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MOTION CONTROL OF OMNIDIRECTIONAL WHEELCHAIR CONSIDERING PATIENT COMFORT

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Abstract: An omnidirectional wheelchair is highly maneuverable in narrow or crowded areas such as residences, offices and hospitals. In this paper, a novel motion control system for an omnidirectional wheelchair is proposed. In order to ensure a comfortable ride for the patient, the controller is designed using a hybrid shape approach that considers both time and frequency characteristics. The effectiveness of the proposed system is evaluated by the output signal of a sensor attached to the wheelchair and by a descriptive inspection by several users.

Keywords: Human-machine interface, Medical applications, Human-centered design, Mobile robots, Wheels

1. INTRODUCTION

The development of technology that facilitates the rehabilitation of people with severe and multiple handicaps in everyday life is desirable. An omnidirectional wheelchair is highly maneuverable in narrow or crowded areas such as residences, offices and hospitals. Several kinds of omnidirectional vehicles have been developed in robotics fields (West and Asada, 1992) and (Pin and Killough, 1994); moreover, some of these have been applied to wheelchairs (Hoyer and Jochheim, 1999) and (Kitagawa and Terashima, 2001). In these researches, new mechanism, hierarchical control and obstacle avoidance of wheelchairs are proposed. However, there remains another problem.

With the increase in the degrees of freedom accompanying omnidirectional wheelchairs, it has become more important than in the past to develop a smooth and vibrationless motion control system. However, past researches on the motion control of wheelchairs have not considered patient comfort.

In this paper, a novel motion control method for an omnidirectional wheelchair considering the suppression of vibration of both the wheelchair and the patient is proposed. Since the vibration caused by transfer without disturbance is the self-excited vibration, it is essential to determine the velocity control of a wheelchair so that the vibration is not excited. Therefore, it is not necessary to feedback the direct measurement of the vibration. In the proposed control system, the vibration of the wheelchair is suppressed by notching the frequency characteristics at the natural frequency of both the wheelchair and human's organs. The designed controller satisfies various control specifications by using feedback from only one source: the wheelchair's position data.

The effectiveness of the proposed method is evaluated by the output signal of an acceleration sensor attached to the wheelchair and through a descriptive inspection by 15 examinees using the Semantic Differential (SD) method.

2. DEVELOPMENT OF OMNIDIRECTIONAL WHEELCHAIR

2.1 Mechanical design

An omnidirectional wheelchair using omniwheels has been designed and built. Figure 1 is an overview of this omnidirectional wheelchair. The wheelchair is able to move in any arbitrary direction without changing the direction of the wheels.

In this system, four wheels are individually and simply driven by four motors. In deciding on the number of wheels and the number of motors, several factors had to be considered. A four-wheeled wheelchair driven by four motors independently incurs an over-constraint problem, since the wheelchair has only three-degrees-of-freedom (3-DOF) motion. On the other hand, a three-wheeled wheelchair is too unstable, and a four-wheeled vehicle driven by three motors requires a complex mechanism and is not suitable for everyday use.

Figure 2 shows the base unit that generates a holonomic omnidirectional movement, which was developed in our laboratory. The wheelchair is equipped with four omniwheels, 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 omnidirectional movement.

The wheelchair also employs ultrasonic and infrared (PSD) ranging systems for semi-autonomous obstacle avoidance (Kitagawa, et al., 2001) and an omnidirectional power-assist system for nursing care.

2.2 Kinematics

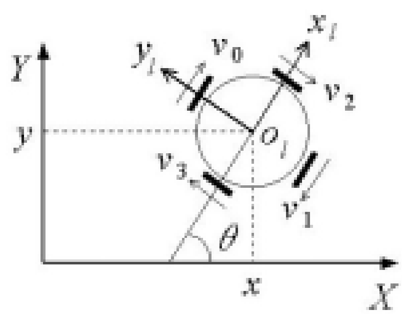
Figure 3(a) shows the coordinate system of the wheelchair. Let v_x and v_y be the translational velocities of the central point o_l in the x_l and y_l directions, respectively. As shown in Fig. 3(b), v_x and v_y are given by

$$v_x = \frac{1}{2}(v_0 - v_1) \tag{1}$$

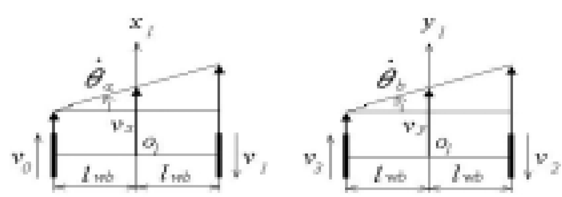
$$v_y = \frac{1}{2}(v_3 - v_2) \tag{2}$$

Fig. 1. Omnidirectional wheelchair

Fig. 2. Base unit composed of 4 omniwheels



(a) Coordinate system



(b) Velocities in x- and y-directions

Fig. 3. Kinematics of the wheelchair

where $v_i (i = 0, 1, 2, 3)$ is the velocity of each wheel.

