Quarry of Modal Information from Environment for Advanced Motion Control

Seiichiro Katsura Member (Nagaoka University of Technology, katsura@vos.nagaokaut.ac.jp)

Kouhei Ohnishi Senior Member (Keio University, ohnishi@sd.keio.ac.jp)

Keywords: motion control, quarry process, decentralized system, Hadamard matrix, environmental information, modal decomposition

Motion control in open environment will be more and more important. The recent machines are required to have an ability to contact to unknown and/or unstructured environment. The environmental information is a key to be compliant to unknown environment. It is obtained from the modal decomposition.

The environment may have infinite modes. On the contrary, the motion control system has finite number of degree-of-freedom (DOF) for its motion. It is necessary for motion controller to quarry the information from the environment at least to the extents of DOF. The quarry process means to obtain of the environmental information and to abstract only the information which is required for motion control.

In this paper, an extension method of the Hadamard matrix is

Fig. 1. Quarry of environmental information by Q_3

Fig. 2. Experimental results of modal decomposition

proposed and quarry matrix is generalized in order to adapt to more complicated environmental situation. The quarry matrix is obtainable from the Hadamard matrix. This paper shows a quarry of the planar environmental modes using the third-order quarry matrix.

The motion of a robot with three supporting points has three modes, which is heaving, rolling and pitching modes. The robot obtains three environmental data as shown in Fig. 1(a). The obtained environmental information are transformed to three environmental modes by the three-order quarry matrix Q_3

$$\begin{bmatrix} g_{ud} \\ g_{rl} \\ g_{id} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & -1 \\ 2 & -1 & -1 \end{bmatrix} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} \\ = \frac{1}{3} Q_3 \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} \dots\dots\dots (1)$$

where g_{ud} , g_{rl} and g_{id} represent heaving, rolling and pitching modes, respectively. The transformed environmental modes are “up & down”, “inclination & declination”, “left & right” as shown in Fig. 1(b).

In order to confirm the validity of the proposed method, experimental results are shown. The obtained information is decomposed into three modes by using the third-order quarry matrix as shown in Fig. 2. Since there is no interference between modes, modal information according to DOF of the motion system is obtained from the environment. Planar terrain information is obtained by integration of the modal information.

As a result, motion control systems are designed in the modal spaces based on quarry process of the environmental mode.

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Seiichiro Katsura* Member
Kouhei Ohnishi** Senior Member

Motion control in open environment will be more and more important. The recent machines are required to have an ability to contact unknown environment. The environmental information is a key to be compliant to unknown environment. It is obtained from the modal decomposition. The environment may have infinite modes. On the contrary, motion control systems have finite number of degree-of-freedom (DOF) for their motion. It is necessary for motion controller to quarry information from the environment at least to the extents of DOF.

This paper develops a novel viewpoint of motion control based on quarry of environmental information. A quarry process of information from the environment using Hadamard matrix has been proposed. An extension method of the Hadamard matrix is proposed and quarry matrix is generalized in this paper. This paper shows a quarry of the planar environmental modes using the third-order quarry matrix. The motion of a robot with three supporting points has three modes, which are heaving, rolling and pitching modes. As a result, compliant motion control to unknown environment is attained in each mode. The modal system design method based on the quarry matrix will be a fundamental technique of design of decentralized system.

Keywords: motion control, quarry process, decentralized system, Hadamard matrix, environmental information, modal decomposition

1. Introduction

Motion control⁽¹⁾ in open environment will be more and more important. The recent machines are required to have an ability to contact to unknown and/or unstructured environment. The environmental information is a key to be compliant to unknown environment. It is obtained from the modal decomposition.

The environment may have infinite modes. On the contrary, the motion control system has finite number of degree-of-freedom (DOF) for its motion. It is necessary for motion controller to quarry the information from the environment at least to the extents of DOF. The quarry process means to obtain of the environmental information and to abstract only the information which is required for robot motion control⁽²⁾. An overview of quarry process of the environmental information is summarized as Fig. 1.

