Collision Avoidance in an Omni-Directional Wheelchair by using Haptic Feedback

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Abstract: The present paper gives a haptic feedback control of a holonomic Omni-directional Mobile Wheelchair (OMW) with a haptic joystick for the operation of disabled people or elderly people considering not only the navigation task but also user's safety. In the present research a haptic joystick was designed and applied with being maneuverable for users and free of joystick's vibrations. A way to build the local map around OMW is presented by considering the reliability of sensors data such as ultrasonic and PSD sensor. If an obstacle is detected in the direction of movement based on the local map information, the impedance of the joystick in this direction is changed. Namely, the closer the obstacle is the bigger the impedance value becomes. By this function, users spontaneously understand that they are in risk of obstacle collision and then users can change the direction of movement by their decision in order to avoid it. Two navigation modes are considered: one of them allows the user to approach a desired goal, and the other protects the user from obstacle collision. The proposed approach is thought to be reasonable as a man-machine existing control system.

Keywords: Omni-directional wheelchair, haptic joystick, collision avoidance

1 Introduction

One of the main features of world population in the 20^{th} century is the increment of elderly people. According to WHO (World Health Organization) by 2025, the increase of population over aged 60 is predicted to reach 23% in North America, 17% in East Asia, 12% in Latin America and 10% in South Asia. There are over 600 million disabled persons in the world constituting nearly 10% of the global population, as stated on the international Day of Disabled Persons in 2003.

These people need positive action on the part of governments, private sector and civil society. So in recent years, more and more convenient facilities and equipments have been developed in order to satisfy the requirements of elderly people and disabled people. Among them, wheelchair is a common one which is used widely. A wheelchair can provide the user with many benefits, such as maintaining mobility, continuing or broadening community and social activities, conserving strength and energy, and enhancing quality of life.

A holonomic Omni-directional Mobile Wheelchair (OMW) as shown in Fig. 1 has been developed in author's laboratory ([1] \sim [4]), which is comprised of three modes such as autonomous, semi-autonomous and power-assist modes. In [1], in order to recognize surrounded environment, it can build a map using ultrasonic and Position Sensitive Device (PSD) sensors, and according to the distance with obstacle, impedance of joystick is varied. Then, user can feel the distance by hand. This is called a Haptic Joystick. User can know if there are obstacles around and therefore user can succeed avoiding those obstacles beforehand. However, in the literature ([1]), impedance control by means of haptic feedback method was insufficient, and vibration phenomenon of joystick was often generated, because only stiffness of the joystick was considered .

The present paper focuses on semi-autonomous mode operation by man-machine cooperation, and gives a haptic feedback control of OMW with a haptic joystick for the operation of disabled people or elderly people considering not only user's safety but also comfort which suppresses the joystick's vibration. Two operational modes of navigation are developed: Mode I, or common navigation mode, which allows the user to reach at a desired goal and, Mode II, or safety navigation mode, which protects the user against obstacle collision regardless of operation fatal error. In Mode II the counter-torque τ is increased until it reaches the input value, T_r . Then, the resultant input and therefore the tilting angle of joystick become 0 and OMW stops in front of the obstacle. For the command input by human joystick operation, velocity control of OMW is carried out by means of frequency shaping using Hybrid Shape Approach proposed by authors in [1], in order to achieve the comfort driving by excluding the specific frequency elements such as natural frequency of OMW and discomfort frequency of human organs. However, this is omitted due to limitation of paper space ([5])

2 Description of omni-directional wheelchair

2.1 Mechanical structure

An OMW using omni-wheels has been built, which is fully described in $[1] \sim [2]$. Figure 1 is an overview of this OMW.



Figure 1: Omni-directional Mobile Wheelchair

OMW 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. The wheelchair 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. The wheelchair also employs ultrasonic and infrared (PSD) ranging systems for semi-autonomous obstacle avoidance ([1]).

2.2 Kinematics

In the coordinate system of OMW, X-axis is defined when the OMW moves forward or backward, Y-axis is defined when the OMW moves towards right or left and rotation direction is according to θ . The coordinate system of joystick is established in the same way as that of OMW. Furthermore, let v_x be the velocity when the OMW moves along X-axis, v_y is the velocity in Y-axis and ω is the angular velocity when the OMW rotates around θ direction. So finally the velocity vector of the OMW is expressed as $v_{omw} = [v_x, v_y, \omega]^T$. The velocity of the OMW is the vector sum of velocities of four omni-wheels. This is shown in Fig. 2. The velocity vector for wheels is written as $v_{wheel} = [v_0, v_1, v_2, v_3]^T$.



