Modal-Space Filtering by Expectation Value Extraction for High-Scaling Bilateral Control

Masaki Takeya* Student Member, Seiichiro Katsura* Senior Member

(Manuscript received Aug. 5, 2014, revised March 6, 2015)

This paper proposes a novel filtering method to reduce the stochastic disturbance in modal space. Recently, macro-micro manipulation has been applied in medical fields, especially for cell manipulation. In conventional approaches, a scaling bilateral control with haptic feedback is one of the key technologies for micro manipulation. However, the quality of haptic information deteriorates because of the influence of stochastic disturbance such as quantization noise caused by the interference between the macro-space and micro-space. To solve this problem, a modal filter that compensates for interference terms in each space is proposed. By dealing with the random variable as a mass fluctuation, the interference term of the stochastic disturbance on the master system can be clarified. Using the proposed method, it is possible to reduce the variance of the random variable and extract the expectation value. The validity of the proposed method is confirmed by simulation and experimental results.

Keywords: real-world haptics, bilateral control, motion control, stochastic disturbance, stochastic process, modal transformation

1. Introduction

In the industrial area such as robots and mechatronic devices, various robots have been put into practical use to create the labor force instead of human. With the technological development of robotics, motion control based on haptic information expected to be used in various fields and improve the quality of robotic motion⁽¹⁾. Haptic information has a bidirectionality that is subject to the law of action and reaction compared with the conventional information such as audio and visual information that has a unidirectionality. Hence, robots are expected to work not only in a closed environment but also in an open environment such as a human society. To focus on the haptic information, it needs to deal with position and force information at the same time whenever robots perform task involving motion constrained by environment. Therefore, a bilateral control that is controlling of master and slave robots has been expected to perform tasks in many application areas in recent years⁽²⁾⁽³⁾. Bilateral control is a method to transfer environmental information to an operator through master and slave robots. With this control scheme, the operator is able to perform tasks with acquiring unknown environmental impedance.

Major processing in bilateral control is a scaling that is mainly used for micro manipulation such as robotic surgeries. In the field of medical treatment, the development of cell manipulation technology represented by light tweezers is carried out⁽⁴⁾. This technology has been attracting its attention as a technique to help with cell treatment. It becomes more important to expand the operation range of the micro space where the manipulator cannot reach. In previous approaches, a scaling bilateral control with haptic feedback is one of the

key technologies for micro manipulation⁽⁵⁾. Shimono et al. proposed the scaling bilateral control system based on acceleration control in the modal space⁽⁶⁾. Taking the high-performance motion control into account, robots are needed to compensate friction^{(7)–(9)} and control current precisely⁽¹⁰⁾. For the realization of the robust motion control without force sensor, acceleration control system is constructed by the disturbance observer (DOB)⁽¹¹⁾⁽¹²⁾ and reaction force observer (RFOB)⁽¹³⁾. However, the quality of haptic information deteriorates because of the influence of stochastic disturbance such as quantization noise caused by interference between the macro-space and micro-space. In the conventional bilateral control system, Yajima et al. presented the interference of a force controller and a position controller when the structures of the master and slave systems are different⁽¹⁴⁾. Sakaino et al. proposed oblique coordinate control in order to eliminate the interference⁽¹⁵⁾. However, macro-micro bilateral control with the stochastic process such as the quantization noise has not been discussed. High precision of scaling bilateral control is closely related to reduction of the influence by the noise and performance of robust acceleration control⁽¹⁶⁾.

In this paper, the interference terms in each space induced by stochastic process are considered. It is able to comprehend the motion equation with application of stochastic fluctuation of position as the stochastic fluctuation of mass. By dealing with the mass fluctuation as a random variable, the interference term of the stochastic disturbance on the master system is clarified. When the random variable is mixed in the slave system, the variance of the dispersion space occurs. Accordingly, modal-space filtering by expectation value extraction in the modal space is proposed. Kalman filter⁽¹⁷⁾ is applied in the modal-space filter based on an optimal time-series data processing. Using the proposed method, it is possible to reduce the variance of the random variable and improve the operability of master system.

