Contact Motion in Unknown Environment

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Abstract— **This paper describes a contact motion in unknown environment. It is required to take in a kinematic and a dynamic information of unknown environment in order to utilize for control of contact motion. However, an environmental information is obtained only after the robot contacts with environment. Hence, it is difficult to enhance the robustness of the force for contact motion. The design method with the clear characteristic of a contact motion will be required.**

In this paper, two examples of typical contact motion control are shown. One is a bilateral control and the other is a control of a paddle foot for biped walking. Both controllers are based on acceleration control and the characteristic of systems are clarified by using Hadamard matrix. In order to improve the propect of the system, the information of environmental mode is quarried by using Hadamard matrix. Modal transmission from environment to the final posture should change adaptively according to the situation. The viability of these approaches for contact motion is shown in numerical simulations.

I. Introduction

Advanced robot development requires its ability to work in human environment. Human environment is complex and the condition is often unknown. In this case, contact motion is indispensable in order to attain the environmental information and to deal with the environmental disturbances. For example, telesurgery device has to reproduce the contact motion of slave and convey its haptic sense to the master. Biped robot needs to keep contact with the ground always since biped robot stabilizes its posture applying the floor reaction force.

Recently, many researches on a motion control based on robust acceleration control have shown effectiveness of its implementation not only in robust position control, but also in robust force control. This motion control has show its ability in simple task with low degrees-of-freedom (DOF) applications, such as X-Y table of machine tool, joint control of industrial robot and so on. Such applications exist in the closed space, and the motion area is limited in a small space. However so-called human-friendly machines have begun to spread in society. The first one can be pet robot, human-like robot, high performance home robot and so on. The highly developed country will need such machines due to the fast aging society. We have studied how biped robot quarries the modes from environment[1]. However, it is difficult to achieve the desired contact motion since contact motion contains a nonlinear collision problem.

In order to achieve stable contact motion, effective controller depending on individual tasks should be designed. Unfortunately, there are still no explicit design methods for the controller of stable contact motion.

In this paper, we propose a method to transfer the coordinates on each sensor to the coordinates on each mode that the whole control system should reply to. This transformation provides an unobstructed view for the control design on compliance motion in open environment since controllers that reply to each mode can be designed individually.

Two examples, bilateral system and biped robot, are shown as the application of this method in order to confirm this method.

This paper is composed of four sections. Section I introduction. Bilateral control method is shown in Section II. The other example biped robot is represented in Section III. Finally, it is concluded in Section IV.

II. Bilateral Control

At first, 1 DOF system on master and slave manipulators are considered. It is presumed that no communication delay exists.

A. Dynamics

Here, interaction between master and slave manipulators is observed. The dynamic equation for master and slave manipulators is expressed as follows.

$$\boldsymbol{J}_{ms}s^2\boldsymbol{x}_{ms} + \boldsymbol{D}_{ms}s\boldsymbol{x}_{ms} = \boldsymbol{F}_{ms} - \boldsymbol{F}_{ms}^{ext} \qquad (1)$$

Here,

$$\boldsymbol{J}_{ms} = \begin{bmatrix} J_m & 0 \\ 0 & J_s \end{bmatrix}, \boldsymbol{D}_{ms} = \begin{bmatrix} D_m & 0 \\ 0 & D_s \end{bmatrix},$$

$$\boldsymbol{x}_{ms} = \begin{bmatrix} x_m \\ x_s \end{bmatrix}, \boldsymbol{F}_{ms} = \begin{bmatrix} F_m \\ F_s \end{bmatrix}, \boldsymbol{F}_{ms}^{ext} = \begin{bmatrix} F_m^{ext} \\ F_s^{ext} \end{bmatrix}$$

$\boldsymbol{x}_{ms}$ is the position of manipulator, $\boldsymbol{D}_{ms}$ is the viscous coefficient, $\boldsymbol{F}_{ms}$ is the driving torque. Superscript "ext" denotes the external force/torque that affect each system.

Three indices, position and force tracking performance and maneuverability, appreciate the performance of bilateral system. Position tracking performance is an index that represents how small the position error between master and slave becomes, while force tracking performance represents how small the force error between master and slave becomes. Maneuverability is an index that represents how both master and slave move in the same direction.

