NAVIGATION WITH COMFORT OF OMNI-DIRECTIONAL WHEELCHAIR DRIVEN BY JOYSTICK

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Abstract: Wheelchairs are the most common used device in order to allow elderly and handicapped people more independence and greater interaction in their communities. The purpose of this research is to control the motion of an Omni-directional Mobile Wheelchair (OMW) while considering user's comfort. A human model is built for evaluating the proposed controller, considering that the human upper body consists of two rigid parts: head and torso. The proposed controller can not only control OMW fast and effectively but can also improve users' comfort greatly by suppressing vibration caused mainly by inappropriate acceleration while driving.

Keywords: Mobile robots, Man/machine interface, Resonant Frequencies, Genetic algorithms, Velocity control, Human-centered design, Interactive vehicle control

1. INTRODUCTION

One of the main features of world population in the 20^{th} century is the increment of elderly people in both developing and developed countries. According to WHO (World Health Organization), by 2025 the increase of population aged 60 and over is estimated 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 requirment 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.

Autonomous mobile wheelchairs are really useful for people who cannot move their upper bodies freely for some reasons. However, wheelchair has to be fitted with a central unit and some high level-sensors capable of realizing complex navigation and obstacle avoidance tasks, based on the description of the environment and final objectives marked out by those sensors. Although it can work very well only in the special environment, this mode limits users' freedom greatly.

In order to offer users with a higher degree of independence, the user-controlled movement mode, or semi-autonomous mode which is operated under absolute control of users by an interface such as joystick, switch, monitor etc, has been developed. The main difference between autonomous and semi-autonomous system is that, in semi-autonomous mode, users interact in real time to do some tasks in dynamic environment. Under control of users, it can go wherever users want to go, therefore, this mode permits a great independence for user, or is governed mainly by operator.

Following this ideas, a holonomic Omni-directional Mobile Wheelchair (OMW) as shown in Fig. 1 has been developed in the author's laboratory ((Kitagawa *et al.*, 2001) $\sim$ (Terashima *et al.*, 2004)), which is comprised of three modes such as autonomous, semi-autonomous and power-assist modes. Because of its omni-directional movement, it is able to navigate smoothly in structured inner environments. In previous research in author's laboratory a haptic joystick has been used for warning the user of proximity of obstacles ((Kitagawa *et al.*, 2001), (Urbano *et al.*, 2004)). Moreover comfort has been studied in autonomous mode without joystick ((Kitagawa *et al.*, 2002) $\sim$ (Terashima *et al.*, 2004)) but just when OMW moves in a single direction, X or Y.

In this paper, comfort is studied when OMW moves in any direction, such as an slanting direction, by practical semi-autonomous operation mode with joystick. 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 (Yano *et al.*, 2000), in order to achieve the comfort driving by excluding the specific spectrum elements such as natural frequency of OMW and discomfort frequency of human organs.

In order to evaluate the comfort, a human model which considers human upper body composed of two parts: torso and head, has been developed and used in order to test the effectiveness of the proposed approach. This research is still in simulation stage, but simulation results will be tested by experiments in a very near future.

2. DESCRIPTION OF OMNI-DIRECTIONAL WHEELCHAIR

2.1 Mechanical structure

An OMW using omniwheels has been built, which is fully described in ((Kitagawa *et al.*, 2001) $\sim$ (Kitagawa *et al.*, 2002)). Figure 1 is an overview of this OMW. 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 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 omni-directional movement. The wheelchair also employs ultrasonic and infrared (PSD) ranging systems for semi-autonomous obstacle avoidance (Kitagawa *et al.*, 2001).

Fig. 1. Omni-directional Mobile Wheelchair

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 the same as that of the 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. Let the left motor m_0, right motor m_1, front motor m_2 and back motor m_3. Accordingly, v_0 is the velocity of left wheel, v_1 is the velocity of right wheel, v_2 is the velocity of front wheel and v_3 is the velocity of back wheel. This is shown in Fig. 2. The velocity vector for wheels is written as $V_{wheel} = [v_0, v_1, v_2, v_3]^T$.

