Yaw Motion Control of Power-assisted Wheelchairs under Lateral Disturbance Environment

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***Abstract*—Wheelchairs are important devices for people with leg disabilities. There are many kinds of wheelchairs being developed to minimize injury while improve ease of operation. Power-assisted wheelchairs were developed for the same reason. However, due to effects of gravity, power assist alone is not sufficient to make movement on slopes easy. 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, we propose yaw motion control of power-assisted wheelchairs. Using 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.**

I. Introduction

The wheelchair is an important device for people who are unable to walk by themselves. There are many kinds of wheelchairs, and the most commonly seen in public places are manually operated wheelchairs. They are equipped with large wheels the user can use to propel the wheelchair, and have no motor or joystick. The user's propulsion force becomes the manual wheelchair's driving force. In contrast, the electric-powered wheelchair uses electric motors to propel the wheelchair. Usually a joystick is used to operate an electric-powered wheelchair. Special wheelchairs such as those designed for sport or using particular type of tires also exist.

Fig. 1. Power-assisted Wheelchair (YAMAHA JW II)

The wheelchair allows a disabled user to move around at long distances. However, propulsion a wheelchair manually may often cause pain and joint degeneration in the users' arms [1]. To reduce the risk of such injury, power-assisted wheelchairs were developed. As motors assist propulsion of wheelchair, users may decrease physiologic and biomechanical effort in propulsion wheelchairs [2], [3].

Power-assisted wheelchairs have easy maneuverability and are expected to be effective for rehabilitation [4]. To make power-assisted wheelchair safer and easier to manipulate, many researches have been conducted. Tashiro et al. focus on assisting caregivers [5]. They propose power assist control for caregivers to pass through unleveled ground easily. Seki and his colleagues designed straight road driving control for driving when both wheels are on different road environments [6].

On slopes, effects of gravity make operating a wheelchair difficult [8], [9]. Moreover, power assist control via feed-forward torque amplification by itself is not enough to make wheelchairs usable on slopes. Therefore, we propose a yaw motion control system of power-assisted wheelchairs. The proposed controller uses the torque difference between the left and right hand propulsion torque as a reference and a yaw gyroscope for feedback. With the proposed yaw motion control, the wheelchair is not affected by the lateral force due to gravity, resulting in improvement of handling.

II. Power-assisted Wheelchair

Figure 1 shows the power-assisted wheelchair, JW II (YAMAHA), used in experiments. Motors that assist the user are equipped in each wheel.

Assist torque T_a is defined as follows:

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

where T_h is the user's propulsion torque, and α is assist gain [10], [11].

To improve the handling of the wheelchair, the time constant τ is defined as follows:

$$\tau = \begin{cases} \tau_1 & (\frac{d}{dt}T_h \geq 0) \\ \tau_2 & (\frac{d}{dt}T_h < 0) \end{cases} \quad (2)$$

By choosing small τ_1, assist torque T_a will increase quickly when user propels the wheelchair. By choosing large τ_2, assist torque T_a will decrease slowly, so that motor will assist the user for a while even after the user release the hand rim. τ_1 and τ_2 were designed in experiments to obtain good performance.

Figure 2 shows power assist block diagram, where J is inertia coefficient of wheelchair and user, and B is damping coefficient of wheelchair and user.

III. Yaw Motion Control

A. Yaw Motion Control using Yaw Moment Observer

Figure 3 shows a block diagram of the proposed yaw motion control system. Yaw dynamics is formulated as follows:

$$I\dot{\gamma} = N_z + N_d \quad (3)$$

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:

$$\gamma = \frac{1}{I_n s} N_z \quad (4)$$

To reduce effect of disturbance , we propose a two-degree-of-freedom control system, composed of feed forward control, feedback control, and a yaw moment observer (YMO) [13] .

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

1) Yaw Rate Feed Forward Controller: From (4), 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 $I_n s$.

