# Two-dimensional Assist Control for Power-assisted Wheelchair considering Straight and Rotational Motion Decomposition

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***Abstract*—There are many types of wheelchairs. Users are able to choose suitable wheelchair for their purposes. Power-assisted wheelchairs are one type of wheelchairs, which use both propelling torque from human and output torque from motors for their driving force. To improve assist performance, many assist control systems were proposed. One of conventional assist 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 assist control. In this paper, a novel two-dimensional assist control for power-assisted wheelchairs is proposed. The proposed assist 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.**

## I. Introduction

As several types of wheelchairs were developed, wheelchair users are able to select a suitable wheelchair for their purposes. Power-assisted wheelchairs are one type of wheelchair, that have a motor in each wheel to assist user's force and a torsion sensor in each hand-rim to detect user's propelling torque.

The purpose of wheelchair research is to make wheelchair safer and have better maneuver. Oh et al. focus on safety problem of power-assisted wheelchair [1]. They propose a control system to prevent tip-over problem. Excessive assist will cause wheelchair to tip-over, which may lead to a severe accident. Oh et al. analyze velocity and acceleration in pitch direction, and figure out the relation between tip-over and velocity and acceleration in pitch direction. Using the relation between them, Oh et al. 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 [1] . In environment with disturbance, it is difficult to control wheelchair. 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.

Seki et al. focus on downhill and propose regenerative braking system [2]. As wheelchairs are accelerated by gravity, it is dangerous to ride wheelchair downhill. However, the proposed system prevents speed-up problem. By using the proposed system, wheelchairs can be improved both in terms of safety and energy. By using regenerative braking system, some energy can be saved on downhill.

To enhance manipulation performance, Nam et al. propose a controller which can manipulate a wheelchair with tongue [3]. 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 they choose movement of tongue to control the wheelchair. They control the wheelchair with EEG code which is affected by movement of tongue.

There are also research groups which research on 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 [4]. They analyze load on joint when human uses manual wheechair. Tanimoto et al. analyze transfer motion [6].

To improve manipulation performance of power-assisted wheelchair, we propose a new assist control system in this paper. In section II, previous assist control system is introduced. In section III, torque analysis for straight and rotational motion in wheelchair is discussed. In section IV, proposed assist control system is introduced. Comparison experiments and its result will be shown in section V and VI. and discussion about experimental result will be shown in section VII. At last, conclusion of this paper and future work for this research will be shown in section VIII.

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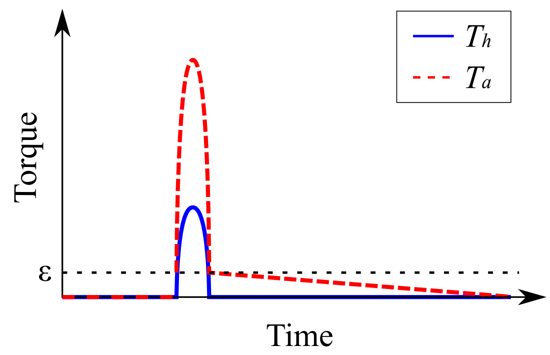


Fig. 1. Human torque and assist torque of previous modified proportional assist control system [9]

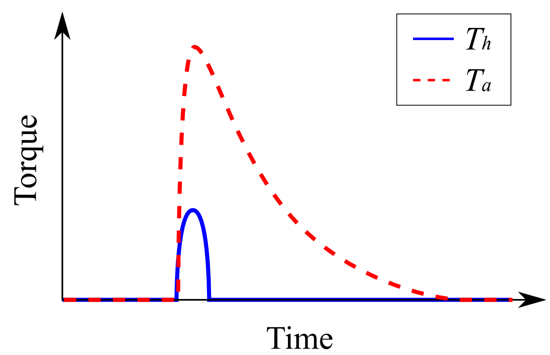


Fig. 2. Human torque and assist torque of previous assist control system considering straight motion [10]

## II. Previous Assist Control System

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

Simple proportional assist control causes sharp decrease in assist torque. Therefore, Cooper et al. propose a modified proportional assist control to prevent signal from becoming zero rapidly [9]. Figure 1 shows human torque and assist torque of previous modified proportional assist control system. $\epsilon$ is dead zone to avoid effect of noise on sensor signal.

Seki et al. propose an assist control system for power-assisted wheelchair considering straight motion [10]. Figure 2 shows human torque and assist torque of previous assist control system considering straight motion. In this section, we will introduce assist control proposed by Seki et al.