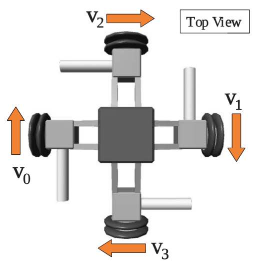

Fig. 2. Velocity vectors of omni-wheels

From the above figure, the following equations are obtained

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

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

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

Written in a matrix form, it becomes as follows.

$$V_{omw} = B \cdot V_{wheel} \quad (4)$$

, 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 of the OMW ω is divided into two parts: ω_1 produced by v_0 and v_1 and ω_2 produced by v_2 and v_3. These relations are expressed in the following equations.

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

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

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

By using the above equations, it is possible to get

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

V_{omw} can be expressed by the following way.

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

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.

$$V_{wheel} = B^{*-1} \cdot V_{omw} \quad (10)$$

, where

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

, where 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

Control systems of OMW is shown in Fig. 3. In this diagram, $v_r = [\dot{x}_r, \dot{y}_r, \dot{\theta}_r]^T$ is a reference velocity of OMW, $v = [\dot{x}, \dot{y}, \dot{\theta}]^T$ is the velocity of OMW, $u = [u_0, u_1, u_2, u_3]$ is the control input voltage, 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 $P_i(s) = \frac{v_i(s)}{u_i(s)} = \frac{K_i}{1+T_i(s)}$ $(i = 0, 1, 2, 3)$. Controller $K(s)$ is designed by Hybrid Shape Approach (Yano *et al.*, 2000) 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.

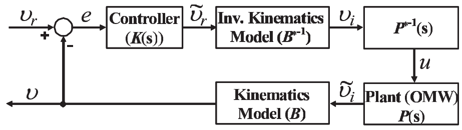

Fig. 3. Control system of OMW

3. MOTION CONTROL CONSIDERING USER'S COMFORT BY HYBRID SHAPE APPROACH

In general, comfort while riding in vehicle depends on not only the amplitude of vibrations, but also the frequency band. Natural frequency of the wheelchair and human organ is strongly related with the patient or user's uncomfort while riding. Natural frequency of OMW has been computed from input-output ratio of acceleration sensors attached to OMW, and then natural frequency of forward-backward (X-direction) and left-right (Y-direction) are respectively 2.4 [Hz] and 2.45 [Hz]. On the other hand, the natural frequency of human's organ is in the range of $4 \sim 8$ [Hz], and it is adopted as 6.0 [Hz].

The control system is based on a Hybrid Shape Approach (HSA)recently developed in our laboratory (Yano *et al.*, 2000). Optimization problems formulated in both the time and the frequency domains is considered. Controller design is composed of the following elements.

(1) Selection of controllers
(2) Formulation of design specifications
(3) Formulation of an optimization problem
(4) Computation of a controller

3.1 Selection of Controller

A PI controller is chosen in order to avoid the offset caused by the integrator of the OMW's servo system and compensate the steady state error. It is expressed by the following equation:

$$K_1(s) = K_p + K_I/s \quad (11)$$

Two notch filters are used to prevent the controller from exciting vibration of the OMW or user's organs.

$$K_2(s) = \frac{s^2 + 2\zeta_1\omega_1 s + \omega_1^2}{s^2 + \omega_1 s + \omega_1^2} \quad (12)$$

$$K_3(s) = \frac{s^2 + 2\zeta_2\omega_2 s + \omega_2^2}{s^2 + \omega_2 s + \omega_2^2} \quad (13)$$

, where natural frequency of the OMW, ω_1 = 15.08[rad/s] (2.40[Hz]), in case of Y axis, ω_1 = 15.39[rad/s] (2.45[Hz]); natural frequency of human's organs, ω_2 = 37.70[rad/s] (6.00[Hz]); damping ratio $\zeta_1 = \zeta_2 = 0.0001$.