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

2. Macro-Micro Bilateral Control

2.1 Structure of Scaling Bilateral Control First, the basis of scaling bilateral control implemented between the master and slave systems is introduced to deal with the haptic information. The goals of bilateral teleoperation are considered as the reproduction of environmental impedance at master, and the realization of small operational force. Thus, control targets of the scaling bilateral control are expressed as follows

$$x_M - \alpha x_S = 0 \quad \dots\dots\dots (1)$$

$$f_M + \beta f_S = 0, \quad \dots\dots\dots (2)$$

where x and F mean position and force, and subscripts M and S are the master and the slave, respectively. Then, α and β denote scaling gain, respectively. (1) and (2) indicate that the correspondence of positions, and the achievement of the action-reaction law between the master and the slave, respectively. To realize targets of the bilateral control, a method of modal transformation is utilized by using a quarry matrix⁽¹⁸⁾ with scaling factors S_2 as follows

$$S_2 = \begin{bmatrix} 1 & \beta \\ 1 & -\alpha \end{bmatrix} \quad \dots\dots\dots (3)$$

The position and force information is transformed from the real space into the modal space by a quarry matrix as follows

$$X = S_2 x \quad \dots\dots\dots (4)$$

$$F = S_2 f \quad \dots\dots\dots (5)$$

Here, x and X mean position vectors of actuator space and modal space

$$x = \begin{bmatrix} x_M & x_S \end{bmatrix}^T \quad \dots\dots\dots (6)$$

$$X = \begin{bmatrix} x_C & x_D \end{bmatrix}^T \quad \dots\dots\dots (7)$$

As well as this f and F mean force vectors of actuator space and modal space

$$f = \begin{bmatrix} f_M & f_S \end{bmatrix}^T \quad \dots\dots\dots (8)$$

$$F = \begin{bmatrix} F_C & F_D \end{bmatrix}^T, \quad \dots\dots\dots (9)$$

where subscripts C and D denote a common mode value and a differential mode value, respectively. Thus, in the bilateral control system, (1) and (2) can be rewritten as follows

$$x_D = 0 \quad \dots\dots\dots (10)$$

$$F_C = 0. \quad \dots\dots\dots (11)$$

Figure 1 shows the block diagram of bilateral control with scaling factors. In order to attain the robustness of this system, acceleration control is implemented by using a disturbance observer (DOB). Then, external force is estimated by a reaction force observer (RFOB). Here, by using a position controller C_p and force controller C_f , the reference values of each modal space are calculated as follows

$$\begin{aligned} F_p &= -C_p M X \\ &= -(K_p + K_v s) M X \quad \dots\dots\dots (12) \end{aligned}$$

Fig. 1. Block diagram of the scaling bilateral control

$$\begin{aligned} F_f &= -C_f F \\ &= -K_f F, \quad \dots\dots\dots (13) \end{aligned}$$

where K_p , K_v , K_f denote a position gain, a velocity gain and force gain, respectively. Then, subscripts p , f and s denote the references of position, force controllers and Laplace operator, respectively. Therefore, the force reference of modal space F^{ref} is calculated as

$$F^{ref} = (I - S)F_f + SF_p, \quad \dots\dots\dots (14)$$

where I and S denote a unit matrix and a selection matrix, respectively. Accordingly, the bilateral control with high transparency is achieved.