Figure 2: Velocity vectors of omni-wheels

From the above figure:

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

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

$$\omega = \frac{1}{4l_{\omega b}} (-v_0 - v_1 - v_2 - v_3) \tag{3}$$

Written in a matrix form, it becomes as follows.

$$v_{omw} = B \cdot v_{wheel} \tag{4}$$

, where

$$B \equiv \begin{bmatrix} \frac{1}{2} & -\frac{1}{2} & 0 & 0\\ 0 & 0 & \frac{1}{2} & -\frac{1}{2}\\ -\frac{1}{4l_{\omega b}} & -\frac{1}{4l_{\omega b}} & -\frac{1}{4l_{\omega b}} & -\frac{1}{4l_{\omega b}} \end{bmatrix}$$

, where $l_{\omega b}$ is the distance from the center of the OMW to the circumference of the omni-wheels.

Since generally a matrix should be square in order to calculate its inverse matrix, the coefficient matrix in Eq. (4) should be square in order to calculate v_{wheel} from v_{omw} . Keeping this in mind, the angular velocity ω of the OMW is divided into two parts: ω_1 produced by v_0 and v_1 , and ω_2 produced by v_2 and v_3 .

$$\omega_1 = \frac{1}{2l_{\omega b}} (-v_0 - v_1) \tag{5}$$

$$\omega_2 = \frac{1}{2l_{\omega b}} (-v_2 - v_3) \tag{6}$$

$$\omega = \frac{1}{2}(\omega_1 + \omega_2) \tag{7}$$

By using the above equations, it is possible to get

$$\begin{bmatrix} v_x \\ v_y \\ \omega_1 \\ \omega_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & -\frac{1}{2} & 0 & 0 \\ 0 & 0 & \frac{1}{2} & -\frac{1}{2} \\ -\frac{1}{2l_{\omega b}} & -\frac{1}{2l_{\omega b}} & 0 & 0 \\ 0 & 0 & -\frac{1}{2l_{\omega b}} & -\frac{1}{2l_{\omega b}} \end{bmatrix} \begin{bmatrix} v_0 \\ v_1 \\ v_2 \\ v_3 \end{bmatrix}$$
(8)

Then, v_{omw} can be expressed by

$$\begin{bmatrix} v_x \\ v_y \\ \omega \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega_1 \\ \omega_2 \end{bmatrix}$$
(9)

To avoid the slip of the wheels, the constraint of $\omega_1 = \omega_2$ which also can be expressed as $v_0 + v_1 = v_2 + v_3$ is imposed. By letting $\omega = \omega_1 = \omega_2$, Eq. (8) is expressed as follows.

$$v_{wheel} = B^{*-1} \cdot v_{omw} \tag{10}$$

, where

$$B^{*-1} \equiv \begin{bmatrix} 1 & 0 & -l_{\omega b} \\ -1 & 0 & -l_{\omega b} \\ 0 & 1 & -l_{\omega b} \\ 0 & -1 & -l_{\omega b} \end{bmatrix}$$

Here, B^{*-1} is a pseudo-inverse matrix that allows to obtain the velocity of each wheel from the velocity of OMW.

2.3 Total Structure of Control Systems

The control system of OMW is shown in Fig. 3.



Figure 3: Control system of OMW

In this diagram, $v_r = [\dot{x}_r, \dot{y}_r, \dot{\theta}_r]^T$ is a reference velocity of OMW, $v_{omw} = [v_x, v_y, \omega]^T$ is the output velocity of OMW, $u = [u_0, u_1, u_2, u_3]$ is the control input voltage, \tilde{v}_r is the compensated reference velocity with considering comfort driving by Hybrid Shape Approach (HSA)([2]) and P(s) is a transfer matrix from control input voltage added to a motor driver to wheel velocity, which is given by $P(s) = diag.[P_1(s), P_2(s), P_3(s), P_4(s)]$, where $P_i(s) = \frac{v_{wheel}^i(s)}{u_i(s)} = \frac{K_i}{1+T_i(s)}$ (i = 0, 1, 2, 3). Controller K(s) is designed by HSA [5] including time domain and frequency domain specifications, comprised of notch filters, low pass filters and so on for the purpose of suppression of OMW's vibration.

