DEVELOPMENT OF POWER ASSIST ON OMNI-DIRECTIONAL MOBILE WHEELCHAIR CONSIDERING OPERATIONALITY AND COMFORT

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Abstract: In this paper, a power assist system of Omni-directional Mobile Wheelchair(OMW) for attendants aiming at the reduction of incidence by operation of attendants is presented. The OMW presented in this paper, has 3 degrees of freedom, so it is important to consider operationality. The control system must be developed considering both operationality and comfort. A Power assist controller using fuzzy reasoning is proposed to estimate the navigation direction for the force given by the attendant, and the necessity of parameter tuning in the membership functions is described according to the individual characteristics. Further, the second order lag controller which transforms the force given by the attendant into the velocity of OMW, is presented to develop the rider's comfort.

1 INTRODUCTION

An omni-directional wheelchair is highly maneuverable in narrow or crowded areas such as residences, offices and hospitals. Several kinds of omni-directional vehicles have been developed in robotics fields (West and Asada, 1992), (Pin and Killough, 1994); moreover, some of these have been applied to wheelchairs (Wada and Asada, 1999), (H.Kitagawa and K.Terashima, 2004), (Urbano et al., 2005). In these researches, new mechanism, hierarchical control and obstacle avoidance of wheelchairs are proposed. However, past researches on the motion control of omni-directional wheelchairs have not considered transport wheelchair that is pushed by an attendant. This paper proposes a novel power assist system for omni-directional transport wheelchairs.

A power assist system of an omni-directional vehicle has been developed in (H. Maeda and Yamashita, 2000). However, it still has some problems in rotation and in rider's comfort since this system was developed for a food tray carry vehicle in a hospital.

The purpose of this research is to develop a power assist system for omni-directional transport wheelchairs considering attendant's manipulability and rider's comfort. A power assist controller using fuzzy reasoning is proposed to estimate the navigation direction for the force given by the attendant. Further, the second order lag controller which transforms the force given by the attendant into the velocity of OMW, is presented to develop the rider's comfort.

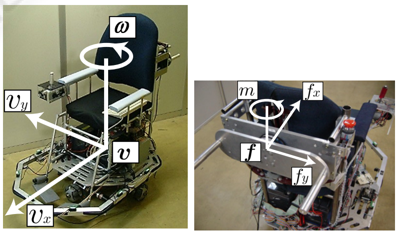

Figure 1: Omni-directional wheelchair (OMW)

2 OMNI-DIRECTIONAL WHEELCHAIR

An omni-directional wheelchair (OMW) using omni-wheels has been designed and built. Figure 1 is an overview of the OMW. The OMW is able to move in any arbitrary direction without changing the direction of the wheels.

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The OMW is equipped with four omni-wheels, and each wheel has passively driven free rollers at the circumference. The wheel that rolls perpendicular to the direction of movement does not stop the movement because of the passively driven free rollers. These wheels allow a holonomic omni-directional movement.

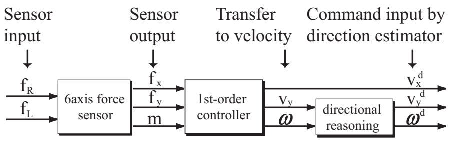


Figure 2: Block diagram of power assist system

The OMW is also equipped with a handle and a six-axis force sensor as shown in Fig.1. Input force to the handgrips of the handle by the attendant is measured using the force sensor.