The velocity of the wheelchair $\dot{x} = \left[\dot{x}, \dot{y}, \dot{\theta}\right]^T$ with reference to the fixed frame O-XY is given by

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \dot{\theta} \end{bmatrix}. \tag{3}$$

On the other hand, the rotational velocity $\dot{\theta}$ is given by

$$\dot{\theta} = -\frac{1}{4l_{wb}}(v_0 + v_1 + v_2 + v_3) \tag{4}$$

where l_{wb} is the distance between o_l and each wheel. By substituting Eqs. (1), (2) and (4) into Eq. (3), $\dot{x}$ is related to the wheel velocity vector $u = [v_0, v_1, v_2, v_3]^T$ by

$$\dot{x} = Bu \tag{5}$$

$$B = \begin{bmatrix} \frac{\cos\theta}{2} & -\frac{\cos\theta}{2} & \frac{\sin\theta}{2} & -\frac{\sin\theta}{2} \\ \frac{\sin\theta}{2} & -\frac{\sin\theta}{2} & -\frac{\cos\theta}{2} & \frac{\cos\theta}{2} \\ -\frac{1}{4l_{wb}} & -\frac{1}{4l_{wb}} & -\frac{1}{4l_{wb}} & -\frac{1}{4l_{wb}} \end{bmatrix}. \tag{6}$$

In order to compute the inverse matrix, the rotational velocity $\dot{\theta}$ is decomposed as

$$\dot{\theta} = \dot{\theta}_a + \dot{\theta}_b \tag{7}$$

$$\dot{\theta}_a = -\frac{1}{4l_{wb}}(v_0 + v_1) \tag{8}$$

$$\dot{\theta}_b = -\frac{1}{4l_{wb}}(v_2 + v_3) \tag{9}$$

in this system. From Eqs. (5), (6), (8), (9) and , $\dot{\tilde{x}} = \left[\dot{x}, \dot{y}, \dot{\theta}_a, \dot{\theta}_b\right]^T$, the velocity of the wheelchair is related to the wheel velocity vector by

$$\dot{\tilde{x}} = \tilde{B}u \tag{10}$$

$$\tilde{B} = \begin{bmatrix} \frac{\cos\theta}{2} & \frac{\cos\theta}{2} & \frac{\sin\theta}{2} & \frac{\sin\theta}{2} \\ \frac{\sin\theta}{2} & \frac{\sin\theta}{2} & \frac{\cos\theta}{2} & \frac{\cos\theta}{2} \\ -\frac{1}{4l_{wb}} & -\frac{1}{4l_{wb}} & 0 & 0 \\ 0 & 0 & -\frac{1}{4l_{wb}} & -\frac{1}{4l_{wb}} \end{bmatrix}. \tag{11}$$

By computing the inverse matrix of Eq. (11), the inverse kinematics model is given by

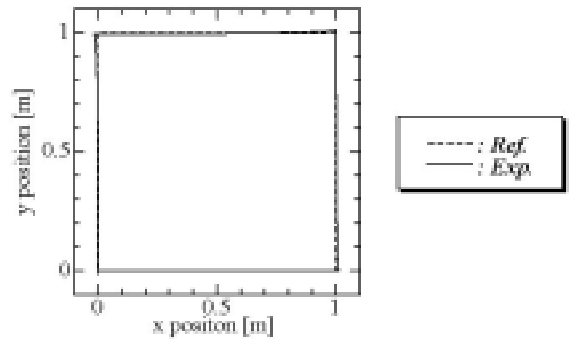
$$u = \tilde{B}^{-1}\dot{\tilde{x}} \tag{12}$$

$$\tilde{B}^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & -l_{wb} & 0 \\ -\cos\theta & -\sin\theta & -l_{wb} & 0 \\ \sin\theta & -\cos\theta & 0 & -l_{wb} \\ -\sin\theta & \cos\theta & 0 & -l_{wb} \end{bmatrix}. \tag{13}$$

