博士論文

Motion Control of a Power-Assisted Wheelchair and Implementation

- Human-friendly Control System to Improve Safety, Mobility and Ease of Use -

（パワーアシスト車椅子のモーションコントロールとその実用化
ー安全性・移動性・便宜性向上のための人間親和型制御システムー）

by

Kayoung Kim

（金　佳英）

A dissertation submitted to the
Department of Electrical Engineering and Information Systems
for the degree of
Doctor of Philosophy
at
The University of Tokyo

Supervisor:
Professor Yoichi Hori
Associate Professor Hiroshi Fujimoto

DEPARTMENT OF ELECTRICAL ENGINEERING AND INFORMATION SYSTEMS
THE UNIVERSITY OF TOKYO
DECEMBER 2014

Motion Control of a Power-Assisted Wheelchair and Implementation

- Human-friendly Control System to Improve Safety, Mobility and Ease of Use -

For my family and friends

ACKNOWLEDGEMENTS

Thank god for giving me every opportunity to do all of my work.

I would like to thank with the deepest of gratitude my loving family and good friends. Special thanks to Professor Hori, Professor Fujimoto and Professor Oh. They gave me good advise and encourage me to finish my work.

It was great to work with Mr. Uemura and Mr. Ito from YAMAHA. Thank you very much.

TABLE OF CONTENTS

LIST OF FIGURES

Figure

LIST OF TABLES

Table

LIST OF APPENDICES

Appendix

LIST OF ABBREVIATIONS

ABSTRACT

Motion Control of a Power-Assisted Wheelchair and Implementation
- Human-friendly Control System to Improve Safety, Mobility and Ease of Use -

by

Kayoung Kim

Supervisor: Prof. Yoichi Hori and Prof. Hiroshi Fujimoto

The wheelchair is an important device that offers a method of transport to mobility-impaired people. There are many kinds of wheelchairs being developed to minimize injury while improving the ease of maneuver. Power-assisted wheelchairs were developed for the same reason. The power-assisted wheelchair is an electric wheelchair that has a motor in each of the two main wheels and a torque sensor in each handrim. When the user pushes a handrim, the user's pushing force is measured by torsion sensor in that handrim. The motors will output assist torque, that which is calculated in the assistive control system. The power-assisted wheelchair lightens the physical burden on the user by providing assistance, while encourages maintenance of arm function as well as improvement of health and fitness through handrim use. Furthermore, it is possible to apply control system to power-assisted wheelchair. By controlling both motors appropriately, wheelchair functionality as well as performance factors such as safety, comfort, handling and mobility can be enhanced. In this thesis, human-friendly control systems - assistive control, yaw motion control and one-handed propulsion control - are proposed to improve safety, mobility, and ease of use.

First, a novel two-dimensional assistive control for power-assisted wheelchairs considering straight and rotational motion decomposition is proposed in this thesis. To improve assist performance, many assistive control systems were proposed. One of conventional assistive control,

proposed by Seki et al., is designed for motion of traveling in straight line. However, it is inconvenient to rotate using conventional assistive control. The proposed assistive control is designed for wheelchair both going straight and rotating. Assist rate and time constant of going straight and rotating, is able to adjust independently. Therefore, power assist performance in rotating motion is improved compared to conventional system.

Second, yaw motion control under lateral disturbance environments is proposed in this paper to improve safety and quality of life of wheelchair user. On lateral slope, lateral disturbances make the wheelchair's speed as well as direction unable to manage, which can cause accidents and may lead to injury. To overcome this problem, two-degree-of-freedom yaw motion control is proposed in this thesis. Using the proposed yaw motion control, a wheelchair would not be subject to influence from yaw directional disturbance, and hence overall performance of the wheelchair would improve. To demonstrate the effectiveness of the yaw motion control, two kinds of experiments have been performed: going straight on the slope, and turning on the slope. Effectiveness of the proposed control system has been verified by experiments.

Third, one-handed propulsion control system for a power-assisted wheelchair is proposed. For people also with hemiplegia or a hand/arm injury, a wheelchair operable with one hand is necessary. However, it is impossible to control a standard manual wheelchair or power-assist wheelchair with only one hand. The one-handed propulsion control system for a power-assisted wheelchair was proposed previously. Conventional one-handed propulsion control system allows the user to go straight, do pure rotations, and turn while running. However, turning movement is different from general turning movement of wheelchair in conventional system. Wheelchair user feels a sense of incompatibility with conventional control system. In this thesis, an improved one-handed propulsion system that realizes advanced turning motion is proposed. Advanced turning motion is focused in two-handed propulsion wheelchair. Analysis result of human torque in two-handed propulsion is applied to turning motion in one-handed propulsion control system.

Last, implementation of proposed control systems is introduced in this thesis. There are difficulties to apply novel control system to daily use welfare device. There are many academic researches on welfare devices, however, not all of them interact with user of welfare devices. Gap between valuable academic research and daily use technology is one of difficulties in practical

application. Another difficulty comes from the cost of the device. It will be hard to use devices, if the cost of the device is expensive, even the device is helpful. Good devices, such as sensors with high resolution, are expensive. In this research, a new wheelchair system is constituted for practical application. Proposed assistive control, yaw motion control and one-handed propulsion control are applied to the new wheelchair system. To lower the cost, yaw motion control using encoder instead of gyroscope is considered. Effectiveness of the implementation has verified by subject experiments of yaw motion control and one-handed propulsion control. Three group of people - advanced wheelchair users, beginners, and researchers - participated experiments and answered the questionnaire.

CHAPTER I

Introduction

1.1 Importance of Welfare Research

According to World Health Survey, more than a billion people are estimated to have some form of disability. It is about 15% of the world's population. Population with disabilities is growing due to increasing of ageing population, as older people have a higher risk of disability.

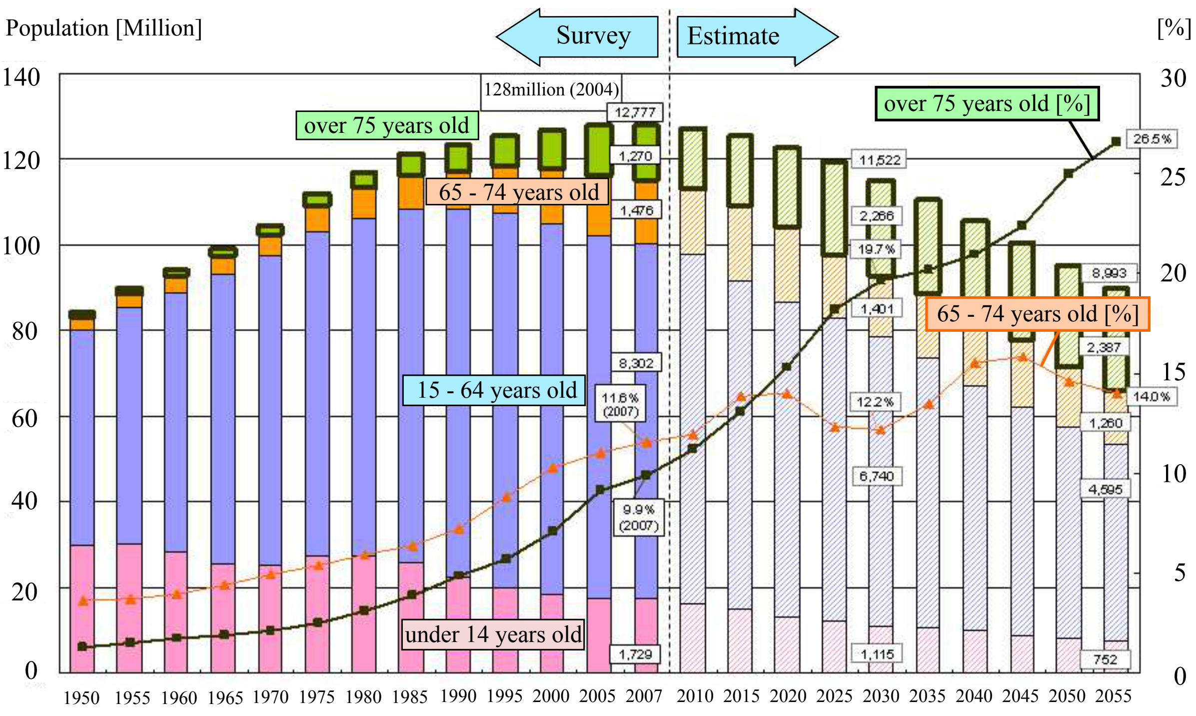


Figure 1.1: Population of elder people in Japan (Ministry of health, labour and welfare 2009)

Increasing of ageing population become critical problem in Japan. Figure 1.1 shows population of elder people in Japan. It is predicted that elder population of Japan will be more than 30% in 2020.

1.2 Overview of Previous Wheelchair Research

Mobility-impaired people need assistive devices for movement. There are many welfare devices which offer mobility-impaired people method of transport. Recently, exoskeletons have been developed as one such device, and there are many researches that focus on development and improvement of exoskeletons (*Dollar and Herr*, 2008),(*Strickland*, 2012),(*Ugurlu et al.*, 2012). However, wheelchairs are still one of the most commonly used welfare device world-wide. As many different types of wheelchairs have been developed, wheelchair users are able to select a suitable wheelchair for their needs.

The main purposes of wheelchair research are to improve safety of the wheelchair. There is research that focus on safety driving on the slope. Overspeed on downhill is one of the most fearful situation for wheelchair users. To overcome overspeed problem braking control using regenerative braking system is proposed(*Seki et al.*, 2009). The proposed system prevents speed-up problem on downhill and saves energy.

Furturemore, a control system was proposed to prevent tip-over problem (*Oh et al.*, 2008b). Excessive assist will cause tip-over, which may lead to a severe accident. Oh et al. analyze velocity and acceleration in pitch direction. They figure out the relation between tip-over and velocity and acceleration in pitch direction, and define "proper safety zone", "semi-safety zone", and "dangerous zone", regarding tip-over. By reducing assist rate in dangerous zone, it is possible to prevent tip-over. Oh et al. also propose longitudinal and lateral disturbance observer. It is difficult to control the wheelchair in environment with disturbance. By using the proposed control system, the usage of wheelchair is safer in both downhill and lateral slope as the control system removes longitudinal and lateral disturbance.

Stairs are one of the most troublesome situation by using wheelchair. To climb the stairs, new structure wheelchair were proposed, such as wheelchairs that have wheel clusters with actuator (*Lawn and Ishimatsu*, 2003), or rolling multi-wheeled wheelchair (*Cooper et al.*, 2006b). There are researches which are not suitable for stairs but make it possible to climb a step. Casters, in front wheel, are the reason that make wheelchair impossible to climb up the step. Some researches were focusing to remove effect of casters by making wheelchair wheelie (*Takahashi et al.*, 1999),(*Seki et al.*, 2006a).

Some of the researches are focused on caregiver. In aging society, caregiver of the wheelchair user become elder people, such as husband/wife of the wheelchair user. Therefore, it is necessary to assist not only the wheelchair user, but also the caregiver. Power assistive control of electric wheelchair for a caregiver is proposed (*Miyata et al.*, 2008). The proposed system is applied to a inverted-pendulum-controlled two wheeled wheelchair, which does not have casters. Same research group also focused step climbing. They suggest step climbing control for caregiver to decrease burden of caregiver when climbing the step (*Hirata and Murakami*, 2006), (*Tashiro and Murakami*, 2008).

To enhance manipulation performance, many new controller is proposed, such as controller that uses tongue (*Nam et al.*, 2012) or EEG (*Tanaka et al.*, 2005), (*Rebsamen et al.*, 2010), (*Bi et al.*, 2013). Usually movement of tongue is not affected by cory injury and response of tongue is fast enough to make input signal of wheelchair movement as it has special muscle. Therefore, Nam et al. choose movement of tongue to control the wheelchair (*Nam et al.*, 2012). They control the wheelchair with EEG code which is affected by movement of tongue. Tanaka et al. first developed a brain-controlled robotic wheelchair (*Tanaka et al.*, 2005). Their left or right turning movements are directly controlled by corresponding motion commands translated from user brain signals while imagining left or right limb movements, and tested this system in real-world situations.

There are also researches about dynamic of wheelchair or user's movement on wheelchair. Chénier et al. analyze wheelchair dynamics with casters, front wheels of wheelchair. Usually, casters were neglected in other researches, however, if the front part of the wheelchair become heavy by movement of user or by environment, caster part is no longer negligible. They consider dynamics with casters, which allow analysis for more variety of wheelchair movement. Desroches et al. analysis human movement on wheelchair (*Chenier et al.*, 2011). They analyze load on joint when human uses manual wheechair. Tanimoto et al. analyze transfer motion (*Tanimoto et al.*, 2008).

1.3 Motivation

The purpose of this research is to realize wheelchair which is safer, easier of manipulate and better mobility than existing wheelchairs. Furthermore, this research is to make wheelchair users to realize high quality of life. In this paper, three novel control systems are proposed. First, an assistive control system is proposed to improve manipulation performance of power-assisted wheelchair. The proposed assistive control system is designed for both straight and rotational motion of wheelchair, therefore, power assist performance in rotating motion is improved compared to conventional system.

Second, a yaw motion control system is proposed. Lateral disturbances make the wheelchair's speed as well as direction unable to manage, which can cause accidents leading to injury. To overcome this problem, a yaw motion control system of power-assisted wheelchairs is proposed. Using proposed yaw motion control, a wheelchair would not be subjected to influence from lateral disturbance, and hence overall performance of the wheelchair would improve. To demonstrate the effectiveness of the yaw motion control, two kinds of experiments have been performed: going straight on the slope, and turning on the slope. Effectiveness of the proposed control system has been verified by experiments.

Third, an one-handed propulsion control system is proposed. It is impossible to control a standard manual wheelchair or power-assist wheelchair with only one hand. An one-handed propulsion control system for a power-assisted wheelchair that allows the user to go straight and do pure rotations was proposed previously, but this system didn't allow the user to turn the wheelchair while moving. In this paper, an improved one-handed propulsion system including advanced turning mode is proposed.

1.4 Thesis Outline

Figure 1.2 shows thesis outline. In chapter II, experimental device, power-assisted wheelchair, will be introduced. Two-dimensional assistive control considering straight and rotational motion decomposition is proposed in chapter III. In chapter IV, yaw motion control for improvement of handling on slopes is proposed. Proposed One-handed propulsion control with straight, pure rotation and advanced turning mode is introduced in chapter V. Implementation of proposed control system are introduced in chapter VI. At last, conclusion of this paper and future work for this research will be shown in chapter VII.

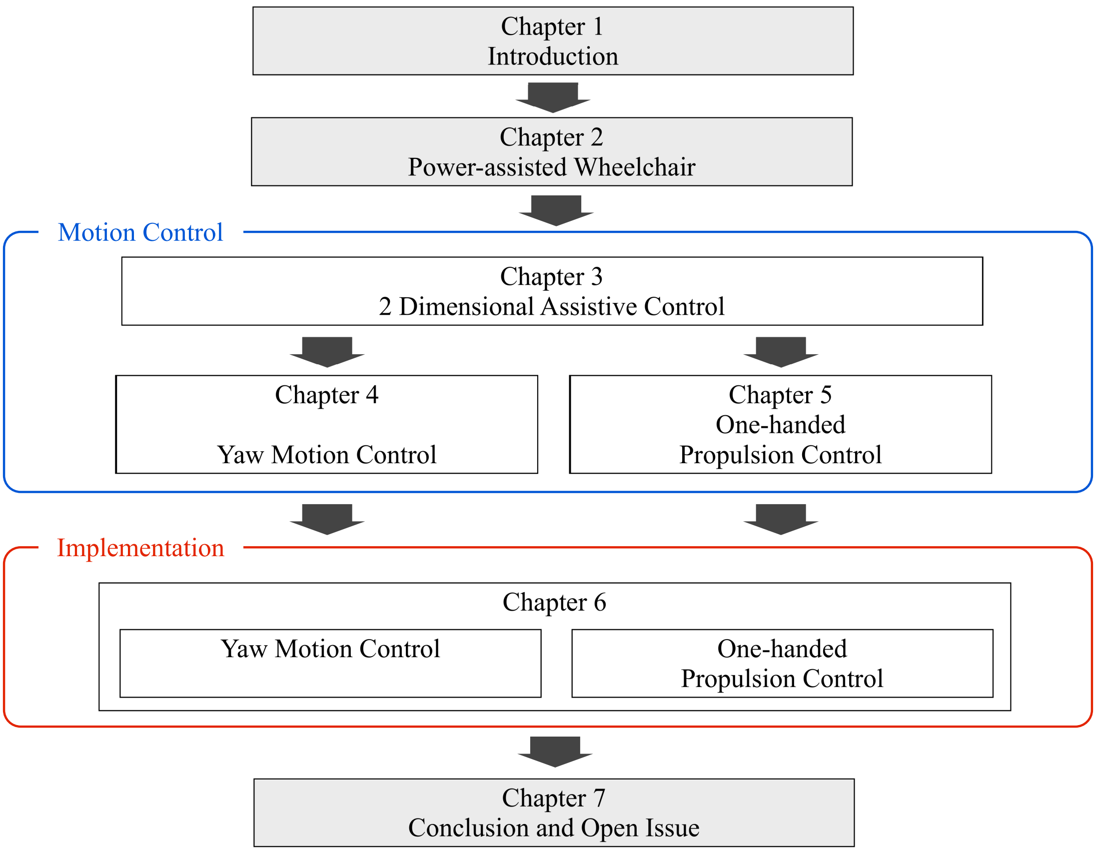


Figure 1.2: Thesis outline

CHAPTER II

Power-Assisted Wheelchair

2.1 What is Power-Assisted Wheelchair?

The power-assisted wheelchair is an electric wheelchair that has a motor in each of the two main wheels and a torque sensor in each handrim. The power-assisted wheelchair has been developed and researched (*Cooper et al.*, 1999), (*Cooper et al.*, 2002a).

Figure 2.1 shows the concept of the power-assisted wheelchair. When the user pushes a handrim, the user's pushing force is measured by torsion sensor in that handrim. The motors will output assist torque, that which is calculated in the assistive control system. The power-assisted wheelchair lightens the physical burden on the user by providing assistance, while encourages maintenance of arm function as well as improvement of health and fitness through handrim use. Furthermore, by controlling both motors appropriately, wheelchair functionality as well as

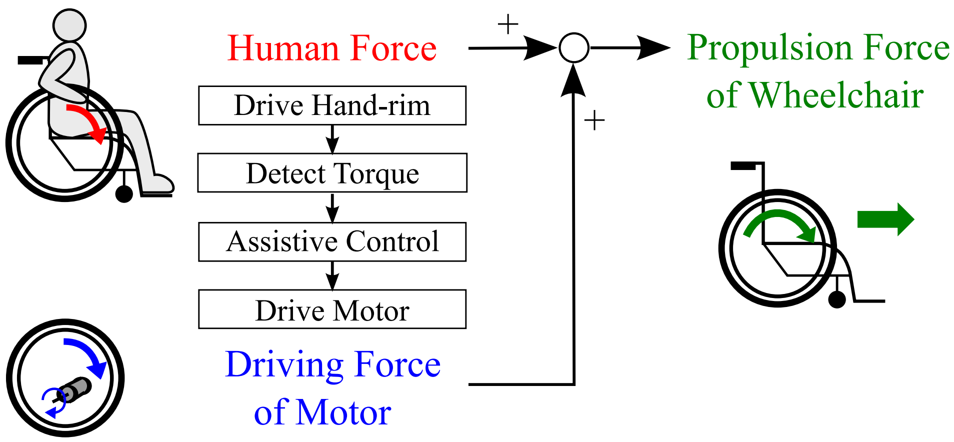


Figure 2.1: Concept of power-assisted wheelchair

performance factors such as safety, comfort, handling and mobility can be enhanced.

2.2 Merit and Demerit of Power-assisted Wheelchair

The power-assisted wheelchair has the advantages below,

- less burden on the user compared with the manual wheelchair
- required the user to push the handrims, which becomes exercise
- easy to apply control systems
- lightweight compared to most fully-electric wheelchairs
- suitable frame can be choosen by oneself

2.3 Design a New Wheelchair System to Apply Control System

A new wheelchair system to apply control system is designed. A power-assisted wheelchair JW-II is used in experiments. Figure 2.2 shows the power-assisted wheelchair JW-II. JW-II has built-in torque sensors and motors DC motors in both side of wheel units. Sensors, such as

Figure 2.2: Power-assisted wheelchair *(Yamaha JW-II)*

Table 2.1: Information of experimental devices and sensors

		Model number	Manufacturer
Power-assisted wheelchair		JW-II	YAMAHA
DC motor			
Torque sensor			
Digital signal processor		s-BOX	mtt Corporation
Gyroscope	Yaw direction	CRS03-01R	SILICON SENSING
	Pitch direction	HS-EG3 TSUKASA 21	S.T.L. Japan
3-axis analog accelerometer		KXM52-1050	Kionix
Optical encoders		RE20F-100-200	COPAL ELECTRONICS
Micro computer		AKI-H8-3052F	Akitsuki densi

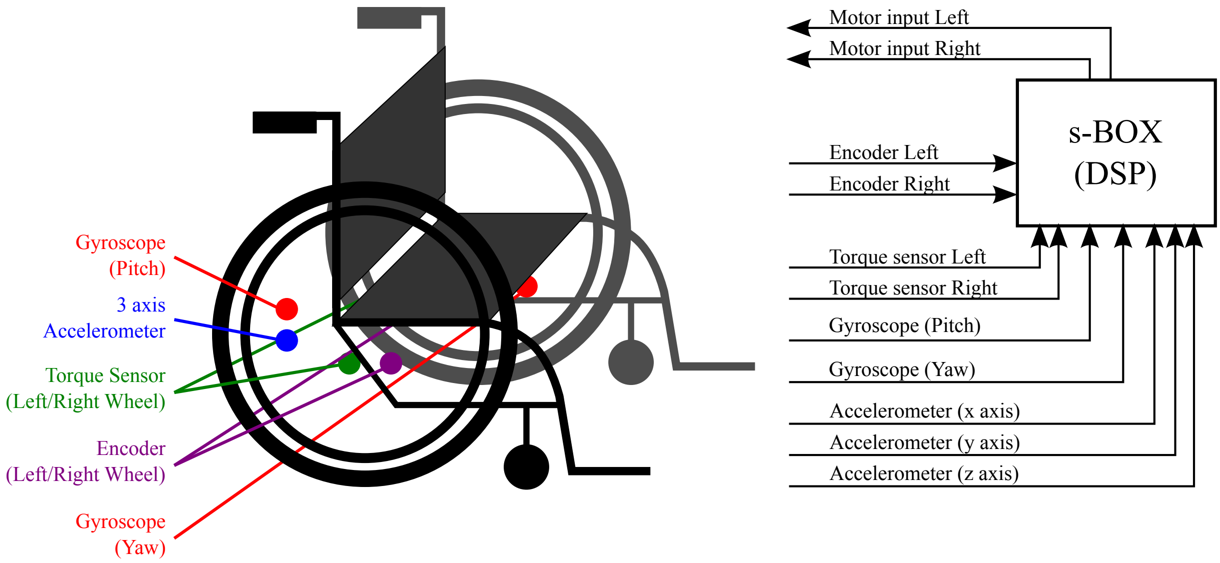


Figure 2.3: Schematic of hardware system of experimental power-assisted wheelchair

encoders, accelerometer and gyroscope are mounted additionally. Table 2.1 shows device and sensor information of the new system. Figure 2.3 shows the schematic of hardware system of experimental power-assisted wheelchair. Hardware information of experimental power-assisted wheelchair is shown in Fig. 2.4.

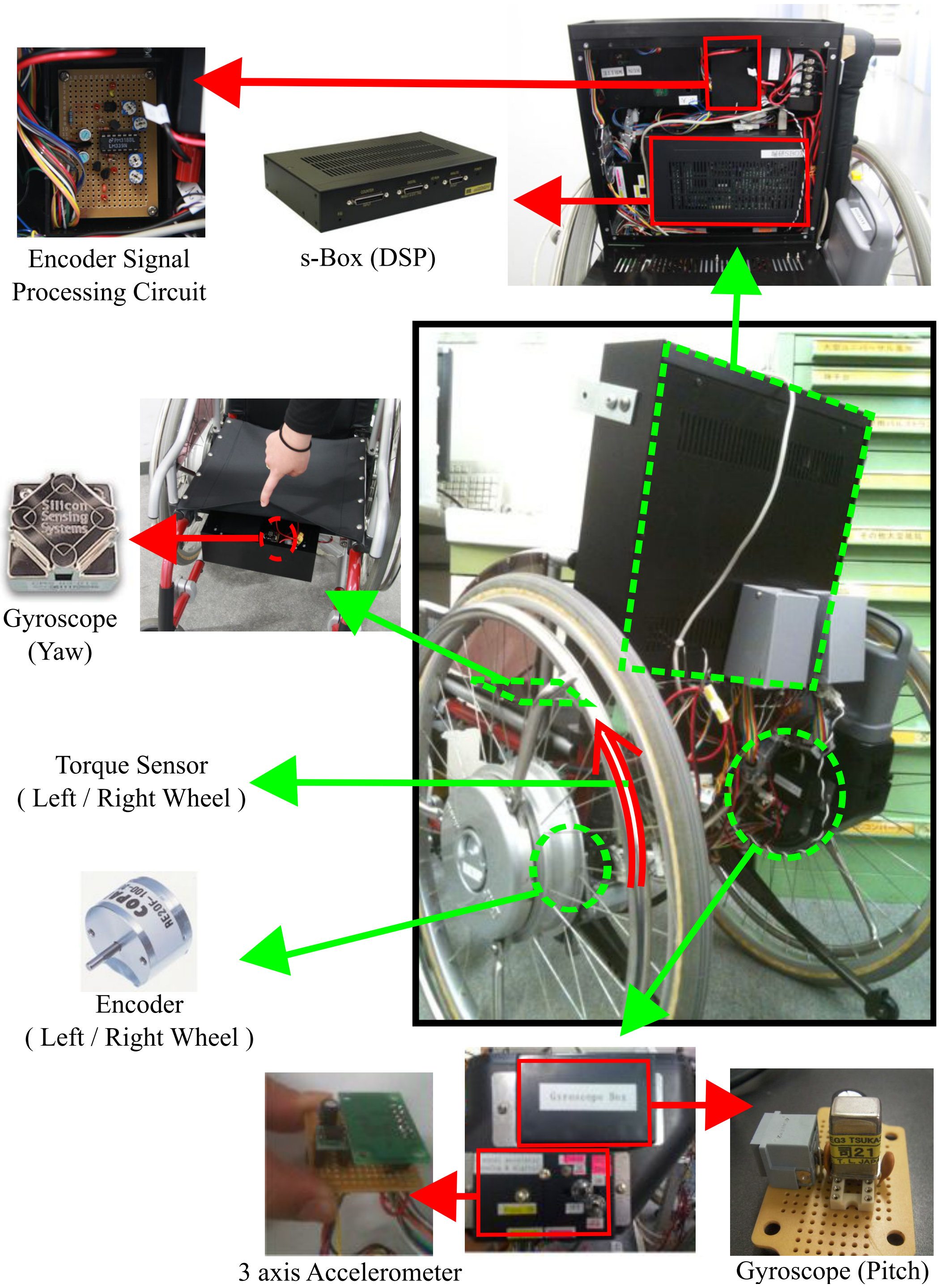


Figure 2.4: Hardware information of experimental power-assisted wheelchair

CHAPTER III

Two-dimensional Assistive Control considering Straight and Rotational Motion Decomposition

3.1 Introduction

Assistive control is the most basic control system in power-assisted wheelchair. The proposed assistive control system is designed for both straight and rotational motion of wheelchair, therefore, power assist performance in rotating motion is improved compared to conventional system.