Furthermore, a low pass filter is also applied to reduce the influence of high-order vibraiton and noise.

$$K_4(s) = \frac{1}{T_n s + 1} \quad (14)$$

Finally, the controller is given as

$$K(s) = \prod_{i=1}^{4} K_i(s)$$
$$= \frac{(K_p s + K_I)(s^2 + 2\zeta_1\omega_1 s + \omega_1^2)(s^2 + 2\zeta_2\omega_2 s + \omega_2^2)}{s(s^2 + \omega_1 s + \omega_1^2)(s^2 + \omega_2 s + \omega_2^2)(T_n s + 1)} \quad (15)$$

In this equation, K_p, K_I and T_n are unknown parameters. Therefore, all these parameters should be determined resonably by solving an optimization problem. In Genetic Algorithms (GA), the initial values of unknown parameters are chosen randomly and after some loops, the best values can be found. What's more, GA have proved to be a very robustness and useful method in locating the global optimum instead of getting confused with the local optimum, so it is chosen for solving this problem.

3.2 Formulation of design specifications

Specifications of the controller are formulated by using a penalty function. Penalty is given if any of the following restrictions can not be satisfied.

- The controller and the closed-loop system should be stable.

$$Re[r_c] < 0, Re[r_{cl}] < 0 \quad (16)$$

$$K_I > 0, T_n > 0 \quad (17)$$

- The controller gain is less than $0[dB]$ at the natural frequency of OMW, $\omega_1 = 15.08[rad/s]$ (X axis) or $\omega_1 = 15.39[rad/s]$ (Y axis) and at that of user's organ's, $\omega_2 = 37.7[rad/s]$.

$$|K(\omega_1)| < 0[dB], |K(\omega_2)| < 0[dB] \quad (18)$$

- The controller gain is less than $0[dB]$ at $T_n = 314[rad/s](50Hz)$ in order to decrease the influence of the higher-order vibration and noise.

$$|K(T_n)| < 0[dB] \quad (19)$$

- The magnitude of the input voltage u to the dc motor does not exceed $24[V]$.

$$max|u| < 24[V] \quad (20)$$

- The magnitude of the maximum overshoot does not exceed 0.01[m/s].

$$max(O_s) < 0.01[m/s] \quad (21)$$

3.3 Formulation of an optimization problem

The relationship between the reference tilting angle of joystick and the reference velocity of OMW is given as:

$$v_r = Aq_r \quad (22)$$

, where $q_r = [\alpha_{xr} \ \ \alpha_{yr}]^T$ is the input angle to the joystick. A is given by the following equation:

$$A = \begin{bmatrix} V_{max}/\alpha_{max} & 0 \\ 0 & V_{max}/\alpha_{max} \end{bmatrix} \quad (23)$$

, where V_{max} is the maximum speed of OMW in X direction or in Y direction and α_{max} is the maximum tilting angle of joystick in X direction or in Y direction.

In real case, it is impossible to implement this relationship, because there always exists response time which means that OMW won't move imediately when the user moves the joystick. So, the real relationship between the output velocity of OMW and the reference tilting angle of the joystick can be expressed by the following equation.

$$v = \frac{A}{T_d s + 1} q_r \quad (24)$$

In this case, if the response time is too long, the user feels uncomfortable because OMW won't move soon even if he moves the joystick. Furthermore, he will give additional input before the velocity of OMW becomes the proposed velocity. Therefore it is very important to reduce the response time in order to improve user's comfort and give the right input. Based on the previous analysis, the cost function is chosen as,

$$minJ = T_d + J_p \quad (25)$$

, where T_d is the time when velocity reaches 63.2% of the maximum velocity, and $J_p = 10^8$ is given as penalty function if constraints are not satisfied.

3.4 Computation of a controller

By using GA, the unknown values K_P, K_I and T_n are found as shown in Table 1.

Table 1. Results of Optimization

Parameter	X-axis	Y-axis
K_P	16.57	20.03
K_I	56.29	29.40
T_n	0.12	0.58

4. HUMAN UPPER BODY MODEL AND EVALUATION OF CONTROLLER

In order to know users' sway, a human model shown in Fig.4, considering the human upper body consisting of two rigid parts; head and torso, is built. User is considered to be supported on the wheelchair only at one point: point A, because the contact pressure is the strongest at this point. Point a and b are the center of gravity of torso and head, respecitvely. l_a is defined by the distance between point A and point a, and l_b is the distance between point B and point b. Characteristic of user's elements are shown in Table 2.