3 POWER ASSIST SYSTEM

3.1 First order controller for power assist

The first order controller converts the output signal of the force sensor $F = [f_x, f_y, m]^T$ to the reference velocity $V_{omw} = [v_x^d, v_y, \omega]^T$ of the OMW. The input force can be converted to the reference velocity by using a controller that contains an integral element. Moreover, the controller should also have viscosity as the following equation since the OMW have to stop safely when F becomes zero.

$$G_i(s) = \frac{V_i(s)}{F_i(s)} = \frac{K_i}{T_i s + 1}, (i = x, y, m) \quad (1)$$

The reference velocity V_{omw} exponentially converges to zero by using this controller when the attendant stop pushing the handle. If the time constant T_i is too small, the effect of vibration of input force or noise becomes large. If the time constant T_i is too large, the manipulability of the OMW becomes bad because of its slow response. In this paper, paremeters were determined as K_x = 0.0003, K_y = 0.0002, K_m = 0.0007, T_x = 0.6, T_y = 0.75 and T_m = 0.75 by trial and error.

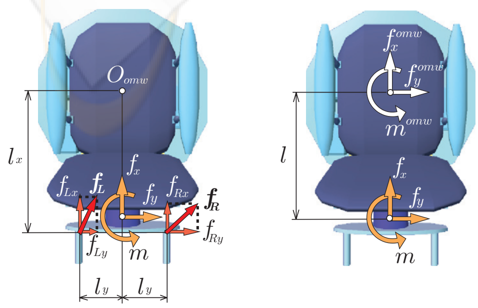


Figure 3: Working force

Table 1: Fuzzy reasoning rules

Rule	Antecedent	Consequent
1	$v_y > 0$ and $\omega < 0$	$v_y^d > 0$ (Right Slide)
2	$v_y < 0$ and $\omega > 0$	$v_y^d < 0$ (Left Slide)
3	$v_y \approx 0$ and $\omega \approx 0$	$v_y^d \approx 0$ (Not Slide)
4	$v_y \geq 0$ and $\omega > 0$	$\omega^d > 0$ (CCW Turn)
5	$v_y \leq 0$ and $\omega < 0$	$\omega^d < 0$ (CW Turn)
6	$v_y \approx 0$ and $\omega \approx 0$	$\omega^d \approx 0$ (Not Turn)

Table 2: Parameters of menbership functions

Rule Number	Antecedent			
	name	a	b	c
1	YPS	7	0.3	-
	ONS	7	-0.3	-
2	YNS	7	-0.3	-
	OPS	7	0.3	-
3	YZS	-	-	1000
	OZS	-	-	1000
4	YPT	7	0.3	-
	OPT	7	0.3	-
5	YNT	7	-0.3	-
	ONT	7	-0.3	-
6	YZT	-	-	1000
	OZT	-	-	1000

3.2 Direction estimator of navigation for force input

When the user tries to rotate OMW around its gravity center, OMW begans to slide and the radius of rotation becomes very big. Then, rotation around the center is very difficult. For solving this problem, direction inference is developed by using the fuzzy rules shown in Table 1. The block diagram of the system is shown in Fig. 2. In order to establish the rules of direction inference, first, the force applied to the grips of the force sensor are changed to the center of OMW, as shown in Fig. 3. Note that the input of the direction estimator is velocity V_{omw}, not force F. It may seem more reasonable to use F for the estimation of the attendant's intention, however, it is very difficult to derive transform equations from F because of an effect of vibration of input force or noise. v_x is not included since forward and backward motion can be realized without direction estimation. Features of slide motion is expressed by rules 1 and 2, and that of rotation by rules 4 and 5. Rules 3 and 6 are added not to generate the reference velocity when input velocity is zero.

Figure 4 shows the graph of membership functions of the first rule. The membership function of the antecedent of 1, 2, 4 and 5 is

$$\mu_{name} = \tan^{-1}\{a_{name}(\beta_i - b_{name})\}/\pi + 0.5 \quad (2)$$

where β_i is input ($\beta_1 = v_y$, $\beta_2 = \omega$) and a_{name} and b_{name} are tuning parameters. '$name$' is replaced by the name of each membership function. The first letter of 'name' of antecedents indicates sensor output(v_y^d:Y, ω^d:O), the second letter indicates sign (Positive:P, Negative:N, Zero:Z), and the third letter indicates realized motion (Slide:S, Turn:T).