Figure 3 shows a block diagram of previous assist 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 side$T_{tR}$ are defined as follows:

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

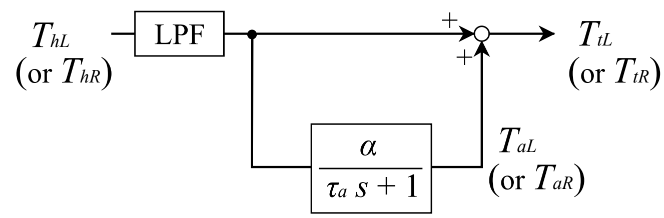


Fig. 3. Block diagram of previous assist control system considering straight motion

$$T_{tR} = T_{hR} + T_{aR} = T_{hR} \times \left(1 + \frac{\alpha}{\tau_a s + 1}\right) \tag{2}$$

where $\alpha$ is assist rate and $\tau_a$ is time constant.

Time constant $\tau_a$ is defined as follows:

$$\tau_a = \begin{cases} \tau_{fast} & \left(\frac{dT_h}{dt} \geq 0\right) \\ \tau_{slow} & \left(\frac{dT_h}{dt} < 0\right) \end{cases} \tag{3}$$

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

Time response of assist control is affected by value of time constant $\tau_a$. When user propels the wheelchair, immediate assist is desirable. By choosing small $\tau_a$, motor will assist user's propelling torque immediately. Therefore, small value $\tau_{fast}$ should be used when $\frac{dT_h}{dt} \geq 0$. However, with small $\tau_a$, 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 $\tau_{slow}$should be chosen when $\frac{dT_h}{dt} \geq 0$.

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

[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], $\tau_{slow}$ which is larger than $t_{off}$ should be chosen. By doing so, motors will keep assisting user's propelling torque during [Period 2].

$$\tau_{slow} > t_{off} \tag{4}$$

As mentioned above, by choosing appropriate assist rate $\alpha$ and time constant $\tau_\alpha$, this assist control can be set to assist immediately or keep assisting when it is required. By designing $\tau_{slow}$ 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 assist control will help reduce user's load.

However, once user forces wheelchair to turn, it will keep turning with this $\tau_{slow}$. Turning motion is different from straight motion. When going straight, user desires to keep

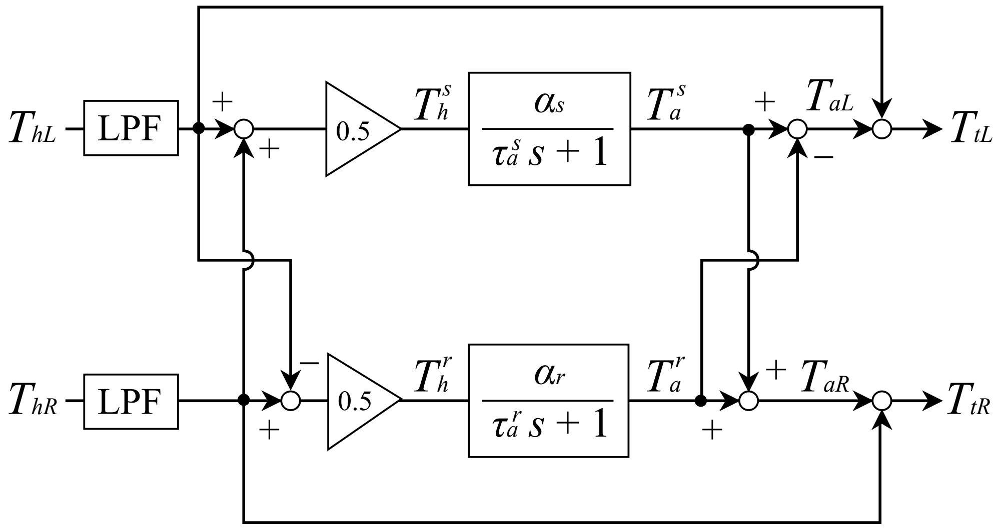


Fig. 4. Block diagram of proposed assist control for straight and rotational motion

going straight, however, it is hard to find situation that requires wheelchair to keep turning in daily life. Considering turning motion, $\tau_{slow}$ should become smaller, which would not make wheelchair keep turning; however, suitable $\tau_{slow}$ for turning motion is too small for straight motion, Small $\tau_{slow}$ will not assist properly when going straight. Therefore, using same $\tau_{slow}$ is unsuited for power-assisted wheelchair.