3.2 Conventional Assistive Control Systems

Assistive control exerts an important role in improving performance of maneuver of power-assisted wheelchair. Assistive control makes users feel more comfortable, however, sometimes it lead to other inconvenience, which is a trade-off. To minimize such inconvenience, many assistive control had been proposed.

Simple proportional assistive control causes sharp decrease in assist torque. Therefore, Cooper et al. propose a modified proportional assistive control to prevent signal from becoming zero rapidly (*Cooper et al.*, 2002a). Figure 3.1 shows human torque and assist torque of previous modified proportional assistive control system. ϵ is dead zone to avoid effect of noise on sensor signal.

Seki et al. propose an assistive control system for power-assisted wheelchair considering straight motion (*Seki et al.*, 2004). Figure 3.2 shows human torque and assist torque of previous

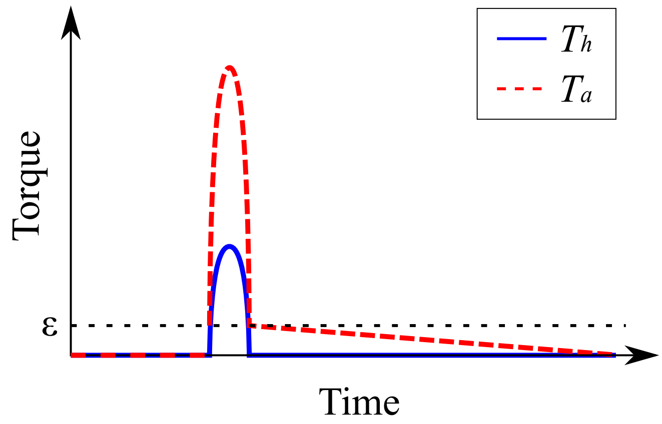


Figure 3.1: Human torque and assist torque of previous modified proportional assistive control system (*Cooper et al.*, 2002a)

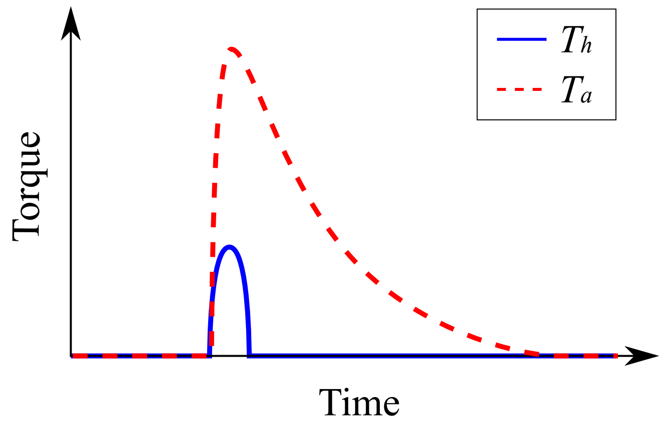


Figure 3.2: Human torque and assist torque of previous assistive control system considering straight motion (*Seki et al.*, 2004)

assistive control system considering straight motion. In this section, one of the previous assistive control proposed by Seki et al will be introduced.

Figure 3.3 shows a block diagram of previous assistive control system. T_{hL} and T_{hR} are user's propelling torque of left and right side, and T_{aL} and T_{aR} are motor's output torque of left and right side. Total torque of left side T_{tL} and right sideT_{tR} are defined as follows:

$$T_{tL} = T_{hL} + T_{aL} = T_{hL} \times \left(1 + \frac{\alpha}{\tau_a s + 1}\right) \tag{3.1}$$

$$T_{tR} = T_{hR} + T_{aR} = T_{hR} \times \left(1 + \frac{\alpha}{\tau_a s + 1}\right) \tag{3.2}$$

where α is assist rate and τ_a is time constant.

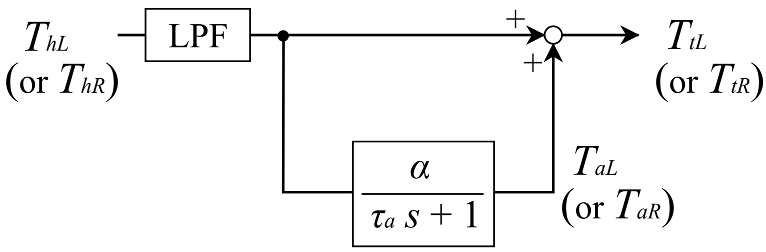


Figure 3.3: Block diagram of previous assistive control system considering straight motion

Time constant τ_a is defined as follows:

$$\tau_a = \begin{cases} \tau_{fast} & \left(\dfrac{d|T_h|}{dt} \geq 0\right) \\ \tau_{slow} & \left(\dfrac{d|T_h|}{dt} < 0\right) \end{cases} \tag{3.3}$$

where T_h represents T_{hL} or T_{hR}, which is human's propelling torque.

Time response of assistive control is affected by value of time constant τ_a. When user propels the wheelchair, immediate assist is desirable. By choosing small τ_a, motor will assist user's propelling torque immediately. Therefore, small value τ_{fast} should be used when $\frac{d|T_h|}{dt} \geq 0$. However, with small τ_a, motor's assist torque will reduce sharply when user takes off his/her hand from hand-rim. When going straight, it is impossible to propel the wheelchair continuously, and it is desirable to output assist torque by motor in no human input zone. In other word, big τ_{slow} should be chosen when $\frac{d|T_h|}{dt} \geq 0$.

Once user pushes the hand-rims, he/she should take off his/her hands from hand-rims to push it again. When user propels the wheelchair to go stright, propelling process is as follows,

[Period 1] : grab the hand-rims and push them

[Period 2] : take off his/her hand from hand-rims

[Period 3] : grab the hand-rims again

Length of the time in [Period 2] is defined as t_{off}, which is the time user takes off his/her hand from hand-rim. To design a system which keeps assisting during [Period 2], τ_{slow} which is larger than t_{off} should be chosen. By doing so, motors will keep assisting user's propelling

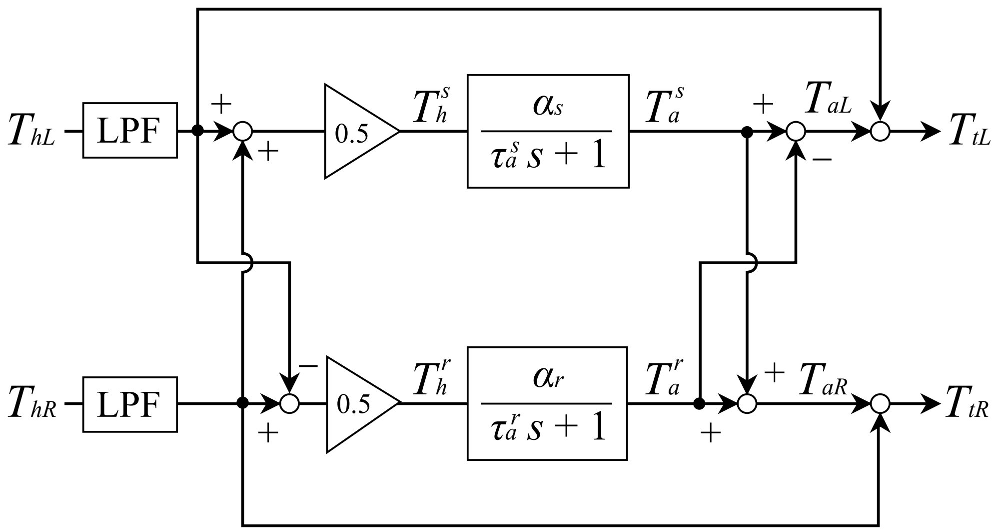


Figure 3.4: Block diagram of proposed assistive control for straight and rotational motion

torque during [Period 2]. Therefore,

$$\tau_{slow} > t_{off}. \tag{3.4}$$

As mentioned above, by choosing appropriate assist rate α and time constant τ_α, this assistive control can be set to assist immediately or keep assisting when it is required. By designing τ_{slow} to be $\tau_{slow} > t_{off}$, wheelchair will keep going straight even though user take off his/her hand from it. In other word, this assistive control will help reduce user's load.

However, once user forces wheelchair to turn, it will keep turning with this τ_{slow}. Turning motion is different from straight motion. When going straight, user desires to keep going straight, however, it is hard to find situation that requires wheelchair to keep turning in daily life. Considering turning motion, τ_{slow} should become smaller, which would not make wheelchair keep turning; however, suitable τ_{slow} for turning motion is too small for straight motion, Small τ_{slow} will not assist properly when going straight. Therefore, using same τ_{slow} is unsuited for power-assisted wheelchair.

3.3 Torque Decomposition of Straight and Rotational Motion

Movement of wheelchairs are combination of straight motion and rotational motion.

Define T_L and T_R as torque of left and right wheel. As T_L^s and T_R^s are torque which are belong to straight motion, and T_L^r and T_R^r are torque which is belong to rotational motion, T_L and T_R are defined as follows:

$$T_L = T_L^s + T_L^r \tag{3.5}$$

$$T_R = T_R^s + T_R^r \tag{3.6}$$

In straight motion, magnitude and direction of left and right torque are the same, and in rotational motion, direction of left and right is reverse.

$$T_L^s = T_R^s \tag{3.7}$$

$$T_L^r = -T_R^r \tag{3.8}$$

From equation (3.6) to equation (3.8), T_R can also be expressed as follows:

$$T_R = T_L^s - T_L^r \tag{3.9}$$

Therefore,

$$T_L^s = T_R^s = \frac{T_L + T_R}{2} \tag{3.10}$$

$$T_L^r = -T_R^r = \frac{T_L - T_R}{2} \tag{3.11}$$

Also, as $T^s = T_R^s$ and $T^r = T_R^r$, equation (3.5) and equation (3.6) become

$$T_L = T^s - T^r \tag{3.12}$$

$$T_R = T^s + T^r \tag{3.13}$$

3.4 Two-dimensional Assistive Control System

As mentioned in section 3.2, it is difficult to assist straight motion and rotational motion using previous assistive control system. To solve this problem, a new two-dimentional assistive control, which assist straight and rotational motion independently, will be proposed in this section.

Every movement is combination of straight and rotational motion. Sum of left and right torque belongs to straight motion, and difference of left and right torque belongs to rotational motion. Figure 3.4 shows new assistive control. α_s and α_r are assist rate for straight and rotational motion, and τ_a^s and τ_a^r are time constant for straight and rotational motion.

With the same nature as equation (3.10) and (3.11), T_h^s and T_h^r are defined as follows:

$$T_h^s = \frac{T_{hL} + T_{hR}}{2} \tag{3.14}$$

$$T_h^r = -\frac{T_{hL} - T_{hR}}{2} \tag{3.15}$$

Similarly, based on equation (3.12) and (3.13), assist torque of left and right side T_{aL} and T_{aR} are

$$T_{aL} = T_a^s - T_a^r = \frac{\alpha_s}{\tau_a^s s + 1} T_h^s - \frac{\alpha_r}{\tau_a^r s + 1} T_h^r \tag{3.16}$$

$$T_{aR} = T_a^s + T_a^r = \frac{\alpha_s}{\tau_a^s s + 1} T_h^s + \frac{\alpha_r}{\tau_a^r s + 1} T_h^r \tag{3.17}$$

From equation (3.14) to equation (3.17),

$$T_{aL} = \frac{1}{2} T_{hL} \left(\frac{\alpha_s}{\tau_a^s s + 1} + \frac{\alpha_r}{\tau_a^r s + 1} \right) + \frac{1}{2} T_{hR} \left(\frac{\alpha_s}{\tau_a^s s + 1} - \frac{\alpha_r}{\tau_a^r s + 1} \right) \tag{3.18}$$

$$T_{aR} = \frac{1}{2} T_{hL} \left(\frac{\alpha_s}{\tau_a^s s + 1} - \frac{\alpha_r}{\tau_a^r s + 1} \right) + \frac{1}{2} T_{hR} \left(\frac{\alpha_s}{\tau_a^s s + 1} + \frac{\alpha_r}{\tau_a^r s + 1} \right) \tag{3.19}$$

Therefore, total torque of the left side T_{tL} and of the right side T_{tR}, are defined as follows:

$$
\begin{aligned}
T_{tL} &= T_{hL} + T_{aL} = T_{hL} + (T_a^s - T_a^r) && (3.20)\\
&= T_{hL} + \frac{1}{2}T_{hL}\left(\frac{\alpha_s}{\tau_a^s s+1} + \frac{\alpha_r}{\tau_a^r s+1}\right) + \frac{1}{2}T_{hR}\left(\frac{\alpha_s}{\tau_a^s s+1} - \frac{\alpha_r}{\tau_a^r s+1}\right) && (3.21)\\
T_{tR} &= T_{hR} + T_{aR} = T_{hR} + (T_a^s + T_a^r) && (3.22)\\
&= T_{hR} + \frac{1}{2}T_{hL}\left(\frac{\alpha_s}{\tau_a^s s+1} - \frac{\alpha_r}{\tau_a^r s+1}\right) + \frac{1}{2}T_{hR}\left(\frac{\alpha_s}{\tau_a^s s+1} + \frac{\alpha_r}{\tau_a^r s+1}\right) && (3.23)
\end{aligned}
$$

τ_a^s and τ_a^r are defined as follows:

$$
\tau_a^s = \begin{cases} \tau_{fast}^s & \left(\frac{d|T_h^s|}{dt} \geq 0\right) \\ \tau_{slow}^s & \left(\frac{d|T_h^s|}{dt} < 0\right) \end{cases} \tag{3.24}
$$

$$
\tau_a^r = \begin{cases} \tau_{fast}^r & \left(\frac{d|T_h^r|}{dt} \geq 0\right) \\ \tau_{slow}^r & \left(\frac{d|T_h^r|}{dt} < 0\right) \end{cases} \tag{3.25}
$$

, where $\tau_{fast}^s < \tau_{slow}^s$, $\tau_{fast}^r < \tau_{slow}^r$, and $\tau_{slow}^s > \tau_{slow}^r$.

As mentioned above, it is difficult to find suitable time constant τ_{slow} in previous assistive control system, however, two-dimentional assistive control system solve this problem using sum and difference of left and right torque. By deciding time constant of straight motion τ_{slow}^s and rotational motion τ_{slow}^r, new system is able to control straight and rotational motion independently.

3.5 Comparison Experiments of Conventional and Proposed Assistive Control System

3.5.1 Experimental Environments

Experiments were performed to compare previous and proposed assistive control system for straight and rotational motion. In experiments, user pushes both hand-rims with same force in

Table 3.1: Parameters used in experiments

Previous assistive control system			
assist rate	α		2.5
time constant	τ_a	τ_{fast}	0.08 s
		τ_{slow}	4.0 s
Proposed assistive control system			
assist rate (straight)	α_s		2.5
time constant (straight)	τ_a^s	τ_{fast}^s	0.08 s
		τ_{slow}^s	4.0 s
assist rate (rotation)	α_r		2.5
time constant (rotation)	τ_a^r	τ_{fast}^r	0.08 s
		τ_{slow}^r	1.0 s

the same direction to go straight, and then pushes hand-rims in opposite direction to rotate. In rotational motion, user push the hand-rim frequently so that difference between left and right torque become sine wave. For fair comparison same input, human's propelling torque, is applied to both assistive control systems, and compare characteristic of them. Assist torque of left side T_{aL} and right side T_{aR} is given for left and right motor input.

User's propelling torque of left and right, T_{hL} and T_{hR}, are measured by torsion sensors embedded in each hand-rim of JW-II.

Table 5.1 shows parameters used in these experiments. Purpose of these experiments is to confirm the influence of time constant of rotational motion τ_{slow}^r, and verifying independence of assist system straight and rotational motion. These parameters are decided empirically.

3.5.2 Results of comparison experiment of previous and proposed assistive control system

Figure 3.5 and figure 3.6 show the experimental results. User pushes the hand-rims to go straight during $t = 0$ to 20 s, and pushes the hand-rims to rotate during $t = 20$ to 40 s.

Figure 3.5 is the experimental result of previous assistive control system. In straight motion zone, assist torque increases immediately when human torque is increasing. However, assist

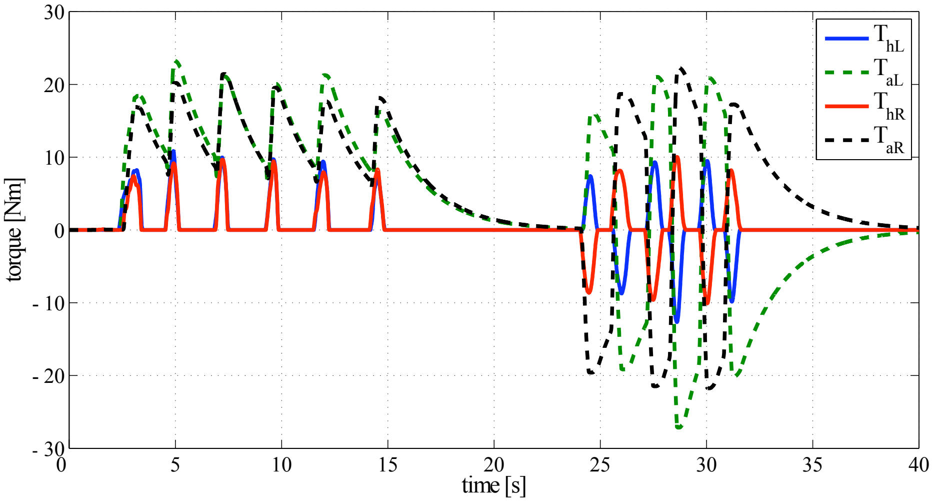


Figure 3.5: Experimental result of previous assistive control system

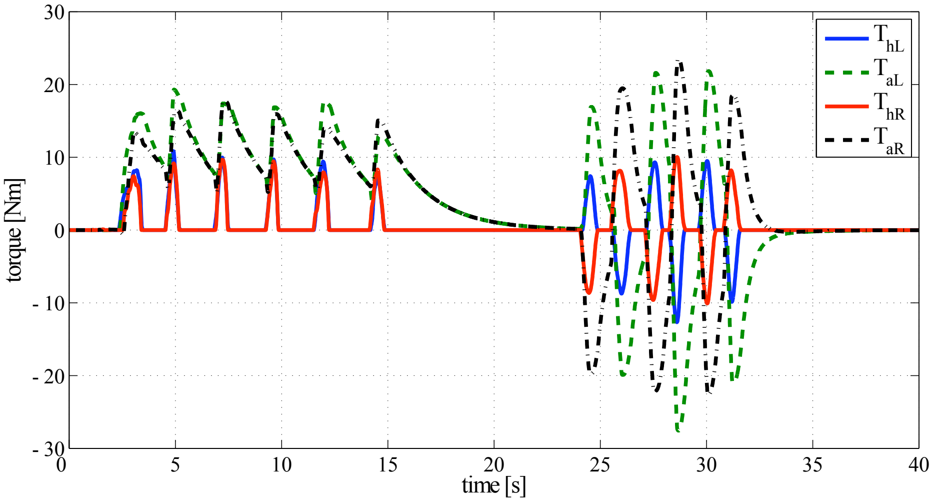


Figure 3.6: Experimental result of proposed assistive control system

torque decreases slowly, when human torque is decreasing, and it keeps assisting until human propels the wheelchair again. In rotational motion zone, assist torque have the same tendency as straight motion zone. It is increasing immediately and decreasing slowly. It is clear that assist torque for straight and rotational motion of previous system have the same tendency, which keep assisting, from period $t = 15$ to 23 s and $t = 31.5$ to 39.5 s.

Figure 3.6 is the experimental result of the proposed assistive control system. In straight motion zone, assist torque is performing as previous system. It assists immediately when user starts to push the wheelchair and keeps assisting even though user's propelling torque is decreasing. In rotational motion zone, assist torque increases immediately when user starts to push the wheelchair, however, it decreases faster than that of straight motion. It is clear that assist torque for straight and rotational motion of proposed system have different tendency, from $t = 15$ to 23 s and $t = 31.5$ to 39.5 s. Assist torque converges to zero faster in rotational motion than straight motion.

Comparing assist torque in straight motion zone of the proposed system with previous one, amplitude of assist torque in the previous system is larger than the proposed one, however, they have the same tendency of increasing and decreasing. In rotational zone, difference between previous and the proposed system is remarkable. Changing rate of assist torque in previous system is slower than the proposed system, due to the existence of the remaining assist torque of last user's propelling torque. Therefore, the result shows that the proposed system is effective in reducing the continuation of rotational motion.

3.5.3 Discussion

As mentioned in section 3.3, rotational motion is different from straight motion. When user tries to go straight, longer assist will help user move easier, as straight motion often requires continuing input. However, longer assist is not needed in rotation, because it is hard to find the situation that requires wheelchair to keep turning. Therefore, it is necessary to make a system which is able to control straight motion and rotational motion independently.

In experimental results from section 3.5.2, the proposed system's assist torque has the same tendency with previous system in straight motion, but has difference tendency in rotational motion. In other word, it is possible to keep assisting in straight motion to make it easy to go straight, and prevent wheelchair from keeping turning in rotational motion. From figure 3.6, it is verified that it is possible to control assist torque separately in the proposed system. In straight motion, the system keeps assisting from t =14.5 to 23 s and it is shorter in rotational motion from t =31 to 33 s.

3.6 Chapter Summary

In this chapter, a new two-dimensional assistive control system for power-assisted wheelchair is proposed.

In conventional assistive control system, it is difficult to design the controller which is suitable for both straight and rotational motion. To control straight and rotational motion separately, a novel two-dimensional assistive control system is proposed. Experiments verified the validity of the proposed system.

In the experiment, there were some reduction of amplitude in straight motion, which means straight and rotational motion is not entirely independent. Therefore, for future work, improvement of independency is required.

This novel two-dimensional assistive control is able to apply to other control systems. It is expected to improve performance by integrating the proposed assistive control into other control systems.

CHAPTER IV

Yaw Motion Control for Improvement of Handling on Slopes

4.1 Introduction

Lateral disturbances make the wheelchair's speed as well as direction unable to manage, which can cause accidents leading to injury. To overcome this problem, a yaw motion control system of power-assisted wheelchairs is proposed. Using proposed yaw motion control, a wheelchair would not be subjected to influence from lateral disturbance, and hence overall performance of the wheelchair would improve. To demonstrate the effectiveness of the yaw motion control, two kinds of experiments have been performed: going straight on the slope, and turning on the slope. Effectiveness of the proposed control system has been verified by experiments.

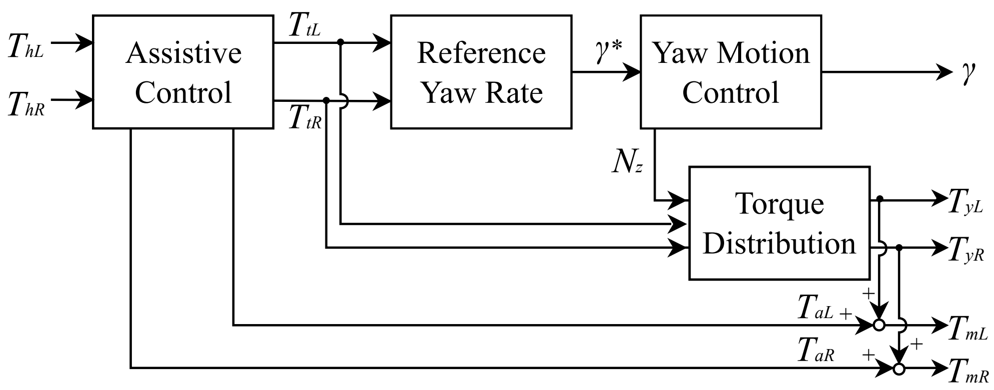


Figure 4.1: Block diagram of whole system of yaw motion control

4.2 Wheelchair Dynamics of Yaw Motion

A yaw plane model is introduced in this section. Figure 4.2 shows yaw plane representation. Yawing motion equation is given by

$$I\dot{\gamma} = l_f(F^x_{fl}sin\delta_L + F^x_{fr}sin\delta_R + F^y_{fl}cos\delta_L + F^y_{fr}cos\delta_R) - l_r(F^y_{rl} + F^y_{rr}) + N_z \tag{4.1}$$

, where I is the inertia of yaw moment, γ is the yaw rate, $F_{fl}(,F_{fr})$ is the force that applied to front left(,right) wheelchair, $F_{rl}(,F_{rr})$ is the force that applied to rear left(,right) wheelchair.