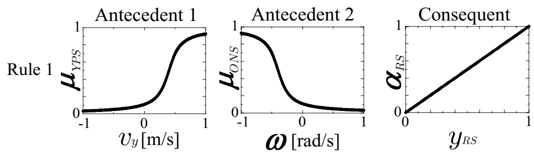


Figure 4: Membership functions of rule 1

The membership function of the antecedent of 3 and 6 is

$$\mu_{name} = \exp(-c_{name} \cdot \beta_i^2) \quad (3)$$

where c_{name} is a tuning parameter

3.3 Experimental results

In order to verify the effectiveness of the control system, laboratory experiments were conducted. The results shown correspond to a first order controller. Parameters of the membership function of Fig. 4 are shown in Table 2.

The trajectory and velocity v_{omw}^d of slide motion to right are shown in Fig.5 and Fig.6, respectively. As seen in the trajectory of v_y^d, vibration of the velocity was reduced. The trajectory and velocity v_{omw}^d of rotation around its center in counter-clockwise are shown in Fig.7 and Fig.8, respectively. As seen in Fig.7, the rotation around its center was realized by using the direction estimator. The effectiveness of the direction estimator is shown especially in case of rotation.

4 TUNING OF MEMBERSHIP FUNCTIONS

4.1 Necessity of tuning

Figure 9 shows the experimental results of using fuzzy reasoning, where a 60 year-old woman operated OMW. In Fig. 9, f is a force added by attendant,

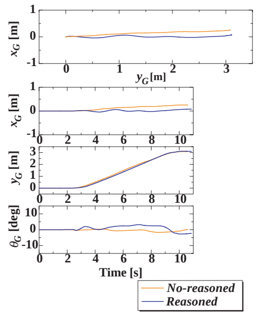


Figure 5: Trajectory of right slide

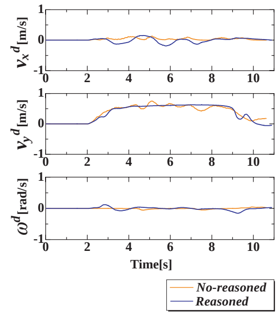


Figure 6: Velocity v_{omw}^d of right slide

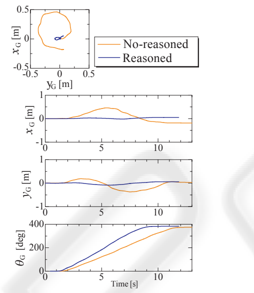


Figure 7: Trajectory of rotation (CCW)

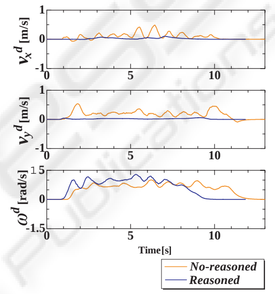


Figure 8: Velocity v_{omw}^d of rotation (CCW)

v_d is a velocity command, (x_g, y_g) is the position of OMW in the global coordintes and θ_g is a posture of OMW.

Here, OMW moves in the following order: Forward (1) $\Rightarrow$ Backwards (2) $\Rightarrow$ 180^0 Left rotation (3) $\Rightarrow$ Right slide (4) $\Rightarrow$ Left slide (5).

Then, Fig. 10 shows the results by fuzzy reasoning. Horizontal axis is a translation velocity v_y before fuzzy reasoning, vertical axis is a rotational velocity ω before fuzzy reasoning, darkness degree in the cockpit indicator shows the translation velocity v_y^d and the rotational command velocity ω^d after fuzzy reasoning, and the real line in Fig. 10 shows the v_y and ω operated by attendant in order to get the obtained movement as shown in Fig. 9

This woman uses the region of $v_y > 0$ and $\omega \approx 0$ while moving towards the right slide. However, while using the parameter of membership function used in the previous section, $v_y^d \approx 0.2$ [m/s], and $\omega^d \approx 0.4$ [rad/s] are estimated. Here, this woman intends to move towards right without rotation, but really moves towards right with rotation.