An quarry process of the information from the environment using Hadamard matrix has been proposed⁽³⁾. Two examples have been introduced in⁽³⁾. One is the joint drive, where the friction is independently estimated with the second-order Hadamard matrix⁽⁴⁾. The stick-slip motion is avoidable by the friction-free drive in the very low speed. Another is a control of paddle foot for the walking machine. It is important for such a machine to know the information of the roughness of the terrain beforehand. Reference⁽³⁾ attached touching sensors to the four corners of the paddle foot and detected the

Fig. 1. Quarry process of environmental information

gap signal between the corner and the surface of the terrain. The fourth-order Hadamard matrix abstracts the modes of the environment, i.e. up & down, inclination & declination, left & right slope and non-flatness. The quarry process based on Hadamard matrix abstracts the environmental modes successfully.

The Hadamard matrix exists for 2^n ($n = \text{integer}$) order. The extension of the Hadamard matrix is demanded for more complex modal system design. In this paper, an extension method of the Hadamard matrix is proposed and quarry matrix is generalized in order to adapt to more complicated environmental situation. The quarry matrix is obtainable from the Hadamard matrix. This paper shows a quarry of the planar environmental modes using the third-order quarry matrix. The motion of a robot with three supporting points has three modes, which are heaving, rolling and pitching modes. Since there is no interference between modes, motion control is designed in each mode. Modal system design will be effective for decentralized control system.

This paper is organized as follows. The following section shows a quarry method of friction information by the

* Department of Electrical Engineering, Nagaoka University of Technology

1603-1 Kamitomiokamachi, Nagaoka, Niigata 940-2188

** Department of System Design Engineering, Keio University
3-14-1, Hiyoshi, Kohoku-ku, Yokohama 223-8522

Fig. 2. Overview of friction-free joint system

second-order Hadamard matrix. In Section 3, a quarry method of rough terrain information by the fourth-order Hadamard matrix is shown. Derivation and generalization method of quarry matrix is proposed in Section 4. A quarry method of planar terrain information by the third-order quarry matrix is described in Section 5. Furthermore, experimental results are presented and the validity of the proposed method is confirmed. At the last section, this paper is summarized.

2. Quarry of Friction Information

First, the second-order Hadamard matrix H_2 is used for quarry of environmental information. An example is a friction-free joint system. Overview of the friction-free joint system is shown in Fig. 2. As shown in Fig. 2, the system is composed of two motors and one differential gear. Two similar motors rotate inversely with the velocity of $\dot{\theta}_R$ and $\dot{\theta}_L$ each other.

The motion equations of each motor are described as follows,

$$J\ddot{\theta}_R = \tau_{mR} - \tau_l - \tau_f \quad (1)$$

$$J\ddot{\theta}_L = \tau_{mL} + \tau_l - \tau_f \quad (2)$$

where J denotes motor inertia, τ_m denotes torque generated by actuator, τ_l denotes mechanical output-load and τ_f denotes friction. Friction in each motor drive system has the same characteristics versus the rotational velocity. Note that the differential motion is output of the system.

The second-order Hadamard matrix transforms each variable in the common and differential mode, respectively,

$$\begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \dot{\theta}_c \\ \dot{\theta}_d \end{bmatrix} = H_2 \begin{bmatrix} \dot{\theta}_c \\ \dot{\theta}_d \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} \tau_{mR} \\ \tau_{mL} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \tau_{m_c} \\ \tau_{m_d} \end{bmatrix} = H_2 \begin{bmatrix} \tau_{m_c} \\ \tau_{m_d} \end{bmatrix} \quad (4)$$

where $\dot{\theta}_c$ and $\dot{\theta}_d$ denote the virtual rotational velocity in the common and differential mode, respectively. τ_{m_c} and τ_{m_d} denote the virtual generated torque in the common and differential mode, respectively. The friction-free joint system is decomposed into two virtual modes by using the second-order Hadamard matrix; common and differential modes.

The motion equations of the virtual common and differential motors are described as follows,

 Fig. 3. Quarry process of friction information using H_2

$$J\ddot{\theta}_c = \tau_{m_c} - \tau_f \quad (5)$$

$$J\ddot{\theta}_d = \tau_{m_d} - \tau_l \quad (6)$$

In the common mode, the virtual motor is rotating with bias velocity and the only disturbance is friction. It is possible to have high gain only in the common mode to suppress friction. This technique realizes friction-free drive. Motion control for output is designed only in the differential mode. The quarry process of friction is summarized in Fig. 3.