The position precision of compliance control decreases as the force gain becomes larger. However in interactive control system, the highest force tracking performance is achieved with position control excluding force control. Indeed, the control system in this paper is designed based on position response and maneuverability. New coordinate system based on these indices is also introduced in this paper. A proposed concept is shown in Fig.1

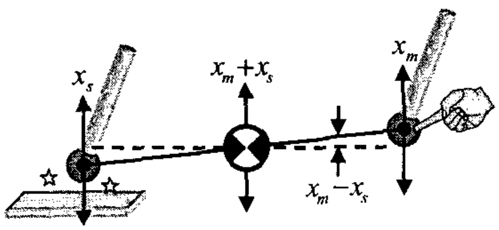


Fig. 1. Bilateral control

The coordinate system is composed of sum coordinate and difference coordinate. Sum coordinate represents the sum of master and slave position. Sum coordinate addresses maneuverability that describes how easy the movement are performed. In contrast, difference coordinate represents the difference of master and slave position. Difference coordinate addresses position tracking performance since position tracking performance shows how small the difference between master and slave is. x_{vs} and x_{vd} denote the position on sum coordinate and the position on difference coordinate respectively. The relationship between position of master and slave x_m,x_s and x_{vs},x_{vd} is shown in eq.(2).

$$\begin{bmatrix} x_{vs} \\ x_{vd} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} x_m \\ x_s \end{bmatrix} = \frac{1}{2}\boldsymbol{H}_2\begin{bmatrix} x_m \\ x_s \end{bmatrix} \quad (2)$$

Here, $\boldsymbol{H}_2$ is a quadratic Hadamard matrix. In general, n-degree Hadamard matrix has common form shown as follows.

$$\boldsymbol{H}_n^T\boldsymbol{H}_n = n\boldsymbol{I}_n \quad (3)$$

The coordinate transformation of torque is derived as eq.(4) from the static relationship.

$$\begin{bmatrix} F_m \\ F_s \end{bmatrix} = \frac{1}{2}\boldsymbol{H}_2^T\begin{bmatrix} F_{vs} \\ F_{vd} \end{bmatrix} = \frac{1}{2}\boldsymbol{H}_2\begin{bmatrix} F_{vs} \\ F_{vd} \end{bmatrix} \quad (4)$$

Here, F_{vs},F_{vd} are torque on sum coordinate and difference coordinate.

From eq.(1) to eq.(4), dynamic equation on sum and difference coordinate system is derived as follows.

$$\boldsymbol{J}_v s^2\boldsymbol{x}_v + \boldsymbol{D}_v s\boldsymbol{x}_v = \boldsymbol{F}_v - \boldsymbol{F}_v^{ext} \quad (5)$$

where

$$\boldsymbol{J}_v = (\boldsymbol{H}_2^T\boldsymbol{J}_{ms}\boldsymbol{H}_2) = \begin{bmatrix} J_m + J_s & J_m - J_s \\ J_m - J_s & J_m + J_s \end{bmatrix}$$

$$\boldsymbol{D}_v = (\boldsymbol{H}_2^T\boldsymbol{D}_{ms}\boldsymbol{H}_2) = \begin{bmatrix} D_m + D_s & D_m - D_s \\ D_m - D_s & D_m + D_s \end{bmatrix}$$

$$\boldsymbol{F}_v = \begin{bmatrix} F_{vs} \\ F_{vd} \end{bmatrix}, \boldsymbol{F}_v^{ext} = \begin{bmatrix} F_{vs}^{ext} \\ F_{vd}^{ext} \end{bmatrix}$$

$\boldsymbol{J}_v$ and $\boldsymbol{D}_v$ are the equivalent inertia matrix and equivalent viscous matrix respectively.

B. Acceleration decoupling with workspace observer

Workspace observer is applied to the control system in order to design two controllers, which is based on position tracking performance and maneuverability, independently.

The nominal system is described as follows.

$$\boldsymbol{J}_{vn}s^2\boldsymbol{x}_v = \boldsymbol{F}_v - \boldsymbol{F}_v^{dis} \quad (6)$$

$\boldsymbol{J}_{vn} = diag\{J_{vsn}, J_{vdn}\}$ is derived as diagonal matrix in order to achieve acceleration decoupling. From eq.(5) and eq.(6), the disturbance on nominal system is derived as follow.

$$\boldsymbol{F}_v^{dis} = \boldsymbol{F}_v - \boldsymbol{J}_{vn}s^2\boldsymbol{x}_v \quad (7)$$
$$= \boldsymbol{F}_v^{ext} + \boldsymbol{D}_v s\boldsymbol{x}_v + (\boldsymbol{J}_v - \boldsymbol{J}_{vn})s^2\boldsymbol{x}_v \quad (8)$$