Figure 11 shows attendant's intention representing direction to make OMW move using v_y and ω added by attendant.

In the present fuzzy parameters given by the previous section, the attendant such as $examinee$ 1 can operate OMW well.

On the other hand, the attendant such as $examinee$ 2 wants to make OMW move towards right in the re-

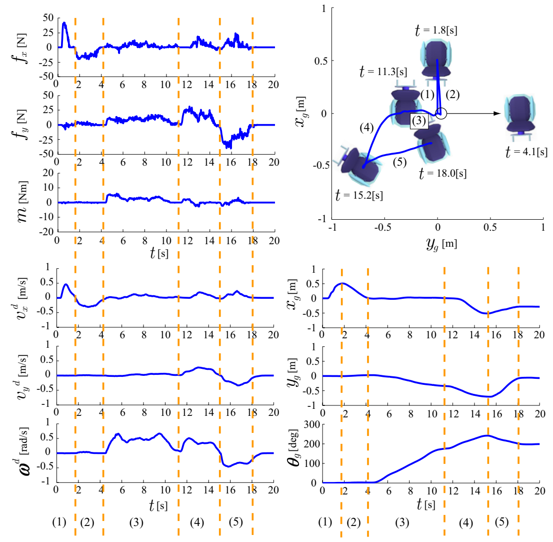
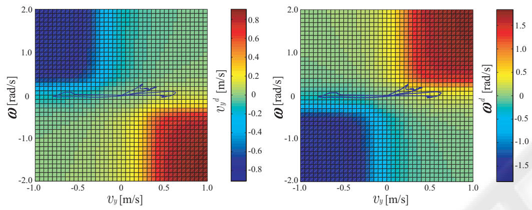


Figure 9: Experimental results with fuzzy resoning



(a) Velocity of slide (b) Velocity of turn

Figure 10: Fuzzy reasoning

gion of $v_y > 0$ and $\omega \approx 0$.

Then, when fuzzy membership function is fixed for all examinees, the attendant with having the tendency like *examinee 2* feels the difficulty to operate OMW. Therefore, it is necessary to adjust the parameters of fuzzy membership functions according to the driving characteristics of individual persons.

4.2 Tuning system

The parameters in the membership functions are $\{a_{name}, b_{name}, c_{name}\}$ as shown in "(2)" and "(3)".

The number of $\{a_i, b_i, c_i\}$ $\{i = name\}$ in Antecedent part of fuzzy rule is 20. However, the number of $\{a_i, b_i\}$ is 16, because c_i doesn't give a big effect on the whole result.

Here, a_{name} is related with the slope of membership function, while b_{name} is with shift quantity in the movement region. Therefore, the parameter of b_{name} is more effective one as the tuning parameter.

Then, eight parameters of b_{name} are tuned. Among them, $\{b_{YPS},\ b_{YNS}\}$, $\{b_{YPT},\ b_{YNT}\}$, $\{b_{ONS},\ b_{OPS}\}$ and $\{b_{OPT},\ b_{ONT}\}$ have the relation