The yaw moment N_z is

$$N_z = \frac{d}{2}(F^x_{rr} - F^x_{rl}) + \frac{d_c}{2}(F^x_{fr}\ cos\delta_R - F^x_{fl}\ cos\delta_L). \tag{4.2}$$

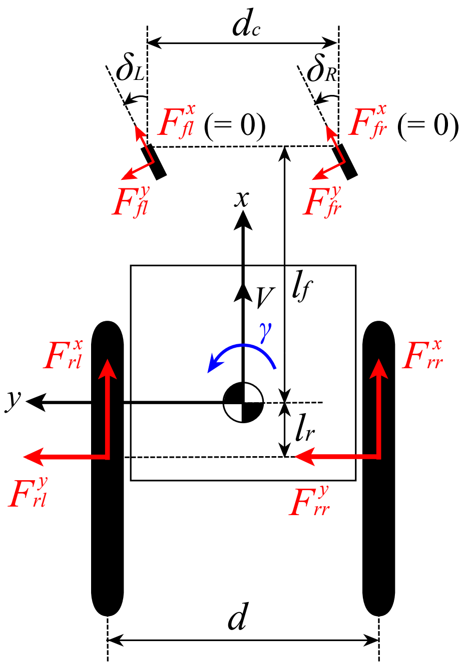


Figure 4.2: Schematics of wheelchair in yaw direction (Top view)

Assumptions in dynamics of wheelchair in yaw direction are follows,

- It is only affected to rear wheels that driving force of motor and wheelchair user. Therefore, driving force of front wheel is 0.

$$F^x_{fl} = F^x_{fr} = 0$$

- There are no lateral force lies on tire.

$$F^y_{fl} = F^y_{fr} = F^y_{rl} = F^y_{rr} = 0$$

- It is differential torque of rear wheel which causes cornering.

By assumption, equation (4.1) and (4.2) will be simplified as

$$I\dot{\gamma} = N_z \tag{4.3}$$

$$N_z = \frac{d}{2}(F^x_{rr} - F^x_{rl}). \tag{4.4}$$

4.3 Reference Yaw Moment N_z^*

Reference yaw moment is generate from torque difference between left and right hand side. From (4.4), reference yaw moment is defined as follows:

$$N_z^* = \frac{d}{2}\left(F_R - F_L\right) \tag{4.5}$$

where F_L and F_R are forces applied to left and right wheels, and d is width of the wheelchair.

Assuming that there is no slip between the wheel and surface, the torques exerted by the user on the hand rims will translate to wheelchair propulsion forces. In this case, equation (4.5) is redefined as follows:

$$N_z^* = \frac{d}{2}\frac{T_R - T_L}{r} \tag{4.6}$$

where T_L and T_R are torques applied to left and right wheels. T_L and T_R are user's propulsion torque of left and right wheel (T_{hL} and T_{hR}), measured by hand rim torsion sensor of each side. r is radius of the wheel respectively.

4.4 Yaw Motion Control System using Yaw Moment Observer

Figure 4.3 shows a block diagram of the proposed yaw motion control system. Yaw dynamics is formulated as follows:

$$I\dot{\gamma} = N_z + N_d \tag{4.7}$$

, where I is the inertia of yaw moment, N_z is the yaw moment generated by the difference between user's left and right propulsion torque, and N_d is the yaw moment generated by disturbances. The nominalized system can be expressed as follows:

$$\gamma = \frac{1}{I_n s} N_z \tag{4.8}$$

A two-degree-of-freedom control system, composed of feed forward control, feedback control, and a yaw moment observer (YMO) (*Fujimoto et al.*, 2004), will be proposed in this section to reduce effect of disturbance.

The gyroscope measures only yaw direction and not longitudinal direction, and the proposed controller controls only yaw.

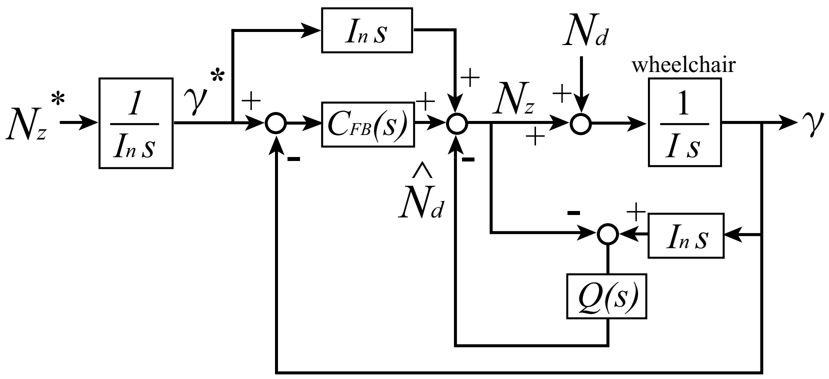


Figure 4.3: Block diagram of proposed yaw motion control system

4.4.1 Yaw Rate Feed Forward Controller

From (4.8), the nominalized system is expressed as $\frac{1}{I_n s}$. Yaw rate feed forward control is realized by using inverse of the nominal model $I_n s$.

4.4.2 Yaw Rate Feedback Controller

The input of yaw rate feedback controller $C_{FB}(s)$ is the difference between the reference and the measured yaw rate $\gamma^* - \gamma$. The feedback controller is used to stabilize the system to ensure the actual yaw rate converges to the desired yaw rate. The system can be stabilized by considering the following transfer function.

$$\frac{\gamma}{\gamma^*} = \frac{\frac{1}{I_n s}\, C_{FB}(s)}{1 + \frac{1}{I_n s}\, C_{FB}(s)} = \frac{C_{FB}(s)}{I_n s + C_{FB}(s)} \tag{4.9}$$

Proportional control was adopted for yaw rate feedback control.

$$C_{FB}(s) = K_p \tag{4.10}$$

From (4.9) and (4.10), pole of this system is

$$s = -\frac{C_{FB}(s)}{I_n} = -\frac{K_p}{I_n} \tag{4.11}$$

The proportional gain in the yaw rate feedback controller defined as K_p (from (4.10)), was chosen so that the pole of the close loop system become 2π rad/s.

4.4.3 Yaw Moment Observer (YMO)

From (4.7), disturbance yaw moment $\hat{N}_d$ is estimated as follows:

$$\hat{N}_d = (\gamma I_n s - N_z)\ Q(s) \tag{4.12}$$

where Q(s) is

$$Q(s) = \frac{1}{\tau_i s + 1} \tag{4.13}$$

where τ_i is the time constant.

Yaw rate γ is measured by gyroscope.

4.5 Torque Distribution of Yaw Motion Control

Compensation torque of left and right (T_{yL} and T_{yR}) are calculated as follows:

$$\begin{bmatrix} T_{yR} \\ T_{yL} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ \frac{d}{2r} & -\frac{d}{2r} \end{bmatrix}^{-1} \begin{bmatrix} T \\ N_z \end{bmatrix} \tag{4.14}$$

, where $T = T_{hL} + T_{hR}$.

4.6 Experimental Verification of Proposed Yaw Motion Control

Two types of experiments have been done to verify the effectiveness of yaw motion control. The first experiment is of the wheelchair going straight along slope, with constant lateral disturbance while moving. Second experiment is of the wheelchair turning on the slope, where the direction and magnitude of the disturbance changes while moving.

4.6.1 Experimental Setup

Values of parameters used in the experiment are shown in Table. 4.1.

Table 4.1: Parameters of power-assisted wheelchair

assist gain	α	2.5
fast time constant	τ_1	0.08 s
slow time constant	τ_2	4 s
width of wheelchair	d	0.47 m
radius of the wheel	r	0.26 m
mass of the wheelchair	M	30 kg

4.6.2 Experiment 1: Going straight on the slope

Figure 4.4 shows experimental environment of experiment 1. Lateral disturbance due to gravity acts towards the left side of the wheelchair. The purpose of experiment 1 is to verify the effectiveness of the proposed yaw motion control and lateral DOB under a constant disturbance.

4.6.3 Experiment 2: Turning on the slope

Figure 4.5 shows experimental environment of experiment 2. The purpose of experiment 2 is to verify the effectiveness of the proposed yaw motion control and compare it with lateral DOB when turning on the slope.

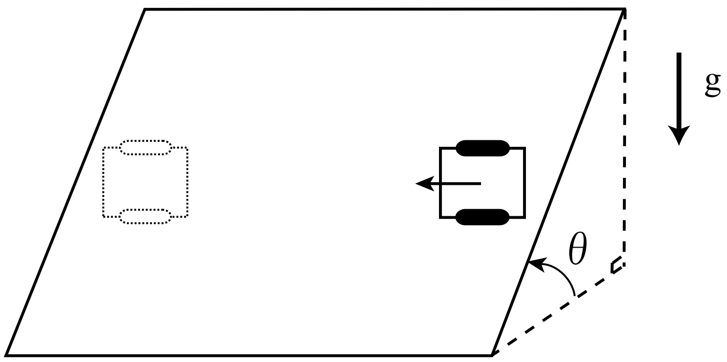


Figure 4.4: Experiment 1: Going straight on the lateral slope

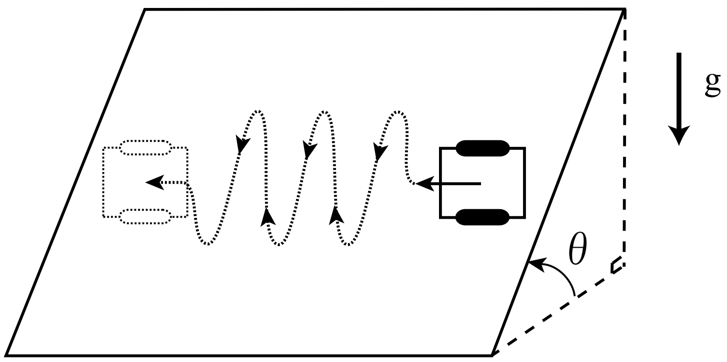


Figure 4.5: Experiment 2: Turning on the lateral slope

4.6.4 Lateral Disturbance Observer

A controller that can control both longitudinal and lateral movement had been proposed by Oh et al. (*Oh et al.*, 2008b). In this chapter, only lateral disturbance is considered. In this section, the lateral direction disturbance observer (Lateral DOB) designed by Oh et al. will be introduced.

Figure 4.6 shows a block diagram of lateral DOB. T_R and T_L are torque to right and left wheel. d_R and d_L are disturbance in right and left side. e_R and e_L are error of angular velocity caused by disturbance, and e_{lat} is defined as $e_{lat} = e_R - e_L$. y_R and y_L are angular velocity of right and left wheel. $P_R(s)$ and $P_L(s)$ are plant of right and left, and $P_n(s)$ is nominal model of wheelchair. Controller $C_{lat}(s)$ is defined as follows:

$$C_{lat}(s) = \frac{1}{2}\frac{P_n^{-1}(s)}{\tau_l\ s + 1} \tag{4.15}$$

where τ_l is time constant.

4.6.5 Experimental results

4.6.5.1 Experiment 1: Going straight on the slope

Experimental results of going straight on the slope are shown in Fig. 4.7 to Fig. 4.9.

Figure 4.7 shows the result of going straight on the slope without control. The first graph

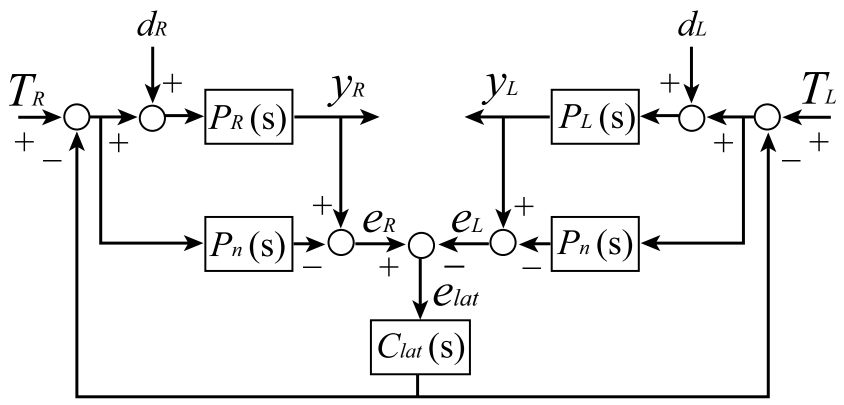


Figure 4.6: Lateral Disturbance Observer

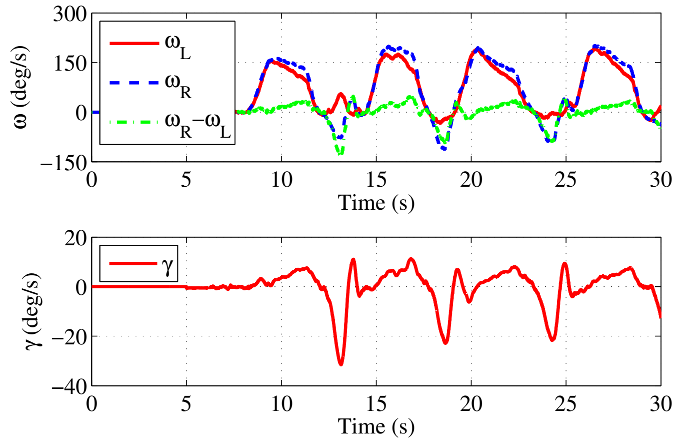


Figure 4.7: Experiment 1: Going Straight on the slope (without control)

shows angular velocity of both wheels. Red solid line shows angular velocity of left wheel ω_L, and blue dashed line shows that of right wheel ω_R. Green dash-dot line shows difference of both wheels' angular velocity, $\omega_R - \omega_L$. The second graph shows yaw rate γ in red solid line.

There are 4 periods of patterns in angular velocity graph. First, both wheels' angular velocity are increasing. Second, both of them start to decrease. Then, the difference of both wheels' angular velocity sharply changes to negative. At last, difference of both wheels' angular velocity sharply changes to positive.

When the angular velocity is increasing - where the wheelchair is accelerating - the difference of both wheels' angular velocity is small, less than 30 deg/s in 19 to 20.5 s and less than 10 deg/s in other increasing period. In this period, yaw rate is less than 5 deg/s.

When the angular velocity is decreasing - where the wheelchair is decelerating - the difference of both wheels' angular velocity becomes bigger than that during increasing period. At 17 s, the difference between both wheels' angular velocity becomes 50 deg/s. In this period, yaw rate is bigger than that during increasing period. It is up to 10 deg/s at 17 s.

The difference of both wheels' angular velocities spikes negative right after the deceleration period. At 13 s, angular velocity difference is up to 130 deg/s, and it is up to 90 deg/s in other period. In this period, yaw rate is up to -30 deg/s at 13 s.

Right after the first negative yaw rate spike, the difference of both wheels' angular velocities goes positive to 50 deg/s, and yaw rate is up to 10 deg/s at 13.5 s.

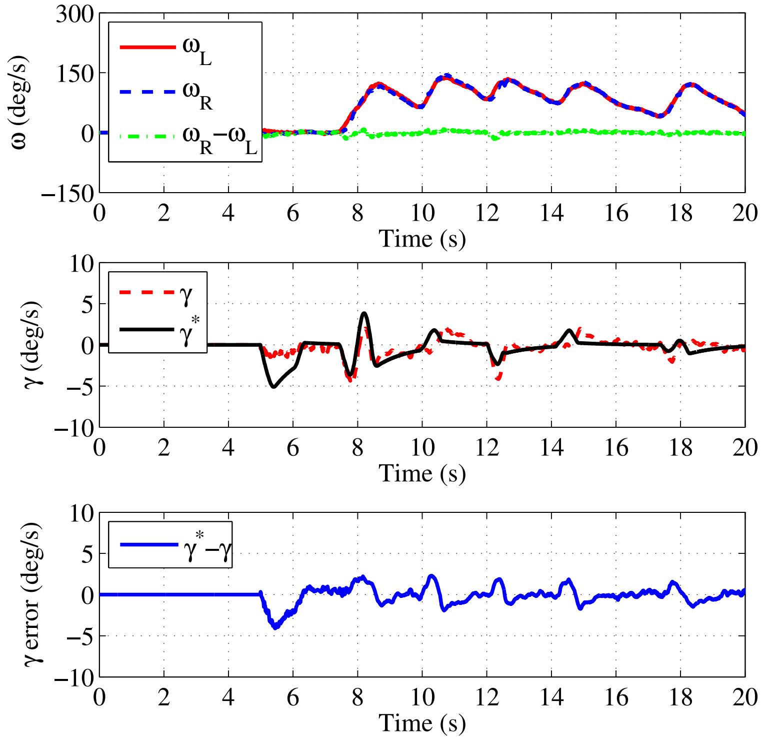


Figure 4.8: Experiment 1: Going Straight on the slope (with Yaw Motion Control)

Figure 4.8 shows the result of going straight experiment with yaw motion control. The first graph shows angular velocities of both wheels, and the color code of each line is the same as that of Fig. 4.7. The second graph shows yaw rate. Red dotted line shows the measured yaw rate, and black solid line shows the reference yaw rate. The third graph shows yaw rate error.

The difference of both wheels' angular velocity is smaller in Fig. 4.8 (with yaw motion control) than that of Fig. 4.7 (without control). Both wheels' angular velocity are positive, since wheelchair starts to move. Yaw rate is approximately -5 to 5 deg/s, and yaw rate error , which shows difference between wheelchair's measured yaw rate and reference yaw rate, is approximately -3 to 3 deg/s .

Figure 4.9 shows the result of going straight experience with lateral DOB. The first graph shows angular velocity of both wheels and the second graph shows yaw rate. Information of each lines is the same as that of Fig. 4.7.

The difference of both wheels' angular velocity, -20 to 20 deg/s, is smaller than that of Fig.

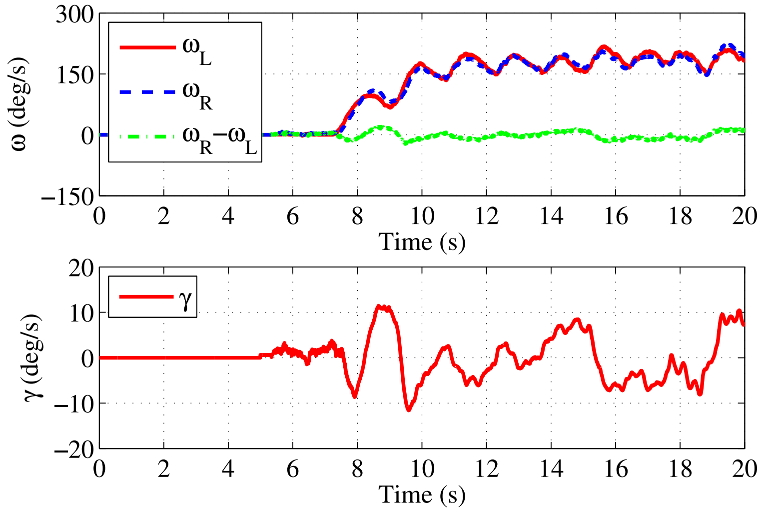


Figure 4.9: Experiment 1: Going Straight on the slope (Lateral DOB)

4.7 (without control) and bigger than that of Fig. 4.8 (with yaw motion control). Yaw rate is approximately -10 to 10 deg/s.

4.6.5.2 Experiment 2: Turning on the slope

Experimental results of turning on the slope are shown in Fig. 4.10 to Fig. 4.12.

Figure 4.10 shows the result of turning on the slope without control. The first graph shows angular velocity of both wheels and the second graph shows yaw rate. The color code of each line is same as that of Fig. 4.7.

In this experiment, the wheelchair turns right during 14 to 15 s, 22 to 23 s, and turns left during 18 to 19 s, and 26 to 27 s.

During 8 to 14 s, where the wheelchair starts to move up to the point prior to turning, wheel velocities are positive and yaw rate lies between -10 to 10 deg/s.

Angular velocity of right wheel becomes negative when the wheelchair turns right. During 22 to 23 s yaw rate reaches -20 deg/s, and during 14 to 15 yaw rate is greater than -15 deg/s.

When the wheelchair turns left, angular velocity of left wheel is negative, and yaw rate is greater than 20 deg/s.

Figure 4.11 shows the result of turning on the slope with yaw motion control. The first graph shows angular velocity of both wheels, the second graph shows yaw rate, and the third graph

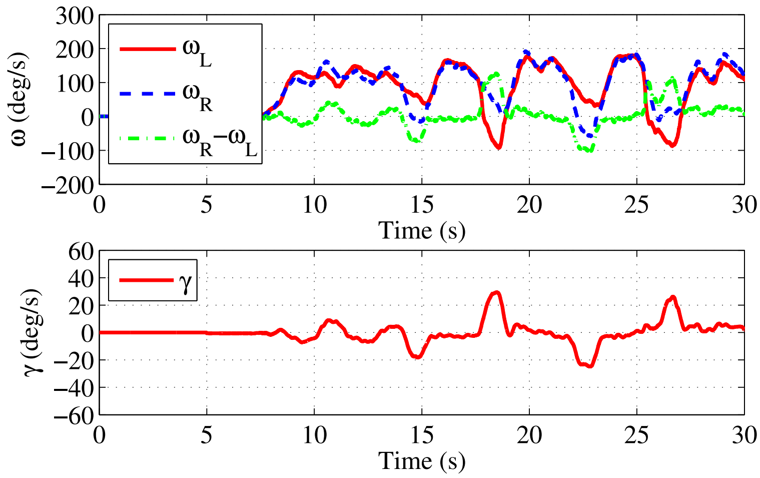


Figure 4.10: Experiment 2: Turnig on the slope (without control)

shows yaw rate error. The color code of each line is the same as that of Fig. 4.8.

In this experiment, the wheelchair turns right during 13 to 14 s and 22 to 23 s, and turns left during 9 to 11 s, 17 to 18 s and 25 to 28 s.

The angular velocity of both wheels are almost equal, except when the wheelchair is turning.

Yaw rate is greater than -60 deg/s when the wheelchair turns right, and it is greater than 60 deg/s when the wheelchair turns left. When the wheelchair goes straight, yaw rate is approximately -10 to 10 deg/s.

Figure 4.12 shows the result of turning on the slope with lateral DOB. The first graph shows angular velocity of both wheels and the second graph shows yaw rate. The color code of each line is the same as Fig. 4.7.

In this experiment, the wheelchair turns right during 11 to 13 s, 19 to 21 s, and 27 to 29 s, and turns left during 9 to 10 s, 16 to 17 s, and 23 to 24.5 s.

Absolute value of yaw rate is greater than 60 deg/s at turning points, and there are some points which have yaw rate greater than 20 deg/s.

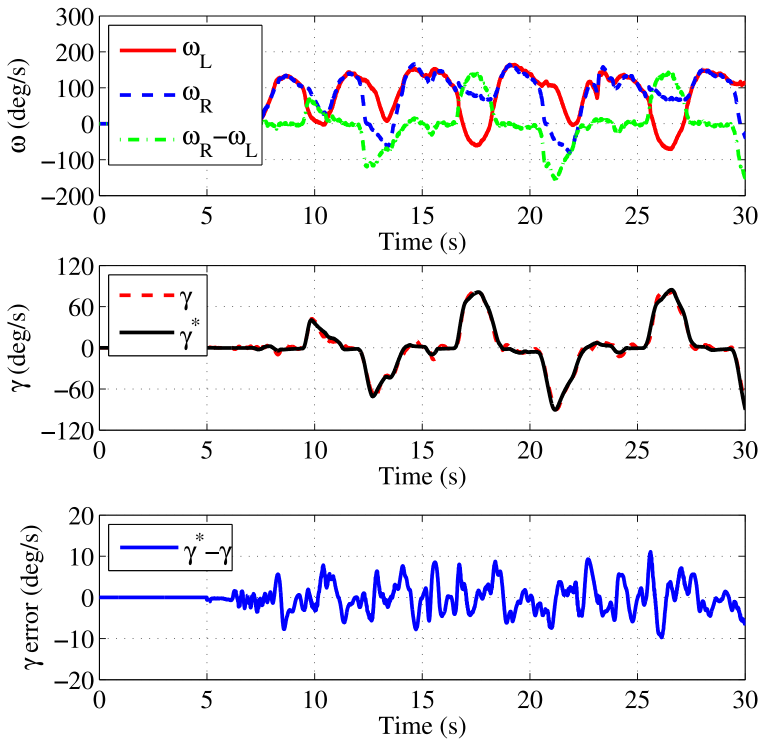


Figure 4.11: Experiment 2: Turnig on the slope (with Yaw Motion Control)

4.7 Discussion

4.7.1 Experiment 1: Going straight on the slope

Without control, as shown in Fig. 4.7, the difference of angular velocity between both wheels may be small when the wheelchair accelerates, but the difference in angular velocity of the right and left wheels increases when the wheelchair decelerates. From these results, it can be said that wheelchair goes straight while the user is propulsion the wheelchair, and turns counterclockwise due to gravity when user is not propulsion the wheelchair. Furthermore, yaw rate of the wheelchair becomes greatly negative, when angular velocity of left wheel is bigger than that of right wheel. Which means user was forced to turn the wheelchair clockwise, to balance the counterclockwise rotation caused by the gravity.

The difference of angular velocity between both wheels in Fig. 4.8 (with yaw motion control) and Fig. 4.9 (with lateral DOB), is smaller than that shown in Fig. 4.7 (without control). In

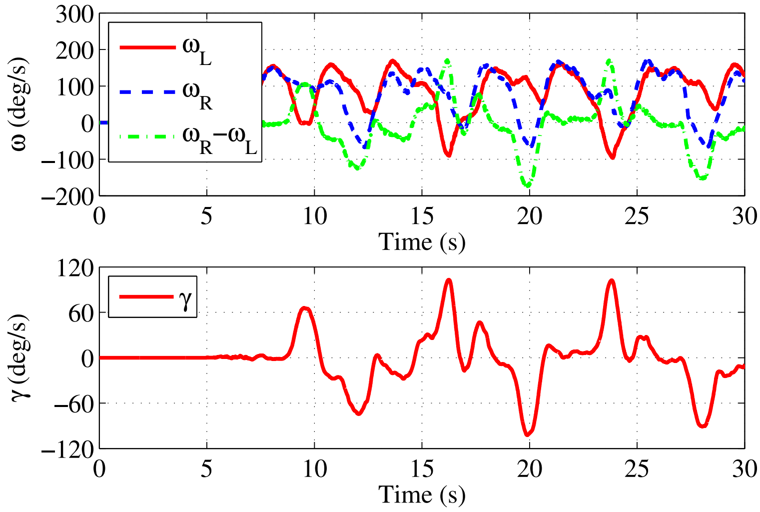


Figure 4.12: Experiment 2: Turnig on the slope (with Lateral DOB)

Fig. 4.8, yaw rates are approximately -5 to 5 deg/s (with the error being -3 to 3 deg/s), which is several times smaller than that of the system without control, approximately -25 to 10 deg/s.