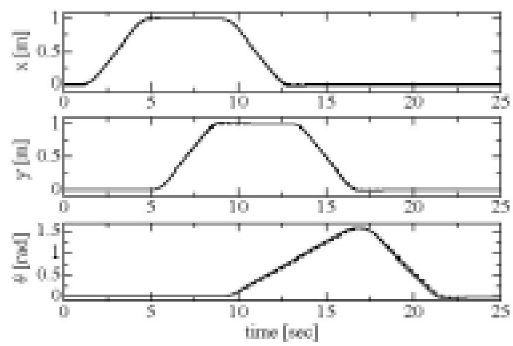
3. TRAJECTORY TRACKING CONTROL

In order to confirm the ability of the omnidirectional wheelchair, a trajectory tracking experiment by a PD controller is conducted. The proportional gain K_p and derivative gain K_d are tuned by simulation not to generate a vibrant velocity input.

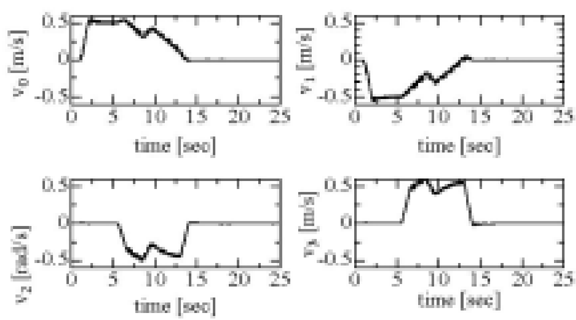
The experimental results are shown in Fig. 4. At the initial condition $(x, y, \theta) = (0, 0, 0)$, the wheelchair is facing the $+x$ direction.



(a) Trajectory



(b) Trajectory of time series



(c)Velocity of each wheel

Fig. 4. Experimental result by PD contorol

As seen in Fig. 4(b), the reference trajectory is composed of forward motion (1sec to 5sec), slide motion (5sec to 9sec), translation while rotating (9sec to 17sec) and rotation in the same place (17sec to 22sec). The positioning control is achieved as seen in this figure.

4. MOTION CONTROL CONSIDERING PATIENT COMFORT BY HYBRID SHAPE APPROACH

The control system is based on a hybrid shape approach recently developed in our laboratory

(Yano and Terashima, 2000). Optimization problems formulated in both the time and the frequency domains have scarcely been found in the other researches.

In this paper, a dynamic model of vibration is not utilized in the control design step, because it would be difficult to mathematically model the vibrations of the wheelchair and the patient using it. In the design of a controller, the natural frequency of the wheelchair and of the patient's organs are utilized as *a priori* information. Controller design is composed of the following elements.

(1)*Selection of controllers :* Controllers are constructed by several fundamental control elements such as a notch filter, low-pass filter, PID elements, and so on.

(2)*Formulation of design specifications :* The design specifications in the frequency and the time domains are expressed by penalty functions.

(3)*Formulation of an optimization problem :* An optimization problem is formulated with constraints expressed by penalty terms.

(4)*Computation of a controller :* The parameters of the controller are computed by solving an optimization problem. In this paper, the Simplex method is applied to solve the problem.

Here, the controller is designed in the x direction for the first step. In this system, the controller is supposed to be designed in three (x, y, θ) directions independently, which seems to be achieved easily.

4.1 Selection of controller

The wheelchair is controlled by a servo system with an integrator. According to the Internal model principle, a proportional control (P control) system is sufficient to avoid the offset. Therefore, a proportional gain is given as an element of this controller

$$K_1(s) = K_P. \tag{14}$$

Two notch filters prevent the controller from exciting vibration in the wheelchair or in the patient's organs, as

$$K_2(s) = \frac{s^2 + 2\zeta\omega_w s + \omega_w^2}{s^2 + \omega_w s + \omega_w^2} \tag{15}$$

$$K_3(s) = \frac{s^2 + 2\zeta\omega_0 s + \omega_0^2}{s^2 + \omega_0 s + \omega_0^2} \tag{16}$$

where the parameters are given as the natural frequency of the wheelchair $\omega_w = 15.5$ [rad/s], of human's organ $\omega_0 = 37.7$ [rad/s] and $\varsigma = 0.0001$. Since the natural frequencies of the patient's organs range from 4[Hz] to 8[Hz], the intermediate value is adopted.

In order to reduce the influence of higher-order vibration and noise, a low-pass filter, which is the low gain in the high-frequency domain, is given as

$$K_4(s) = \frac{\omega_l^2}{s^2 + 2\varsigma_l\omega_l s + \omega_l^2} \tag{17}$$

where the parameters are given as $\varsigma_l = 0.7$.