3. Quarry of Rough Terrain Information

Second, the fourth-order Hadamard matrix H_4 is used for quarry of the environmental information. The same technique of the second-order Hadamard matrix is applied to the paddle foot of walking machine. Environment has infinite modes. The motion system can use the environmental information if it is represented by inner variables of the motion system. It is necessary to get such information for well adaptability to the unknown and/or unstructured environment. It is assumed that a gap between the corner of the foot and the ground surface is measured by inner sensor just before the foot lands on the ground. Thus, the paddle foot quarries the environmental information from rough terrain by the inner gap sensors.

The motion of the paddle foot with four supporting points has three modes, that is heaving, rolling and pitching is Fig. 4. Heaving mode affects translating motion. Rolling and pitching modes show the tilt of the foot. The paddle foot obtains four environmental data as shown in Fig. 5(a).

The obtained environmental information are transformed to four environmental modes by using the fourth-order Hadamard matrix H_4 ,

$$\begin{aligned} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \end{bmatrix} &= \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \begin{bmatrix} g_h \\ g_r \\ g_p \\ g_t \end{bmatrix} \\ &= \begin{bmatrix} H_2 & H_2 \\ H_2 & -H_2 \end{bmatrix} \begin{bmatrix} g_h \\ g_r \\ g_p \\ g_t \end{bmatrix} \\ &= H_4 \begin{bmatrix} g_h \\ g_r \\ g_p \\ g_t \end{bmatrix} \quad (7) \end{aligned}$$

where g_h , g_r , g_p and g_t represent heaving, rolling, pitching and twisting modes, respectively. The environmental modes are obtained as follows,

Fig. 4. Motion modes of the foot

(a) Quarry of environmental information

(b) Roughness of terrain for inner variable

Fig. 5. Quarry of environmental information by H_4

Fig. 6. Quarry process of rough terrain information using H_4

$$\begin{bmatrix} g_h \\ g_r \\ g_p \\ g_t \end{bmatrix} = H_4^{-1} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \end{bmatrix} = \frac{1}{4} H_4 \begin{bmatrix} g_1 \\ g_2 \\ g_3 \\ g_4 \end{bmatrix} \dots \dots \dots (8)$$

The transformed environmental modes are “up & down”, “right & left slope”, “inclination & declination” and “non-flatness” as shown in Fig. 5(b). The corresponding modes of

$$Q_4 \rightarrow Q_3$$

$$\begin{bmatrix} 1 \\ 1-1=0 \\ 1+1=2 \\ 1-1=0 \end{bmatrix} \times \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

Same rank

$$Q_3 = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & -1 \\ 2 & -1 & -1 \end{bmatrix}$$

Fig. 7. Derivation process of $Q_4 \rightarrow Q_3$

$$Q_3 \rightarrow Q_2$$

$$\begin{bmatrix} 1 \\ 0+1=1 \\ 2-1=1 \end{bmatrix} \times \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & -1 \\ 2 & -1 & -1 \end{bmatrix}$$

Same rank

$$Q_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} = H_2$$

Fig. 8. Derivation process of $Q_3 \rightarrow Q_2$

motion are heaving, rolling, pitching and twisting, respectively. Non-flatness mode manifests itself when either of the vertex or rectangular foot is in contact with rough environment. The rigid paddle foot is non-sensitive to the non-flatness mode. As a result, the fourth-order Hadamard matrix is useful to quarry the roughness of terrain from the environment.

These quarry process of the environmental modes from rough terrain is summarized as shown in Fig. 6.

4. Derivation and Generalization of Quarry Matrix

Hadamard matrix is a good tool to quarry the modal information from the environment. However, the Hadamard matrix exists for 2^n (n = integer) order. The extension of the Hadamard matrix is demanded for more complex modal system design. In this paper, an extension method of the Hadamard matrix is proposed and quarry matrix is generalized in order to adapt to more complicated environment.