4.7.2 Experiment 2: Turning on the slope

Without control, as shown in Fig. 4.10, yaw rate is greater than -20 deg/s when the wheelchair turns right, and greater than 20 deg/s when the wheelchair turns left. With yaw motion control, shown in Fig. 4.11, yaw rate error is quite small It means the movement of the wheelchair follows the reference value. With the lateral DOB, results shown in Fig. 4.12, yaw rate is similar to that of yaw motion control when turning. However, yaw rate fluctuations when not turing are larger.

4.8 Chapter Summary

In this chapter, the motion of the wheelchair on the slope is considered. When there is lateral disturbance, it is quite difficult to go straight without control. However, it is verified by the experiment that it is possible to go straight on the slope using the proposed yaw motion control.

Without control, the user needs to apply great force to counteract disturbances. However, it is verified experimentally that yaw rate follows its reference, even if there is a lateral disturbance. Therefore, it is possible for the wheelchair to move towards the user's desired direction in any sloped environment.

When using lateral DOB, it is possible to go straight even if there is lateral disturbance. However, in some periods yaw rate fluctuation become larger than that with yaw motion control. As a result, using yaw motion control is proved to be more effective than lateral DOB.

The effectiveness of the proposed controller on a slope of constant incline angle is verified from experiments.

CHAPTER V

One-handed Propulsion Control with Straight, Pure Rotation and Advanced Turning Mode

5.1 Introduction

It is impossible to control a standard manual wheelchair or power-assist wheelchair with only one hand. A one-handed propulsion control system for a power-assisted wheelchair that allows the user to go straight and do pure rotations was proposed previously, but this system didn't allow the user to turn the wheelchair while moving. In this paper, an improved one-handed propulsion system including advanced turning mode is proposed.

5.2 Previous Approach of One-handed Drive Wheelchair

In order to allow people with disabilities to participate in society actively and to enjoy a high quality of life, a method of mobility that can be used freely and with comfort is required. The wheelchair is an important welfare device that provides these people with a method of transport There are many types of wheelchairs. A standard manual wheelchair is operated and gains propulsion by the user pushing its handrims with both hands. However, it is impossible for users with hemiplegia or a hand/arm injury to operate such a wheelchair. Furthermore, even if the wheelchair user is able to use both hands, there are many situations where the user may need to do something else with their hand while moving, such as opening doors or holding objects while moving.

In order to realize a wheelchair which can be operated by one hand, various one hand drive

(a) Joystick (b) Multi-rim

(c) TrackChair (d) ProfHand

Figure 5.1: Previous one-handed wheelchairs (*Sakai and Yasuda*, 2013)(*Profhand*, 2013)

wheelchairs have been developed. The most popular way to operate a wheelchair with one hand is with a joystick. A joystick can be used even with a small movement of the hand, therefore, putting less burden on the user than a manual wheelchair would. However, even though using a joystick does not need much strength, there are users who have difficulty using a joystick (*K.Arshak*, 2006). Therefore, new interfaces and control systems are being developed, such as the neuronal joystick (*Rabhi et al.*, 2013). However, one major drawback of joystick use is, as the range of hand movement is small, muscle weakening will result in the absence of rehabilitation.

There is research focused on mechanical developments for realization of one-handed wheelchairs. One form of mechanical development is examples of wheelchairs with multiple handrims. These types of wheelchairs have handrims typically for going straight and turning, and the user pushes the appropriate hand rim to move in the desired manner. Recently, there are multi-rim wheelchairs that provide power assistance to reduce the burden on the user (*Sakai and Yasuda*, 2013),(*Sakai et al.*, 2010). However, having multiple handrims makes the wheelchair wider, and therefore unable to move around in confined spaces.

TrackChair, a wheel assembly kit for manual wheelchairs, is another example of mechanical development There are two handrims on each wheel — one drives the adjacent wheel while the other drive the opposite wheel. The user can either push one handrim of each side simultaneously or push both handrims of one side simultaneously to go straight. The main advantage of TrackChair is the ability to operate with both hands or with either hand. However, a large grip force is required to grab both handrims on a single side simultaneously.

Profhand is a pedaled wheelchair developed by TESS (*Profhand*, 2013). Unlike previous manual wheelchairs, Profhand is driven by pedaling like a bicycle, and direction is controlled by hand. It can keep the user active and free up one hand. However, it cannot be operated by users who cannot use both legs. Furthermore, the turning radii for left and right turns are different and are non-zero, which can make it difficult to navigate confined spaces.

5.3 Conventional One-handed Propulsion Control System

One-handed propulsion control for the power-assisted wheelchair was previously proposed (*Oh and Hori*, 2005). Figure 5.2 shows part of the conventional one-handed propulsion control system block diagram, where disturbance observer is omitted in this figure. In (*Oh and Hori*, 2005), only straight motion and turning motion was realized. Mode coefficient K is decided by both the value and derivative of human torque, that is T_H and $\dot{T}_H$. Fuzzy division is implemented and sigmoid function is used to prevent rapid change. K is defined as follows:

$$K(T_H, \dot{T}_H) = sgn(T_H)\frac{1}{1 + e^{-\beta(\dot{T}_H - \dot{T}_0)}} \tag{5.1}$$

where $\dot{T}_0$ is a torque derivative threshold.

From Eq. (5.1), K can take values between 0 and 1. When K takes the value 1, the torque

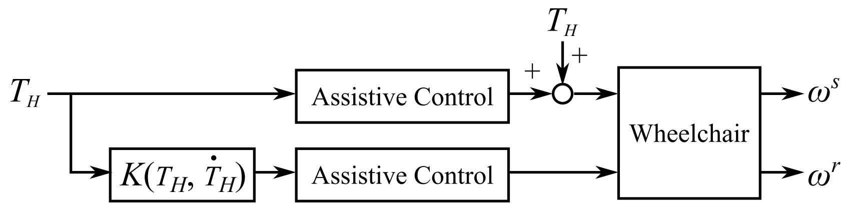


Figure 5.2: Part of conventional one-handed propulsion control system block diagram

delivered to both wheels are equal, which makes the wheelchair go straight. After K becomes 1, straight mode (i.e. the state where $K = 1$) is kept until the wheelchair speed ω and human torque T_H become 0. When K is 0, the wheel opposite to the one being hand-driven has zero torque, which makes the wheelchair turn. Although straight motion and turning motion were realized, pure rotation was not possible with this control system.

To improve the capability and performance of one-handed propulsion, another control system was proposed (*Payne et al.*, 2012). The control system that realizes straight motion, turning motion and pure rotation motion was proposed. K was defined as follow,

$$K(T_H, \dot{T}_H) = \begin{cases} -1 & (T_H \dot{T}_H \leq 0) \\ \bar{K} & (T_H \dot{T}_H > 0) \end{cases} \tag{5.2}$$

$$\bar{K} = \begin{cases} -1 & (|\dot{T}_H| < \dot{T}^r_{thr}) \\ 2\dfrac{|\dot{T}_H| - \dot{T}^r_{thr}}{\dot{T}^s_{thr} - \dot{T}^r_{thr}} - 1 & (\dot{T}^r_{thr} < |\dot{T}_H| < \dot{T}^s_{thr}) \\ 1 & (|\dot{T}_H| > \dot{T}^s_{thr}) \end{cases} \tag{5.3}$$

where $\dot{T}^r_{thr}$ and $\dot{T}^s_{thr}$ are torque derivative thresholds for pure rotation and straight motion respectively.

The state flow chart for the conventional system (*Payne et al.*, 2012) is shown in Fig.5.3. When K reaches 1, the wheelchair goes straight. Straight mode is kept for at least the duration t_{min}. While the wheelchair longitudinal speed exceeds ω^s_{off}, straight mode is maintained. When the speed drops below ω^s_{off}, straight mode ceases and the system enters stationary mode.

While K is -1, the torque delivered to the wheels are equal in magnitude but in opposition, which makes the wheelchair do pure rotations. This pure rotation was not possible with (*Oh and Hori*, 2005). Furthermore, a "pure rotation mode" which allows for rapid rotation was introduced in (*Payne et al.*, 2012). When the yaw rate ω^r exceeds the threshold ω^r_{on}, pure rotation mode is held. When the yaw rate drops below ω^r_{off}, pure rotation is no longer held and the system enters stationary mode.

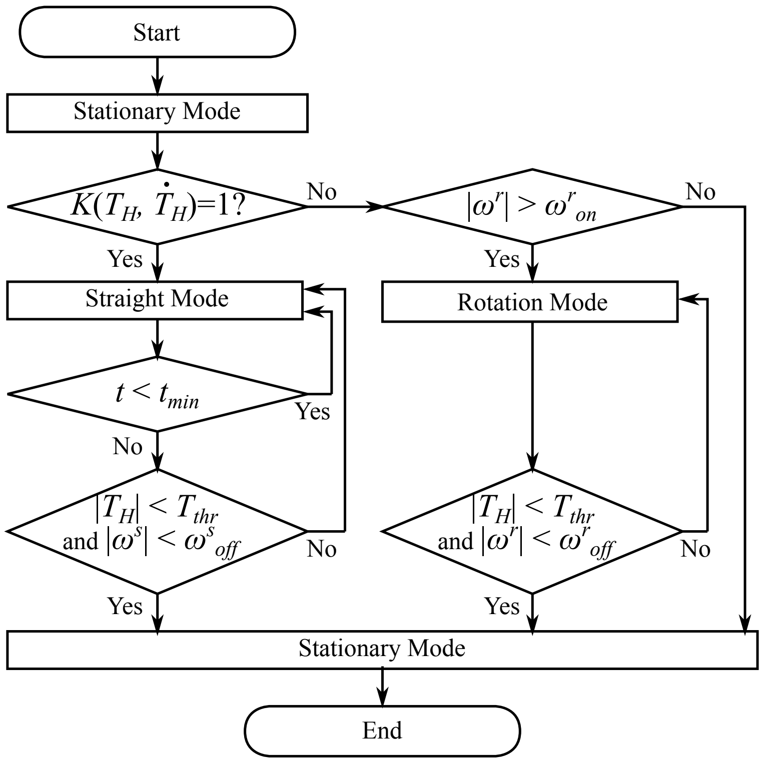


Figure 5.3: State flow chart of conventional operation mode: No turning mode

5.4 Proposed Control System with Straight Motion, Pure Rotation and Advanced Turning Mode

As mentioned in section 5.3, conventional system (*Payne et al.*, 2012) made improvements on (*Oh and Hori*, 2005) by making possible pure rotation by allowing K to take -1, and rapid rotation by introducing a pure rotation mode. However, the ability for the user to turn while moving straight was not implemented. To extend the capabilities of (*Payne et al.*, 2012), an improved one-handed propulsion control system is proposed in this section.

Figure 5.4 shows a block diagram of the proposed one-handed propulsion control system. It is assumed that the user will push only one of the handrims. T_H denotes the left (or right) human torque. The operation mode block decides K based on the human torque signal along with its derivative and the wheel velocities. d_L and d_R denote unexpected disturbance, such as gravity. The assistive control block calculates the assist torque to be generated by the motors. Torque inputs to the assistive control block are T_H for the same side as the user's operating hand, and KT_H for the other side. The assistive control system contains two variable-bandwidth low-pass filters, one to amplify straight torque and the other to amplify rotational torque, to provide assistance for straight motion and rotational motion independently (*Kim et al.*, 2012). The disturbance observer estimates external torques, and these estimates are fed back negatively to compensate for environmental disturbances and modeling errors.

5.4.1 Definition of K

Human torque T_H and its derivative $\dot{T}_H$ are used to decide operation mode. K is defined by Eq. (5.2) and Eq. (5.3). When $T_H\dot{T}_H > 0$ and $|\dot{T}_H| > \dot{T}^s_{thr}$, K will take the value 1, where pushing the handrim will make the wheelchair go straight. On the other hand, K will be -1 when $T_H\dot{T}_H < 0$ or $|\dot{T}_H| < \dot{T}^r_{thr}$, where pushing the handrim will make the wheelchair rotate. When $T_H\dot{T}_H > 0$ and $\dot{T}^r_{thr} < |\dot{T}_H| < \dot{T}^s_{thr}$, K will be between -1 and 1.

5.4.2 Straight mode

Figure 5.5 shows the state flow chart of the operation mode block. If K becomes 1 while in stationary mode or turning mode, the mode will change to "straight mode". There is a minimum straight mode hold time of t_{min}. This minimum hold time facilitates fine control of straight movement while straight mode is held, which is achieved by the user initially pushing the handrim a moderate but high-derivative torque (such that K becomes 1). After entering straight mode, when $|T_H| < T_{thr}$, $K < 1$ and $|\omega^s| < \omega^s_{off}$, i.e. when the user doesn't touch the handrim and the wheelchair slows down, the mode will change to stationary mode.

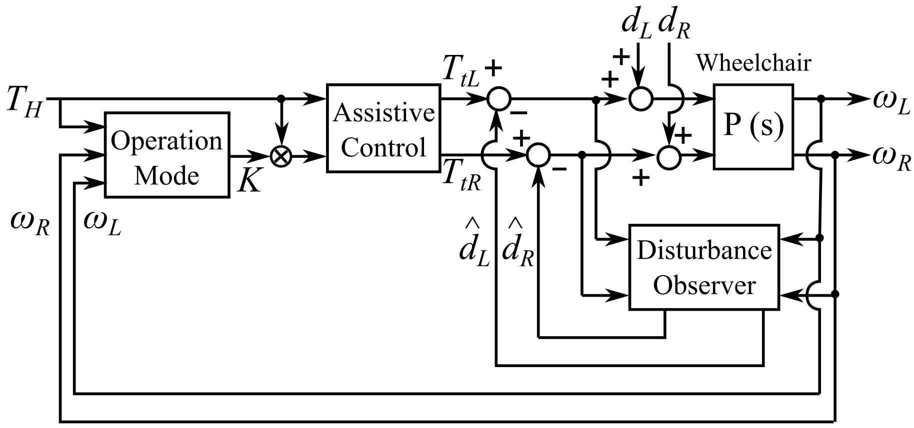


Figure 5.4: Block diagram of proposed one-handed propulsion control system

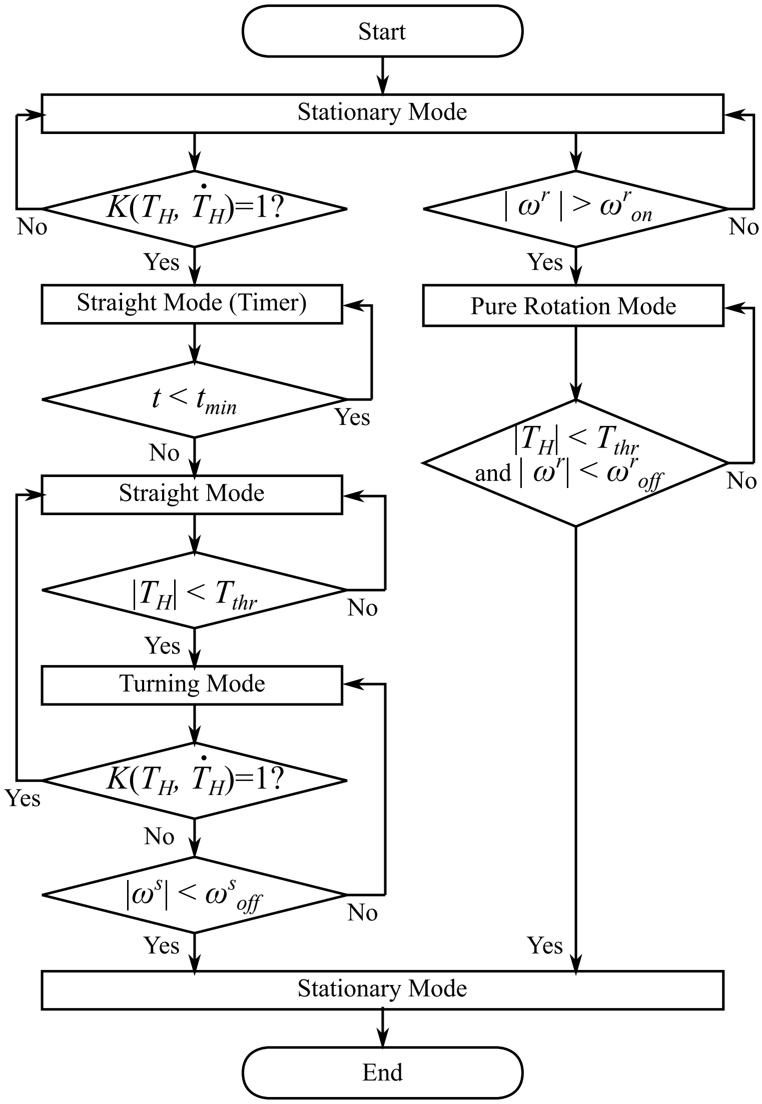


Figure 5.5: State flow chart of operation mode: turning mode included

5.4.3 Pure rotation mode

If $K < 1$ and $|\omega^r| > \omega^r_{on}$, i.e. when the human torque isn't sudden and the yaw rate exceeds the threshold $R\omega^r_{on}$, the system will enter "pure rotation mode". While in pure rotation mode, K is held at -1, and therefore the use can make the wheelchair rotate rapidly by applying far greater torque. When $|T_H| < T_{thr}$ and $|\omega^r| < \omega^r_{off}$, the system will return to stationary mode.

5.4.4 Turning mode

Changing direction while the wheelchair is moving straight is made possible by the "turning mode". This is biggest difference between the previous one-handed propulsion control system

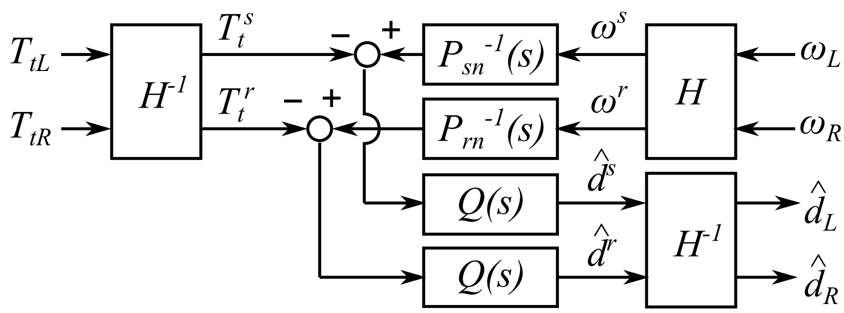


Figure 5.6: Block diagram of disturbance observer

and the one proposed in this paper. After entering straight mode, when the handrim is not being operated and time t_{min} has passed, the system enters turning mode. In this mode, the user is able to turn the wheelchair by pushing the handrim with torque such that $K < 1$. The user can also continue to propel the wheelchair straight by pushing the handrim with torque such that $K = 1$, i.e. with sufficient torque derivative. By using this algorithm, turning without stopping the wheelchair is made possible.

5.5 One-handed Propulsion Control System with Disturbance Observer

Block diagram of disturbance observer is shown in Fig. 5.6.

H is a transformation matrix, defined in (5.4), that turns wheel velocities expressed as left-right components, ω_L and ω_R, into straight-rotational components, ω^s and ω^r.

$$H = \begin{bmatrix} 1/2 & 1/2 \\ -1 & 1 \end{bmatrix}, H^{-1} = \begin{bmatrix} 1 & -1/2 \\ 1 & 1/2 \end{bmatrix} \tag{5.4}$$

T_{tL} and T_{tR} are the total torques of the left and right side respectively, which are the addition of human torque and assist torque. T_t^s and T_t^r the total torques expressed as straight and rotational components. ω_L and ω_R are the left and right wheel velocities. d_L and d_R are the disturbance torques on the wheels, and $\hat{d}_L$ and $\hat{d}_R$ are their estimates. Disturbance estimation is done in terms of straight and rotational components, and the converted into left and right components. $P_{sn}(s)$ and $P_{rn}(s)$ are nominal models of the straight and rotational dynamics of the wheelchair, and $P_{sn}^{-1}(s)$ and $P_{rn}^{-1}(s)$ are their inverses. $Q(s)$ represents a filter that is required to realize the inverse models.

5.6 Experimental Verification

5.6.1 Experimental environment

The purpose of the experiment in this section is to verify turning operation with the proposed control system. Figure 5.7 shows the experimental environment. Turning operation was verified with a single right-hand turn while moving forward. Parameters used in experiments are shown in Table 5.1.

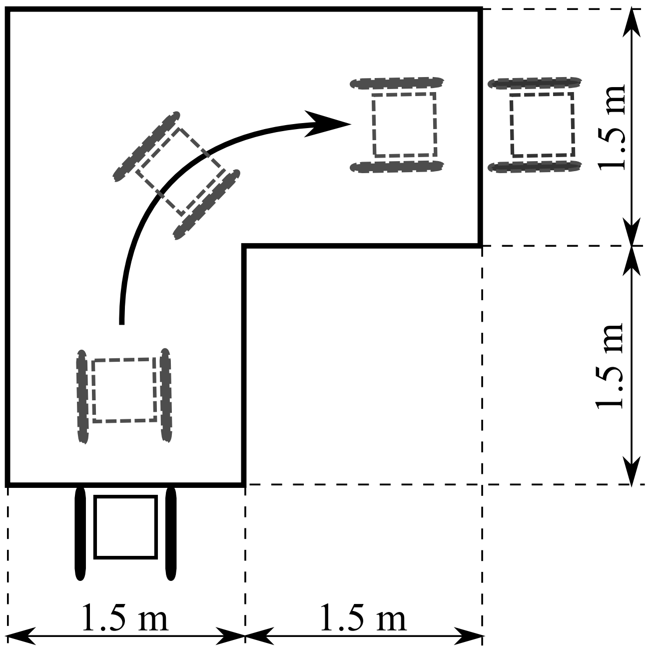


Figure 5.7: Experiment: Right turn *(Top view)*

Table 5.1: Parameters used in experiments

assist rate (straight)	α_s		2.0
time constant (straight)	τ_a^s	τ_{fast}^s	0.08 s
		τ_{slow}^s	1.5 s
assist rate (rotation)	α_r		2.5
time constant (rotation)	τ_a^r	τ_{fast}^r	0.08 s
		τ_{slow}^r	1.0 s
Forward high threshold	$\dot{T}_{thr}^s$		70.5 Nm/s
Differential torque low threshold	$\dot{T}_{thr}^r$		69.5 Nm/s

5.6.2 Conventional one-handed propulsion control system

The experimental result for the conventional control system is shown in Fig. 5.8. The first graph shows the left and right wheel velocities as a red solid line and a blue dashed line respectively, and the difference between the two is shown as a green dash-dot line. The second graph shows human propulsion torque T_H and torque of the opposite side KT_H as a red solid line and a blue dashed line respectively, and the difference between the two is shown as a green dash-dot line. The third graph shows K and the system's mode of operation. Stationary mode is 1, straight mode is 2, and pure rotation mode is 3. The last graph shows yaw rate γ of the wheelchair, as measured by the on-board gyroscope.

Between 9 and 16 seconds and between 21 and 30 seconds, the angular velocity of the two wheels are almost the same and the yaw rate is small. Between 16 and 21 seconds, the angular velocity the two wheels are roughly equal and opposite, and the yaw rate is large. The results

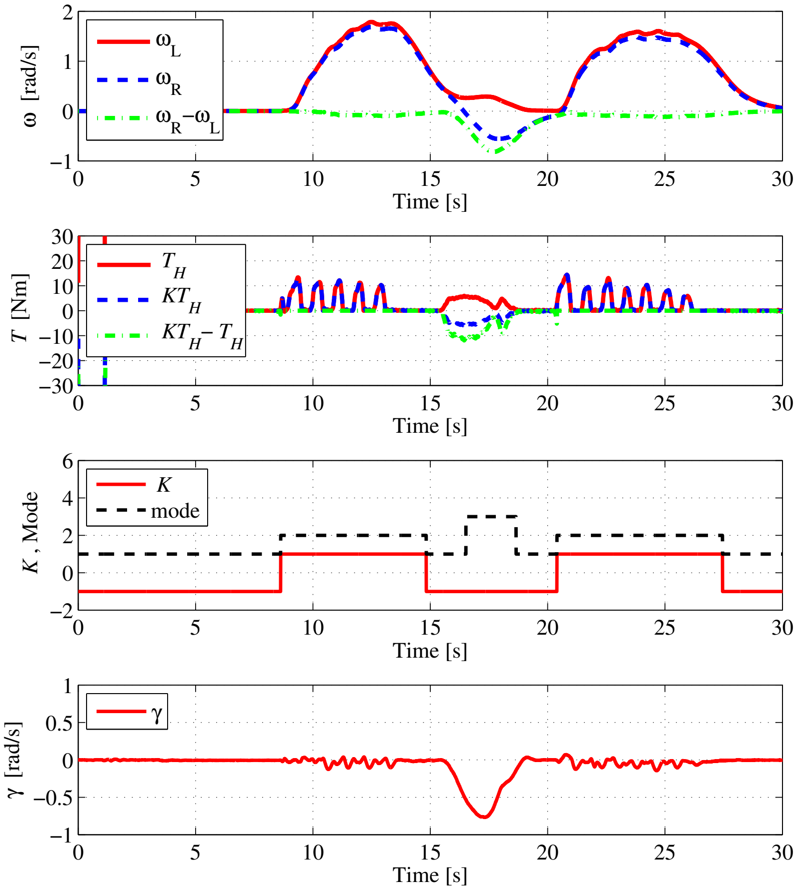


Figure 5.8: Experimental result of conventional control system

indicate that the wheelchair moves forward from a stationary state, stops, does a pure clockwise rotation, stops, moves forward again, and finally stops.

The conventional system does not allow the user to make the wheelchair turn while it is moving longitudinally. Therefore, in order to turn a corner or even adjust heading, the user must stop the wheelchair to change modes. This is shown in the results, between 15 and 16.5 seconds and between 18 to 20.5 seconds, where user stops the wheelchair to change mode.

5.6.3 Proposed one-handed propulsion control system

The experimental result for the proposed control system is shown in Fig. 5.9. Graph information is the same as in Fig.5.8 except for the mode numbers in the third graph. There are 5 modes in the proposed control system: stationary mode is 0, straight mode (timer) is 1, pure rotation mode is 2, turning mode is 4, and straight mode is 5.