## III. Torque for 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:

$$T_L = T_L^s + T_L^r \tag{5}$$
$$T_R = T_R^s + T_R^r \tag{6}$$

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.

$$T_L^s = T_R^s \tag{7}$$
$$T_L^r = -T_R^r \tag{8}$$

From equation (6) to equation (8), $T_R$ can also be expressed as follows:

$$T_R = T_L^s - T_L^r \tag{9}$$

Therefore,

$$T_L^s = T_R^s = \frac{T_L + T_R}{2} \tag{10}$$
$$T_L^r = -T_R^r = \frac{T_L - T_R}{2} \tag{11}$$

Also, as $T^s = T_R^s$ and $T^r = T_R^r$, equation (5) and equation (6) become

$$T_L = T^s - T^r \tag{12}$$
$$T_R = T^s + T^r \tag{13}$$

## IV. Proposed assist control system

As mentioned in section II, it is difficult to assist straight motion and rotational motion using previous assist control system. To solve this problem, we propose a new two-dimentional assist control which assist straight and rotational motion independently.

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 4 shows new assist control. $\alpha_s$ and $\alpha_r$ are assist rate for straight and rotational motion, and $\tau_a^s$ and $\tau_a^r$ are time constant for straight and rotational motion.

With the same nature as equation (10) and (11), $T_h^s$ and $T_h^r$ are defined as follows:

$$T_h^s = \frac{T_{hL} + T_{hR}}{2} \tag{14}$$
$$T_h^r = -\frac{T_{hL} - T_{hR}}{2} \tag{15}$$

Similarly, based on equation (12) and (13), assist torque of left and right side $T_{aL}$ and $T_{aR}$ are

$$T_{aL} = T_a^s - T_a^r = \frac{\alpha_s}{\tau_a^s s + 1} T_h^s - \frac{\alpha_r}{\tau_a^r s + 1} T_h^r \tag{16}$$
$$T_{aR} = T_a^s + T_a^r = \frac{\alpha_s}{\tau_a^s s + 1} T_h^s + \frac{\alpha_r}{\tau_a^r s + 1} T_h^r \tag{17}$$

Fig. 5. Power-assisted wheelchair (YAMAHA JW-II)

From equation (14) to equation (17),

$$\begin{aligned} T_{aL} &= \frac{1}{2}T_{hL}\left(\frac{\alpha_s}{\tau_a^s s+1}+\frac{\alpha_r}{\tau_a^r s+1}\right) \\ &+\frac{1}{2}T_{hR}\left(\frac{\alpha_s}{\tau_a^s s+1}-\frac{\alpha_r}{\tau_a^r s+1}\right) \end{aligned} \quad (18)$$

$$\begin{aligned} T_{aR} &= \frac{1}{2}T_{hL}\left(\frac{\alpha_s}{\tau_a^s s+1}-\frac{\alpha_r}{\tau_a^r s+1}\right) \\ &+\frac{1}{2}T_{hR}\left(\frac{\alpha_s}{\tau_a^s s+1}+\frac{\alpha_r}{\tau_a^r s+1}\right) \end{aligned} \quad (19)$$

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

$$T_{tL} = T_{hL}+T_{aL} = T_{hL}+(T_a^s-T_a^r) \quad (20)$$

$$\begin{aligned} &= T_{hL}+\frac{1}{2}T_{hL}\left(\frac{\alpha_s}{\tau_a^s s+1}+\frac{\alpha_r}{\tau_a^r s+1}\right) \\ &+\frac{1}{2}T_{hR}\left(\frac{\alpha_s}{\tau_a^s s+1}-\frac{\alpha_r}{\tau_a^r s+1}\right) \end{aligned} \quad (21)$$

$$T_{tR} = T_{hR}+T_{aR} = T_{hR}+(T_a^s+T_a^r) \quad (22)$$

$$\begin{aligned} &= T_{hR}+\frac{1}{2}T_{hL}\left(\frac{\alpha_s}{\tau_a^s s+1}-\frac{\alpha_r}{\tau_a^r s+1}\right) \\ &+\frac{1}{2}T_{hR}\left(\frac{\alpha_s}{\tau_a^s s+1}+\frac{\alpha_r}{\tau_a^r s+1}\right) \end{aligned} \quad (23)$$

