Functional Mode Estimation Using Principal Component Analysis of Grasping/Manipulating Motion

Hiroki Nagashima† Student Member, Seiichiro Katsura† Senior Member

(Manuscript received Aug. 24, 2012, revised Feb. 19, 2013)

Recently, significant developments have been made in motion control technology. Robots are used not only in industry but also in everyday human society. Hereafter, in order to extend the range of the work and the types of motion, it is necessary to think about what being human means. Human beings are able to do a variety of work using the fingers, arms, and eyes. The motion trajectory and force adjustment are different in each of motion. Hence, which component is dominant for a particular work must be identified. In the conventional method for the quantitative analysis of human motion, it is presupposed that the functional mode is predefined, such as the grasping mode and the manipulating mode. In this paper, an estimation method using the principal component analysis (PCA) of the functional mode for human motion is proposed. Using this method, the dominant function is directly estimated from the motion information. The validity of the proposal is confirmed by three types of experiments. To confirm their effectiveness, these experiments are conducted under a condition whose theoretical value is known to exist. The experimental results in this paper are compared with the theoretical value, and a good agreement is observed.

Keywords: bilateral control, motion control, disturbance observer, acceleration control, principal component analysis

1. Introduction

In recent years, technological capability in motion control (14–17) is more and more developed. In industry, a lot of production processes are automated controlled by using industrial robots. Not only for industry but also robots for human society are actively researched and developed. For adaptation of human society and human support, it has many problems. For example, robot control in space existing interaction with human is needed. Also, human itself, researcher of robot, has to understand what human is. There are many researches of evaluation of human motion and function such as finger (14), bipedal locomotion (15), eyes (16–17). For quantitatively evaluation, abstraction method of human motion is needed. As an abstraction method of visual information, motion capture has been researched (16). However, it is difficult to abstract force adjustment of human because of visual information based. In case of interaction with people and work for object, force information is important, thus abstraction method of force information is necessary.

As a method for control and abstraction of position and force simultaneously, bilateral control has been researched (18–20). Based on modal transform (13), position synchronism and the law of action and reaction between a master and slave system can be achieved. Therefore, it is possible to abstract not only position information but also force information on human motion simultaneously. However, even if precise motion information is abstracted, position trajectory and force adjustment for one of tasks are different in each case. Also, the value of motion information changes accordingly depending on work objects. In case of robot control, it is possible to evaluate the system in terms of following capability and disturbance rejection capability by the presence of command for the system. This point causes us difficulty to evaluate human motion quantitatively. To evaluate the abstracted human motion information quantitatively, evaluation index for human motion is needed. Based on the index, it is needed to make clear what component dominant is. This component is called function of human motion (16–17), and it is thought that human work by using some functions skillfully.

There are many studies to focus on functional mode of human motion. By defining orthogonal functional mode such as grasping/manipulating mode (16) in virtual space, it becomes possible to design control systems on each functional mode independently. In addition, there are studies to abstract motion based on defined functional mode. These methods presuppose the definition of functional mode for control system design and abstraction of motion. For these methods, it is only possible to abstract and evaluate quantitatively on predefined functional mode. Functional mode of many studies is predefined (20). Also, estimation with time series variation for functional mode is not conducted. In other words, there

* Department of System Design Engineering, Keio University
3-14-1, Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan
are few studies focused on the generalized relation between human motion and function of motion. Therefore, in this paper, function estimation method using principal component analysis (PCA) for human motion is proposed. It is possible to estimate a dominant function of motion regardless of work object and motion. The overview of conventional method and the proposal for functional mode is shown in Fig. 1. Fig. 1 is constructed by two elements: motion and function. Though definition in detail is conducted in following section, function is component of motion making a change to work object such as grasping and manipulating of the object. On the other hand, motion consists of combination of these functions, and it is described in quantitative information such as motion trajectory and amount of the force applied to object. In conventional method, robot control and evaluation of motion are conducted based on hybrid control considering functional mode. On the other hand, the proposed method is estimated the function of human motion directly. The relation of conventional method and proposed method is that the former is assumed to direct problem, the position of the latter, that is the proposed method, is the process of solving its inverse problem. The proposal in this paper will be expected to be fundamental representation for generalization of function in human motion.