3 Local map building and results

A local map is generated around OMW by using ultrasonic and infrared sensors (PSD) which layout is shown in Fig. 4. The local map centered on OMW radially divides 72 x 60 cells with a spacing of 5 degrees and 0.05 [m] as shown in Fig. 5. OMW occupies 611 cells. Sensor readings are translated into a probability that a specific cell is occupied by some object. The probability of occupancy is represented as a value between 0 and 255. Each cell value represents the degree of certainty about the existence of an object at the grid cell. Since the number of external sensors is limited, interpolation between adjacent sensing areas is necessary to estimate the probability of occupancy in areas that are invisible to the sensors. An occupancy grid map system is implemented for complete coverage around the wheelchair while it is moving. Map is built according to the following steps:

- 1. Add a value (plotting constant) to the corresponding cell, from sensor readings.
- 2. The value in each cell is transferred to cells which distance from the original cell is the same distance that OMW moves in each cycle.
- 3. Multiply the value in each cell by the oblivion coefficient.

Steps 1 to 3 are repeated at 16 Hz, which is the sampling rate of the external sensors. The presence of an obstacle at each cell is estimated by threshold processing, and a cell whose value exceeds the threshold level is named an obstacle cell. Misunderstanding of obstacles, caused by a misreading of sensors, is prevented by adding the plotting constant, which value is less than the threshold value, at every sampling period. Moreover, this makes full coverage around the wheelchair possible. Note that, as the plotting constant becomes smaller, the obstacle estimation becomes more reliable. However, it takes more time to exceed the threshold level.



Figure 4: Sensors layout



Figure 5: Grid map

The oblivion coefficient implies updating the coefficient of each cell value. Note that, as the coefficient becomes larger, the coverage becomes easier; however, responding to quick changes in the environment becomes more difficult. The oblivion coefficient also has the effect of decreasing the odometry error accumulation.

Figure 6 shows experimental results of map building. In a hallway, the wheelchair moves forward about 2 [m] and slides

right about 1 [m] without changing its orientation. In this experiment, the threshold value has been selected as 127, the plotting constant as 37 and the oblivion coefficient as 0.957. The plotting constant is determined so that the obstacle is recognized within 1 [s]. The oblivion coefficient is also determined so that the fully occupied (255) obstacle cell vanishes (becomes less than 127) within 1 [s]. An appropriate local map has been built. The presence of obstacles outside of the sensing areas is shown by this map building procedure.



Figure 6: Experimental results of grid map occupancy

4 Description and motion equations of haptic joystick

In the present research, a haptic joystick shown in Fig. 7 was designed and applied with being maneuverable for users. Then, the desired velocity and moving direction of OMW is generated proportionally to the tilting angle of joystick and the tilting direction of joystick, respectively. In order to compensate the safety against human operational error, information provided by ultrasonic sensors and PSD sensors installed to OMW allow operators to present a local map about environment. Users can mainly move OMW according to their preference, and obstacles are detected using their own eyes. However there are sometimes obstacles which they do not recognize, and in these cases, the method of building a local map has been given by using a finite number of ultrasonic sensors and PSD sensors to maintain the safety against human error, in a previous paper by authors([1]).



Figure 7: Frontal and top views of Haptic Joystick

Thus, in this paper, based on the past research, if an obstacle is detected in the direction of movement, the impedance of the joystick in this direction is changed. Namely, the closer the obstacle is the bigger the impedance value becomes. By this function, users spontaneously understand that they are in risk of obstacle collision and then users can change the direction of movement by their decision in order to avoid it. The proposed approach is thought to be reasonable as a human-machine existing control system. The block diagram of the OMW-joystick system is shown in Fig. 8 where $T_r = [T_r^x, T_r^y]^T$ is input torque, q is joystick's tilting angle in the input direction, A is the conversion factor from angular position q to reference velocity $v_r = [\dot{x}_r, \dot{y}_r, \dot{\theta}_r]^T$ of OMW and $X = [x, y, \theta]^T$.