By the coordinate transformation of actuator space and the mode space, the motion equation of actuator space is derived as follow

$$m\ddot{x} = f \quad \dots\dots\dots (15)$$

where m denotes mass matrix expressed by using mass of master system m_M and slave system m_S as

$$m = \begin{bmatrix} m_M & 0 \\ 0 & m_S \end{bmatrix} \quad \dots\dots\dots (16)$$

Similarly, the motion equation of modal space is derived as follows

$$M\ddot{X} = F, \quad \dots\dots\dots (17)$$

where M indicates an equivalent mass matrix whose elements are shown below

$$\begin{aligned} M &= S_2^{-T} m S_2^{-1} \\ &= \frac{1}{\alpha + \beta} \begin{bmatrix} \beta m_M + \alpha m_S & \alpha(m_M - m_S) \\ \beta(m_M - m_S) & \alpha m_M + \beta m_S \end{bmatrix}, \quad \dots\dots\dots (18) \end{aligned}$$

Therefore, the difference of mass between the master and the slave system can cause interference between position and force control.

2.2 Interference by Stochastic Disturbance The position information measured by digital sensor has finite resolution in actual. In the macro-micro bilateral control, the slave system performs micro movements. Thus, the position information of the slave side is affected greatly by the stochastic disturbance. When the stochastic disturbance such as the quantization noise is applied to the position of the slave motor, the position information result in having uncertainty as follows

$$x_S^{sen} = x_S^{res} + \Delta x_S, \dots \quad (19)$$

where subscript *sen* and $\Delta \circ$ denote the encoder signal and the stochastic disturbance caused by sensor's finite resolution, respectively. Taking the external force f^{ext} into account, the motion equation of the slave motor is transformed into

$$M\ddot{x}_S^{sen} = s^2 M(x_S^{res} + \Delta x_S) = f_S^{ext} + \Delta f_S \dots \quad (20)$$

Eqs. (19) and (20) are expressed as the stochastic differential equation because of including the stochastic processes. In the case of the scaling bilateral control system, the relations of the position and the force between the master and the slave motors are expressed as follows

$$x_M^{res} - \alpha(x_S^{res} + \Delta x_S) = 0 \dots \quad (21)$$

$$f_M^{ext} + \beta(f_S^{ext} + \Delta f_S) = 0. \dots \quad (22)$$

Hence, the position and the force information of the master motor are remarkably affected by the scaled stochastic disturbance of the slave one.

Here, (19) derived in actuator space can be rewritten as follows

$$x^{sen} = x + \Delta x \dots \quad (23)$$

where Δx means stochastic disturbance vector of the position responses

$$\Delta x = [\Delta x_M \quad \Delta x_S]^T \dots \quad (24)$$

As shown in (23), the motion equation of the actuator space is expressed as follows

$$s^2 m(x + \Delta x) = f + \Delta f \dots \quad (25)$$

where Δf means stochastic disturbance vector of the force responses

$$\Delta f = [\Delta f_M \quad \Delta f_S]^T \dots \quad (26)$$

In order to obtain the inverse matrix of x , a pseudo-inverse matrix x^+ is defined. By the matrix, (25) is transformed into

$$s^2(m + m\Delta x x^+)x = f + \Delta f \dots \quad (27)$$

Focusing on the dimension of $\Delta x x^+$, this term becomes dimensionless parameter. In other words, the dimension of $m\Delta x x^+$ is the multiplication of the mass with random variable. In this paper, the influence of the noise is dealt with the change of mass m as random variable. Therefore, motion equation with the mass change is expressed as follows

$$s^2(m + \Delta m)x = f + \Delta f \dots \quad (28)$$

where Δm means stochastic disturbance vector of the mass change

$$\Delta m = [\Delta m_M \quad \Delta m_S]^T \dots \quad (29)$$

Taking the equivalent mass matrix M into account, (28) can be rewritten as follows

$$\begin{aligned} S_2^{-T}(m + \Delta m)S_2^{-1} &= S_2^{-T}mS_2^{-1} + S_2^{-T}\Delta mS_2^{-1} \\ &= M + \Delta M. \dots \end{aligned} \quad (30)$$

This equation shows that the interference between the master and the slave systems become unignorable in case that Δm_M does not correspond with Δm_S . In other words, the master side is affected by the interference of quantization noise caused by position sensor of the slave side.