This paper is organized as follows: The following section describes definition of motion and function, then based on this, abstraction of human motion is introduced. In Section 3, as a conventional method, functional mode of grasping/manipulating mode is explained. Compared to this, function estimation method using principal component analysis for human motion is proposed. In order to confirm to validity of the proposed method, experimental results are described in Section 4. In this paper, the proposed method is applied to grasping/manipulating motion. Finally, this paper is concluded in Section 5.

2. Definition and Abstraction of Motion
2.1 Definition of Motion and Function The aim of this paper is to estimate function of human motion and to evaluate them quantitatively. Therefore, the meaning of motion and function need to be defined for estimation and evaluation. Motion in this paper is defined as follows:

- Motion is represented by position information and force information in work space.
- Motion consists of free motion and contact motion.
- Motion is constructed from some functions.

Based on these definition, abstraction of motion information and estimation of functional mode are conducted.

2.2 Abstraction of Human Motion In this section, bilateral control is introduced as an abstraction method of motion information. A block diagram of the bilateral control system is shown in Fig. 2. Bilateral control is control method which transfers information bidirectionally between master system and slave system. Bilateral control has two goals. One is realization of law of action and reaction between operator’s force and reaction force from environment, which is expressed as

\[ f_M + f_S = 0 \]

where \( f \) denotes the force, and subscript \( M \) and \( S \) mean the master system and slave system. The other is synchronism of position of master system and slave system, which is expressed as

\[ x_M - x_S = 0 \]

where \( x \) denotes the position. In Fig. 2, \( \ddot{x}, M, K_r, K_f, K_p, K_d, s \) denote the acceleration, mass of motor, force coefficient, force gain, position gain, velocity gain and Laplace operator, respectively. Superscripts \( \text{res}, \text{ref}, \text{ext} \), " \( \text{res} \), \( \text{ref} \), \( \text{ext} \), " mean response, reference, external and estimation, respectively. Subscripts \( n \), \( c \) and \( d \) denote nominal value, common mode and differential mode, respectively. The master system and slave system construct the acceleration control system using the disturbance observer (DOB)\textsuperscript{(20)-(22)}. External forces of the master and slave system are estimated by the reaction force observer.
Functional Mode Estimation of Human Motion (Hiroki Nagashima et al.)

(RFOB) [23]. In order to realize the control goal represented as (1) and (2), the control variables are transformed from the work space on the real–world to the virtual space by using a quarry matrix [24]. By using quarry matrix, control variables transformed into orthogonal common mode space and differential mode space each other. Therefore, it is possible for (1) and (2) to construct control system independently. The second–order quarry matrix \( Q_2 \) is defined as

\[
Q_2 = \begin{bmatrix}
1 & 1 \\
1 & -1
\end{bmatrix}
\]

By using the estimation force of the master system \( f_m \) and slave system \( f_s \), the force of the common and differential mode are expressed as

\[
\begin{bmatrix}
f_C \\
f_D
\end{bmatrix} = Q_2 \begin{bmatrix}
f_m \\
f_s
\end{bmatrix}
\]

\[
= \frac{1}{2} \begin{bmatrix}
1 & 1 \\
1 & -1
\end{bmatrix} \begin{bmatrix}
f_m \\
f_s
\end{bmatrix}
\]

Besides, by using the position response of master and slave system, the position of the common and differential mode are expressed as

\[
\begin{bmatrix}
x_C \\
x_D
\end{bmatrix} = Q_2 \begin{bmatrix}
x_m \\
x_g
\end{bmatrix}
\]

\[
= \frac{1}{2} \begin{bmatrix}
1 & 1 \\
1 & -1
\end{bmatrix} \begin{bmatrix}
x_m \\
x_g
\end{bmatrix}
\]

In bilateral control, the force of common mode \( f_{c_C} \) and the position of differential mode \( x_{d_D} \) are used as control variables. The acceleration references with respect to the common and differential mode are represented as

\[
x_{c_C} = -K_f f_{c_C} \quad \text{........................................ (6)}
\]

\[
x_{d_D} = -(K_p + K_d s)x_{d_D} \quad \text{.......................... (7)}
\]