Figure 8: Block diagram of joystick's motion

The desired dynamic equation of the joystick reference model of control counter-torque is given by

$$\tau = J_d \ddot{q} + D_d \dot{q} + K_d q \tag{11}$$

, where τ is torque of the joystick's motors (counter-torque), K_d is joystick's desired stiffness, D_d is joystick's desired damping and J_d is joystick's desired inertia.

Then, the real dynamics of the joystick becomes as follows $T_r - \tau = J_a \ddot{q} + D_a \dot{q} + K_a q$ (12)

, where K_a is joystick's physical stiffness, D_a is joystick's physical damping and J_a is joystick's physical inertia.

Substituting Eq. (11) into Eq. (12), it follows that

$$(J_d + J_a)\ddot{q} + (D_d + D_a)\dot{q} + (K_d + K_a)q = T_r$$
(13)

Here, we shall assume that J_d and D_d are considered to be constant and only the stiffness of the haptic joystick is not fixed but varies according to the following equation:

$$K_d = K_0 \cdot \left(\frac{\frac{v}{v_{max}} + \alpha}{\left(\frac{r}{r_{max}}\right)^2} + 1\right)$$
(14)

, where K_0 is stiffness initial value, v is OMW's velocity, v_{max} is OMW's maximum velocity, r is distance to the obstacle, r_{max} is maximum measurable distance of ultrasonic sensors and α is a constant that holds the effect of r when v is 0.

However, when OMW becomes very near to obstacles (around 20 [cm]), problems of forward and backwards vibration appear in the joystick due to the nonlinear behavior of the system if only desired stiffness term is adopted ($J_d = 0$, $D_d = 0$). This vibration communicates to the users' hand and causes discomfort to them, and furthermore gives oscillating movement to OMW. In order to solve this problem, not only stiffness but also haptic joystick's desired damping (D_d) and desired inertia (J_d) term should be taken into consideration. In this paper, optimal values of stiffness, damping and inertia coefficients are determined through simulation.

5 Results of haptic feedback simulation

Simulation is developed for the case in which OMW is in the center of a square room of 5 [m] side. Walls of the room are assumed as obstacles that must be avoided. Rotation is not included in simulation presented in this paper. The values of J_a , D_a and K_a are given as 0.005 [N·m·s²/rad], 0.1 [N·m·s/rad]

and 0.5 [N·m/rad] respectively by considering basic experimental results. As shown in Eq. (14), the value of K_d varies with distance to the obstacle and velocity of OMW. In Eq. (14), K_0 = 0.2 [N·m/rad], $v_{max} = 1$ [m/s], $r_{max} = 5$ [m] and $\alpha = 0.13$. When just K_d is considered, that is $J_d = 0$ and $D_d = 0$, vibration is present in joystick when going near to obstacles, as shown in Fig. 9. Suitable values of J_d and D_d must be used in order to avoid this phenomenon. It has been found, by simulation, that the best values are $J_d = 0.005$ [N·m·s²/rad] and D_d = 0.05 [N·m·s/rad]. When these values are used, it is possible to eliminate vibration as shown in Fig. 10. Now, in this paper, two-mode navigation by haptic joystick is described in the following, where each mode is realized by given the appropriate parameters J_d and D_d of impedance control.



Figure 9: Joystick behavior in the case of $J_d = 0$ and $D_d = 0$



Figure 10: Joystick behavior in the case of $J_d = 0.005$ and $D_d = 0.05$

5.1 Mode I (Operation support mode by haptic joystick)

Mode I is used basically when user wants to approach a goal. It is possible to navigate using this mode, too. In this mode, the values of J_d and D_d are 0.005 [N·m·s²/rad] and 0.05 [N·m·s/rad] respectively, as mentioned in the previous paragraph. Simulation results for the case when T_r^x is 0.5 [N·m] and T_r^y is 0.7 [N·m] are shown in Fig. 11. Here, T_r^y is higher than T_r^x , then τ_Y becomes high while τ_X is still low. When τ_Y reaches a value of 0.2 [N·m], it is assumed that the user can

know that there is an obstacle nearby and spontaneously reduces the input until 0, stopping OMW by his joystick operation. Considering OMW as a rectangle, with center in the coordinate system X-Y, the trajectory in X-Y, in the simulation results of this paper, is described by the position of the right inferior corner of this rectangle, indicated by point A in (c) in Fig. 11.

anteed in the case of Mode I by impedance control, although OMW can be driven to a target place.