3. Proposed Filtering Method of Stochastic Disturbance

3.1 Modal-Space Filtering In this paper, a novel concept of modal space is presented by regarding expectation and dispersion in the random variable. As mentioned above, the slave system deals with random variables while the master system takes definite values. Note that the coordinate transformation of the scaling bilateral control is a projection from the space including the probability element. In other words, as for the modal transformation matrix to perform the coordinate transformation between actuator space and modal space, it works as a space projection matrix compounded in a micro and a macro space. Here, the expectation space and the dispersion space in the random variable are derived as follows

$$E[x_D] = \bar{x}_D \dots \quad (31)$$

$$E[(x_D - \bar{x}_D)^2] = \sigma_x^2 \dots \quad (32)$$

$$E[F_C] = \bar{F}_C \dots \quad (33)$$

$$E[(F_C - \bar{F}_C)^2] = \sigma_F^2, \dots \quad (34)$$

where $\bar{\circ}$ and $\sigma_{\circ}$ denote average value and variance, respectively. Taking the expectation space and the dispersion space into account, (1) and (2) in the scaling bilateral control system can be rewritten as follows

$$\bar{x}_D = 0 \dots \quad (35)$$

$$\bar{F}_C = 0. \dots \quad (36)$$

When the random variable is mixed in the slave system, the variance of the dispersion space occurs as shown in Fig. 2. Accordingly, modal-space filtering by extracting only expectation value in the modal space is proposed. As shown in (27), Δx relatively influences the differential mode x_D . In response to this problem, modal-space filtering in the differential mode is conducted. Consequently, the proposed block diagram with modal-space filtering is shown as Fig. 3.

3.2 Estimation of Modal Expectation Using Kalman Filter Given that stochastic disturbance Δx is white Gaussian noise, the expectation of Δx is expressed as follows

$$E[\Delta x] = 0. \dots \quad (37)$$

Hence, the expectation of the position vector in the actuator space is derived as

Fig. 2. The conventional block diagram of motor-space filtering

Fig. 3. The proposed block diagram with modal-space filtering

$$E[x^{sen}] = E[x] + E[\Delta x] = x \dots \dots \dots (38)$$

However, in the case that Δx is not white Gaussian noise or the filtering method does not completely work, a supposition of (37) is no more valid. Accordingly, the interference by the mass fluctuation affected by Δx occurs as shown in (27). In this paper, the Kalman filter is applied on the robots in the modal space based on an optimal time-series data processing algorithm. The Kalman filter equation can be formulated in the slave system as

$$x_{S(k+1)} = x_{S(k)} \dots \dots \dots (39)$$

$$x_{S(k)}^{sen} = x_{S(k)} + \Delta x_{S(k)}, \dots \dots \dots (40)$$

where k represents the sampling instant. The process of the Kalman filter consists of the prediction phase and the update phase. In the predicted equation, the state estimate from the previous time step is used to produce an estimate of the state at the current time step as follows

$$\hat{x}_{S(k)} = x_{S(k-1)} \dots \dots \dots (41)$$

$$\hat{P}_{S(k)} = P_{S(k-1)} + Q_{S(k-1)}, \dots \dots \dots (42)$$

where P is error covariance matrix, Q is the covariance matrix of the system noise. Then, $\hat{\delta}$ denotes the advance estimation value of Kalman filter. In the filtering step, the actual position information at that time is measured and combined with the current predicted equation. Hence, the estimated state value x_S and the error matrix P are updated by encoder signal x^{sen} and the Kalman filter gain matrix K as follows

$$K_{S(k)} = \frac{\hat{P}_{S(k)}}{\hat{P}_{S(k)} + R_{S(k)}} \dots \dots \dots (43)$$

$$x_{S(k)} = \hat{x}_{S(k)} + K_{S(k)}(x_{S(k)}^{sen} - \hat{x}_{S(k)}) \dots \dots \dots (44)$$

$$P_{S(k)} = (I_S - K_{S(k)})\hat{P}_{S(k)} \dots \dots \dots (45)$$

where R is the covariance matrix of the observation noise. As well as the modal space, the state estimate is used as

$$\hat{x}_{D(k)} = x_{D(k-1)} \dots \dots \dots (46)$$

$$\hat{P}_{D(k)} = P_{D(k-1)} + Q_{D(k-1)} \dots \dots \dots (47)$$

Therefore, the state estimate x_S has less noise by the Kalman filter in modal space. The algorithm of the Kalman filter is summarized as shown in Fig. 4. The Kalman filter is designed to be an optimal low-pass filter (LPF) whose cut-off frequency is decided mathematically.