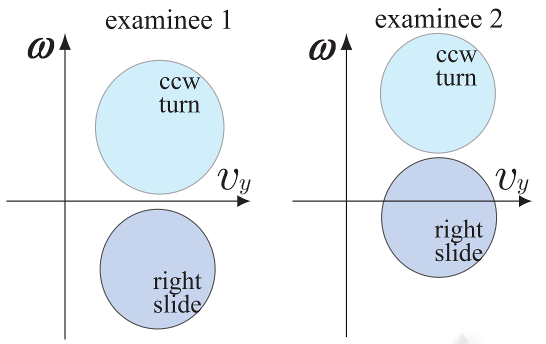
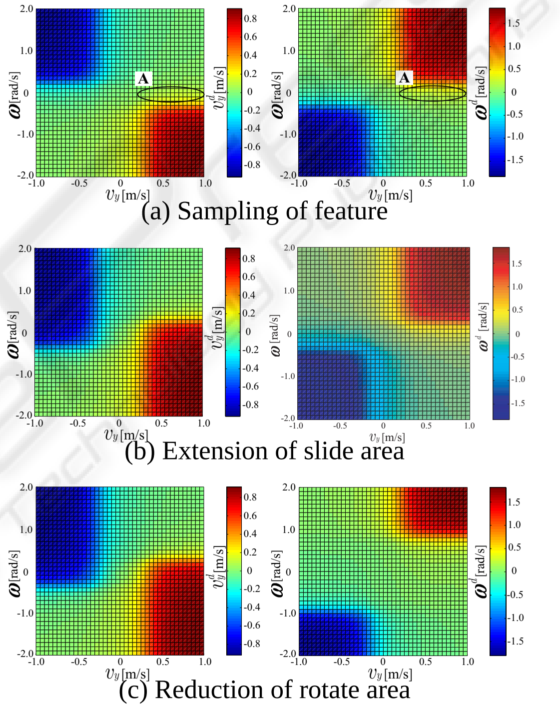


Figure 11: Attendant's intention



(a) Sampling of feature

(b) Extension of slide area

(c) Reduction of rotate area

Figure 12: Tuning method in the case of slide movement

such as $|b_{ONS}|$ and $|b_{OPS}|$ is the same, and their sign is opposite.

Hence, the task for parameter tuning is to determine four parameters $\{b_{YPS},\ b_{YPT},\ b_{ONS},\ b_{OPT}\}$ and it is thought to be a comparably easy task.

As a concrete example, let us consider the case of slide movement. Operator intends to move OMW towards right. Then, moment ω was 0.3 when operator wished OMW to move towards right.

In this state, the region A is different from operator intention, because v_y^d and ω_y^d are 0, as shown in (a) of Fig. 12

Thus, the parameters b_{name} in Table 2, obtained by trial and error, must be changed. Then, b_{ONS} is changed from -0.3 to 0.3, and b_{OPS} from 0.3 to -0.3, due to the opposite sign. By this operation, the region of slide is extended, and then it enables OMW to moves towards right even if ω = 0.3, as shown in the left figure of Fig. 12 (b).

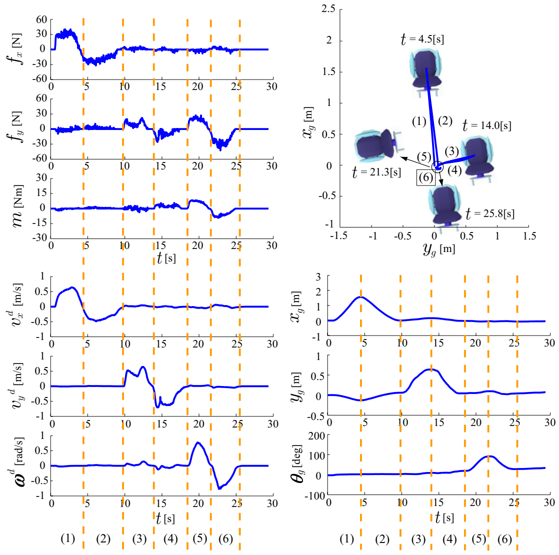
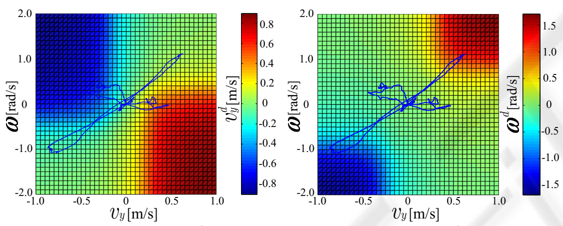


Figure 13: Experimental results with fuzzy resoning



(a) Velocity of slide (b) Velocity of turn

Figure 14: Fuzzy reasoning after tuning

However, ω^d will generate in the region A, when ω = 0.3 is used. Then, OMW will simultaneously rotate with right slide.