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.

$$\frac{\gamma}{\gamma^*} = \frac{\frac{1}{I_n s} C_{FB}(s)}{1 + \frac{1}{I_n s} C_{FB}(s)} = \frac{C_{FB}(s)}{I_n s + C_{FB}(s)} \quad (5)$$

Proportional control was adopted for yaw rate feedback control.

$$C_{FB}(s) = K_p \quad (6)$$

From (5) and (6), pole of this system is

$$s = -\frac{C_{FB}(s)}{I_n} = -\frac{K_p}{I_n} \quad (7)$$

The proportional gain in the yaw rate feedback controller defined as K_p (from (6)), was chosen so that the pole of the close loop system become 2π rad/s.

3) Yaw Moment Observer (YMO): From (3), disturbance yaw moment $\hat{N}_d$ is estimated as follows:

$$\hat{N}_d = (\gamma I_n s - N_z)\ Q(s) \quad (8)$$

where Q(s) is

$$Q(s) = \frac{1}{\tau_i s + 1} \quad (9)$$

where τ_i is the time constant.

Yaw rate γ is measured by gyroscope.

B. Reference Yaw Moment N_z^*

The controller we propose uses torque difference between left and right hand side as a reference.

Reference yaw moment is defined as follows:

$$N_z^* = (F_R - F_L)\ \frac{d}{2} \quad (10)$$

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

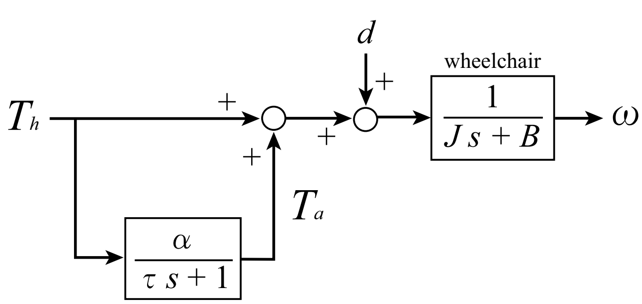

Fig. 2. Block diagram of power assist control

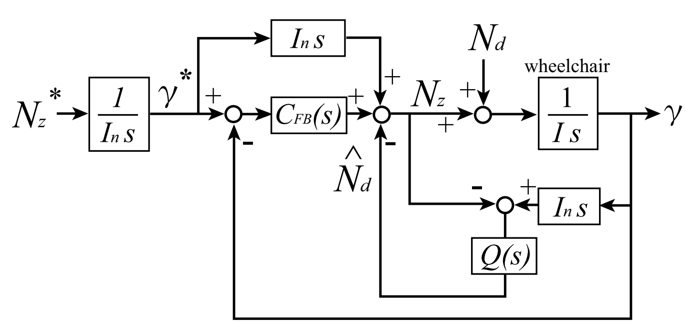

Fig. 3. Block diagram of proposed yaw motion control system

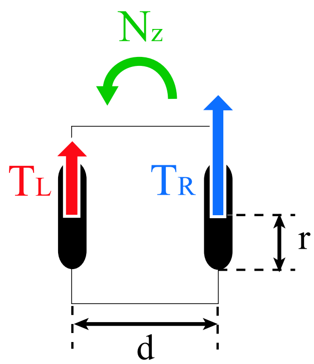

Fig. 4. Yaw moment N_z

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 (10) is redefined as follows:

$$N_z^* = \frac{T_R - T_L}{r} \frac{d}{2} \tag{11}$$

where T_L and T_R are torques applied to left and right wheels. In this paper, 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.

Figure 4 shows relation of yaw moment N_z and user's propulsion torque.

C. Torque Distribution

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

$$T_{yL} = -\frac{r}{d}(N_z - N_z*) \tag{12}$$

$$T_{yR} = \frac{r}{d}(N_z - N_z*) \tag{13}$$

IV. Lateral Disturbance Observer

A controller that can control both longitudinal and lateral movement had been proposed by Oh et al. [8]. In this paper, we consider only lateral disturbance. In this section, we will introduce the lateral direction disturbance observer (Lateral DOB) designed by Oh et al..