Fig. 4. The algorithm of Kalman filter

Table 1. Parameters of simulations and experiments

Parameters	Descriptions	Value
T_s	Sampling time	0.1 ms
K_p	Proportional gain	10000
K_d	Differential gain	200
K_f	Force gain	3
K_m	Nominal torque coefficient	3.33 N/A
M_n	Nominal mass	0.245 kg
g_{dis}	Cut-off frequency of DOB	100 rad/s
g_{reac}	Cut-off frequency of RFOB	100 rad/s
ΔX	Resolution of position sensor	1.0×10^{-6} m
K_e	Elastic coefficient of environment	1000
D_e	Viscous coefficient of environment	10
K_h	Elastic coefficient of human	1000
D_h	Viscous coefficient of human	10
α	Position scaling gain	50
β	Force scaling gain	50

4. Simulations and Experiments

4.1 Setup

In order to confirm the validity of the proposed method, simulations and experiments are conducted. First, simulations are conducted for the case in which observation noise is added to only the slave system by using white Gaussian noise and its maximum value is set to be same as the resolution of position encoder. Table 1 shows the parameters of simulations. In these simulations, DOB and RFOB are implemented in both master and slave systems. Focusing on the filtering, the conventional method employed the Kalman filter in both master and slave systems. On the other hand, the proposed method employed the filter in the slave system and the differential mode. In order to compare the performance of filtering methods only focusing on the space which is utilized Kalman filter, the conventional method and the proposal of R and Q are set to be same value, respectively. The covariance matrix of observation noise R is determined as follows⁽¹⁹⁾

$$R = \frac{\Delta X^2}{12} \frac{1}{T_s} \dots \dots \dots (48)$$

In addition, Q is determined by using simulations⁽²⁰⁾.

Next, in the experiments, the 1-DOF linear motors are used as master and slave systems, and the position responses of each motor are acquired by position encoders. In addition, another 1-DOF linear motor is utilized as input motor which

Fig. 5. Experimental system

Fig. 6. Simulation results without filtering

is realized human motion virtually. In order to compare the performance enhancement of the conventional method with the proposal, same command motion in bilateral control is achieved by using the additional third motor. Figure 5 shows the experimental system. In the experiments, a cork block is utilized as the environment while the simulations use a spring-damper model. The values of experimental parameters are shown in Table 1.

4.2 Simulation Results The simulation results are shown in Figs. 6, 7 and 8. First, the simulation results of the position and force responses without filtering between the master and the slave motors are shown in Figs. 6(a) and 6(b). These figures clarify that the stochastic disturbance in slave system affected the master system clearly. In other words, the interference terms of each space due to the scaled stochastic disturbance occur.

Second, in the conventional method, the influence of noise is reduced in the slave system in the case that the Kalman filter is carried out completely as shown in Fig. 7. Focusing on the proposed method, it is clear that the influence of noise is reduced both in the master and the slave systems from the result of Fig. 8. Therefore, modal-space filtering improves the interference of stochastic disturbance in macro and micro space.

4.3 Experiment Results The experimental results

Fig. 7. Simulation results of the position responses

are shown in Figs. 9 and 10. First, the experimental results of the position responses between the master and the slave motors are shown in Fig. 9. From the result of Fig. 9, the position response of master system is improved compared to the conventional one. These figures show that modal-space filtering achieves superior performance in reducing the influence of stochastic disturbance Δx in the differential mode.