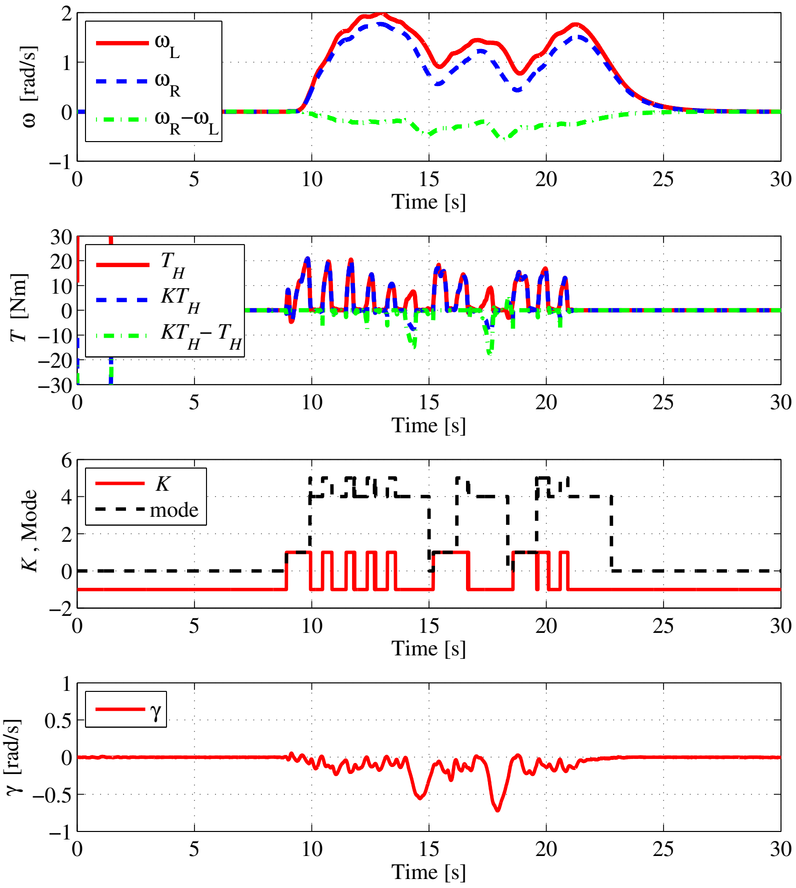


Figure 5.9: Experimental result of proposed control system

Between 9 and 10.5 seconds, the angular velocities of the two wheels are roughly the same, and the wheelchair is moving forward. Between 10.5 and 23 seconds, the angular velocity of the left wheel is more positive than that of the right wheel, which indicates the wheelchair is turning right while moving forward.

Between 9 and 21 seconds, the wheel is continually in motion and does not stop. The user continually pushes the handrim to make the wheelchair go straight or turn right, and does not make the wheelchair stop.

The system's mode of operation is shown in the third graph. Between 9 and 10 seconds, the system is in straight mode (timer). Afterwards, between 10 and 14 seconds, the system switches between straight mode and turning mode depending on whether the user pushes the handrim to go straight or to turn. Between 14 and 15 seconds, the system stays in turning mode, and the yaw rate is shown to get large. This process is repeated between 15 and 18 seconds and between 18 and 23 seconds.

5.7 Chapter Summary

This paper proposes an improved one-handed propulsion control system for the power-assisted wheelchair, which adds the ability to turn while the wheelchair is moving longitudinally. The system's mode of operation is controlled by state flow logic, and is primarily decided by the derivative of the user's handrim torque signal.

With the proposed system, it is also possible to make the wheelchair go straight, do pure-rotation and turn on the move, all by operating the wheelchair with one hand. It is verified experimentally that the proposed control system realizes turning on the move, which was impossible with the previous control system. With the previous system, the user has to stop the wheelchair to change the system's mode of operation. The experiment shows that with the proposed system, the user is able to change between straight mode and turning mode while the wheelchair is in motion.

CHAPTER VI

Implementation and Evaluation of Human-friendly Motion Control of Power-Assisted Wheelchair

6.1 Introduction

6.1.1 Difficulties of Practical Application

In section 1.2, previous wheelchair researches are introduced. Most of them are academic researches and not all of them interact with user of welfare devices. Gap between valuable academic research and daily use technology is one of difficulties in practical application. The research that has high academic value does not always become useful and valuable product. Furthermore, needs from users are not directly related to academic research.

Another difficulty comes from the cost of the device. It will be hard to use devices, if the cost of the device is expensive, even the device is helpful. High performance comes from good devices. However, high performance and cost is trade-off in most device. Good devices, such as sensors with high resolution, are expensive. Therefore, to make helpful welfare device, the research has to focus on not only better performance but also low cost. Welfare device is not same with other devices in terms of cost. There are government subsidize for welfare devices. However, government subsidize is not applied for all welfare devices. It is important to develop the welfare device which has potential to get government subsidize.

6.1.2 New Wheelchair System for Implementation

New wheelchair system is constituted for implementation. A power-assisted wheelchair JWX-II is released from YAMAHA on August 2013. JWX-II is used for implementation of control systems. Figure 6.1 shows the power-assisted wheelchair JWX-II. JWX-II has built-in torque sensors and motors AC servo motors in both side of wheel units. Encoders and gyroscope are mounted additionally. Table 6.1 shows device and sensor information of the new system.

Figure 6.1: Power-assisted wheelchair *JWX-II* (YAMAHA) for practical implementation

Table 6.1: Information of devices and sensors for practical application

	Model number	Manufacturer
Power-assisted wheelchair	JWX-II	YAMAHA
Micro computer		
AC servo motor		
Torque sensor		
Gyroscope	ENC-03R	mtt
Optical encoder	RE12D-100-201-1	COPAL ELECTRONICS

6.2 Implementation of Yaw Motion Control System

6.2.1 Yaw Motion Control System

The purpose of yaw motion control system is to improve safety and handling of the wheelchair by preventing unexpected movement of yaw direction. The system which is introduced in Chapter IV is implemented to the wheelchair. Gyroscope is used for detecting yaw rate of the wheelchair.

Gyroscope is an additional sensor of the product. Therefore, disturbance observer using encoder is also considered. Disturbance observer using encoder is introduced in one-handed propulsion control system. Figure 5.6 shows the block diagram of disturbance observer of one-handed propulsion control system. For the fair comparison, only rotational part of the disturbance observer is implemented to the power-assisted wheelchair.

6.2.2 Subject information

Three groups of people participate in experiments. This experiment got certificate of approval on research ethics by "Subcommittee on research ethics of Life Science Committee" (identified number: 14-159). The document of certificate of approval is shown in Appendix B. Participations listened to the purpose, procedure, and other information of this research to participate in this research study. They checked informed consent documents and agree to participate in this research.

* **Group A** : A group of advanced wheelchair users, who rode wheelchair for more than a year.

Table 6.2: Participant demographics of yaw motion control system (Group A)

Subject	Age	Gender	Years of Wheelchair Use	Mobility Device	Disability Type	Handedness
A - 1	66	Male	48 years	MWC	Osteogenesis Imperfecta	Right
A - 2	47	Male	16 years	PAPAW	Cervical Cord Injury	Right
A - 3	32	Male	25 years	MWC (inside) EPW (outside)	Mitochondrial Disease	Left

* MWC: Manual Wheelchair, PAPAW: Pushrim-Actived Power-Assisted Wheelchair, EPW: Electric Powered Wheelchair

* **Group B** : A group of beginners, who never or had a few chance to ride wheelchairs.

* **Group C** : A group of researchers, who research on wheelchairs or do related work.

Group A, B and C had different experimental environments, such as angle of the slope. Furthermore, there are different experimental environments within Group A.

General subject demographics for participants is shown in Table 6.2 to Table 6.4.

Table 6.3: Participant demographics of yaw motion control system (Group B)

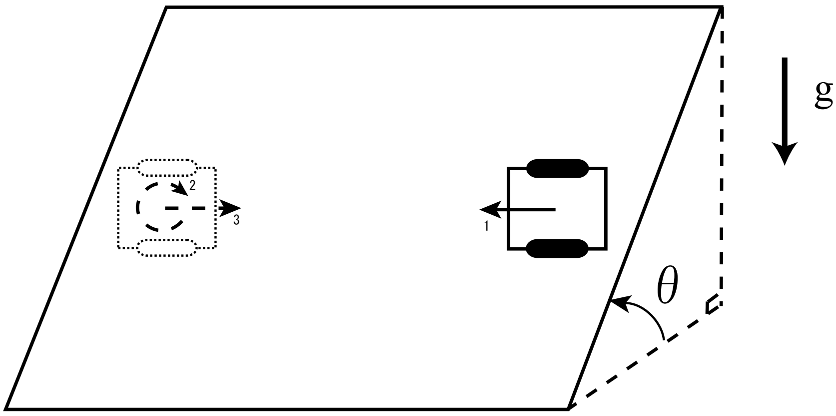
Subject	Age	Gender	Handedness
B - 1	23	Female	Right
B - 2	31	Male	Right
B - 3	25	Male	Right
B - 4	25	Male	Right
B - 5	24	Male	Right
B - 6	25	Male	Right
B - 7	23	Male	Right

Table 6.4: Participant demographics of yaw motion control system (Group C)

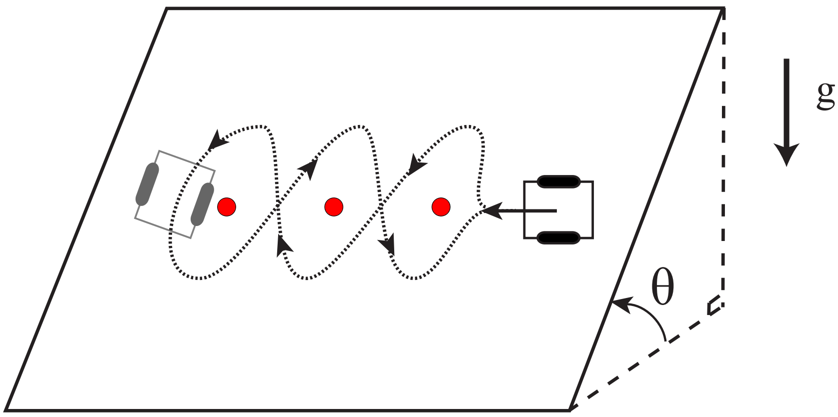
Subject	Age	Gender	Years of Wheelchair Research	Handedness
C - 1	N/A	Male	7 years	Right
C - 2	47	Male	11 years	N/A
C - 3	36	Male	2 years	Right
C - 4	44	Male	N/A	Right
C - 5	39	Male	2 years	Right
C - 6	N/A	Male	7 years	Right
C - 7	25	Male	N/A	Right
C - 8	51	Male	7 years	Right
C - 9	47	Male	4 years	Right
C - 10	N/A	Male	3.5 years	Right
C - 11	56	Male	7 years	Right
C - 12	45	Male	7 years	Right

6.2.3 Experimental environment of yaw motion control

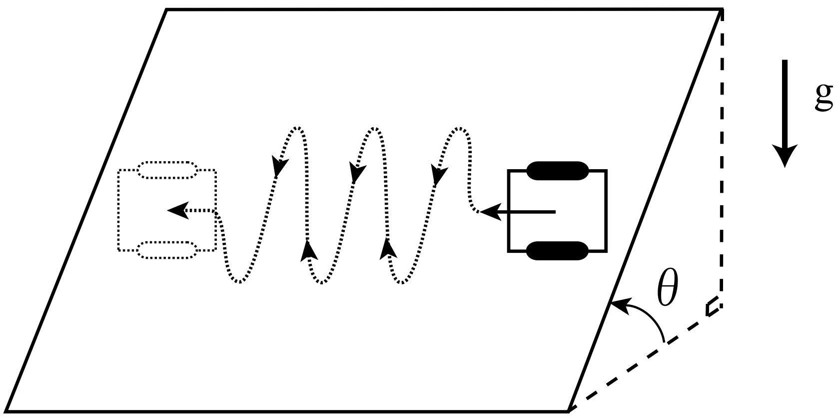
Figure 6.2 shows the experimental environment of yaw motion control system.



(a) Experiment of going straight on lateral slope



(b) Experiment of turning on lateral slope for Group A & C (Slalom)



(c) Experiment of turning on lateral slope for Group B (Slalom)

Figure 6.2: Experimental environment of yaw motion control system

6.2.3.1 Experiment of going straight

Figure 6.2(a) shows experiment of going straight in lateral disturbance environment. Lateral disturbance due to gravity acts towards the left or right side of the wheelchair. Experiment process are as follows:

1. go forward (gravity acts towards the left side)
2. pure rotation (180 degree)
3. go forward (gravity acts towards the right side)
4. pure rotation (180 degree)
5. try 1. - 3. again

The purpose of this experiment is to verify the effectiveness of the proposed yaw motion control and lateral DOB under a constant disturbance.

6.2.3.2 Experiment of turning

Figure 6.2(b) shows experimental environment of turning for Group A and C. Three cones are putted at regular intervals. Cones are marked as red points in figure. Participants drive wheelchair between cones.

Figure 6.2(c) shows experimental environment of turning for Group B. Participants make free turning experiments. Width or distance of turning point is not fixed. In the experiment, the effectiveness of the proposed yaw motion control, when turning on the slope, is verifed.

6.2.4 Experimental results of yaw motion control system

Table 6.5 - 6.7 show questionnaire results of yaw motion control system by researchers and wheelchair user. In five-grade evaluation, bigger number stands for good and smaller number stands for poor, 5 - Very good, 4 - Good, 3 - Average, 2 - Poor, 1 - Very poor in ease of operation, feeling of safety, comfort, mobility, and praticality rating. In required physical efforts and concentration, the numbers stand for 5 - Very low, 4 - Low, 3 - Average, 2 - High, 1 - Very High. In difference from level ground driving, 3 - Same, 2 - Little bit different, 1- Completely different.

Table 6.5: Questionnaire results of yaw motion control system by wheelchair users (Group A)

Questionnaire results about yaw motion control system (five-grade evaluation)

	w/o control	w/ control using gyroscope	w/ control using encoder
Ease of operation	3.00±0.00	5.00±0.00	4.67±0.33
Feeling of safety	3.33±0.33	4.33±0.67	4.33±0.67
Comfort	2.67±0.33	4.67±0.33	4.67±0.33
Mobility	3.00±0.58	4.67±0.33	4.67±0.33
Required physical effort	3.00±0.00	4.33±0.33	4.33±0.33
Required concentration	3.67±0.33	4.00±0.00	4.00±0.00
Practicality rating	3.00±0.00	4.33±0.33	4.33±0.33

Difference from level ground driving (three-grade evaluation)

	w/o control	w/ control using gyroscope	w/ control using encoder
Difference from level ground driving	1.00±0.00	3.00±0.00	3.00±0.00

Necessity of yaw motion control

Necessary	Maybe necessary	Maybe not necessary	Not necessary
2	1	0	0

Table 6.6: Questionnaire results of yaw motion control system by wheelchair user (Group B)

Questionnaire results about yaw motion control system (five-grade evaluation)

	w/o control	w/ control using gyroscope	w/ control using encoder
Ease of operation	2.57±0.30	4.42±0.20	4.57±0.20
Feeling of safety	2.86±0.26	4.29±0.18	4.43±0.20
Comfort	3.00±0.49	4.29±0.18	4.29±0.18
Mobility	2.86±0.55	4.29±0.18	4.29±0.18
Required physical effort	2.57±0.37	4.29±0.29	4.29±0.18
Required concentration	2.71±0.42	4.00±0.38	4.14±0.26
Practicality rating	3.00±0.31	4.57±0.20	4.58±0.20

Difference from level ground driving (three-grade evaluation)

	w/o control	w/ control using gyroscope	w/ control using encoder
Difference from level ground driving	1.00±0.00	2.43±0.20	2.43±0.20

Necessity of yaw motion control

Necessary	Maybe necessary	Maybe not necessary	Not necessary
7	0	0	0

Table 6.7: Questionnaire results of yaw motion control system by researchers (Group C)

Questionnaire results about yaw motion control system (five-grade evaluation)

	w/o control	w/ control using gyroscope	w/ control using encoder
Mobility	1.75 ± 0.72	4.21 ± 0.56	4.42 ± 0.49
Required physical effort	2.08 ± 0.95	3.92 ± 0.86	3.92 ± 0.86
Required concentration	2.33 ± 1.18	4.25 ± 0.60	4.33 ± 0.62
Practicality rating		4.21 ± 0.38	4.25 ± 0.47

Difference from level ground driving (three-grade evaluation)

	w/o control	w/ control using gyroscope	w/ control using encoder
Difference from level ground driving	1.83 ± 0.90	2.79 ± 0.38	2.75 ± 0.43

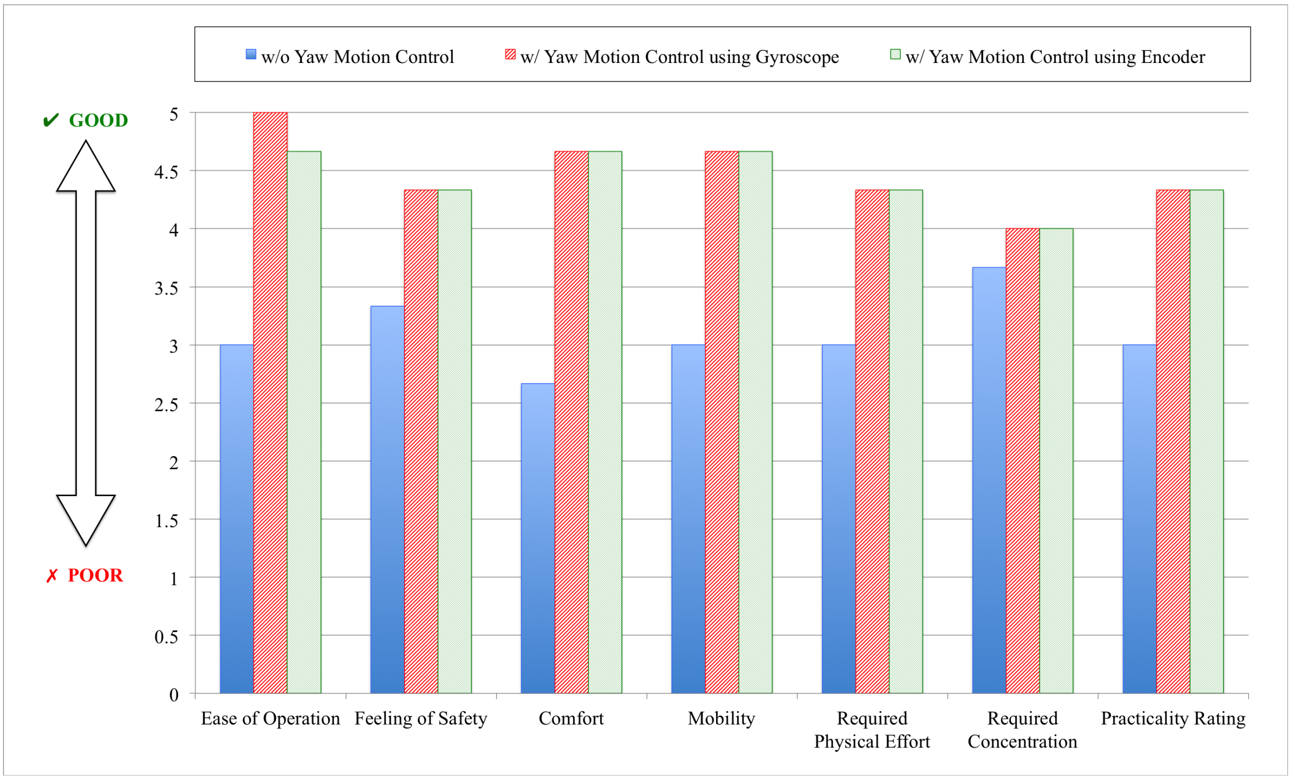


Figure 6.3: Questionnaire results of yaw motion control system (Group A)

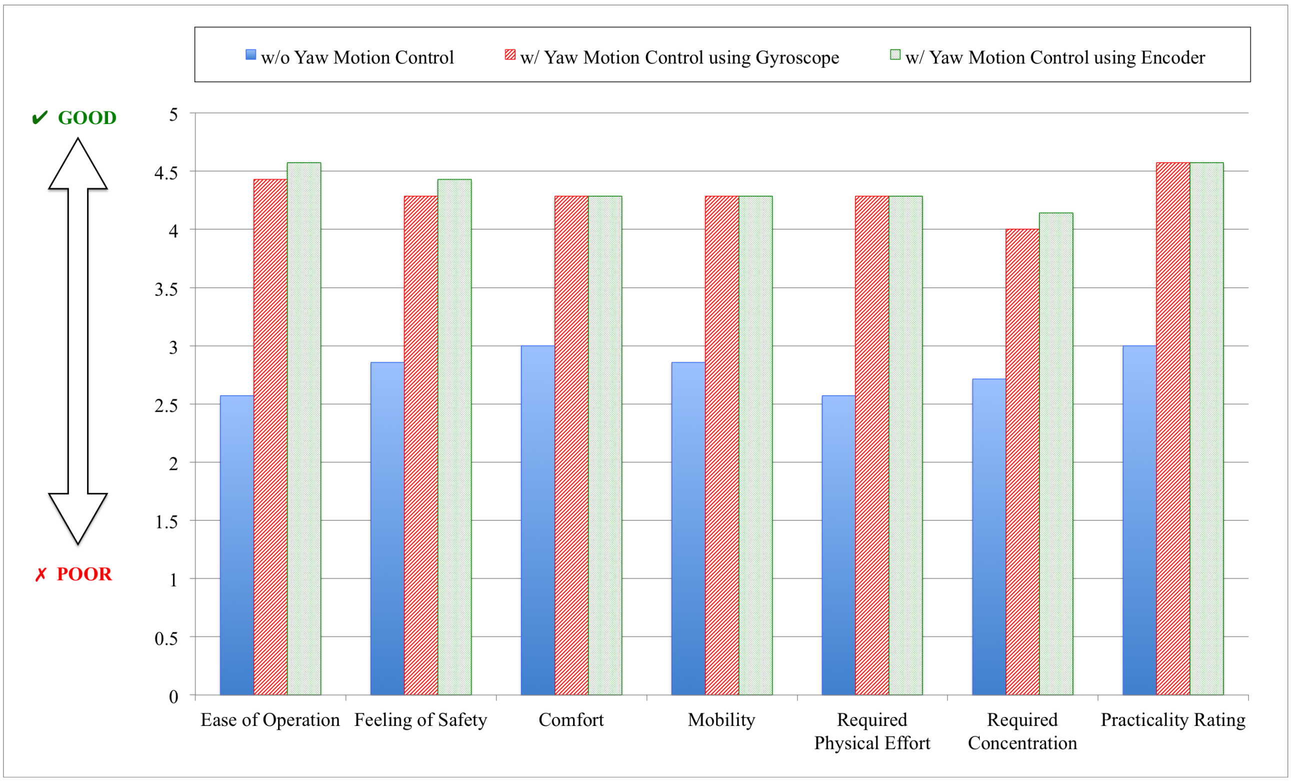


Figure 6.4: Questionnaire results of yaw motion control system (Group B)

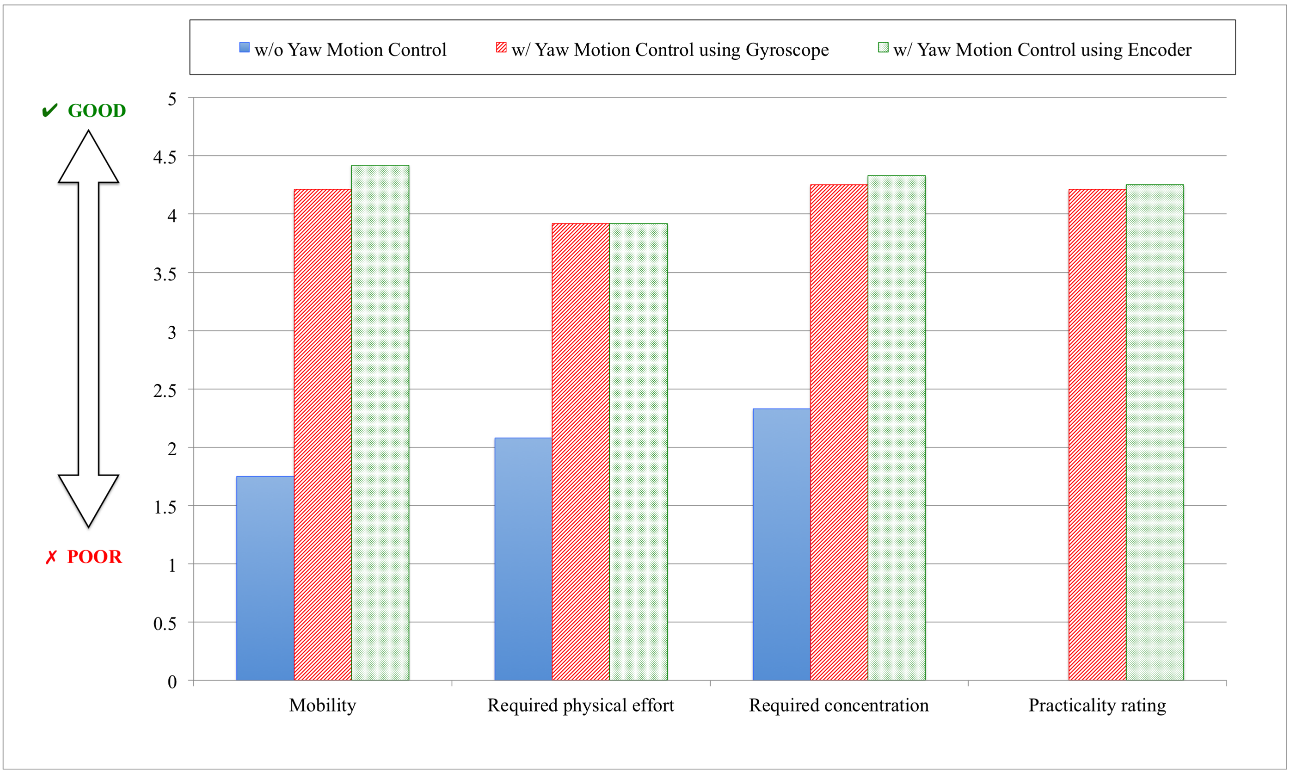


Figure 6.5: Questionnaire results of yaw motion control system (Group C)

6.2.5 Discussion on yaw motion control system

Figure 6.3 - 6.5 show results of questionnaire. Proposed yaw motion control got good points in questionnaire results from participants in every group. Group A, advanced wheelchair users, give more than 4 points (4 - good, 5 - very good) in five-level evaluation, which includes ease of use, feeling safety, comfort, mobility,required physical effort/concentration, and practicality rating. Group B and C, beginner and researchers, have similar answers. Group A give around 3 points (3- average) to without control in five-level evaluation. Group B and C had lower points, 1.5 to 3 points in without control. There were questionnaire about difference between driving lateral slope with/without proposed control and level ground in three-grade evaluation (3 - same, 2- little bit different, 1- completely different). From Table 6.5 - 6.7 , Group A answered driving lateral slope with proposed control is same with level ground driving (3 points) and completely different without control(1 point). Group B had same answer with Group A, completely different, in

without control(1 point), and feel slight difference (2.43 points) in with proposed control. Group C felt little bit different without control(1.85 point), and slight difference (2.75 points) in with proposed control." From these results, advanced user feel same in driving lateral slope with proposed control and driving level ground and other group feel almost no difference. About the necessity of yaw motion control all participations in Group A and B, answered "Necessary" or "Maybe necessary".