$\tau_a^s$ and $\tau_a^r$ are defined as follows:

$$\tau_a^s = \begin{cases} \tau_{fast}^s & \left(\dfrac{dT_h^s}{dt} \geq 0\right) \\ \tau_{slow}^s & \left(\dfrac{dT_h^s}{dt} < 0\right) \end{cases} \quad (24)$$

TABLE I
PARAMETERS USED IN EXPERIMENTS

| Previous assist control system | | | |
|---|---|---|---|
| assist rate | $\alpha$ | | 2.5 |
| time constant | $\tau_a$ | $\tau_{fast}$ | 0.08 s |
| | | $\tau_{slow}$ | 4.0 s |
| **Proposed assist control system** | | | |
| assist rate (straight) | $\alpha_s$ | | 2.5 |
| time constant (straight) | $\tau_a^s$ | $\tau_{fast}^s$ | 0.08 s |
| | | $\tau_{slow}^s$ | 4.0 s |
| assist rate (rotation) | $\alpha_r$ | | 2.5 |
| time constant (rotation) | $\tau_a^r$ | $\tau_{fast}^r$ | 0.08 s |
| | | $\tau_{slow}^r$ | 1.0 s |

$$\tau_a^r = \begin{cases} \tau_{fast}^r & \left(\dfrac{dT_h^r}{dt} \geq 0\right) \\ \tau_{slow}^r & \left(\dfrac{dT_h^r}{dt} < 0\right) \end{cases} \quad (25)$$

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 $\tau_{slow}$ in previous assist control system, however, two-dimentional assist control system solve this problem using sum and difference of left and right torque. By deciding time constant of straight motion $\tau_{slow}^s$ and rotational motion $\tau_{slow}^r$, new system is able to control straight and rotational motion independently.

## V. Comparison Experiments of Previous and Proposed Assist Control System

Experiments were performed to compare previous and proposed assist control system for straight and rotational motion. In experiments, user pushes both hand-rims with same force in 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 we apply same input, human's propelling torque, to both assist 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.

Figure 5 shows experimental setup, power-assisted wheelchair JW-II (Yamaha). 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 I shows parameters used in these experiments. Purpose of these experiments is to confirm the influence of time constant of rotational motion $\tau_{slow}^r$, and verifying independence of assist system straight and rotational motion. These parameters are decided empirically.

## VI. Result of Comparison Experiment of Previous and Proposed Assist Control System

Figure 6 and figure 7 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.