Second, the experimental results of the force responses between the master and the slave motors are shown in Fig. 10. Something can also be said for the responses. Conventionally, Kalman filter is surely demanded to reduce the influence of stochastic disturbance in the scaling bilateral control. On the other hand, there is an advantage that the proposed control structure achieves the performance improvement of haptic transmission compared with the conventional filtering method.

In this paper, each experiment is conducted 5 times to confirm the reproducibility of the proposed method. Also, the root mean square deviation of position and force responses are calculated. The results are summarized as shown in Table 2. By the proposed method, therefore, it is possible to reduce the variance of random noise and improve the operability of master system. In addition, high-precise macro-micro bilateral control can be conducted by optimizing the Kalman gain Q in modal space.

Fig. 8. Simulation results of the force responses

Fig. 9. Experimental results of the position responses

Fig. 10. Experimental results of the force responses

Table 2. RMSE with respect to position and force responses

Number of Trials		1	2	3	4	5
Conventional Method	Position (mm)	0.222	0.235	0.346	0.215	0.309
	Force (N)	0.0735	0.0971	0.231	0.0697	0.184
Proposed Method	Position (mm)	0.208	0.215	0.245	0.209	0.262
	Force (N)	0.0523	0.0542	0.0642	0.0526	0.108

5. Conclusions

In this paper, a novel filtering method to reduce the stochastic disturbance on the modal space was proposed. In order to reduce the influence of the stochastic disturbance, a modal filter that compensates for interference terms in each space is constructed. By dealing with a random variable as the mass fluctuation in conventional motion equation, the interference term of the stochastic disturbance on the master system was clarified. Using the proposed method, it became possible to reduce the variance of the random variable and extract the expectation value. The validity of the proposed method was confirmed by simulation and experimental results, and the proposed method improved the operability of master system.

Acknowledgment

This work was partially supported by JSPS KAKENHI Grant Number 24686037.

References

- (1) R.C. Goertz: "Fundamentals of General-Purpose Remote Manipulators", *Nucleonics*, Vol.10, No.11, pp.36–42 (1952)
- (2) D.A. Lawrence: "Stability and Transparency in Bilateral Teleoperation", *IEEE Trans. on Robotics and Automation*, Vol.9, No.5, pp.624–637 (1993)
- (3) S. Katsura, W. Iida, and K. Ohnishi: "Medical Mechatronics—An Application to Haptic Forceps", *IFAC Annual Reviews in Control*, Vol.29, No.2, pp.237–245 (2005)
- (4) Y. Hiratsuka and S. Maruo: "Development of Optically Controlled Micro-manipulation Systems by using Two-photon Microstereolithography", *IEEJ*