The disturbance in workspace is observed through low-pass filter $diag\{\boldsymbol{Q}(s)\} = \{Q_{vs}(s), Q_{vd}(s)\}$ in order to cut off the noise in high frequency area.

$$\hat{\boldsymbol{F}}_v^{dis} = \boldsymbol{Q}(s)\left(\boldsymbol{F}_v^{ext} + \boldsymbol{D}_v s\boldsymbol{x}_v + (\boldsymbol{J}_v - \boldsymbol{J}_{vn})s^2\boldsymbol{x}_v\right) \quad (9)$$

Robust acceleration control system is achieved by using the feedback from estimated disturbance.

$$\boldsymbol{F}_v = \boldsymbol{F}_v^{ref} + \hat{\boldsymbol{F}}_v^{dis} \quad (10)$$
$$\boldsymbol{F}_v^{ref} = \boldsymbol{J}_{vn}s^2\boldsymbol{x}_v \quad (11)$$

The system equation is described as follow.

$$s^2\boldsymbol{x}_v^{res} = s^2\boldsymbol{x}_v^{ref} + (\boldsymbol{I} - \boldsymbol{Q}(s))\boldsymbol{F}_v^{dis} \quad (12)$$

C. Position control

Position tracking performance is achieved by PD control. Acceleration reference value for PD control is derived as follow. Here, K_p,K_v are position and velocity gains.

$$\ddot{x}_{vd}^{ref} = \ddot{x}_{vd}^{cmd} + K_p(x_{vd}^{cmd} - x_{vd}^{res}) + K_v(\dot{x}_{vd}^{cmd} - \dot{x}_{vd}^{res}) \quad (13)$$

The position characteristic is shown as follow.

$$x_{vd}^{res} = x_{vd}^{cmd} - (s^2 + K_v s + K_p)^{-1} + J_{vdn}^{-1}(1 - Q_{vd}(s))F_{vd}^{dis} \quad (14)$$

D. Force control

Master and slave move to the same direction in answer to the force value acting on environment. Hence, maneuverability essentially depends on force control. How small the equivalent inertia becomes shows the performance of maneuverability. The acceleration reference value is shown as follow.

$$\ddot{x}_{vs}^{ref} = M_v^{-1}(F_{vs}^{cmd} - F_{vs}^{res} - B_v\dot{x}_{vs}^{res}) \quad (15)$$

Here, M_v is diagonal virtual inertia matrix in workspace, B_v is diagonal virtual viscous matrix.

$$F_{vs}^{res} = B_e \dot{x}_{vs}^{res} + K_e x_{vs}^{res} \quad (16)$$

The characteristic of force control is given as follows.

$$\begin{aligned} F_{vs}^{res} &= (M_v s^2 + (B_e + B_v)s + K_e)^{-1}(B_e s + K_e) \\ & (F_{vs}^{cmd} - (1 - Q(s)F_{vs}^{dis})) \end{aligned} \quad (17)$$

E. Numeical Results

Fig.2 is position and force tracking performance of master and slave manipulators by using only a position controller in the difference coordinates. This control structure becomes same as traditional position symmetric control. The characteristic of this controller is well-known as the worse maneuverability. Fig.3 is position and force tracking performance of master and slave manipulators by using a position controller in difference coordinates and a force controller in sum coordinates. The control parameters are shown in Table.I The force tracking performance shows that maneuverability is lighter, when the slave is not in contact with environment. Both responses are improved.

TABLE I

SYSTEM AND CONTROL PARAMETERS

Mass	J_m, J_s	0.5 [kg]
Damping	D_m, D_s	0.1 [kg/s]
Position feedback gain	K_p	900 [(rad/s)^2]
Speed feedback gain	K_v	60 [rad/s^2]
Observer gain	g	600 [rad/s]
Virtual mass	M_v	0.5 [kg]
Virtual viscous coef.	B_v	0.1 [kg/s]
Environmental stiffness	K_e	4000.0 [N/m]
Environmental damping	B_e	150.0 [N/m s]