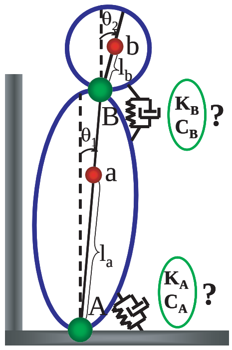

Fig. 4. Human model

Table 2. Characteristics of user's elements

Element	Torso (i=1)	Head (i = 2)
Mass m_i	31.7 [kg]	4.9 [kg]
Moment of Inertia J_i	1.1 [N·m·s^2]	0.016 [N·m·s^2]
Length of segment l_i	0.5 [m]	0.2 [m]
Center of gravity l_{ia}	0.28 [m]	0.11 [m]

The equation of motion using generalized coordinates can be expressed as:

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} + g(q) = \{Q\} \quad (26)$$

, where $q = \{\theta_1, \theta_2\}$ are the generalized coordinates, $Q = 0$ is the applied force and,

$$[M] = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \quad (27)$$

, where

$$M_{11} = m_1 l_a^2 + m_2 l_1^2 + J_1, \quad (28)$$

$$M_{12} = m_2 l_1 l_b \cos(\theta_1 - \theta_2), \quad (29)$$

$$M_{21} = m_2 l_1 l_b \cos(\theta_1 - \theta_2), \quad (30)$$

$$M_{22} = m_2 l_b^2 + J_2, \quad (31)$$

$$[C] = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \quad (32)$$

, where

$$C_{11} = C_A + C_B, \quad (33)$$

$$C_{12} = m_2 l_1 l_b \sin(\theta_1 - \theta_2)\dot{\theta}_2 - C_B, \quad (34)$$

$$C_{21} = -m_2 l_1 l_b \sin(\theta_1 - \theta_2)\dot{\theta}_2 - C_B, \quad (35)$$

$$C_{22} = C_B, \quad (36)$$

$$[K] = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} \quad (37)$$

, where

$$K_{11} = K_A + K_B, \quad (38)$$

$$K_{12} = -K_B, \quad (39)$$

$$K_{21} = -K_B, \quad (40)$$

$$K_{22} = K_B, \quad (41)$$

$$[g] = \begin{bmatrix} g(\theta_1) \\ g(\theta_2) \end{bmatrix} \quad (42)$$

, where

$$g(\theta_1) = (m_2 l_1 \ddot{x} + m_1 l_a \ddot{x}) \cos\theta_1, \quad (43)$$

$$g(\theta_2) = m_2 l_b \ddot{x} \cos\theta_2, \quad (44)$$

Here, $\ddot{x}$ is lineal acceleration of OMW and, K_A, spring constant between torso and seat; C_A, damping constant between torso and seat; K_B, spring constant between torso and head; and C_B, damping constant between torso and head are the values that must be determined in order to identify the model.

Experiments by means of motion capture devices are done in order to identify the above model. Swing angle of torso θ_1 and that of head θ_2 are used to evaluate the vibration of the user's torso and the vibration of head. The values of the unknown parameters, K_A, C_A, K_B, C_B, are shown in Table 3. K_A and K_B are in [N·m/rad]; C_A and C_B are in [N·m·s/rad].

Table 3. Parameters for Human Model Identification

K_A	C_A	K_B	C_B
0.35	0.01	5.00	0.01

According to experiments conducted by applying the desired velocity to OMW and attaching an acceleration sensor to the head of user in order to measure the vibration of head, the natural frequency of head in X-axis was found to be 8.17 [rad/s](1.3 [Hz]). Then, a new notch filter, designed in order to suppress the natural frequency of head is added to the controller shown in Eq. (15). The new notch filter is expressed as:

$$K_5(s) = \frac{s^2 + 2\zeta_3\omega_3 s + \omega_3^2}{s^2 + \omega_3 s + \omega_3^2} \quad (45)$$

, where $\zeta_3 = 0.001$, $\omega_3 = 8.17[rad/s](1.3[Hz])$.