6.3 Implementation of One-handed Propulsion Control System for Power-assisted Wheelchair

6.3.1 One-handed Propulsion Control System

The purpose of one-handed propulsion control system is to realize a power-assisted wheelchair which is possible to manipulate with only one hand. The control system is introduced in Chapter V.

6.3.2 Subject information

Three groups of people participate in experiments. This experiment got certificate of approval on research ethics by "Subcommittee on research ethics of Life Science Committee" (identified number: 14-47 and 14-158). The document of certificate of approval is shown in Appendix B. Participations listened to the purpose, procedure, and other information of this research to participate in this research study. They checked informed consent documents and agree to participate in this research.

* **Group A** : A group of advanced wheelchair users, who rode wheelchair for more than a year.
* **Group B** : A group of beginners, who never or had a few chance to ride wheelchairs.
* **Group C** : A group of researchers, who research on wheelchairs or do related work.

Group A, B and C had different experimental environments, such as length and wide of the test course. Furthermore, there are different experimental environments within Group A.

General subject demographics for participants is shown in Table 6.8 to Table 6.10.

Table 6.8: Participant demographics of one-handed propulsion control system (Group A)

Subject	Age	Gender	Years of Wheelchair Use	Mobility Device	Disability Type	Handedness	
						Writing	Pushing
A - 1	66	Male	48 years	MWC	Osteogenesis Imperfecta	Right	Right
A - 2	47	Male	16 years	MWC (Inside) EWC (Outside)	Mitochondrial Disease	Left	Right

* MWC: Manual Wheelchair, EPW: Electric Powered Wheelchair

Table 6.9: Participant demographics of one-handed propulsion control system (Group B)

Subject	Age	Gender	Handedness		Footedness	
			Writing	Pushing something heavy	Kicking a ball	Controlling a ball
B - 1	24	Male	Right	Right	Right	Right
B - 2	23	Male	Right	Right	Right	Right
B - 3	33	Male	Right	Right	Right	Right
B - 4	25	Male	Right	Right	Right	Right
B - 5	25	Male	Right	Right	Right	Right
B - 6	31	Male	Right	Right	Right	Right
B - 7	25	Male	Right	Right	Right	Right
B - 8	25	Male	Right	Right	Right	Right
B - 9	25	Male	Right	Right	Right	Right

Table 6.10: Participant demographics of one-handed propulsion control system (Group C)

Subject	Age	Gender	Years of Wheelchair Research	Handedness
C - 1	N/A	Male	7 years	Right
C - 2	47	Male	11 years	N/A
C - 3	36	Male	2 years	Right
C - 4	44	Male	N/A	Right
C - 5	39	Male	2 years	Right
C - 6	N/A	Male	7 years	Right
C - 7	25	Male	N/A	Right
C - 8	51	Male	7 years	Right
C - 9	47	Male	4 years	Right
C - 10	26	Male	N/A	Right
C - 11	N/A	Male	N/A	Right
C - 12	24	Male	N/A	Right

6.3.3 Experiment environment of one-handed propulsion control system

Two type of experiments are done in one-handed propulsion control system.

6.3.3.1 Recognition rate

First experiment is a simple experiment to verify ease of manipulation. Wheelchair user will give torque to the wheelchair, right after he/she listen to the explanation about how to operate the wheelchair. First, wheelchair user gives torque to the wheelchair to rotate. Try pure rotation 5 times and count correct movement. After the rotation experiments, user gives torque to the wheelchair to go straight. Try going straight experiments 5 times and count correct movement. Recognition rate will be calculated as follows:

$$n_R = \frac{N_{correct}}{N_{try}} \tag{6.1}$$

where n_R is recognition rate and $N_{correct}$ is number of correct movements. N_{try} is number of experiments, which is 5 in this experiment.

Wheelchair user will practice to get use to the one-handed propulsion control system, after the first recognition experiments. If user feels the thresholds $\dot{T}^r_{thr}$ and $\dot{T}^s_{thr}$ are not suitable for him/her, adjust the thresholds which is suitable for him/her. After the practice the same experiment to calculate the recognition rate of one-handed propulsion control system will be held again. Second recognition experiment is held to verify the effect of the practice.

6.3.3.2 Driving test course

Second experiment is driving test course. Figure 6.6 shows test course one-handed propulsion control system. The purpose of the experiment is to verify one-handed propulsion control system in various movements. Turning operation was verified with left and right turn while moving forward and backward. Three of Group B members, B - 1, B - 2, and B - 6, did same experiment twice.

1. go forward and right turn (forward)

2. right turn (backward) and go backward

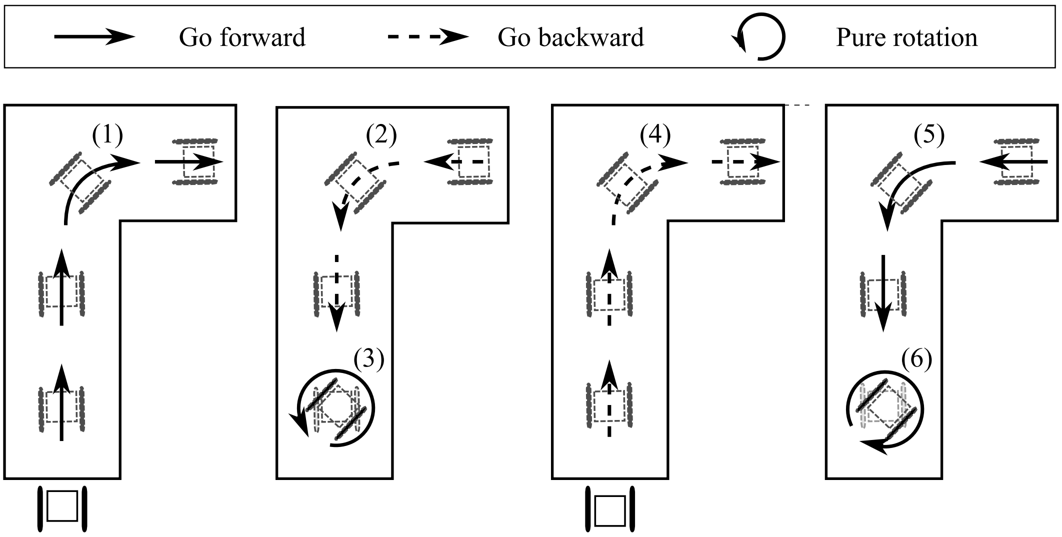


Figure 6.6: Experimental environment: Test course of one-handed propulsion control system

3. pure rotation in counterclockwise (180 degree)
4. go backward and left turn (backward)
5. left turn (forward) and go forward
6. pure rotation in clockwise (180 degree)

6.3.4 Experimental results of first trial drive on one-handed propulsion control system

6.3.4.1 Recognition rate of one-handed propulsion control system

Recognition rates are shown in Table 6.11. Recognition rate is calculated by Eq. (6.1).

Table 6.11: Recognition rate

	Before the Practice		After the Practice		Practice
	Rotation [%]	Going straight [%]	Rotation [%]	Going straight [%]	time [min]
Group B	91.11±4.84	91.11±4.84	84.44±4.44	100.00±0.00	14±4
Group C	81.67±6.26	100.00±0.00	93.33±2.84	95.00±2.61	10 (given)

6.3.4.2 Questionnaire results of one-handed propulsion control system

Table 6.12 - 6.14 show questionnaire results of one-handed propulsion control system. In five-grade evaluation, bigger number stands for good and smaller number stands for poor, as same as evaluation of the yaw motion control system. In five-grade evaluation, the number stands for 5 - Very good, 4 - Good, 3 - Average, 2 - Poor, 1 - Very poor in ease of operation, feeling of safety, comfort, mobility, and praticality rating. In required physical efforts and concentration, the numbers stand for 5 - Very low, 4 - Low, 3 - Average, 2 - High, 1 - Very High.

In possibility of doing everyday task, such as opening/closing of doors, grabbing objects on the move, sports while operating the wheelchair, the number stands for 3 - Possible, 2 - Possible but difficult, and 1 - Impossible.

Table 6.12: Questionnaire results of one-handed propulsion control by wheelchair users (Group A)

Questionnaire results of one-handed propulsion control (five-grade evaluation)

	w/o turning mode	w/ turning mode
Ease of operation	3.00±0.00	3.00±1.00
Feeling of safety	2.50±0.50	1.50±0.50
Comfort	2.50±0.50	2.00±1.00
Mobility	3.00±0.00	2.50±0.1.50
Required physical effort	4.50±0.50	4.00±0.00
Required concentration	2.50±0.50	1.50±0.50
Practicality rating	2.50±0.50	2.00±0.00

Possibility of doing everyday tasks (three-grade evaluation)

	w/o turning mode	w/ turning mode
Possibility of doing everyday task	2.5±0.50	2.50±0.50

Necessity of one-handed propulsion control

Necessary	Maybe necessary	Maybe not necessary	Not necessary
1	1	0	0

Necessity of turning mode

Necessary	Maybe necessary	Maybe not necessary	Not necessary
1	1	0	0

Table 6.13: Questionnaire results of one-handed propulsion control by beginners (Group B)

Questionnaire results of one-handed propulsion control (five-grade evaluation)

	w/o turning mode	w/ turning mode
Ease of operation	3.00±0.47	2.89±0.31
Feeling of safety	3.33±0.41	2.33±0.17
Comfort	3.11±0.48	2.89±0.35
Mobility	2.67±0.37	3.44±0.38
Stop	3.44±0.29	2.78±0.28
Required physical effort	4.00±0.33	3.56±0.38
Required concentration	2.89±0.42	1.78±0.22
Practicality rating	3.33±0.44	3.66±0.41

Possibility of doing everyday tasks (three-grade evaluation)

	w/o turning mode	w/ turning mode
Possibility of doing everyday task	2.11±0.26	2.00±0.29

Necessity of one-handed propulsion control

Necessary	Maybe necessary	Maybe not necessary	Not necessary
6	3	0	0

Necessity of turning mode

Necessary	Maybe necessary	Maybe not necessary	Not necessary
6	2	1	0

Table 6.14: Questionnaire results of one-handed propulsion control system by researchers (Group C)

Questionnaire results about one-handed propulsion control system (five-grade evaluation)

	w/o turning mode	w/ turning mode
Ease of operation		
in straight motion	3.17 ± 1.21	2.58 ± 1.11
in rotation motion	3.17 ± 1.07	2.75 ± 1.09
Required concentration	2.58 ± 0.95	2.04 ± 0.97
Practicality rating	3.00 ± 1.22	2.88 ± 1.00

Necessity of turning while driving

Necessary	Neither	Not necessary
7	3	1

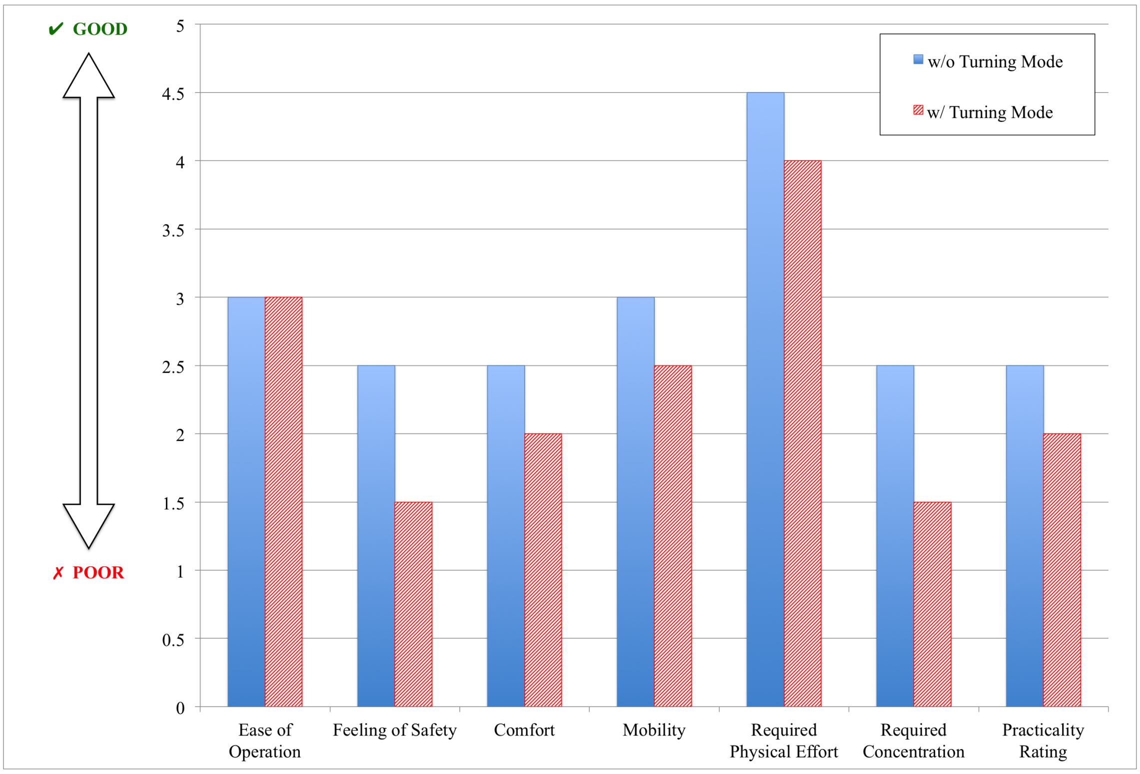


Figure 6.7: Questionnaire results of one-handed propulsion control system (Group A)

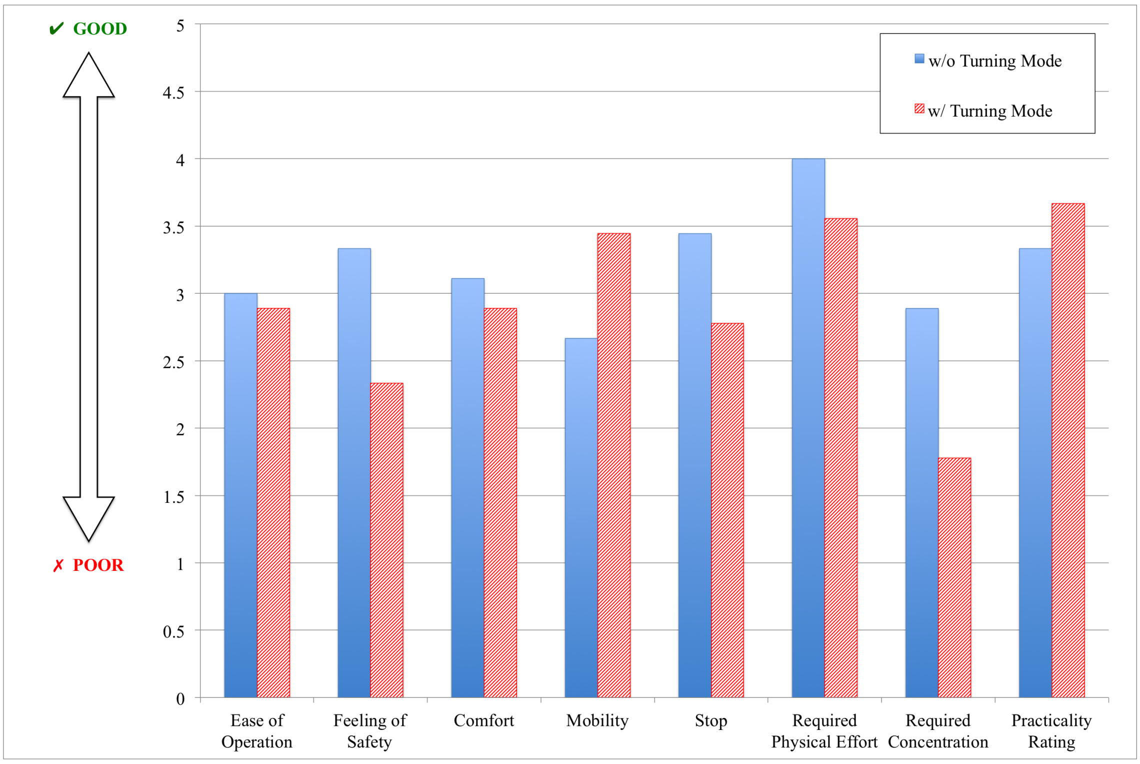


Figure 6.8: Questionnaire results of one-handed propulsion control system (Group B)

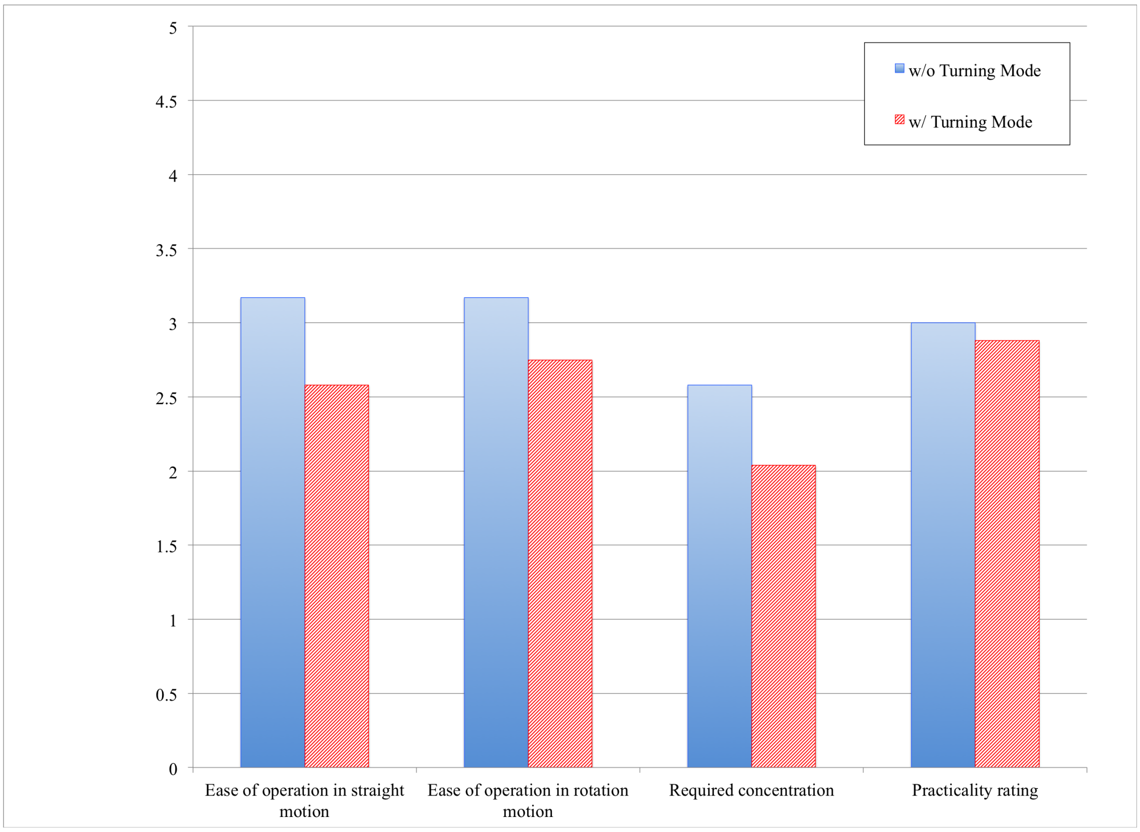


Figure 6.9: Questionnaire results of one-handed propulsion control system (Group C)

6.3.5 Discussion on one-handed propulsion control system

Figure 6.7 - 6.9 show results of questionnaire.

One-handed propulsion control system with turning mode get worse points than without turning mode in all area, except mobility and practicality rating of Group B. Howerever, according to questionnaire which ask the necessit of turning mode (Table 6.12 - 6.14). There were 15 of 22 participants, who gave positive answer on turning mode. There were only 2 of 22 participants, who gave negative answer on turning mode. The reason of the negative evaluation was the hardness of the operation, which is not used to it. There was also comment that if the user get used to the system, it will be great system. However, it is hard to learn how to operate the system in an hour.

6.3.6 Comparison between results of first and second trial drive of one-handed propulsion control system

Three beginners, B - 1, B - 2, and B- 6 of Table 6.9, had second trial drive to evaluate the one-handed propulsion control system to verify influence of the practice experience.

6.3.6.1 Recongnition rate of one-handed propulsion control system

The results of recognition rate are shown in Table 6.15. The recognition rates are calculated by Eq. (6.1).

6.3.6.2 Questionnaire results of one-handed propulsion control system

Table 6.16 - 6.18 show questionnaire results of one-handed propulsion control system evaluated by three beginners. Figure 6.10 - 6.12 show the results in graph.

In five-grade evaluation, bigger number stands for good and smaller number stands for poor, as same as evaluation of the yaw motion control system. In five-grade evaluation, the number stands for 5 - Very good, 4 - Good, 3 - Average, 2 - Poor, 1 - Very poor in ease of operation, feeling of safety, comfort, mobility, and praticality rating. In required physical efforts and concentration, the numbers stand for 5 - Very low, 4 - Low, 3 - Average, 2 - High, 1 - Very High.

In possibility of doing everyday task, such as opening/closing of doors, grabbing objects on the move, sports while operating the wheelchair, the number stands for 3 - Possible, 2 - Possible

Table 6.15: Recognition rate of first and second trial drive of one-handed propulsion control system

		Before the Practice		After the Practice		Practice
		Rotation [%]	Going straight [%]	Rotation [%]	Going straight [%]	time [min]
B - 1	1st	100	100	80	100	7
	2nd	100	100	100	100	3
B - 2	1st	100	100	80	100	9
	2nd	100	100	80	100	3
B - 6	1st	60	60	80	100	4
	2nd	100	80	80	80	3

but difficult, and 1 - Impossible.