Finally, the transfer function of the controller is given as

$$\begin{aligned} K(s) &= \prod_{i=1}^{4} K_i(s) \\ &= \frac{K_P\omega_l^2(s^2 + 2\zeta\omega_w s + \omega_w^2)}{(s^2 + 2\varsigma_l\omega_l s + \omega_l^2)(s^2 + \omega_w s + \omega_w^2)} \\ &\cdot \frac{(s^2 + 2\zeta\omega_0 s + \omega_0^2)}{(s^2 + \omega_0 s + \omega_0^2)}. \end{aligned} \tag{18}$$

In this equation, K_P and ω_l are unknown parameters. Therefore, both parameters should reasonably be determined by solving an optimization problem.

4.2 Formulation of design specifications

The specifications of the controller are formulated by making use of penalty functions. Penalties are given if any of the following relations do not hold.

- The controller and the closed-loop system are stable.

$$Re[r_K] < 0, Re[r_{cl}] < 0 \tag{19}$$

$$K_P > 0, \omega_l > 0 \tag{20}$$

- The controller gain is less than -20[dB] at the natural frequency of the wheelchair $\omega_w = 15.5$[rad/s] or at that of patient's organs $\omega_0 = 37.7$[rad/s].

$$|K(\omega_w)| < -20[dB] \tag{21}$$

$$|K(\omega_0)| < -20[dB] \tag{22}$$

- The controller gain is less than 0[dB] at $\omega_l = 188$[rad/s] in order to decrease the influence of the higher-order vibration and noise.

$$|K(\omega_l)| < 0[dB] \tag{23}$$

- The input voltage u does not exceed a magnitude of 24[V].

$$\max|u| < 24[V] \tag{24}$$

- Maximum overshoot does not exceed the magnitude of 0.001[m].

$$\max O_s < 0.001[m] \tag{25}$$

4.3 Formulation of an optimization problem

The following optimization problem using penalty terms is formulated with Eqs. (19) to (25).

$$\min_{K(s)} J = T_s + J_p \tag{26}$$

where,

$$J_p = w_1 + w_2 + ...w_9 \tag{27}$$

and T_s is the settling time when the target position is 2.0[m] and the admissible error is 0.001[m]. If any of the above penalty conditions are not satisfied, the penalty function w_i is given as $w_i = 10^8 (i = 1, ..., 9)$.

4.4 Computation of a controller

For the optimization of a cost function, the Simplex method is used, where the reflection coefficient $\alpha = 1.0$, the expansion coefficient $\beta = 0.5$ and the contraction coefficient $\gamma = 2.0$. The initial simplex values $K_p = (15, 20, 30)$ and $\omega_l = (30, 40, 50)$ are adopted.

As the results of computation, the minimum value of Eq. (26) was $J = T_s = 7.89$[s], where $K_p = 26.3$ and $\omega_l = 37.1$[rad/s]. The cost function with iteration is shown in Fig. 5.

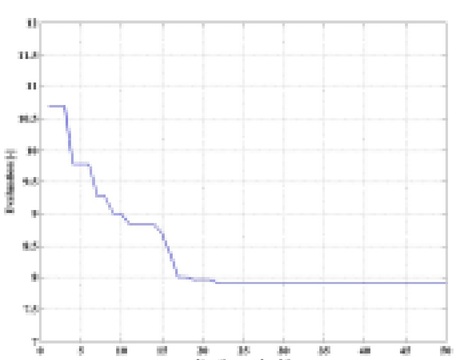
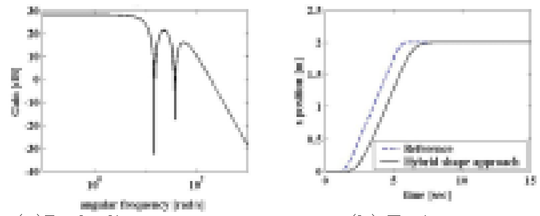


Fig. 5. Cost function



(a)Bode diagram (b) Trajectry

Fig. 6. Simulation result of proposed controller

The frequency response of the controller is shown in Fig.6(a). It can be seen that the high-speed transfer is achieved because the controller is high-gain in the low-frequency domain.

The simulation result of the trajectory tracking is shown in Fig. 6(b). As seen from this figure, it is confirmed that overshoot is not found.

5. EXPERIMENTS

In order to verify the effectiveness of the control system, laboratory experiments are conducted. In these experiments, the wheelchair moves forward 2[m] and halts three times, for 10[s] at a time. Three kinds of controllers are examined.