So the new controller is expressed as:

$$K(s) = \prod_{i=1}^{5} K_i(s) \quad (46)$$

Figure 5 shows the trajectory of OMW when it moves in an slanting direction of 30° with X axis. In this case two independent controllers, one for each axis, are used for suppressing vibration. According to simulation results, shown in Fig. 6 and Fig. 7., the new controller can work well in both axes. In order to test the advantage of the controller considering frequency of head (*CCFH*) over the controller without considering frequency of head (*CWCFH*), simulation results for the vibration of head when OMW moves in X axis are shown in Fig. 8. Clearly, the proposed controller *CCFH* is much better that proportional controller and *CWCFH*.

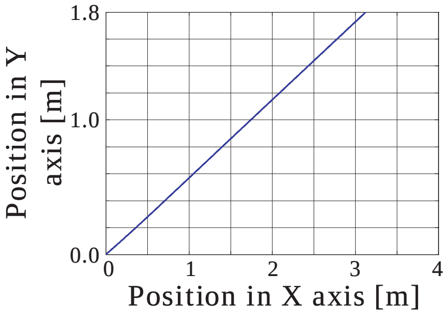

Fig. 5. Slanting trajectory of OMW

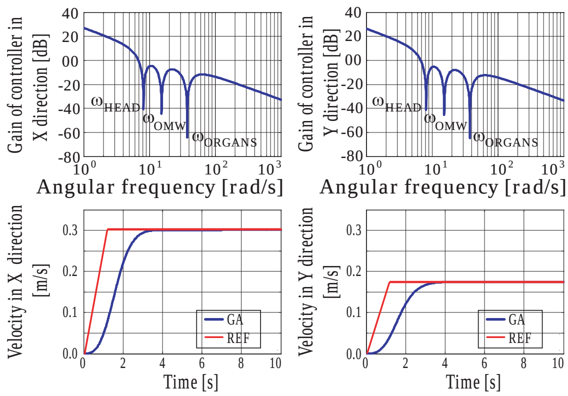

Fig. 6. Bode diagram and velocity in X and Y axes

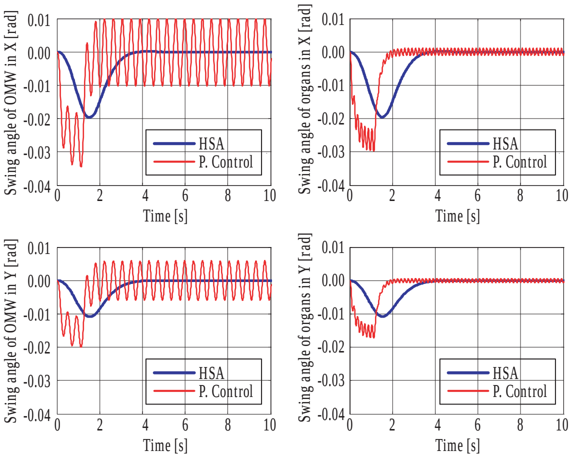

Fig. 7. Swing angle in X and Y axes

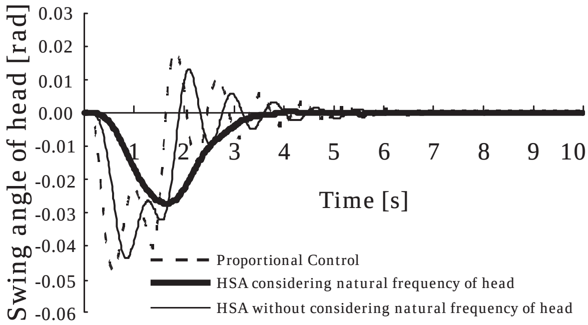

Fig. 8. Swing angle of head

As a next step in this research authors are considering to conduct experiments in order to test in the real world the results obtained by simulation.

5. CONCLUSIONS

(1) Semi-autonomous motion control system of OMW operated by Joystick was built considering the suppression of OMW's vibration and human's comfort.
(2) Human upper body model was built in order to evaluate the comfort or vibration of head and torso.
(3) According to simulation results, the proposed controller designed by Hybrid Shape Approach can improve user's comfort by suppressing vibration almost completely.

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