In order to avoid this, b_{OPT} is changed from 0.3 to 0.9, and b_{ONT} from -0.3 to -0.9. Then, as seen from the right figure of Fig. 12 (c), ω^d doesn't generate in the region A, and therefore OMW moves towards right slide without rotation.

Following this procedure, parameter tuning can be realized by easy manner. A monitor system has been developed such as the result of fuzzy reasoning like Fig. 12, and position and posture of OMW in the global coordinate, can be pictured in real time.

Figure 13 and Fig 14 show the experimental results after tuning for this person. Tuning was conducted such that right slide could be done under the conditions of $v_y > 0$ and $\omega \approx 0$. OMW was moved in the order:

Forward $\Rightarrow$ Right slide $\Rightarrow$ Left slide $\Rightarrow$ 90^0 right turn $\Rightarrow$ 90^0 left turn

She uses the region of ω = 0, when she wants OMW to conduct the slide motion. Then, the required movement was realized by tuning. Thus, the improvement of operation was achieved.

5 IMPROVEMENT OF COMFORT BY USING A SECOND ORDER CONTROLLER

When the first order controller in previous section is used according to previous research, a big jerk (variation of acceleration) appears if the input force changes suddenly. Jerk is considered as the factor that dominates riding comfort. For riding comfort improvement, jerk must be decreased. A method for decreasing jerk is proposed as follows:

i) Decrease the gain K_i, $(i = x, y, \omega)$.
ii) Increase the value of the time constant T_i, $(i = x, y, \omega)$.
iii) Establish the largest restriction of jerk.
iv) Modify the controller.

In item (i), as the output velocity related to the help force becomes smaller, the jerk becomes small too. However, a big force is necessary for achieving the desired velocity. Then, the effect of power assist fades and OMW becomes, once again, very heavy for the attendant.

In items (ii) and (iii), jerk can be made smaller too, but in this case, after the change, the time for reaching the desired velocity increases. This generates a problem of deterioration of operability. In brief, with the proposed method is possible to improve riding comfort, but operability of OMW decays. Then, a second order controller

$$G_i(s) = \frac{V_i(s)}{F_i(s)} = \frac{K(\omega_n)_i^2}{s^2 + 2\zeta_i(\omega_n)_i s + (\omega_n)_i^2}, \quad (i = x, y, m) \tag{4}$$

is chosen as a power assist controller which can provide compatibility for both operability and riding comfort. Here, ζ is the attenuation factor. Even when the help force is fix, if overshoot O_s occurs, certain amount of time is required for the velocity to converge and operability deteriorates. Then, in order to avoid overshoot ζ_i is chosen as ζ_x = 1, ζ_y = 1, ζ_m = 1.

In addition, for the resonant frequency ω_n, in the case when the time constant of the first order controller T_x = 0.4, T_y = 0.4 and T_m = 0.4, is used, it makes difficult for ω_n to be influenced by the noise included in the help force and as a consequence good operability of OMW is obtained. Then, in this case and in order for recovery time to become the same, $\omega_n)$ is chosen, by trial and error, as $(\omega_n)_x$ = 4, $(\omega_n)_y$ = 4, $(\omega_n)_m$ = 4.