Figure 5 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

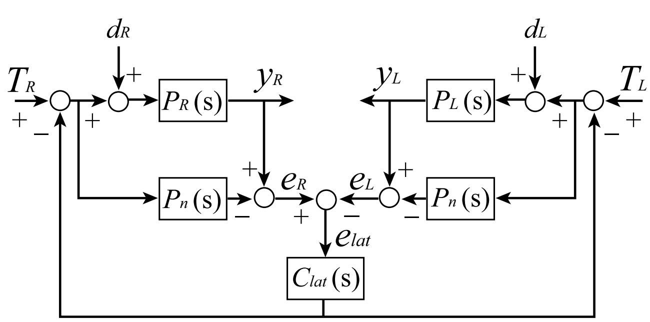

Fig. 5. Lateral Disturbance Observer

TABLE I
Parameters

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

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:

$$C_{lat}(s) = \frac{1}{2} \frac{P_n^{-1}(s)}{\tau_l \ s + 1} \tag{14}$$

where τ_l is time constant.

V. Experiments

To demonstrate the effectiveness of yaw motion control, we performed two kinds of experiments. 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.

A. Experimental Setup

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

B. Experiment 1: Going straight on the slope

Figure 6 shows experimental environment of experiment 1. Lateral disturbance due to gravity acts towards the left side of

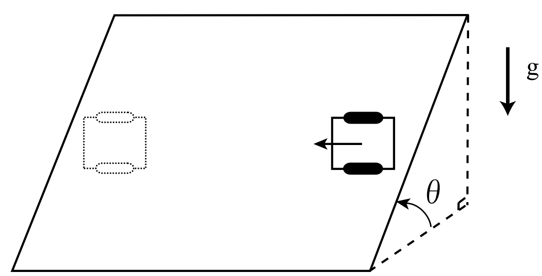

Fig. 6. Experiment 1: Going straight on the slope

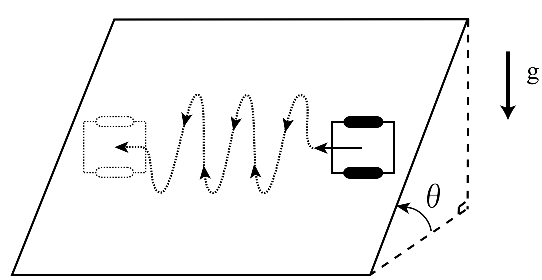

Fig. 7. Experiment 2: Turning on the slope

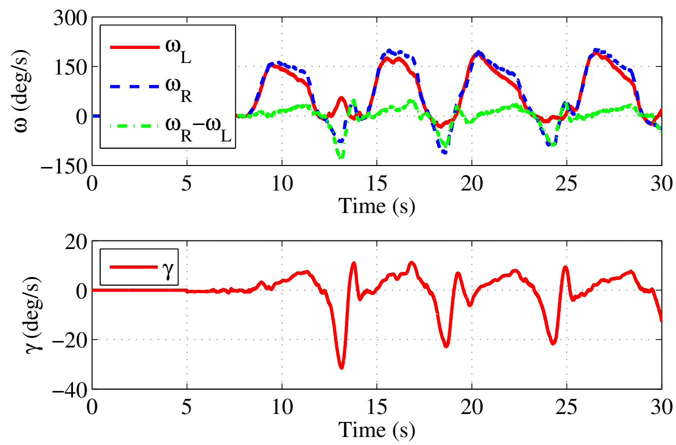

Fig. 8. Experiment 1: Going Straight on the slope (without control)

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

C. Experiment 2: Turning on the slope

Figure 7 shows experimental environment of experiment 2. In experiment 2, we will verify the effectiveness of the proposed yaw motion control and compare it with lateral DOB when turning on the slope.

VI. Experimental result

A. Experiment 1: Going straight on the slope

Experimental results of going straight on the slope are shown in Fig. 8 to Fig. 10.