(c) Environment used for Haptic Simulation

Figure 11: Haptic feedback simulation (Mode I); the case when operator notice the obstacle by haptic feedback is assumed. Operator makes OMW stop before collision by his judgment based on haptic feeling

In order to show clearly whether OMW collides with obstacle or not, (7) in (a) and (7) in (b) of Fig. 11 \sim Fig. 13 are respectively the whole trajectory and the detailed local trajectory near the obstacle. Thus, (7) in (a) and (7) in (b) are quite same map. These result shows that haptic feedback teaches obstacle to operator, in order to progress the safety driving. On the other hand, Fig. 12 shows the example that OMW collides with obstacle because operator did not stop OMW by his joystick operation, although he noticed the existence of obstacle by haptic feeling. Therefore, perfect safety for human error is not guar-



Figure 12: Haptic feedback simulation (Mode I); the case when operator does not notice the obstacle even by haptic feedback. OMW collides against the wall, because operator does not conduct joystick's operation to stop OMW

5.2 Mode II (Safety mode for human error by haptic joystick)

Mode II is used for providing complete safety navigation to the user. In this mode, even when conditions of Fig. 13 are the same as those in Fig. 12, there is not collision against the wall, because the user is protected according to the following procedure: When τ_Y reaches 0.2 [N·m], the user is aware of the existence of an obstacle in the direction of movement. However, by mistake, etc. the user continued to push the joystick in the direction of collision. Then, in this mode, joystick automatically returns to the origin by making the haptic impedance extremely large and therefore OMW can be stopped regardless of human

operator. Namely, the value of J_d^y is calculated according to Eq. (15):

$$J_d^y = 0.005 + \frac{f lag}{r^2} \tag{15}$$



Figure 13: Haptic feedback simulation (Mode II). The case when operator does not notice the obstacle by haptic feedback. As OMW is in safety navigation mode, OMW automatically stops before collision by human error

In Eq. (15), "flag" is an ON-OFF digital number, and the initial value is 0. However, when human does not notice the haptic impedance over 0.2 [N·m] for the time duration of 0.5 [s], the value of "flag" becomes "flag" = 1. By this logic, J_d^y becomes the large value, and therefore the counter torque to joystick τ_Y becomes large, as seen from (5) in (a) and (b) of Fig. 13, compared with that of Fig. 12. Namely, as J_d^y increases, the value of τ_Y increases too, until it is equal to that of T_r^y . At this time, joystick returns to its equilibrium position, when q = 0. Then velocity of OMW, proportional to q, goes to 0 too, and OMW stops, avoiding collision against the wall. Simulation results for the same inputs T_r^x and T_r^y with Fig. 12, are shown in Fig. 13.

Here OMW stops just before colliding against the wall.

Mode II by impedance control means the complete safety driving mode for human error. However, in Mode II, there is one defect, when target place is obstacle such as bed or so on. Then, OMW can not be touched to bed. Therefore, the change from Mode I to Mode II will be needed by switching, which will be done in near future. Now, the integrated system that contains map building and haptic feedback system was developed in OMW. Experimental results by the integrated system will be demonstrated at the presentation time.

6 Experimental work

As the direct test of results obtained by simulation could be risky for the user, the obtained parameters are first tested by building a kind of virtual system consisted of the link between only experimental joystick system constituted by the haptic feedback system in OMW, and computer simulation with respect to the OMW's movement. Satisfactory behavior of joystick was obtained in the developed virtual system. Now, the integrated system that contains map building and haptic feedback system was developed in the present OMW. Experimental results by the integrated system will be demonstrated at the presentation time.

7 Conclusions

By using appropriate values of the impedance control parameters K_d , D_d and J_d , a smooth haptic counter-torque, without vibration, can be fedback to the joystick. Furthermore, a system which can do proper haptic control according to distance and approaching speed to obstacle was built. In the present system, two modes for haptic feedback system were proposed. One is a mode such that user spontaneously stops OMW when user feels strong impedance by haptic feedback. The other is a mode such that OMW automatically stops to avoid obstacle collision when user makes human error. In real application, good navigation by adequate switching of both modes will be possible.

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