The quarry matrix is obtained from the Hadamard matrix. For example, the third-order quarry matrix is obtained from the fourth-order Hadamard matrix. And the second-order

Fig. 9. Motion modes of the system

Hadamard matrix is derived from the third-order quarry matrix.

The generalized method of quarry matrix based on extension of the Hadamard matrix is described as follows:

- (1) The first column and the second one of each row are added.
- (2) Since all values of the first row are 1, by way of exception, the result of the first row is set to 1, i.e. $1 + 1 = 1$.
- (3) Since the last row equals the other row, the last row is removed.
- (4) Then the dimension of the matrix is decreased.

For example, the extension methods from the fourth-order quarry matrix $Q_4 = H_4$ to the second-order quarry matrix $Q_2 = H_2$ are shown from Figs. 7 to 8. From these figures, the extension method mentioned above is very natural and simple. Thus, an extension method of the Hadamard matrix is established and the quarry matrix is generalized.

Since the quarry matrices are the orthogonal matrices, each quarried mode is independent to each other. As a result, the quarry matrices are very useful not only for quarrying the environmental information but also the design of multi-robot systems.

5. Quarry of Planar Terrain Information

5.1 Modal Decomposition This paper shows a quarry of the planar environmental modes using the third-order quarry matrix. The motion of a robot with three supporting points has three modes, which is heaving, rolling and pitching modes. The robot obtains three environmental data as shown in Fig. 10(a). The obtained environmental information are transformed to three environmental modes by the three-order quarry matrix Q_3 .

$$\begin{bmatrix} g_{ud} \\ g_{rl} \\ g_{id} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & -1 \\ 2 & -1 & -1 \end{bmatrix} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} \\ = \frac{1}{3} Q_3 \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} \dots \dots \dots (9)$$

where g_{ud} , g_{rl} and g_{id} represent heaving, rolling and pitching modes, respectively. The transformed environmental modes are “up & down”, “left & right” and “inclination & declination” as shown in Fig. 10(b). The corresponding modes of motion are heaving, rolling and pitching, respectively. Thus, the planar environmental modes are quarried by the third-order quarry matrix.

 Fig. 10. Quarry of environmental information by Q_3

5.2 Control System for Adaptation to Environment

5.2.1 Acceleration Control by Disturbance Observer

High-performance motion controller is a requisite for more skillful and dexterous motion. To attain such high performance, motion systems should be robust against the load change and parameter variation. A conventional minor control loop structure has been effective in one degree-of-freedom motion.

The improvement ratio of the performance to the velocity reference tracking and the disturbance rejection is basically the same in such system. The increase of forward gain leads to more robust performance and makes the control stiffness higher. At the same time, high gain often excites the lowest mechanical resonance mode and makes the total system unstable. There is a limit of the forward gain.

On the other hand, recent dexterous motion requires wide range of control stiffness. For example, an electronic parts inserting machine needs some compliant motion at the tip of the machine. This case requires low or no control stiffness. The control stiffness is defined in the following equation,

$$\kappa = \frac{\partial f}{\partial x} \dots \dots \dots (10)$$

where κ denotes a control stiffness. f denotes generated force and x denotes position. The conventional controller will have very low forward gain, for such a purpose, and will lose robustness as a result. To satisfy such varied requirements, the controller should have variable control stiffness keeping the system highly robust.

Sabanovic mentioned that acceleration controller makes a motion system robust by analyzing sliding mode control⁽⁵⁾. A disturbance observer⁽¹⁾⁽⁶⁾ which was proposed by Ohishi *et al.* is a good candidate for attainment of robust acceleration control. A disturbance observer identifies the total mechanical load torque and parameter change. In other words, the identification of disturbance torque is essential for motion control

Fig. 11. Disturbance observer

robustness to realize various applications.

A disturbance observer is designed to cancel the disturbance torque as quickly as possible. The estimated disturbance torque is obtained from the velocity response $\dot{\theta}$ and the current reference I_a^{ref} as shown in Fig. 11.