Figure 8 shows the result of going straight on the slope without control. The first graph 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

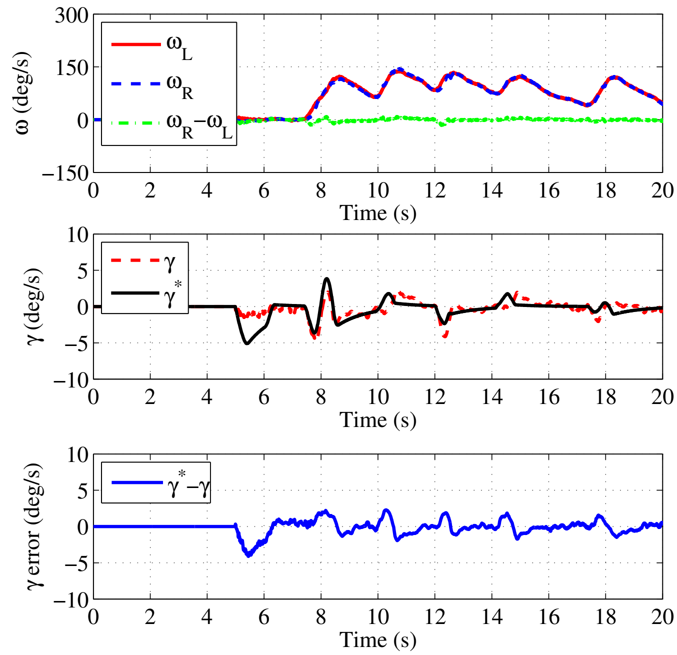

Fig. 9. Experiment 1: Going Straight on the slope (with Yaw Motion Control)

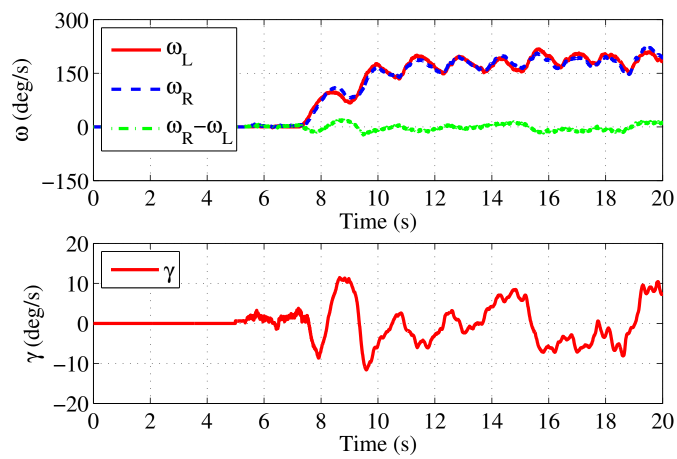

Fig. 10. Experiment 1: Going Straight on the slope (Lateral DOB)

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 9 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

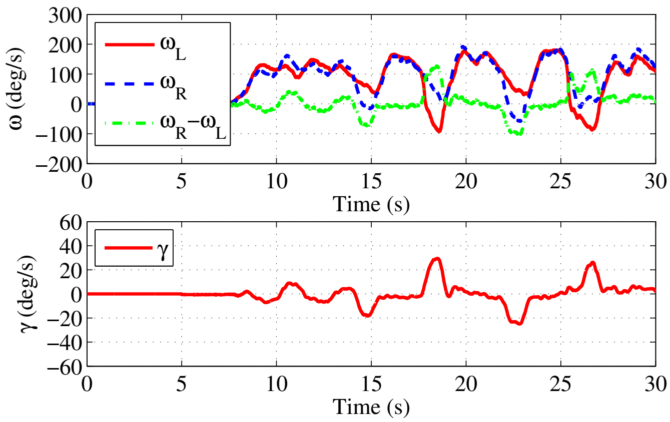

Fig. 11. Experiment 2: Turnig on the slope (without control)

that of Fig. 8. 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. 9 (with yaw motion control) than that of Fig. 8 (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 10 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. 8.

The difference of both wheels' angular velocity, -20 to 20 deg/s, is smaller than that of Fig. 8 (without control) and bigger than that of Fig. 9 (with yaw motion control). Yaw rate is approximately -10 to 10 deg/s.