- PD feedback controller without filter
- PD feedback controller with only a double-notch filter (denoted by Eqs. (15) and (16))
- Proposed controller designed by the hybrid shape approach (denoted by Eq. (18) and optimized by Eq. (26))

The experimental trajectory is shown in Fig. 7. The experimental results are evaluated by the following two steps. In the first step, the output signal of the acceleration sensor attached to the wheelchair is examined to evaluate the vibration suppression. However, the effectiveness of the consideration of the patient's organs cannot be evaluated in this step. In the second step, the effectiveness of the proposed method on patient comfort is evaluated by the SD (Semantic Differential) method (Saito, 1978), which is a kind of inspection using a scale of verbal responses.

5.1 Evaluation by acceleration sensor output

The output of the acceleration sensor attached beneath the seat is shown in Fig. 8. The resultant acceleration and the jerk are suppressed by the hybrid shape approach.

5.2 Evaluation by SD inspection

The SD method is applied to evaluate the effectiveness of the consideration of the patient's

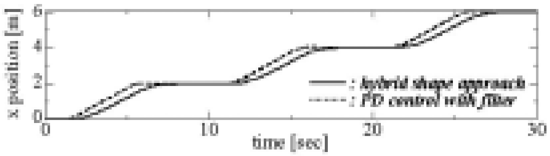


Fig. 7. Experimental trajectory

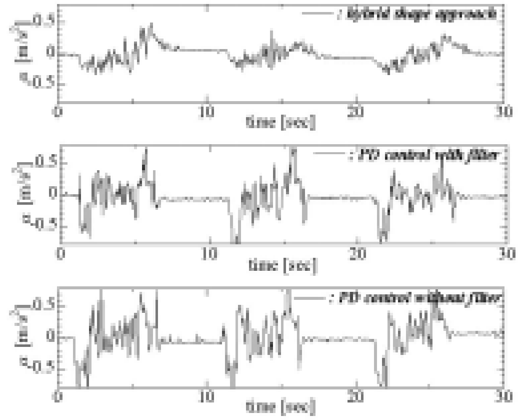


Fig. 8. Output of acceleration sensor

organs. In this method, several pairs of adjectives are adopted to evaluate an object or feeling. Within each pair, the adjectives are antonymous each other. To describe the feeling that he or she is experiencing, the examinee selects one of seven grades that form a scale ranging from the one adjective to the other. This method is especially effective for finding the shades of differences among several objects or feelings.

Figure 9 shows the SD sheet used for the evaluation of the wheelchair in this study. Using his or her impression, each examinee selects one of seven grades for every pair of opposite adjectives listed in Fig. 9.

The wheelchair was evaluated by 15 examinees. The average value of each item is shown in Fig. 10. The hybrid shape approach seems to enable examinees to provide the greatest sense of patient comfort.

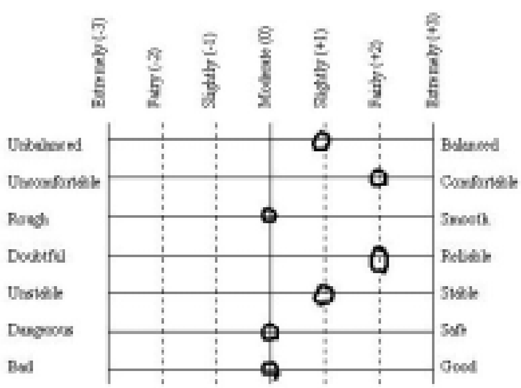


Fig. 9. SD sheet for omnidirectional wheelchair

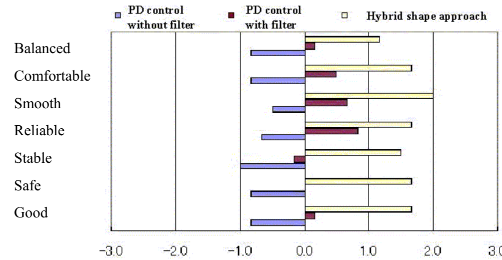


Fig. 10. Experimental result by SD method

6. CONCLUSION

A motion control method for an omnidirectional wheelchair was presented. The effectiveness of the control system was shown by experiments. The following results were obtained.

- A holonomic omnidirectional wheelchair was built, and its positioning ability was confirmed by a trajectory tracking control.
- A controller that considers patient comfort, and that has a simple structure, was designed and implemented.
- The effectiveness of the obtained controller was shown by the output of the acceleration sensor and by the SD method.

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