Experimental comparison of the jerk produced in *x* direction by a first order controller and a second order controller, for the same reference velocity, was conducted. The experimental parameters were: K_x = 0.02CT_x = 0.4Cζ_x = 1.0C$(\omega_n)_x$ = 4.0Csampling time t_s = 0.03[s]. OMW was moved in automatic mode with an input help force given as:

$$f_x = \begin{cases} 0 & (0 \leq t < 1, 4 \leq t < 7, t \geq 10) \\ 50 & (1 \leq t < 4) \\ -50 & (7 \leq t < 10) \end{cases}$$

Jerk was evaluated by differentiating the output of the encoders of OMW's motors. Experimental results are shown in Fig. 15. v_x is the reference velocity, j_x^{omw} shows the actual jerk that was calculated by using the encoders output. As in order to calculate the jerk from the encoders output it is necessary to differentiate the encoders output, there is the problem that even a little noise present in the encoders output will cause big changes in the value of jerk due to differentiations. Here, instead of concentrating in very precise values of jerk, attention is given to the big variations of jerk, so using values of jerk for *(t-1)* and *(t+1)*, where *t* is the actual time, a moving average of jerk is calculated. As the velocity is constant between t=3‘4[s], the jerk observed in this interval of time is due to the erratic reading of encoders and then is ignored. Attention will be focused on the interval of time between t=1‘2[s], in which there is acceleration and deceleration. It has been verified that a second order controller can achieve a maximum reduction of 20% of the value of jerk produced during this period. Then, improvement of riding comfort is assured by using a second order controller. Moreover, comparing this results with the case in which the reference velocity is input to a first order controller, there is almost no delay of time response and then operability is not degraded. For these reasons, it is possible to conclude that in this case second order controller has a better performance than first order controller.

In addition, as riding comfort is something that depends on the subjective judgement of the OMW's occupant, riding comfort was evaluated by using Semantic Differential (SD) method.

OMW was made to move in automatic mode in *x* direction and *y* direction and a questionnaire consisting of 7 items related to driving comfort was presented to 10 different people. The mean value of the results obtained in each item are shown in Fig. 16 for *x* direction and Fig. 17 for *y* direction. Even when the difference for the results in *x* direction and *y* direction is not so big, it is possible to see that the values obtained by the second order controller are much better than that obtained by the first order controller. Then a second order controller will be used as power assist controller because it can improve riding comfort.

6 CONCLUSIONS

A power assist system for omni-directional transport wheelchairs considering both attendant's manipulability and rider's comfort was developed. The reference velocity of the omni-directional wheelchair was derived from attendant's input force. Manipulability of rotation was improved greatly by using the fuzzy direction estimator.

In order to improve riding comfort, the first order controller has been changed by newly giving a second order controller which can improve the riding comfort for reducing the jerk. Comfort has been enhaced by using a second order controller.

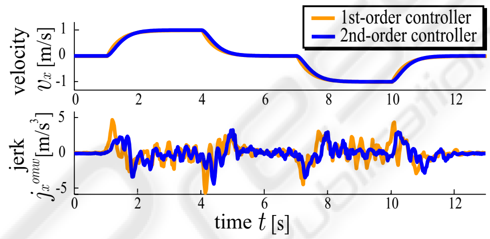


Figure 15: Experimental result of jerk

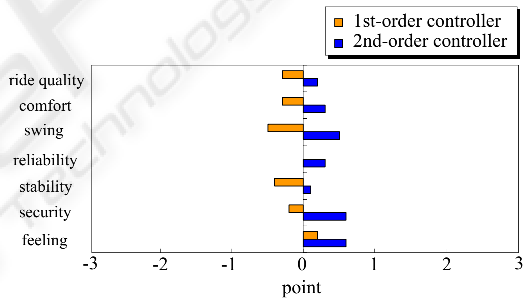


Figure 16: Questionnaire result of x-axis

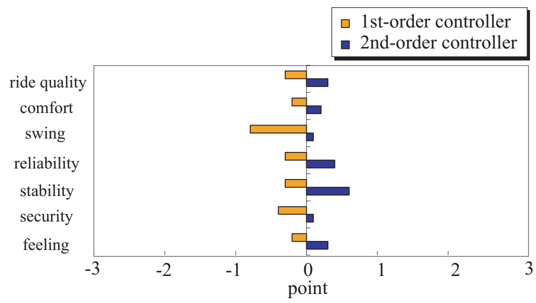


Figure 17: Questionnaire result of y-axis

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