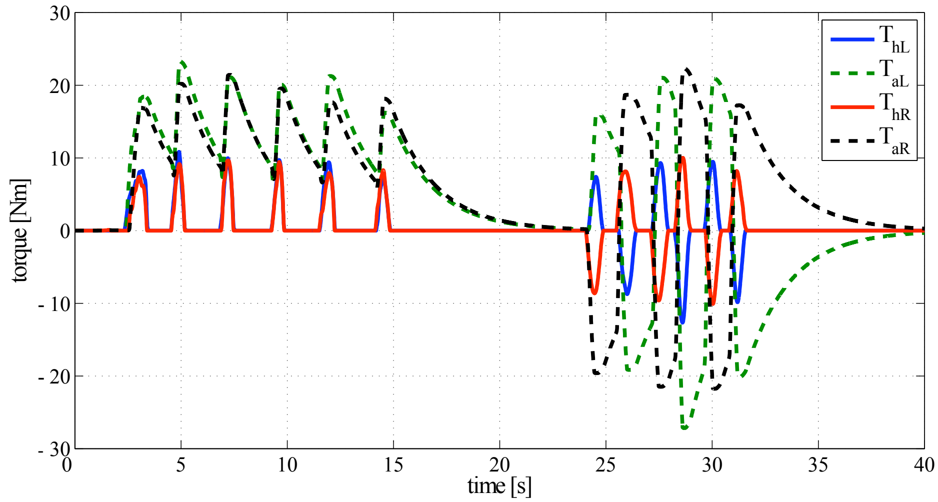


Fig. 6. Experimental result of previous assist control system

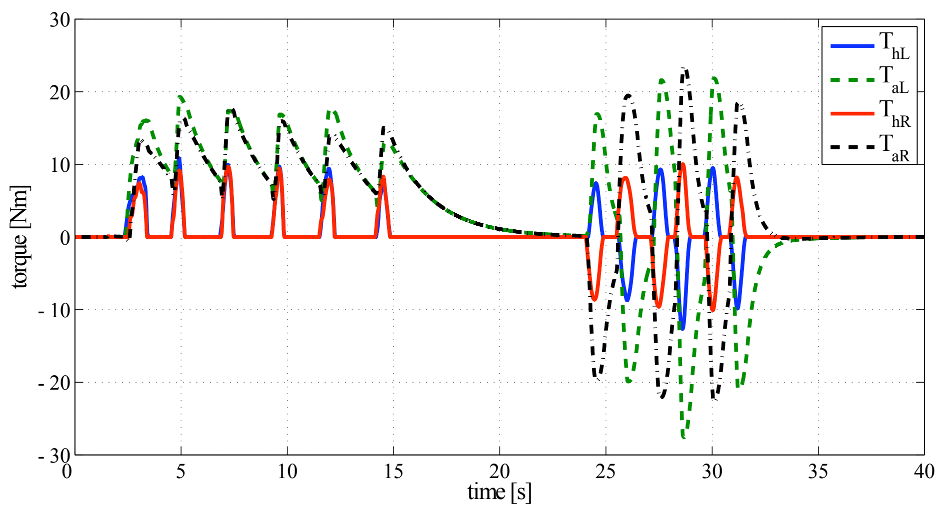


Fig. 7. Experimental result of proposed assist control system

Figure 6 is the experimental result of previous assist control system. In straight motion zone, assist torque increases immediately when human torque is increasing. However, assist 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 7 is the experimental result of the proposed assist 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.

## VII. Discussion

As mentioned in section III, 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, if user tries to, rotate we do not need to assist it longer to keep turning, 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 VI, 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 7, 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.

## VIII. Conclusion and Future work

In this paper, we proposed a new two-dimensional assist control system for power-assisted wheelchair.

In previous assist 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, we propose a novel two-dimensional assist control system. Experiments verified the validity of the proposed system.

In 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 assist control is able to apply to other control systems. It is expected to improve performance by integrating the proposed assist control into other control systems. Application of new assist control is another future work.

## References


[1] S. Oh, N. Hata, and Y. Hori, "Integrated Motion Control of a Wheelchair in the Longitudinal, Lateral, and Pitch Directions," *IEEE Transactions on Industrial Electronics*, Vol. 55, No. 4, pp. 1855-1862, 2008

[2] H. Seki, K. Ishihara, and S. Tadakuma, "Novel regenerative Braking control of Electric Power-Assisted Wheelchair for Safety Downhill Road Driving," *IEEE Transactions on Industrial Electronics*, Vol. 56, No. 5, pp. 1393-1400, 2009

[3] Y. Nam, Q. Zhao, A. Cichocki, and S. Choi, "Tongue-Rudder: A Glossokinetic-Potential-Based Tongue-Machine Interface," *IEEE Transactions on Biomedical Engineering*, Vol. 59, No. 1, pp. 290-299, 2012

[4] F. Chénier, P. Bigras, and R.Aissaoui, "An Orientation Estimator for the Wheelchair's Caster Wheels," *IEEE Transactions on Control Systems Technology*, Vol. 19, No. 6, pp. 1317-1326, 2011

[5] G. Desroches, R. Aissaoui, and D. Bourbonnais, "The Effect of Resultant Force at the Pushrim on Shoulder kinetics During Manual Wheelchair Propulsion: A Simulation Study," *IEEE Transactions on Biomedical Engineering*, Vol. 55, No. 4, pp. 1423-1431, 2008

[6] Y. Tanimoto, K. Nanba, A. Tokuhiro, H. Ukida, and H. Yamamoto, "Measurement System of Transfer Motion for Patients With Spinal Cord Injuries," *IEEE Transactions on Instrumentation and Measurement*, Vol. 57, No. 1, pp. 213-219, 2008

[7] R. A. Cooper, L. A. Quatrano, P. W. Axelson, W. Harlan, M. Stineman, B. Franklin, J. S. Krause, J. Bach, H. Chambers, E. Y. S. Chao, M. Alexander, and P. Painter, "Physical activity and health among people with disabilities," *J. Rehab. Res. Dev.*, Vol. 36, No. 2, pp. 142-154, 1999

[8] D. Ding and R.A. Cooper, "Electric powered wheelchairs," *IEEE Control Systems Magazine*, Vol. 25, No. 2, pp. 22-34, 2005

[9] R. A. Cooper, T. A. Corfman, S. G. Fitzgerald, M. L. Boninger, and D. M. Spaeth, "Performance Assessment of a Pushrim-Actived Power-Assisted Wheelchair Control System", *IEEE Transcactions on Control Systems Technology*, Vol. 10 No. 1, pp. 121-126, 2002