- Trans. on Sensors and Micromachines*, Vol.125, No.12, pp.473–478 (2005)
- (5) K. Kaneko, H. Tokashiki, K. Tanie, and K. Komoriya: “Impedance Shaping Based on Force Feedback Bilateral Control in Macro-Micro Teleoperation System”, *Proc. of IEEE International Conference on Robotics and Automation*, pp.710–717 (1997)
 - (6) T. Shimono, S. Katsura, S. Susa, T. Takei, and K. Ohnishi: “Transmission of Real World Force Sensation by Micro/Macro Bilateral Control Based on Acceleration Control with Standardization Matrix”, *IEEJ Trans. IA*, Vol.128, No.6, pp.726–732 (2008)
 - (7) Y. Mizutani and S. Katsura: “Analysis, Modeling, and Compensation of Friction for Scaled Bilateral Control”, *IEEJ Journal of IA*, Vol.3, No.4, pp.344–349 (2014)
 - (8) K. Sato, K. Tsuruta, and A. Shoji: “Adaptive Friction Compensation Control of Linear Slider with Considering a Periodic Reference Signal”, *IEEJ Trans. IA*, Vol.125, No.11, pp.1022–1029 (2005)
 - (9) M. Iwasaki, Y. Maeda, M. Kawafuku, and H. Hirai: “Improvement of Precise Positioning Performance by Modeling and Compensation for Nonlinear Friction”, *IEEJ Trans. IA*, Vol.126, No.6, pp.732–740 (2006)
 - (10) H. Fujimoto and K. Sakata: “Multirate PWM Control of Precision Stage for Ultrahigh-Speed Nanoscale Positioning”, *IEEJ Journal of IA*, Vol.3, No.3, pp.270–276 (2014)
 - (11) K. Ohnishi, M. Shibata and T. Murakami: “Motion Control for Advanced Mechatronics,” *IEEE/ASME Trans. on Mechatronics*, Vol.1, No.1, pp.56–67 (1996)
 - (12) K. Ohnishi: “Robust Motion Control by Disturbance Observer”, *The Robotics Society of Japan*, Vol.11, No.4, pp.6–13 (1993)
 - (13) T. Murakami, F. Yum and K. Ohnishi: “Torque Sensorless Control in Multidegree-of-freedom Manipulator”, *IEEE Trans. on Ind. Electron.*, Vol.40, No.2, pp.259–265 (1993)
 - (14) Y. Yajima and S. Katsura: “Decoupled Bilateral Control Based on Modal Space Observer in Master-Slave Systems with Different Masses”, *IEEJ Trans. IA*, Vol.133, No.2, pp.172–180 (2013)
 - (15) S. Sakaino, T. Sato, and K. Ohnishi: “Multi-DOF Micro-Macro Bilateral Controller Using Oblique Coordinate Control”, *IEEE Trans. on Ind. Infor.*, Vol.7, No.3, pp.446–454 (2011)
 - (16) A. Ohsumi: “Some Topics in Stochastic Control Theory”, *Transactions of Institute of Systems, Control and Information Engineers*, Vol.42, No.7, pp.363–370 (1998)
 - (17) C. Mitsantisuk, K. Ohishi, and S. Katsura: “Estimation of Action/Reaction Forces for the Bilateral Control Using Kalman Filter”, *IEEE Trans. on Ind. Electron.*, Vol.59, No.11, pp.4383–4393, November, 2012.
 - (18) S. Katsura and K. Ohnishi: “Quarry of Modal Information from Environment for Advanced Motion Control”, *IEEJ Trans. IA*, Vol.126, No.4, pp.372–378 (2006)
 - (19) K. Ito, R. Antonello, and R. Oboe: “Use of MEMS Accelerometers for Performance Improvement of Motion Control System with Low Resolution Position Sensors”, *IEEE International Symposium on Industrial Electronics, ISIE’13-TAIPEI* (2013)
 - (20) S. Bolognani, L. Tubiana, and M. Zigliotto: “Extended Kalman Filter Tuning in Sensorless PMSM Drives”, *IEEE Trans. on Ind. Appl.*, Vol.39, No.6, pp.1741–1747 (2003)

Masaki Takeya

(Student Member) received his B.E. degree in system design engineering from Keio University, Yokohama, Japan, in 2014. Since 2014, he has been Master’s course at Keio University, Yokohama, Japan. His research interests include real-world haptics, and human support space. He is a Student Member of IEEJ, as well as a Student Member of the IEEE, The Japan Society of Mechanical Engineers (JSME).

Seiichiro Katsura

(Senior Member) received the B.E. degree in system design engineering and the M.E. and Ph.D. degrees in integrated design engineering from Keio University, Yokohama, Japan, in 2001, 2002 and 2004, respectively. From 2003 to 2005, he was a Research Fellow of the Japan Society for the Promotion of Science. From 2005 to 2008, he worked at Nagaoka University of Technology, Nagaoka, Niigata, Japan. Since 2008, he has been with Keio University, Yokohama, Japan. His research interests include human support, wave system, systems energy conversion, and industrial electronics. Prof. Katsura received the IEEE Industrial Electronics Society Best Conference Paper Award in 2012.