B. Experiment 2: Turning on the slope

Experimental results of turning on the slope are shown in Fig. 11 to Fig. 13.

Figure 11 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. 8.

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 12 shows the result of turning on the slope with yaw motion control. The first graph shows angular velocity of both

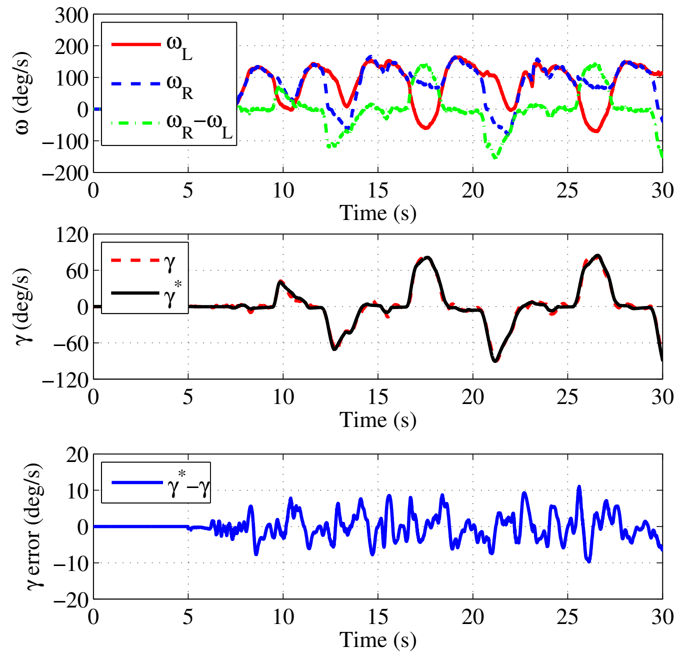

Fig. 12. Experiment 2: Turnig on the slope (with Yaw Motion Control)

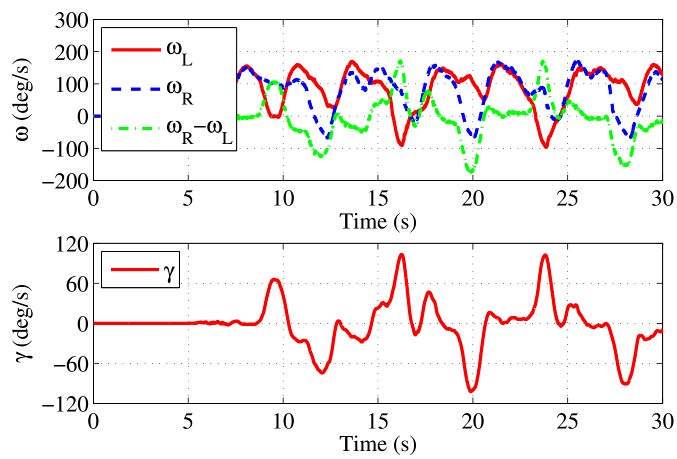

Fig. 13. Experiment 2: Turnig on the slope (with Lateral DOB)

wheels, the second graph shows yaw rate, and the third graph shows yaw rate error. The color code of each line is the same as that of Fig. 9.

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 13 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. 8.

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.

VII. Discussion

A. Experiment 1: Going straight on the slope

Without control, as shown in Fig. 8, 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. 9 (with yaw motion control) and Fig. 10 (with lateral DOB), is smaller than that shown in Fig. 8 (without control). In Fig. 9, 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.

B. Experiment 2: Turning on the slope

Without control, as shown in Fig. 11, 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. 12, 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. 13, yaw rate is similar to that of yaw motion control when turning. However, yaw rate fluctuations when not turing are larger.

VIII. Conclusion

In this paper, we discuss the motion of the wheelchair on the slope. 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.

In this paper, we verified the effectiveness of the proposed controller on a slope of constant incline angle. For future work, we would like to verify the proposed controller in various situations.

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