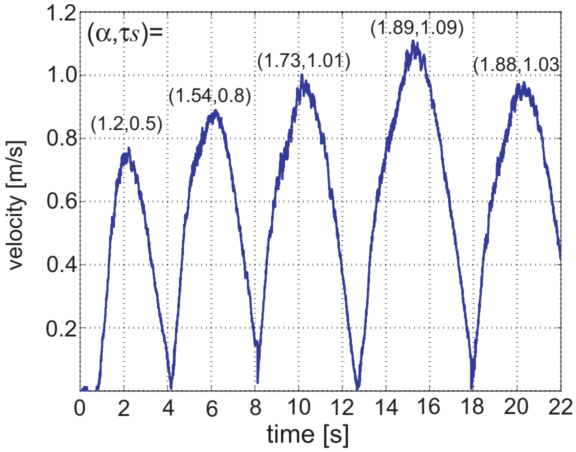


Fig. 19. Driving experimental results on an artificial grass road with the proposed control (driving velocity).

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 for one rowing driving after the control parameters converge. This value's meaning is similar to the fuel efficiency of automobiles.

Fig.20 and Fig.21 show the driving efficiency results of the 4 degree inclined road driving and the artificial grass road driving respectively. These results show the driving efficiency can be improved by the proposed fuzzy control system.

V. DISCUSSION

This study realized the assisted torque control of electric power-assisted wheelchairs for large disturbance road driving such as uphill roads and rough roads. The proposed system has the following advantages.

- The fuzzy rules 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.

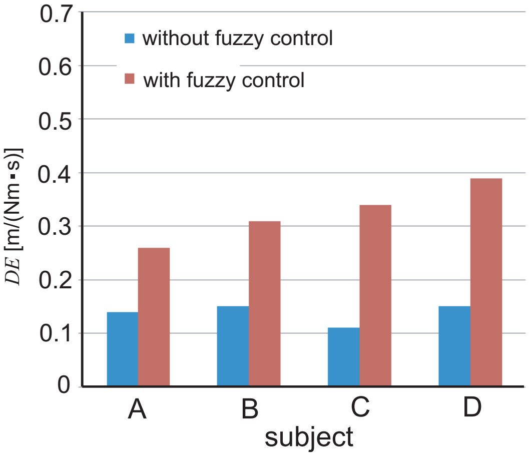


Fig. 20. Results of driving efficiency DE on the 4 degree inclined road.

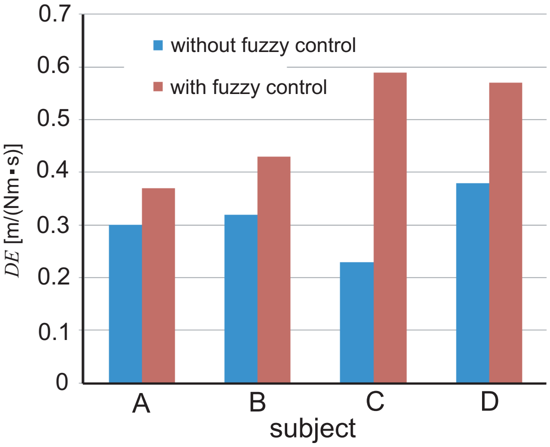


Fig. 21. Results of driving efficiency DE on the artificial grass road.

- The control purpose can be realized without the modeling of human-wheelchair system if the environmental disturbance and rider's weight are in the average range. The proposed system will also show the enough performance on other types of disturbance roads.

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.

- 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.
- Driving experiments were conducted by the proposed fuzzy algorithm with constant parameters in this study, however the automatic parameter adjustment according to users and driving situations should be developed. 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.
- The ride quality and safeness will have to be examined by many operators and disturbance roads.

VI. CONCLUSION

This paper proposed an adaptive driving control scheme of electric power-assisted wheelchairs based on fuzzy algorithm. The proposed system could improve the driving performance on large disturbance roads such as uphill roads and rough roads. 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 last chapter.

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