[10] H. Seki, N. Hata, Y. Koyasu, and Y.Hori, "Novel control scheme of power assisted wheelchair for Preventing Overturn (Part I) - Adjustment of assisted torque and performance evaluation from field test - (in Japanese)", *JIASC*, Vol. 124 No. 3, pp. 318-323, 2004

[11] S. Katsura and K. Ohnishi, "Advanced Motion Control for Wheelchair in Unknown Environment", *Proceedings of IEEE International Conference on Systems, Man and Cybernetic*, Vol. 6, pp. 4926 - 4931, 2006

[12] S. Katsura and K. Ohnishi, "Advanced Motion Control for Wheelchair Based on Environment Quarrier," *IEEJ Transactions on Industry Applications*, Vol. 125, No.7, pp. 698-704, 2005

[13] P. J. Nichols, P. A. Norman, and J. R. Ennis, "Wheelchair user's shoulder? Shoulder pain in patients with spinal cord lesions," *Scandinavian Journal of Rehabilitative Medicine*, Vol. 11, pp. 29-32, 1979

[14] C. E. Levy and J. W. Chow, "Pushrim-activated power-assist wheelchairs: Eleance in motion," *American Journal of Physical Medicine & Rehabilitation*, Vol. 83, pp.166-167, 2004

[15] R. A. Cooper, M. L. Boninger, D. M. Spaeth, D. Ding, Guo Songfeng, A. M. Koontz, S. G. Fitzgerald, R. Cooper, A. Kelleher, and D. M. Collins, "Engineering Better Wheelchairs to Enhance Community Participation," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, Vol. 14, No. 4, 2006

[16] D. Ding and R. A. Cooper, "Electric powered wheelchairs," *IEEE Control Systems Magazine*, Vol. 25, No.2, pp. 22-34, 2005

[17] H. Seki, T. Sugimoto, and S. Tadakuma, "Novel Straight Road Driving Control of Power Assisted Wheelchair Based on Disturbance Estimation of Right and Left Wheels," *IEEJ Transactions on Industry Applications*, Vol. 126, No. 6, pp. 764-770, 2006

[18] R. P. Gaal, N. Rebholtz, R. D. Hotchkiss, and P. F. Pfaelzer, "Wheelchair rider injuries: Causes and consequences for wheelchair design and selection," *Journal of Rehabilitation Research and Development*, Vol. 34, No. 1, pp. 58-71, 1997

[19] S. Oh, N. Hata, and Y. Hori "Proposal of human-friendly motion control; control design for power assistance tools and its application to wheelchair," in *Proceedings of IEEE Annual Conference of the IEEE Industrial Electronics Society*, Vol. 1, pp. 426-441, 2004

[20] R. A. Cooper, L. A. Quatrano, P. W. Axelson, W. Harlan, M. Stineman, B.Franklin, J. S. Krause, J. Bach, H. Chambers, E. Y.S. Chao, M. Alexander, and P. Painter, "Research on Physical Activity and Health among People with Disabilities: A Consensus Statement," *Journal of Rehabilitation Research & Development*, Vol. 36, No. 2, pp. 142-154, 1999

[21] C.E. Brubaker, "Wheelchair prescription : an analysis of factors that affect mobility and performance," *Journal of Rehabilitation Research & Development*, Vol. 23, No. 4, pp. 19-26, 1986

[22] D. Dimnb, R. A. Cooper, S. Guo, and T. A. Corfman, "Analysis of Driving Backward in an Electric-Powered Wheelchair," *IEEE Transactions on Control Systems Technology*, Vol. 12, No. 6, pp. 934-943, 2004

[23] S. Ahmad, M.O. Tokhi, and Z. Hussein, "Rejection of Yaw Disturbance in a Two-Wheeled Wheelchair System," *Proceedings of Asia International Conference on Modelling & Simulation*, pp. 454-459, 2009

[24] C. Acar and T. Murakami, "Motion Control of Dynamically Balanced Two-Wheeled Mobile Manipulator through CoG Manipulation," *Proceedings of IEEE International Workshop on Advanced Motion Control*, pp. 715-720, 2010

[25] S. Nomura and T. Murakami, "Power Assist Control of Electric Wheelchair Using Equivalent Jerk Disturbance under Slope Environment," *Proceedings of IEEE International Workshop on Advanced Motion Control*, pp. 572-576, 2010