Table 6.16: Questionnaire results of comparison experiments between first and second trial ride of one-handed propulsion control (B -1)

Questionnaire results of one-handed propulsion control (five-grade evaluation)

	w/o turning mode		w/ turning mode	
	1st	2nd	1st	2nd
Ease of operation	4	3	3	4
Feeling of safety	4	3	3	4
Comfort	5	3	4	4
Mobility	4	3	3	4
Stop	3	4	2	3
Required physical effort	5	5	5	5
Required concentration	4	2	3	3
Practicality rating	5	3	4	4

Possibility of doing everyday tasks (three-grade evaluation)

	w/o turning mode		w/ turning mode	
	1st	2nd	1st	2nd
Possibility of doing everyday task	3	2	2	3

Necessity of one-handed propulsion control

Necessary	Maybe necessary	Maybe not necessary	Not necessary
1st, 2nd	-	-	-

Necessity of turning mode

Necessary	Maybe necessary	Maybe not necessary	Not necessary
1st, 2nd	-	-	-

Table 6.17: Questionnaire results comparison experiments between first and second trial drive of one-handed propulsion control (B -2)

Questionnaire results of one-handed propulsion control (five-grade evaluation)

	w/o turning mode		w/ turning mode	
	1st	2nd	1st	2nd
Ease of operation	5	4	2	2
Feeling of safety	5	4	2	2
Comfort	4	3	2	3
Mobility	4	4	5	5
Stop	4	5	4	5
Required physical effort	4	4	4	2
Required concentration	4	4	1	1
Practicality rating	5	4	2	2

Possibility of doing everyday tasks (three-grade evaluation)

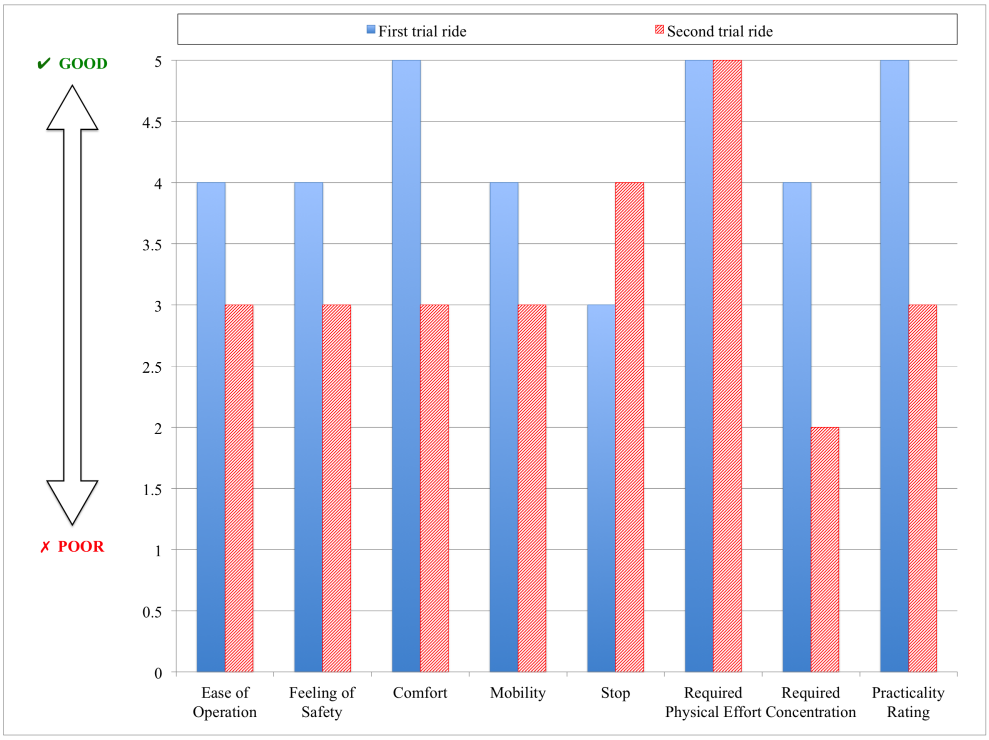
	w/o turning mode		w/ turning mode	
	1st	2nd	1st	2nd
Possibility of doing everyday task	3	3	1	1

Necessity of one-handed propulsion control

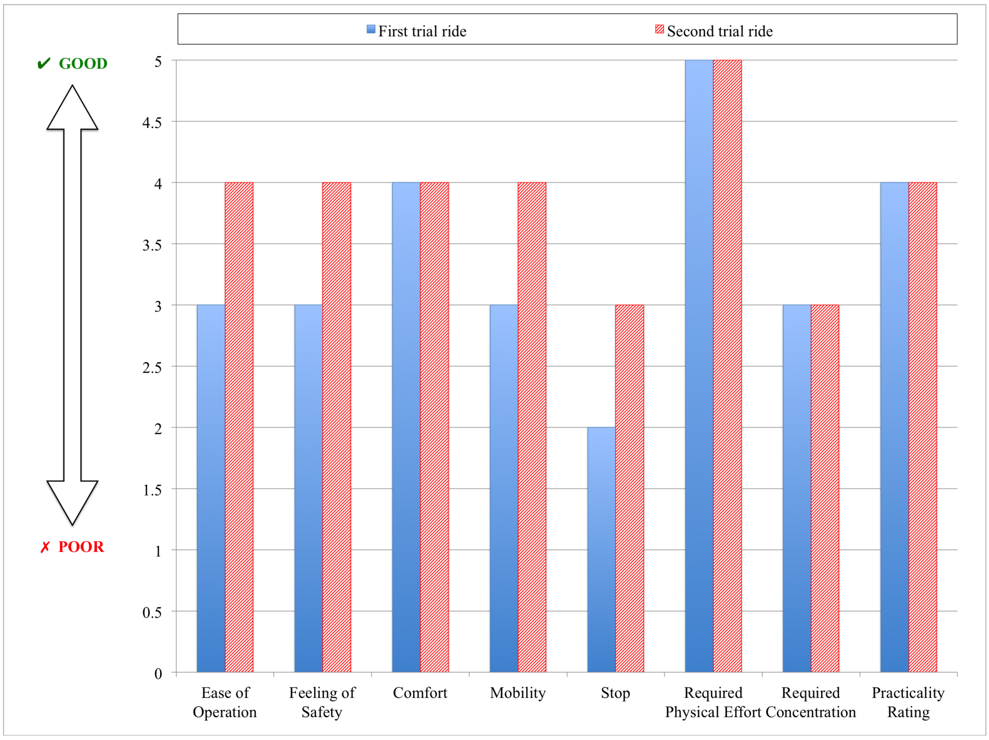
Necessary	Maybe necessary	Maybe not necessary	Not necessary
1st, 2nd	-	-	-

Necessity of turning mode

Necessary	Maybe necessary	Maybe not necessary	Not necessary
2nd	1st	-	-

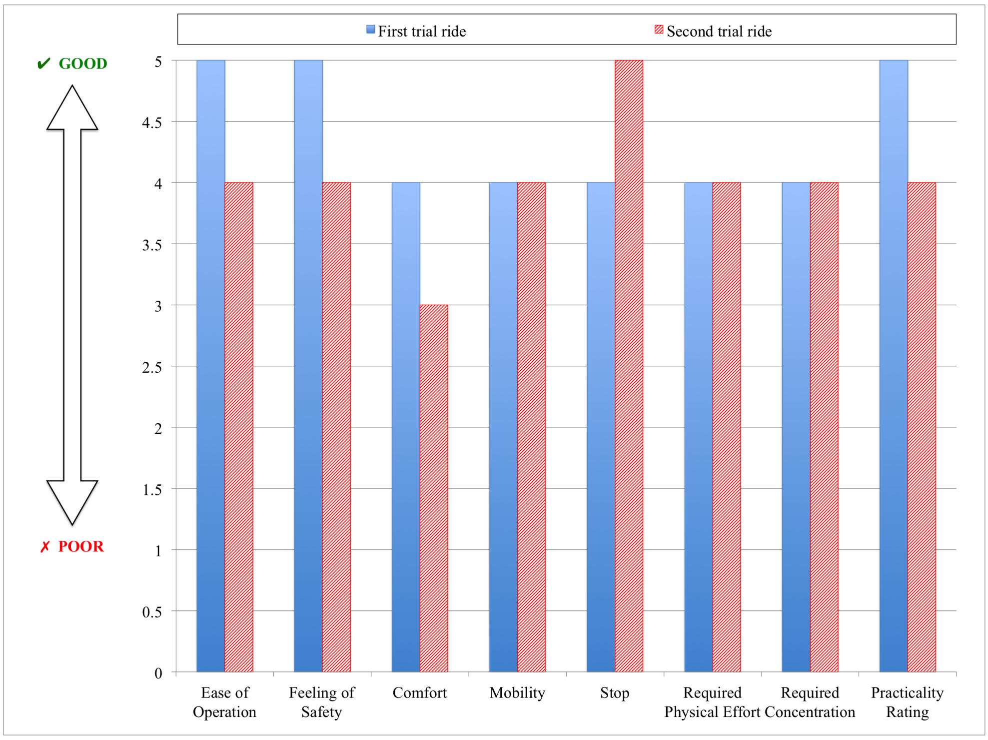


(a) without Turning Mode

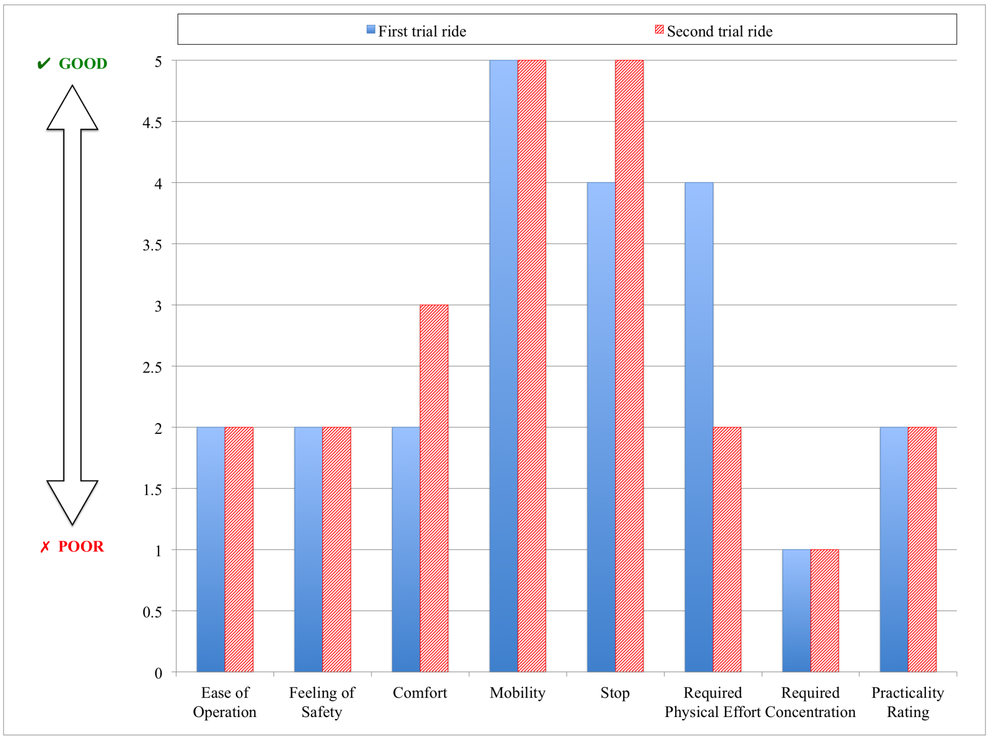


(b) with Turning Mode

Figure 6.10: Questionnaire results of comparison experiments between first and second trial ride of one-handed propulsion control (B - 1)



(a) without Turning Mode



(b) with Turning Mode

Figure 6.11: Questionnaire results of comparison experiments between first and second trial ride of one-handed propulsion control (B - 2)

Table 6.18: Questionnaire results comparison experiments between first and second trial drive of one-handed propulsion control (B - 6)

Questionnaire results of one-handed propulsion control (five-grade evaluation)

	w/o turning mode		w/ turning mode	
	1st	2nd	1st	2nd
Ease of operation	4	4	3	3
Feeling of safety	4	4	3	4
Comfort	4	4	3	3
Mobility	4	4	3	4
Stop	3	3	2	2
Required physical effort	5	3	2	2
Required concentration	5	4	2	2
Practicality rating	4	4	4	4

Possibility of doing everyday tasks (three-grade evaluation)

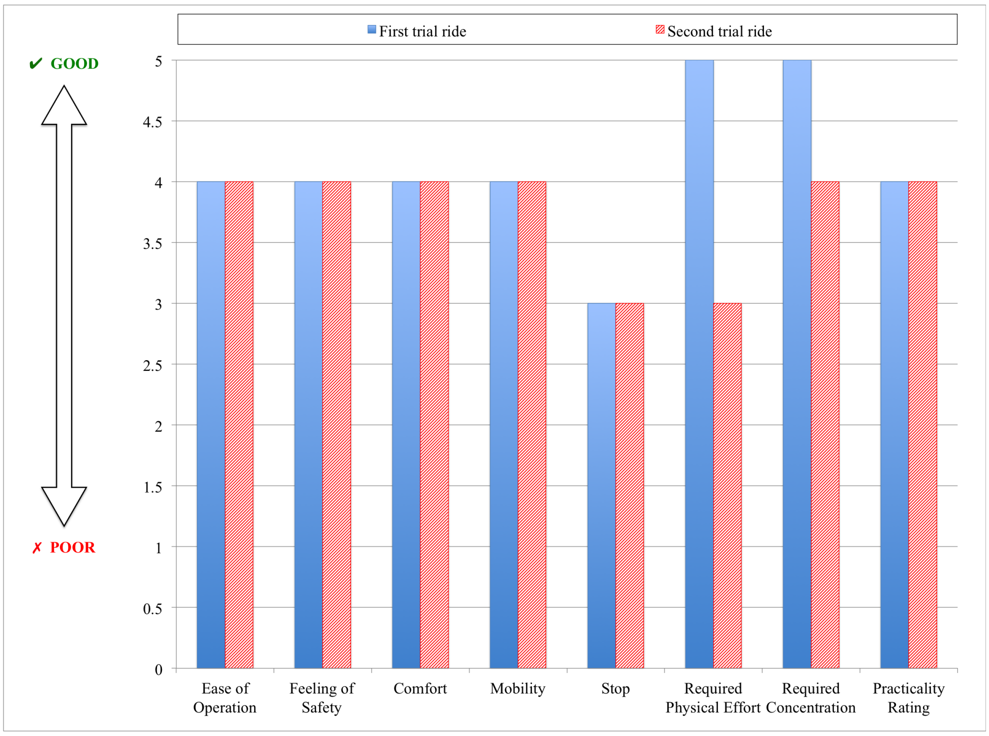
	w/o turning mode		w/ turning mode	
	1st	2nd	1st	2nd
Possibility of doing everyday task	1	3	2	3

Necessity of one-handed propulsion control

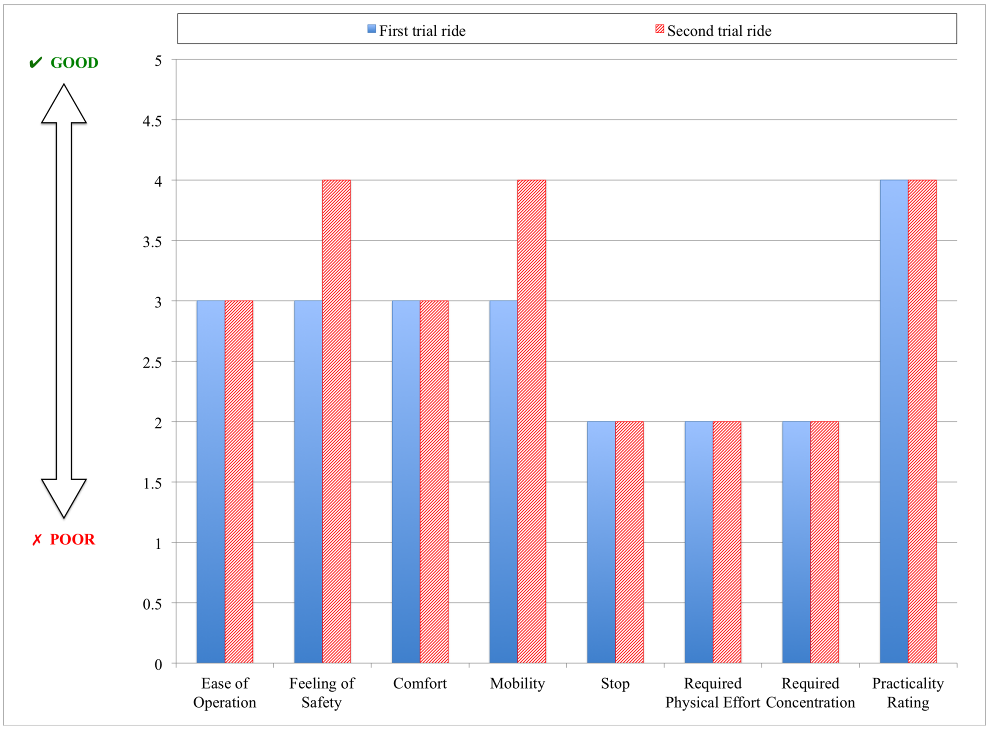
Necessary	Maybe necessary	Maybe not necessary	Not necessary
2nd	1st	-	-

Necessity of turning mode

Necessary	Maybe necessary	Maybe not necessary	Not necessary
1st, 2nd	-	-	-



(a) without Turning Mode



(b) with Turning Mode

Figure 6.12: Questionnaire results of comparison experiments between first and second trial ride of one-handed propulsion control (B - 6)

6.3.7 Discussion on comparison experiments of first and second trial ride on one-handed propulsion control system

According to Fig. 6.10(a), second trial ride without turning mode receive worse or same evaluations than first trial ride, expect evaluation of Stop. It shows opposite result in Fig. 6.10(b). The second trial ride with turning mode receive better or same evaluations than first trial ride. Other participants have about the same results, which are shown in Fig. 6.11 and Fig. 6.12.

From the comparison experiments of first and second trial ride on one-handed propulsion control system, it can be said that if the user is used to the one-handed propulsion control system, the control system with turning mode receive better evaluation than without the turning mode.

From the comments, participants feel uncomfortable without turning mode in second trial ride. In first trial ride, the participants never experience the one-handed propulsion control system with turning mode, so that they gave high points to the system. However, once they tried the turning mode, they feel like change the direction while running which is impossible in without turning mode.

For the system with turning mode, they were not used to it in the first trial ride. However, in the second trial ride, they are able to operate the system better than the first trial ride. The practice time for first trial ride were 30 to 57 minutes, except during the experiments on test course. However the practice time for second trial ride were 3 to 28 minutes, except during the experiments on test course. The practice time decrease more than the half. The whole practice time is 33 to 79 minutes, and they operate much better on their second trial ride.

Stop motion is one of the hardest motion in one-handed propulsion control system, because it is totally different from other wheelchair. From Fig. 6.10 - 6.12, stop motion receive better evaluation on second trial ride than that of first in both without and with turning mode. From this result, it can be said that the stop motion of the control system will be acclimatize by practice.

6.4 Chapter Summary

Yaw motion control system using yaw moment observer is proposed and verify with experiments. Proposed yaw motion control got high evaluated numbers in questionnaire results.

One-handed propulsion control system is proposed. The control system with only going straight and pure rotation is proposed. It got average evaluated numbers in questionnaire results. One-handed propulsion control system with turning mode while driving is also proposed to realize the advanced movement of one-handed propulsion control system. Control system with turning mode got poor evaluate numbers at first trial ride, however, from the comparison experiments of first and second trial ride on one-handed propulsion control system, it is shown that the evaluation of the system improve by the practice.

CHAPTER VII

Conclusions and Open Issues

Improvement of safety and ease of maneuver are important tasks for wheelchair research. In this thesis, human-friendly control systems - assistive control, yaw motion control and one-handed propulsion control - are proposed to improve safety, mobility, and ease of use. Furthermore, proposed control systems improve quality of life of wheelchair users.

First, a novel two-dimensional assistive control for power-assisted wheelchairs considering straight and rotational motion decomposition is proposed. Assistive control is the most basic control system of power-assisted wheelchairs. Therefore, the wheelchair system will greatly influenced by the assistive control system. One of conventional assistive control, proposed by Seki et al., is designed for motion of traveling in straight line. However, it is difficult for wheelchair users to rotate using conventional assistive control. The proposed assistive control is designed for wheelchair both going straight and rotating. Assist rate and time constant of going straight and rotating, is able to adjust independently. Therefore, power assist performance in rotating motion is improved compared to conventional system.

Second, yaw motion control under lateral disturbance environments is proposed in this paper to improve safety and quality of life of wheelchair user. On lateral slope, lateral disturbances make the wheelchair's speed as well as direction unable to manage, which can cause accidents and may lead to injury. To overcome this problem, two-degree-of-freedom yaw motion control system is proposed in this thesis. The proposed yaw motion control system includes feed forward control, feedback control, and yaw moment observer to compensate disturbance of yaw direction. Using the proposed yaw motion control, a wheelchair would not be subject to influence from lateral disturbance, therefore, performance of the wheelchair will be improve. Effectiveness of the yaw motion control is verified by two kinds of experiments, going straight on the slope, and turning on the slope.

Third, one-handed propulsion control system for a power-assisted wheelchair is proposed. For people also with hemiplegia or a arm injury, a wheelchair operable with one hand is necessary. Furthermore, there are many situations that wheelchair users need to do something with a hand, such as holding a bag or opening the door, while moving. Therefore, one-handed propulsion is necessary not only for users who are able to use only one hand, but also are using the two-handed drive manual wheelchair. However, it is impossible to control a standard manual wheelchair or power-assist wheelchair with only one hand. The one-handed propulsion control system for a power-assisted wheelchair was proposed previously. Conventional one-handed propulsion control system allows the user to go straight, do pure rotations, and turn while running. However, turning movement is different from general turning movement of wheelchair in conventional system. Wheelchair user feels a sense of incompatibility with conventional control system. In this thesis, an improved one-handed propulsion system that realizes advanced turning motion is proposed. Advanced turning motion is focused in two-handed propulsion wheelchair. Analysis result of human torque in two-handed propulsion is applied to turning motion in one-handed propulsion control system.

Last, implementation of proposed control systems is introduced in this thesis. There are difficulties to apply novel control system to daily use welfare device. There are many academic researches on welfare devices, however, not all of them interact with user of welfare devices. Gap between valuable academic research and daily use technology is one of difficulties in practical application. The research that has high academic value does not always become useful and valuable product. Furthermore, needs from users are not directly related to academic research. Another difficulty comes from the cost of the device. It will be hard to use devices, if the cost of the device is expensive, even the device is helpful. High performance comes from good devices. However, high performance and cost is trade-off in most devices. Good devices, such as sensors with high resolution, are expensive. Therefore, to make helpful welfare device, the research has to focus on not only better performance but also lower cost. Welfare device is not same with other devices in terms of cost. There are government subsidize for welfare devices. However, government subsidize is not applied for all welfare devices. It is important to develop the welfare device which has potential to get government subsidize. In this research, a new wheelchair system is constituted for practical application. Proposed assistive control, yaw motion control and one-handed propulsion control are applied to the new wheelchair system. To lower the cost, yaw motion control using encoder instead of gyroscope is considered. Effectiveness of the implementation has been verified by experiments and questionnaire from daily wheelchair user, wheelchair researchers and, beginners. Proposed yaw motion control got good evaluate points in questionnaire results. It is verified that proposed yaw motion control system improves performance of ease of operation, feeling of safety, comfort and Mobility on lateral slope. Furthermore, all participations in Group A and B, answered “Necessary” or “Maybe necessary”. Proposed one-handed propulsion control got average evaluate points in without turning mode and poor evaluate points in with turning mode. However, necessity of the turning mode is high. To verify effect of practice, comparison experiment had been done. From the result, participants gave worse points to without turning mode in second trial ride, and gave better points to with turning mode. From the comparison experiments, two things get cleared. First, participants feel discomforts without turning. Second, it is shown that the evaluation of the system with turning mode is improved by the practice. In first trial ride, they did not know mobility of turning mode, therefore, they did not feel discomforts at first time. However, in second trial ride, they try to turn while riding system without turning mode, because they know the high mobility of turning mode. Therefore, participants gave worse point to without turning mode. In turning mode, participants get used to the control system and gave better points to with turning mode.

For implementation, yaw motion control system using low-resolution encoder should be researched for the futurework. For one-handed propulsion control system, if difference between mobility of left and right turn is solved the mobility of one-handed propulsion control will be improved.

APPENDIX

APPENDIX A

Questionnaire

APPENDIX B

Certificate of Approval on Research Ethics

実験前アンケート　Pre-experiment questionnaire

氏名 Name			
年齢 Age	歳	性別 Gender	男 M　女 F
身長 Height	cm	体重 Weight	kg

利き手 Handedness	左利き Left-handed　右利き Right-handed

車椅子の経験 Have you ever use a wheelchair?				有 Yes　無 No
有と答えた場合, If Yes,				
使用目的 Purpose	自分用 Personally	介護用 Nursing care	研究・開発用 Research・Development	その他 etc.
期間と時期 When and how long?				

車椅子のご使用の支障になる可能性のある問題をお持ちですか。 Do you have any problems that may affect your ability to use a wheelchair?

今現在の体調はいかがですか。 How is your physical condition right now?

＊言葉の定義

制御なし:　ヨー運動制御なし

ヨー運動制御1:　ジャイロスコープを用いたヨー運動制御

ヨー運動制御2:　エンコーダを用いたヨー運動制御

実験後アンケート　　Post-experiment questionnaire

各システムに対して，次の項目を評価してください

For each system, please rate the following :

（1）操作性はいかがですか。操作しやすいですか。

操作しやすい　←――――――→　操作しにくい

		非常に良い Very good	良い Good	普通 Average	悪い Poor	非常に悪い Very poor
操作の使いやすさ Ease of operation	制御なし No control	5	4	3	2	1
	ヨー運動制御1 Yaw motion control1	5	4	3	2	1
	ヨー運動制御2 Yaw motion control2	5	4	3	2	1
コメント Comment						

（2）走行中に安心感を感じますか。このシステムを利用した走行は安全だと思いますか。

安全・安心　←―――――――→　不安全・不安

		非常に良い Very good	良い Good	普通 Average	悪い Poor	非常に悪い Very poor
安全・安心感 Feeling of safety	制御なし No control	5	4	3	2	1
	ヨー運動制御1 Yaw motion control1	5	4	3	2	1
	ヨー運動制御2 Yaw motion control2	5	4	3	2	1
コメント Comment						

各システムに対して，次の項目を評価してください
For each system, please rate the following :

（3）快適な走行ができますか。

快適 ←―――――――――――――→ 不愉快

		非常に良い Very good	良い Good	普通 Average	悪い Poor	非常に悪い Very poor
快適性 Comfort	制御なし No control	5	4	3	2	1
	ヨー運動制御1 Yaw motion control1	5	4	3	2	1
	ヨー運動制御2 Yaw motion control2	5	4	3	2	1
コメント Comment						

（4）移動しやすいですか。

移動しやすい ←―――――――――→ 移動しにくい

		非常に良い Very good	良い Good	普通 Average	悪い Poor	非常に悪い Very poor
移動性 Mobility	制御なし No control	5	4	3	2	1
	ヨー運動制御1 Yaw motion control1	5	4	3	2	1
	ヨー運動制御2 Yaw motion control2	5	4	3	2	1
コメント Comment						

各システムに対して，次の項目を評価してください

For each system, please rate the following :

（5）走行により腕や手など身体は疲れますか。どのくらい身体能力を必要としますか。

疲れない ←――――――――――――→ 疲れる

		非常に低い Very low	低い Low	普通 Average	高い High	非常に高い Very High
必要な身体能力 Required physical effort	制御なし No control	5	4	3	2	1
	ヨー運動制御1 Yaw motion control1	5	4	3	2	1
	ヨー運動制御2 Yaw motion control2	5	4	3	2	1
コメント Comment						

（6）操作時どのぐらい集中力が必要ですか。

手軽に漕げる ←――→ 非常に意識して漕ぐ

		非常に低い Very low	低い Low	普通 Average	高い High	非常に高い Very High
必要な集中力 Required concentration	制御なし No control	5	4	3	2	1
	ヨー運動制御1 Yaw motion control1	5	4	3	2	1
	ヨー運動制御2 Yaw motion control2	5	4	3	2	1
コメント Comment						

各システムに対して，次の項目を評価してください
For each system, please rate the following :

（7）各システムについて，総合的な評価をしてください。

		非常に良い Very good	良い Good	普通 Average	悪い Poor	非常に悪い Very poor
実用性評価 Practicality rating	制御なし No control	5	4	3	2	1
	ヨー運動制御1 Yaw motion control1	5	4	3	2	1
	ヨー運動制御2 Yaw motion control2	5	4	3	2	1
コメント Comment						

（7）平地での走行との違いはありますか。

		同様 Same	多少差がある Little bit different	大きな違いがある Completely different
平地走行との違い Difference from level ground drive	制御なし No control	3	2	1
	ヨー運動制御1 Yaw motion control1	3	2	1
	ヨー運動制御2 Yaw motion control2	3	2	1
コメント Comment				

ヨー運動制御システムを搭載した車椅子に慣れるまでどれくらいの練習が必要と感じますか。 How much practice do you feel is required in order to get used to the wheelchair with the yaw motion control system?

ヨー運動制御システムのメリットは何だと思いますか。 Regarding the yaw motion control system, what is the merit of this system?