The disturbance torque τ_{dis} is represented as (11)

$$\begin{aligned}\tau_{dis} &= \tau_l + \Delta J \ddot{\theta} - \Delta K_t I_a^{ref} \\ &= \tau_{int} + \tau_{ext} + F + D\dot{\theta} \\ &\quad + (J - J_n)\ddot{\theta} + (K_m - K_t)I_a^{ref} \dots \dots \dots (11)\end{aligned}$$

where

- J : Motor inertia
- θ : Angle of the motor
- τ_l : Load torque
- τ_{int} : Internal torque
- τ_{ext} : External torque
- F : Coulomb friction
- $D\dot{\theta}$: Viscous friction
- K_t : Torque coefficient
- (subscript) n : Nominal value.

Equation (12) shows that the disturbance torque is estimated through the first-order low-pass filter

$$\hat{\tau}_{dis} = \frac{\frac{J_n}{J} g_{dis}}{s + \frac{K_t}{K_m} \frac{J_n}{J} g_{dis}} \tau_{dis} \dots \dots \dots (12)$$

where g_{dis} denotes the cut-off frequency of the low-pass filter. The disturbance torque estimated by (12) is used for a realization of robust motion control. And a robust motion controller makes a motion system to be an acceleration control system.

In the actual application, the estimated disturbance torque is effective for not only the disturbance compensation but also the parameter identification in the mechanical system. The external force is also identified by using the estimated disturbance⁽⁷⁾. The disturbance observer estimates only the external force as follows,

$$\begin{aligned}\hat{\tau}_{reac} &= \frac{g_{ob}}{s + g_{ob}} (I_a^{ref} K_t + g_{ob} J_n \dot{\theta} \\ &\quad - \tau_{int} - \tau_g - F - D\dot{\theta}) - g_{ob} J_n \dot{\theta} \dots \dots \dots (13)\end{aligned}$$

where

Fig. 12. Reaction torque observer

- $\hat{\tau}_{reac}$: Estimated reaction torque
- τ_g : Gravity torque
- g_{ob} : Gain of reaction torque observer.

The estimation process of the external force is summarized as shown in Fig. 12. Figure 12 is called a reaction torque observer. It is possible to observe wide bandwidth of force information by setting the observer gain g_{ob} .

5.2.2 Motion Controller

The recent machines are required to have an ability to contact unknown environment. In motion control under open environment, robots are required to adapt to interference from other systems and the environment where it changes dynamically. A more sophisticated ability in motion control is necessary for compliant contact with environment. Conventional motion control is not always suitable for future applications due to the lack of adaptive capability to the environment. A motion controller in open environment will require various stiffness corresponding to the task.

The ideal position control should have infinite stiffness; however, the ideal force control should have zero stiffness. Modern motion system requires an ability to be compliant with contact environment. The motion control should take plural modes of environment into account. The environmental information is a key to be compliant to unknown environment. Motion control taking environmental information into account will make various machines including robots more adaptive and versatile.

In order to attain the affinity and adaptability to environment, zero-stiffness motion controller is designed in this paper. The proposed controller is composed of acceleration control based on the disturbance observer as shown in Fig. 13. The acceleration reference is set to 0 in order to realize the law of action and reaction. The acceleration command is given as a disturbance of the system. C_f denotes the control gain of the system. The total control system of each system is shown in Fig. 14. Each motion system controls the reaction force from the environment and compliant motion to the environment is realized.

In the conventional force control, much research has implemented force sensors to detect external force. Force sensors detect strain of the strain gauge. Strain of the strain gauge

Fig. 13. Proposed acceleration control system

Fig. 14. Total control system

Table 1. Descriptions of DC servo motor

Manufacturer	YASKAWA Electric Corporation
Rated power	30 W
Rated torque	0.09506 Nm
Torque constant	0.238 Nm/A
Gear ratio	33 : 1
Encoder resolution	65536 pulse/rev

is assumed external force. Problems of the force sensor are considered as follows⁽⁸⁾,

- Signal noise—since force sensors detect an external force by amplifying a strain of the strain gauge, signal noise is also amplified. High-frequency noise can be reduced by a low-pass filter; however frequency band of force sensing is getting narrow.
- Natural frequency of force sensor—force sensors have a physical natural frequency. It is difficult for force sensors to detect an external force with the frequency band⁽⁹⁾.
- Change of system structure—since force sensors detect a strain of the strain gauge, force sensors have a soft structure. A robot with a force sensor is regarded as a two-mass resonant system. It is difficult to attain the high-frequency force sensing due to the structure.