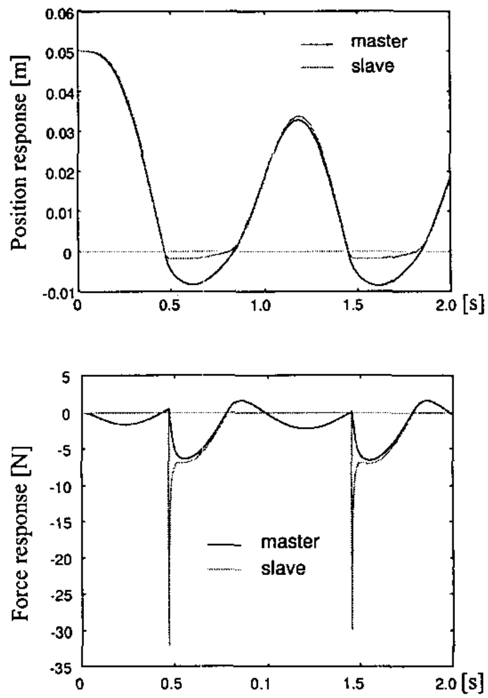


Fig. 2. Position control

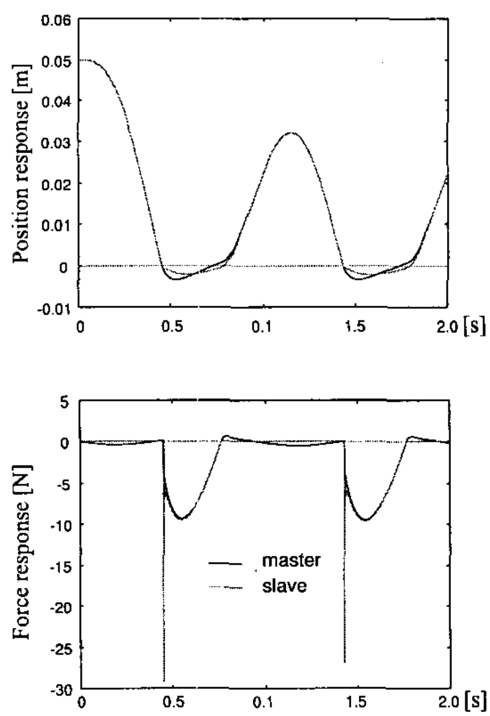


Fig. 3. Position-force control

III. Interactive Control of Environmental Mode

The environment has infinite modes. On the contrary, the motion control has finite degrees-of-freedom (DOF) for its motion. It is necessary for motion controller to quarry the information from environment at least to the extents of DOF. The paper shows a method to quarry the information from the environment using Hadamard matrix. Some of them need compliance with the environment, and the others need robustness against the environment. In order to achieve the stable contact motion with environment, the interactive control of environmental mode (ICEM) which is based on acceleration control is introduced.

The motion of the paddle foot with 4 supporting points has three modes, which is heaving, rolling and pitching motion [1][5]. Heaving mode affects the translational motion. The motion control in the decentralized manner taking environmental modes into account is shown where the compliant and the robust motion control are realized according to its modes.

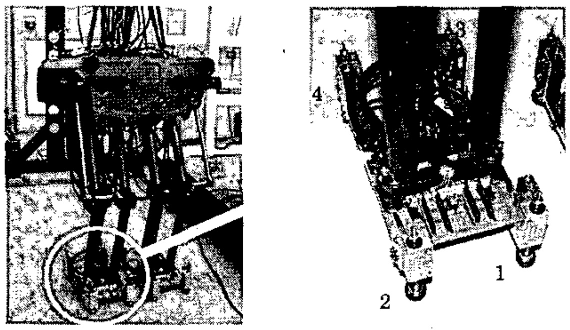


Fig. 4. Paddle foot of the walking machine with gap sensors.

Rolling and pitching motions show the foot tilt. The transformed environmental modes are "up & down", "inclination & declination", "left & right slope" and "non-flatness", as shown in Fig.5. The corresponding modes of motion are heaving, rolling, pitching and twisting, respectively. Non-flatness mode manifests itself when either of the vertexes of the diagonal of rectangular foot is in contact with rough environment. Hence, the rigid paddle foot is non-sensitive to the non-flatness mode.