ヨー運動制御は必要だと思いますか。 Do you think the yaw motion control is necessary?	必要 Yes	多少必要 Maybe	あまり必要ではない Maybe not	不要 No

ヨー運動制御システムに関して，何か改良すべきだと思いますか。 Regarding the yaw motion control system, what do you think should be improved?

もし他にご意見・ご感想があればご記入ください。 If you have any other opinions or thoughts, please express them below?

ご協力ありがとうございます。Thank you very much for your cooperation.

実験前アンケート　　Pre-experiment questionnaire

氏名 Name			
年齢 Age	歳	性別 Gender	男 M　女 F

文章を書く時 Preferred hand when writhing	左手 Left hand　右手 Right hand
重いものを押す時 Preferred hand when pusshing something heavy	左手 Left hand　右手 Right hand

遠くへボールを蹴る時 Preferred foot when kicking a ball afar	左足 Left foot　右足 Right foot
ボールを操る時 Preferred foot when controlling a ball	左足 Left foot　右足 Right foot

車椅子の経験 Have you ever use a wheelchair?				有 Yes　無 No
有と答えた場合, If Yes,				
使用目的 Purpose	自分用 Personally	介護用 Nursing care	研究･開発用 Research･Development	その他 etc.
期間と時期 When and how long?				
片手漕ぎの車椅子に乗ったことがありますか。 Have you ever use one-handed propulsion wheelchair?				有 Yes　無 No
(有と答えた場合) 乗った期間と時期 If Yes, when and how many times have you used it?				

車椅子のご使用の支障になる可能性のある問題をお持ちですか。 Do you have any problems that may affect your ability to use a wheelchair?

今現在の体調はいかがですか。 How is your physical condition right now?

実験後アンケート　Post-experiment questionnaire

各システムに対して，次の項目を評価してください

For each system, please rate the following :

（1）操作性はいかがですか。操作しやすいですか。

操作しやすい　←――――――→　操作しにくい

		非常に良い Very good	良い Good	普通 Average	悪い Poor	非常に悪い Very poor
操作の使いやすさ Ease of operation	走行中旋回なし without turning mode	5	4	3	2	1
	走行中旋回あり with turning mode	5	4	3	2	1
コメント Comment						

（2）走行中に安心感を感じますか。このシステムを利用した走行は安全だと思いますか。

安全・安心　←―――――――→　不安全・不安

		非常に良い Very good	良い Good	普通 Average	悪い Poor	非常に悪い Very poor
安全・安心感 Feeling of safety	走行中旋回なし without turning mode	5	4	3	2	1
	走行中旋回あり with turning mode	5	4	3	2	1
コメント Comment						

各システムに対して，次の項目を評価してください
For each system, please rate the following :

（3）快適な走行ができますか。

快適 ←――――――――――――→ 不愉快

		非常に良い Very good	良い Good	普通 Average	悪い Poor	非常に悪い Very poor
快適性 Comfort	走行中旋回なし without turning mode	5	4	3	2	1
	走行中旋回あり with turning mode	5	4	3	2	1
コメント Comment						

（4）移動しやすいですか。

移動しやすい ←――――――――→ 移動しにくい

		非常に良い Very good	良い Good	普通 Average	悪い Poor	非常に悪い Very poor
移動性 Mobility	走行中旋回なし without turning mode	5	4	3	2	1
	走行中旋回あり with turning mode	5	4	3	2	1
コメント Comment						

各システムに対して，次の項目を評価してください
For each system, please rate the following :

（5）走行により腕や手など身体は疲れますか。どのくらい身体能力を必要としますか。

疲れない ←――――――――――――→ 疲れる

		非常に低い Very low	低い Low	普通 Average	高い High	非常に高い Very High
必要な身体能力 Required physical effort	走行中旋回なし without turning mode	5	4	3	2	1
	走行中旋回あり with turning mode	5	4	3	2	1
		5	4	3	2	1
コメント Comment						

（6）操作時どのぐらい集中力が必要ですか。

手軽に漕げる ←――→ 非常に意識して漕ぐ

		非常に低い Very low	低い Low	普通 Average	高い High	非常に高い Very High
必要な集中力 Required concentration	走行中旋回なし without turning mode	5	4	3	2	1
	走行中旋回あり with turning mode	5	4	3	2	1
コメント Comment						

各システムに対して，次の項目を評価してください

For each system, please rate the following :

(7)各システムについて，総合的な評価をしてください。

		非常に良い Very good	良い Good	普通 Average	悪い Poor	非常に悪い Very poor
実用性評価 Practicality rating	走行中旋回なし without turning mode	5	4	3	2	1
	走行中旋回あり with turning mode	5	4	3	2	1

コメント Comment

(8)各システムに対して，片手漕ぎで車椅子を操作しながら，非操作の手で日常作業(例:ドアの開け閉め，走行中の小さい物の持ち運び，スポーツ)の可能性について評価してください。

For each system, please rate the possibility of doing everyday tasks (e.g. opening/closing of doors, grabbing small objects on the move, sports0 while operating the wheelchair: ;

		作業可能 Possible	可能だが困難 Possible but difficult	不可能 Impossible
(片手で操作中に)非操作の手で作業 Doing tasks while operating the wheelchair with one hand	走行中旋回なし without turning mode	3	2	1
	走行中旋回あり with turning mode	3	2	1

コメント Comment

片手漕ぎシステムを搭載した車椅子に慣れるまでどれくらいの練習が必要と感じますか。 How much practice do you feel is required in order to get used to the wheelchair with the one-handed system?

片手漕ぎシステムのメリットは何だと思いますか。 Regarding the one-handed system, what is the merit of this system?

片手漕ぎシステムは必要だと思いますか。 Do you think the one-handed system is necessary?	必要 Yes	多少必要 Maybe	あまり必要ではない Maybe not	不要 No
走行中旋回は必要だと思いますか。 Do you think turning mode is necessary?	必要 Yes	多少必要 Maybe	あまり必要ではない Maybe not	不要 No

片手漕ぎシステムにかんして，何か改良すべきだと思いますか。 Regarding the one-handed system, what doyou think should be improved?

もし他にご意見・ご感想があればご記入ください。 If you have any other opinions or thoughs, please express them below?

ご協力ありがとうございます。Thank you very much for your cooperation.

追加質問

各システムに対して，次の項目を評価してください
For each system, please rate the following :

(＊)停止したい時に停止できましたか。

停止可能 ←――――――→ 停止不可能(他の動き)

		可能 Possible	可能だが練習必要 Need practice	普通 Average	困難 Very difficult	不可能 Impossible
停止 Stop	走行中旋回なし without turning mode	5	4	3	2	1
	走行中旋回あり with turning mode	5	4	3	2	1
コメント Comment						

AWARD AND PUBLICATIONS

Translation

Certificate of Approval on Research Ethics
倫 理 審 査 申 請 承 認 通 知 書

平成２６年 ７ 月 ３ 日
(Year) (Month) (Day)

平成２６=2014
平成２７=2015

Principal Researcher
申請者

東京大学大学院新領域創成科学研究科
教授　堀　洋一　殿

The University of Tokyo, Graduate School of Frontier Sciences
Professor Yoichi Hori (Supervisor)

東京大学大学院新領域創成科学研究科長
Dean of Graduate School of Frontier Sciences,
The University of Tokyo

下記の研究計画について、承認としましたので、ここに報告します。

Approve the research plan below.

記

Identification Number :

審査番号：　１４－４７
研究課題：　「パワーアシスト車椅子における片手漕ぎ制御の評価実験」

Title of Study:

倫 理 審 査 申 請 承 認 通 知 書

平成２６年 7 月 3 日

申請者
東京大学大学院新領域創成科学研究科
教授　堀　洋一　殿

東京大学大学院新領域創成科学研究科長

下記の研究計画について、承認としましたので、ここに報告します。

記

審査番号：　１４－４７
研究課題：　「パワーアシスト車椅子における片手漕ぎ制御の評価実験」

倫 理 審 査 申 請 承 認 通 知 書

平成２７年 1 月 6 日

申請者
東京大学大学院新領域創成科学研究科
　教授　堀　洋一　殿

東京大学大学院新領域創成科学研究科長

下記の研究計画について、承認としましたので、ここに通知します。

記

審査番号：　１４－１５８（１４－４７の変更）
研究課題：　「パワーアシスト車椅子における片手漕ぎ制御の評価実験（２）」

倫　理　審　査　申　請　承　認　通　知　書

平成２７年 ２ 月 ４ 日

申請者
東京大学大学院新領域創成科学研究科
教授　堀　洋一　殿

東京大学大学院新領域創成科学研究科長

下記の研究計画について、承認としましたので、ここに通知します。

記

審査番号：　１４－１５９
研究課題：　「パワーアシスト車椅子におけるヨー運動制御の評価実験」

AWARD AND PUBLICATIONS

Award

1. "Award of Academic Excellence in Frontier Sciences," The University of Tokyo (Japan), 2012.3

   Received an award for research excellence in yaw motion control of power-assisted wheelchairs.

Journal papers

1. Kayoung Kim, Kanghyun Nam, Sehoon Oh, Hiroshi Fujimoto, and Yoichi Hori, "Yaw Motion Control of Power-assisted Wheelchairs for Improvement of Handling on Slopes," *IEEE/ASME Transactions on Mechatronics*

2. Kayoung Kim, Koji Payne, Sehoon Oh, and Yoichi Hori, "One-handed Propulsion Control of Power-assisted Wheelchair with Straight, Rotation, and Advanced Turning Mode," *IEEE/ASME Transactions on Mechatronics*

International conference papers

1. Kayoung Kim, Koji Payne, Sehoon Oh, and Yoichi Hori, "One-handed Propulsion Control of Power-assisted Wheelchair with Advanced Turning Mode," *The 13th International Workshop on Advanced Motion Control*, pp. 633-638, 2014.

2. Kayoung Kim, Kanghyun Nam, Sehoon Oh, Hiroshi Fujimoto and Yoichi Hori, "Yaw Motion Control of Power-assisted Wheelchair for Improvement of Handling on Slopes," *The 12th Seoul National University — The University of Tokyo Joint Seminar on Electrical Engineering*, pp. 103-108, 2013.

3. Kayoung Kim, Kanghyun Nam, Sehoon Oh, Hiroshi Fujimoto and Yoichi Hori, "Two-dimensional Assist Control for Power-assisted Wheelchair considering Straight and Rota-

tional Motion Decomposition," *38th Annual Conf. on IEEE Industrial Electronics Society*, pp. 4436-4441, 2012.

4. Kayoung Kim, Kanghyun Nam, Sehoon Oh, Hiroshi Fujimoto, and Yoichi Hori, "Yaw Motion Control of Power-assisted Wheelchairs under Lateral Disturbance Environment," *The 37th Annual Conf. of the IEEE Industrial Electronics Society*, pp. 4111-4116, 2011.

Domestic conference papers

1. Kayoung Kim, Kanghyun Nam, Sehoon Oh, Hiroshi Fujimoto and Yoichi Hori, "Novel Assist Control System for Power-assisted Wheelchair considering Straight and Rotational Model," *IEE of Japan Industry Applications Society Conference*, Vol. II, pp.179-182, 2012 (in Japanese).

2. Kayoung Kim, Kanghyun Nam, Sehoon Oh, Hiroshi Fujimoto, and Yoichi Hori, "Human Friendly Yaw Motion Control for Power Assist Wheelchair", *IEE of Japan Industry Applications Society Conference*, Vol.2, pp.II-603–II-606, 2011 (in Japanese).

Co-authored papers

1. Koji Payne, Kayoung Kim, Sehoon Oh, and Yoichi Hori, "One-handed propulsion control of a power-assist wheelchair based on separation of straight and rotational motion", *IEE of Japan Technical Meeting Record*, IIC-12-165, pp.53-58, 2012 (in Japanese)

2. Masaki Higashino, Kayoung Kim, Sehoon Oh, Hiroshi Fujimoto, and Yoichi Hori, "Extended driving observer of power-assist wheelchair with the estimation of the position of driver's center of gravity", *IEE of Japan Technical Meeting Record*, IIC-12-168, pp.71-76, 2012 (in Japanese).

BIBLIOGRAPHY

BIBLIOGRAPHY

Ahmad, S., M. O. Tokhi, and Z. Hussein (2009), Rejection of yaw disturbance in a two-wheeled wheelchair system, in *Asia International Conference on Modelling & Simulation*, pp. 454–459.

Bi, L., X. Fan, and Y. Liu (2013), Eeg-based brain-controlled mobile robots: A survey, *IEEE Trans. on Human-machine Systems*, *43*(2), 161–176.

Brubaker, C. (1986), Wheelchair prescription: an analysis of factors that affect mobility and performance, *Journal of Rehabilitation Research & Development*, *23*(4), 19–26.

Chenier, F., P. Bigras, and R. Aissaoui (2011), An orientation estimator for the wheelchair's caster wheels, *Control Systems Technology, IEEE Transactions on*, *19*(6), 1317–1326.

Cooper, R. (1991), System identification of human performance models, *Systems, Man and Cybernetics, IEEE Transactions on*, *21*(1), 244–252, doi:10.1109/21.101155.

Cooper, R. (1995), Intelligent control of power wheelchairs, *Engineering in Medicine and Biology Magazine, IEEE*, *14*(4), 423–431, doi:10.1109/51.395325.

Cooper, R. (2008), Quality-of-life technology [a human-centered and holistic design], *Engineering in Medicine and Biology Magazine, IEEE*, *27*(2), 10–11, doi:10.1109/EMB.2008.915492.

Cooper, R., D. VanSickle, R. Robertson, M. Boninger, and G. Ensminger (1995), A method for analyzing center of pressure during manual wheelchair propulsion, *Rehabilitation Engineering, IEEE Transactions on*, *3*(4), 289–298, doi:10.1109/86.481968.

Cooper, R., M. Boninger, D. VanSickle, R. Robertson, and S. Shimada (1997), Uncertainty analysis for wheelchair propulsion dynamics, *Rehabilitation Engineering, IEEE Transactions on*, *5*(2), 130–139, doi:10.1109/86.593279.

Cooper, R., D. Jones, S. Fitzgerald, M. Boninger, and S. Albright (2000a), Analysis of position and isometric joysticks for powered wheelchair driving, *Biomedical Engineering, IEEE Transactions on*, *47*(7), 902–910, doi:10.1109/10.846684.

Cooper, R., L. Widman, D. Jones, R. Robertson, and J. Ster (2000b), Force sensing control for electric powered wheelchairs, *Control Systems Technology, IEEE Transactions on*, *8*(1), 112–117, doi:10.1109/87.817696.

Cooper, R., T. Corfman, S. Fitzgerald, M. Boninger, D. Spaeth, W. Ammer, and J. Arva (2002a), Performance assessment of a pushrim-activated power-assisted wheelchair control system, *Control Systems Technology, IEEE Transactions on*, *10*(1), 121–126, doi:10.1109/87.974345.

Cooper, R., et al. (2006a), Engineering better wheelchairs to enhance community participation, *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, *14*(4), 438–455, doi: 10.1109/TNSRE.2006.888382.

Cooper, R. A., M. L. Boninger, R. Cooper, A. R. Dobson, J. Kessler, M. Schmeler, and S. G. Fitzgerald (2002b), Use of the independence 3000 ibot transporter at home and in the community., *The journal of spinal cord medicine*, *26*(1), 79–85.

Cooper, R. A., M. L. Boninger, R. Cooper, and A. Kelleher (2006b), Use of the independence 3000 ibot transporter at home and in the community: A case report, *Disability and Rehabilitation: Assistive Technology*, *1*(1-2), 111–117.

Cooper, R. A., et al. (1999), Research on physical activity and health among people with disabilities: a consensus statement., *Journal of rehabilitation research and development*, *36*(2), 142–154.

Desroches, G., R. Aissaoui, and D. Bourbonnais (2008), The effect of resultant force at the pushrim on shoulder kinetics during manual wheelchair propulsion: A simulation study, *Biomedical Engineering, IEEE Transactions on*, *55*(4), 1423–1431, doi: 10.1109/TBME.2008.918462.

Dicianno, B., D. Spaeth, R. Cooper, S. Fitzgerald, M. Boninger, and K. Brown (2007), Force control strategies while driving electric powered wheelchairs with isometric and movement-sensing joysticks, *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, *15*(1), 144–150, doi:10.1109/TNSRE.2007.891394.

DiGiovine, C., R. Cooper, S. Fitzgerald, M. Boninger, E. Wolf, and S. Guo (2003), Whole-body vibration during manual wheelchair propulsion with selected seat cushions and back supports, *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, *11*(3), 311–322, doi: 10.1109/TNSRE.2003.816872.

Ding, D., and R. Cooper (2005), Electric powered wheelchairs, *Control Systems, IEEE*, *25*(2), 22–34, doi:10.1109/MCS.2005.1411382.

Ding, D., R. Cooper, S. Guo, and T. Corfman (2004), Analysis of driving backward in an electric-powered wheelchair, *Control Systems Technology, IEEE Transactions on*, *12*(6), 934–943, doi: 10.1109/TCST.2004.833638.

Dollar, A. M., and H. Herr (2008), Lower extremity exoskeletons and active orthoses: Challenges and state-of-the-art, *IEEE Trans. on Robotics*, *24*(1), 144–158.

Fujimoto, H., T. Saito, and T. Noguchi (2004), Motion stabilization control of electric vehicle under snowy conditions based on yaw-moment observer, in *Advanced Motion Control, 2004. AMC '04. The 8th IEEE International Workshop on*, pp. 35–40, doi:10.1109/AMC.2004.1297637.

Gaal, R. P., N. Rebholtz, R. D. Hotchkiss, and P. F. Pfaelzer (1997), Wheelchair rider injuries: Causes and consequences for wheelchair design and selection, *J. Rehab. Res. Dev.*, *34*(1), 58–71.

Hirata, K., and T. Murakami (2006), A realization of step passage motion in two-wheel wheelchair systems utilizing variable repulsive compliance control, in *IEEE International Symposium on Industrial Electronics*, pp. 1–6.

ibot (2010), ibot official web site.

K.Arshak, K. K., D.Buckley (2006), Review of assistive devices for electric powered wheelchairs navigation, *ITB Journal*, *13*, 13–23.

Katsura, S., and K. Ohnishi (), Advanced motion control for wheelchair based on environment quarrier, *IEEJ Trans. on Industry Applications*.

Kim, K., K. Nam, S. Oh, H. Fujimoto, and Y. Hori (2011), Yaw motion control of power-assisted wheelchairs under lateral disturbance environment, in *IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society*, pp. 4256–4261, doi:10.1109/IECON.2011.6120007.

Kim, K., K. Nam, S. Oh, H. Fujimoto, and Y. Hori (2012), Two-dimensional assist control for power-assisted wheelchair considering straight and rotational motion decomposition, in *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, pp. 4436–4441, doi: 10.1109/IECON.2012.6389471.

Kim, K., K. Payne, S. Oh, and Y. Hori (2014), One-handed propulsion control of power-assisted wheelchair with advanced turning mode, in *Advanced Motion Control (AMC),2014 IEEE 13th International Workshop on*, pp. 633–638, doi:10.1109/AMC.2014.6823355.

Kuramatsu, T., and T. Murakami (2010), Force sensorless power-assist control of yaw motion direction for two wheels driven wheelchair, in *World Automation Congress (WAC), 2010*, pp. 1–6.

Lawn, M. J., and T. Ishimatsu (2003), Modeling of a stair-climbing wheelchair mechanism with high single-step capability, *IEEE Trans. on Neural Syst. and Rehabil. Eng.*, *11*(3), 323–332.

Levy, C. E., and J. W. Chow (2004), Pushrim-activated power-assist wheelchairs: elegance in motion, *American Journal of Physical Medicine & Rehabilitation*, *83*(2), 166–167.

Miyata, J., Y. Kaida, and T. Murakami (2008), v-$\dot{\phi}$-coordinate-based power-assist control of electric wheelchair for a caregiver, *Industrial Electronics, IEEE Transactions on*, *55*(6), 2517–2524.

Nam, Y., Q. Zhao, A. Cichocki, and S. Choi (2012), Tongue-rudder: A glossokinetic-potential-based tongue-machine interface, *IEEE Trans. on Biomedical Engineering*, *59*(1), 290–299.

Nichols, P. J., P. A. Norman, and J. R. Ennis (1979), Wheelchair user's shoulder? shoulder pain in patients with spinal cord lesions, *Scandinavian Journal of Rehabilitative Medicine*, *11*, 29–32.

Nomura, S., and T. Murakami (2010), Power assist control of electric wheelchair using equivalent jerk disturbance under slope environment, in *IEEE International Works. on Advanced Motion Control*, pp. 572–576.

Oh, S., and Y. Hori (2005), Lateral disturbance rejection and one hand propulsion control of a power assisting wheelchair, in *Industrial Electronics Society, 2005. IECON 2005. 31st Annual Conference of IEEE*, pp. 6 pp.–, doi:10.1109/IECON.2005.1569186.

Oh, S., and Y. Hori (2014), Disturbance attenuation control for power-assist wheelchair operation on slopes, *Control Systems Technology, IEEE Transactions on*, *22*(3), 828–837, doi: 10.1109/TCST.2013.2265396.

Oh, S., N. Hata, and Y. Hori (2004), Proposal of human-friendly motion control and its application to wheelchair, in *SICE 2004 Annual Conference*, vol. 3, pp. 2214–2219 vol. 3.

Oh, S., N. Hata, and Y. Hori (2008a), Integrated motion control of a wheelchair in the longitudinal, lateral, and pitch directions, *Industrial Electronics, IEEE Transactions on*, *55*(4), 1855–1862, doi:10.1109/TIE.2007.908533.

Oh, S., N. Hata, and Y. Hori (2008b), Integrated motion control of a wheelchair in the longitudinal, lateral, and pitch directions, *IEEE Trans. on Industrial Electronics*, *55*(4), 1855–1862.

Oonishi, Y., S. Oh, and Y. Hori (2010), A new control method for power-assisted wheelchair based on the surface myoelectric signal, *Industrial Electronics, IEEE Transactions on*, *57*(9), 3191–3196, doi:10.1109/TIE.2010.2051931.

Payne, K., K. Kim, S. Oh, and Y. Hori (2012), One-handed propulsion control of a power-assist wheelchair based on the separation of straight and rotational motion (in japanese), in *Proc. IEEJ Technical Meeting Record*, pp. IIC–12–165.

Pearlman, J., et al. (2008), Lower-limb prostheses and wheelchairs in low-income countries [an overview], *Engineering in Medicine and Biology Magazine, IEEE*, *27*(2), 12–22, doi:10.1109/EMB.2007.907372.

Profhand (2013), Profhand official web site.

Rabhi, Y., M. Mrabet, F. Fnaiech, and P. Gorce (2013), A feedforward neural network wheelchair driving joystick, in *Electrical Engineering and Software Applications (ICEESA), 2013 International Conference on*, pp. 1–6, doi:10.1109/ICEESA.2013.6578462.

Rebsamen, B., C. Guan, H. Zhang, C. Wang, C. Teo, M. H. A. Jr., and E. Burdet (2010), A brain controlled wheelchair to navigate in familiar environments, *A brain controlled wheelchair to navigate in familiar environments*, *18*(6), 590–598.

Sakai, K., and T. Yasuda (2013), Torque measurement experiments of a torque detection mechanism implemented on hand-rims of a one hand drive wheelchair, in *Advanced Intelligent Mechatronics (AIM), 2013 IEEE/ASME International Conference on*, pp. 1045–1050, doi:10.1109/AIM.2013.6584232.

Sakai, K., T. Yasuda, and K. Tanaka (2009), Improvements of manipulation torque transfer mechanism and assist unit for one hand drive wheelchair with a triple ring, in *Robotics and Biomimetics (ROBIO), 2009 IEEE International Conference on*, pp. 196–201, doi:10.1109/ROBIO.2009.5420622.

Sakai, K., T. Yasuda, and K. Tanaka (2010), Power assist effects of a new type assist unit in a one hand drive wheelchair with a triple ring, in *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, pp. 6040–6045, doi:10.1109/IROS.2010.5653564.

Seki, H., N. Hata, Y. Koyasu, and Y.Hori (2004), Novel control scheme of power assisted wheelchair for preventing overturn (part i) - adjustment of assisted torque and performance evaluation from field test - (in japanese), in *IEEJ Industry Applications Society Conference*, vol. 124, pp. 318–323.

Seki, H., T. Iijima, H.Minakata, and S. Tadakuma (2006a), Novel step climbing control for power assisted wheelchair based on driving mode switching, in *32nd Annual Conf. on IEEE Industrial Electronics*, pp. 3427–2832.

Seki, H., T. Sugimoto, and S. Tadakuma (2006b), Novel straight road driving control of power assisted wheelchair based on disturbance estimation of right and left wheels, *IEEJ Trans. on Industry Applications*, *126*(6), 764–770.

Seki, H., K. Ishihara, and S. Tadakuma (2009), Novel regenerative braking control of electric power-assisted wheelchair for safety downhill road driving, *IEEE Trans. on Industrial Electronics*, *56*(5), 1393–1400.

Strickland, E. (2012), Good-bye wheelchair, *IEEE Spectrum*, *49*(1), 30–32.

Takahashi, Y., S. Ogawa, and S. Machida (1999), Front wheel raising and inverse pendulum control of power assist wheel chair robot, *The 25th Annual Conference of the IEEE Industrial Electronics Society*, pp. 668–673.

Tanaka, K., K. Matsunaga, and H. O. Wang (2005), Electroencephalogram- based control of an electric wheelchair, *IEEE Trans. on Robotics*, *21*(4), 762–766.

Tanimoto, Y., K. Nanba, A. Tokuhiro, H. Ukida, and H. Yamamoto (2008), Measurement system of transfer motion for patients with spinal cord injuries, *Instrumentation and Measurement, IEEE Transactions on*, *57*(1), 213–219, doi:10.1109/TIM.2007.909501.

Tashiro, S., and T. Murakami (2008), Step passage control of a power-assisted wheelchair for a caregiver, *IEEE Trans. on industrial Electronics*, *55*(4), 1715–1721.

Ugurlu, B., M. Nishimura, K. Hyodo, M. Kawanishi, and T. Narikiyo (2012), A framework for sensorless torque estimation and control in wearable exoskeletons, *IEEE Worksh. on Adv. Motion Cont.*, pp. 1–7.