Moreover, external force is detected only at the position where the force sensors are implemented. It will be a problem for complicated environment.

In this paper, a disturbance observer⁽¹⁾⁽⁶⁾ is implemented instead of the force sensor. The disturbance observer can calculate the disturbance torque of motor without force sensors.

5.2.3 Experiment In order to confirm the validity of the proposed method, experimental results are shown. The proposed quarry process is applied for three motor systems. Three motors are controlled by the zero-stiffness force control shown in Fig. 14, and compliant motion to the environment is realized. Each external force is observed by the reaction torque observer and each position response is measured by the position encoder. The descriptions of the experimental

Fig. 15. Experimental results of each system

Fig. 16. Experimental results of modal decomposition

Fig. 17. Quarry process of planar terrain information using Q_3

system are listed in Table 1. The sampling time is 1 ms.

Position and force responses of each system are shown in Fig. 15. The obtained information is decomposed into three modes by using the third-order quarry matrix as shown in Fig. 16. Since there is no interference between modes, modal information according to DOF of the motion system is obtained from the environment. Planar terrain information is obtained by integration of the modal information. The quarry process by using the third-order quarry matrix is summarized as shown in Fig. 17. As a result, motion control systems are designed in the modal spaces based on quarry process of the environmental mode.

6. Conclusions

In this paper, advanced motion control based on quarry of environmental information was considered. The environmental information is a key to be compliant to unknown and/or unstructured environment. An extension method of the Hadamard matrix was proposed and quarry matrix was generalized in this paper. The third-order quarry matrix was obtained from the fourth-order Hadamard matrix. And the second-order Hadamard matrix was derived from the third-order quarry matrix. Since the extension method is very natural and simple, it is easy to extend higher order matrices.

This paper showed a quarry of the planar environmental modes using the third-order quarry matrix. The motion of a robot with three supporting points has three modes, which are heaving, rolling and pitching modes. The experimental results showed the viability of the proposed method.

Since the quarry matrices are the orthogonal matrices, each quarried mode is independent to each other. The quarry matrices are very useful not only for quarrying the environmental information but also the design of multi-robot systems. The modal system design method based on the quarry matrix will be a fundamental technique of design of decentralized system.

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Seiichiro Katsura (Member) received the B.E. degree in system design engineering and the M.E. and Ph.D. degrees in integrated design engineering in 2001, 2002 and 2004, respectively, from Keio University, Yokohama, Japan. From 2003 to 2005, he was a Research Fellow of the Japan Society for the Promotion of Science. From 2004 to 2005, he was a Postdoctoral Fellow of Keio University. Since 2005, he has been with Nagaoka University of Technology, Nagaoka, Niigata, Japan. His research interests include haptics, motion control and robotics. Dr. Katsura received the Best Paper Award from the Institute of Electrical Engineers of Japan (IEEJ) in 2003 and Yasujiro Niwa Outstanding Paper Award in 2004. He is a Member of the IEEJ, IEEE Industrial Electronics Society, Society of Instrumentation and Control Engineers, and the Robotics Society of Japan.

Kouhei Ohnishi (Senior Member) received the B.E., M.E., and Ph.D. degrees in electrical engineering from The University of Tokyo, Tokyo, Japan, in 1975, 1977, and 1980, respectively. Since 1980, he has been with Keio University, Yokohama, Japan. His research interests include power electronics, mechatronics, motion control, and robotics. Dr. Ohnishi received Best Paper Awards from the Institute of Electrical Engineers of Japan and the Japan Society for Precision Engineering, and Outstanding Paper Awards at IECON'85, IECON'92, and IECON'93. He also received the EPE-PEMC Council Award and the Dr.-Ing. Eugene Mittelmann Achievement Award from the IEEE Industrial Electronics Society in 2004. He is an IEEE Fellow.