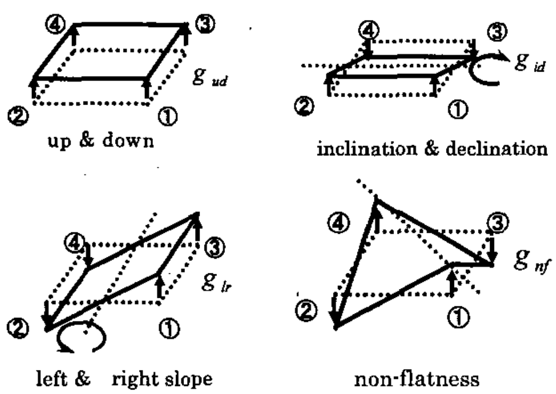


Fig. 5. Quarry of environmental modes.

Quarried environmental information are transformed to four environmental modes by the forth order Hadamard matrix $\boldsymbol{H}_4$.

$$\begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \begin{bmatrix} g_{ud} \\ g_{lr} \\ g_{id} \\ g_{nf} \end{bmatrix}$$

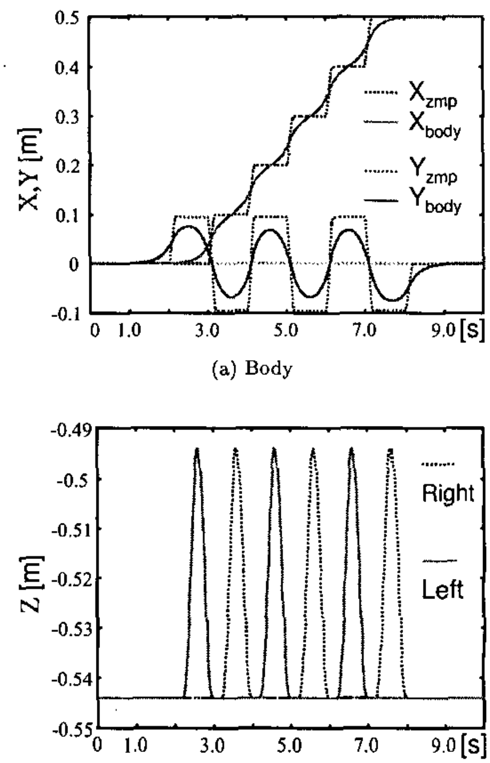
$$= \begin{bmatrix} \boldsymbol{H}_2 & \boldsymbol{H}_2 \\ \boldsymbol{H}_2 & -\boldsymbol{H}_2 \end{bmatrix} \begin{bmatrix} g_{ud} \\ g_{lr} \\ g_{id} \\ g_{nf} \end{bmatrix} \tag{18}$$

$$= \boldsymbol{H}_4 \begin{bmatrix} g_{ud} \\ g_{lr} \\ g_{id} \\ g_{nf} \end{bmatrix} \tag{19}$$

Then, the environmental modes are obtained.

$$\begin{bmatrix} g_{ud} \\ g_{lr} \\ g_{id} \\ g_{nf} \end{bmatrix} = \boldsymbol{H}_4^{-1} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \end{bmatrix} = \frac{1}{4}\boldsymbol{H}_4 \begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \end{bmatrix} \tag{20}$$

The effectiveness of compliant motion by quarry of environmental information is confirmed by dynamic simulator. The responses of environmental modes with ICEM or without ICEM are compared at walking motion. A trajectory of body and swing leg are shown in Fig.6. The trajectory is generated by using the inverted pendulum model. The spring damper model is used for the ground surface in the dynamic simulator.



(a) Body

(b) swing leg

Fig. 6. Environmental modes response with ICEM.

The numerical situation of the quarry process where the walking machine contacts with a flat floor is shown in Fig.7 and Fig.8. The modeling error may cause instability for biped walking. In Fig.8, more stable landing is realized. The numerical results show that the walking machine could adapt itself to environment by compliant motion.

IV. Conclusion

This paper proposes the contact motion in unknown environment. Two examples of application of interactive control are shown. First, the bilateral controller is designed.

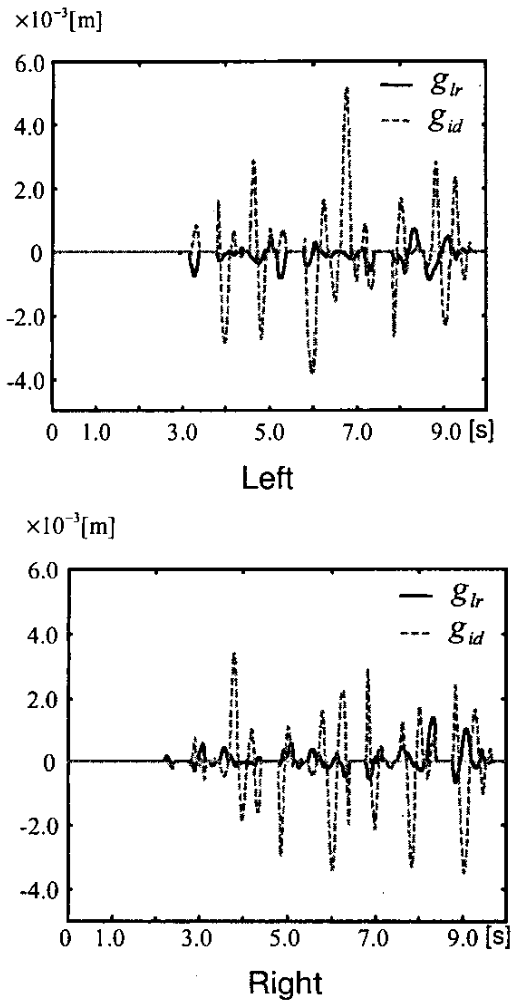


Fig. 7. Environmental modes response without ICEM.

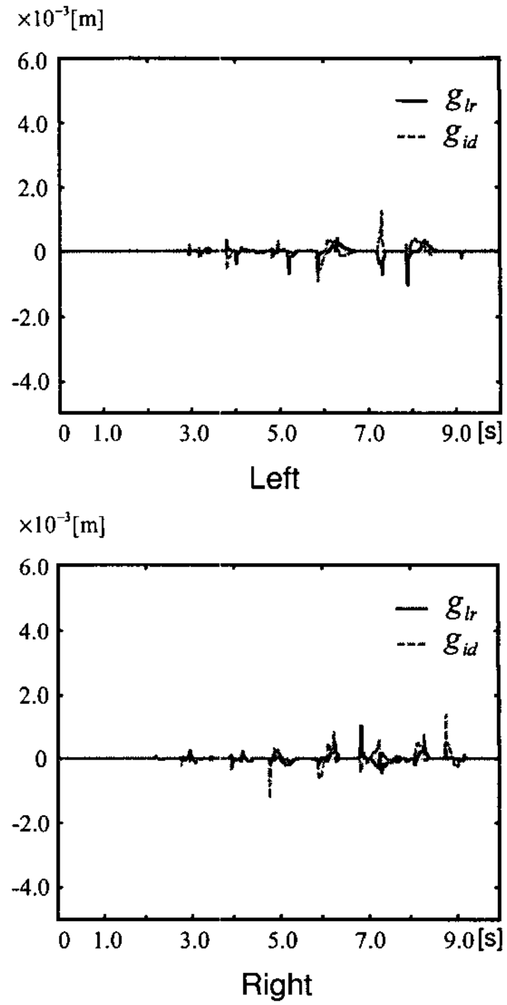


Fig. 8. Environmental modes response with ICEM.

The remarkable feature is that the master-slave system can be realized by a simple position-force control. Sencond application is a compliant motion for paddle of foot of the biped walking. The information mode from the environment is quarried by using forth order Hadamard matrix. The compliant motion for particular environmental modes of the unknown environment is realized.

The coordinate transformation by Hadamard matrix makes the characteristic of a system clear. In both examples, individual modes that system should deal with were quarried in order to achieve the contact motion. Some numerical results show the effectiveness of the proposed method.

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References

[1] M.Morisawa, K.Ohnishi, "Motion Control Taking Environmental Information Into Account," *EPE(European power electronics and drivers) journal*, Vol. 12, No. 4, pp.37-41, 2002

[2] K.Ohnishi, M.Shibata, T.Murakami, "Motion Control for Advanced Mechatronics," *IEEE Trans. on Mechatronics*, Vol. 1, No. 1, pp. 56-67, 1996.

[3] G.J.Raju, "Design Issues in 2-port Network Models of Bilateral Remote Manipulation," *IEEE Int. Conf. on Robotics and Automation*, Vol. 2, pp. 1316-1321, 1989.

[4] Y.Yokokohji, T.Yoshikawa, "Bilateral Control of Master-Slave Manipulators for Ideal Kinesthetic Coupling-Formulation and Experiment," *IEEE Trans. on Robotics and Automation*, Vol. 10, No. 5, pp. 605-619, 1994.

[5] M.Morisawa, K.Ohnishi, "Interactive Control of Environmental Mode for Biped Walking," *IEEE Int. Conf. on IECON '03,*, 2003.