In (6) and (7), relation between position gain \( K_p \) and velocity gain \( K_d \) is set so that response of differential mode is critical damping, which is expressed as

\[
K_d = 2 \sqrt{K_p} \quad \text{........................................ (8)}
\]

By using the inverse quarry matrix \( Q_2^{-1} \), the acceleration references are transformed from the modal space to the work space. Hence, the acceleration references of master system \( x_{c_C}^{\text{ref}} \) and the slave system \( x_{d_D}^{\text{ref}} \) are expressed as

\[
\begin{bmatrix}
x_{c_C}^{\text{ref}} \\
x_{d_D}^{\text{ref}}
\end{bmatrix} = Q_2^{-1} \begin{bmatrix}
x_C^{\text{ref}} \\
x_D^{\text{ref}}
\end{bmatrix}
\]

\[
= \begin{bmatrix}
1 & 1 \\
1 & -1
\end{bmatrix} \begin{bmatrix}
x_C^{\text{ref}} \\
x_D^{\text{ref}}
\end{bmatrix}
\]

In particular, the master–position response \( x_{c_C}^{\text{res}} \) and estimation value of master force \( f_{c_C}^{\text{est}} \) are abstracted as human motion information.

3. Estimation of Functional Mode Using Principal Component Analysis

In this chapter, functional mode based on modal transform is explained as conventional representation. Then, estimation method of principle functional mode using PCA is proposed.

3.1 Functional Mode of Grasping/Manipulating Control

In this section, functional mode of grasping/manipulating control is introduced. As a simple case, the case two robots grasp a object and manipulate is treated as shown in Fig. 3. In this case, the second–order quarry matrix \( Q_2 \) is used as modal transformation matrix from actuator space to functional modal space. For force information, manipulating mode \( f_m \) and grasping mode \( f_g \) are defined as follows:

\[
\begin{bmatrix}
f_m \\
f_g
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
1 & 1 \\
1 & -1
\end{bmatrix} \begin{bmatrix}
f_1 \\
f_2
\end{bmatrix}
\]

\[
\text{for each information, manipulating mode stands for the reaction force of manipulation} \ f_m \text{and center of gravity of two robots} \ x_m. \ \text{Also, grasping mode stands for internal force for grasping} \ f_g \text{and distance between two robots} \ x_g. \ \text{Functional mode represented in equations 10 and 11 is shown in}
\]

\[
\begin{bmatrix}
x_m \\
x_g
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
1 & 1 \\
1 & -1
\end{bmatrix} \begin{bmatrix}
x_1 \\
x_2
\end{bmatrix}
\]

\[
\text{For each information, manipulating mode stands for the reaction force of manipulation} \ f_m \text{and center of gravity of two robots} \ x_m. \ \text{Also, grasping mode stands for internal force for grasping} \ f_g \text{and distance between two robots} \ x_g. \ \text{Functional mode represented in equations 10 and 11 is shown in}
\]

\[
\text{Fig. 3. System model for grasping/manipulating control}
\]

\[
\text{Fig. 4. Grasping/manipulating mode}
\]
the tendency of analysis data, and to represent data using axes calculated by the tendency. In general, PCA is used for whole analytical data. The motion information of analysis is time-variable data. Therefore, by using time window whose width is \( w \), the tendency of data is examined by the time window \( w \) in this paper.

For using PCA, average and variance of analytical data are needed. Average of the position \( \overline{x}_i \), the auto covariance and the cross covariance of position information are represented as

\[
\overline{x}_i[k] = \frac{1}{w} \sum_{j=k-n+1}^{k} x_{ij}, \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots 
and sensitivity of time-variable function are influenced by the window width, the window width is set up enough for the human motion in this experiment. The experimental parameters are shown in Table 1. Position gain $K_p$ and force gain $K_f$ were set to sufficiently-large so that reference value of the current doesn’t exceed the value of the rated current. Also, the value of $K_v$ is calculated so that the value of the acceleration reference becomes critical damping corresponding to the value of $K_p$. In verification experiment, three cases are considered using two linear motors. One is control of the center of gravity position, in other words, only manipulating motion. The aluminum block is not used for this experiment because force command is not added. The theoretical value in this experiment $\theta_x$ is 45°. This value means control of grasping mode of position. Secondly, control of internal force for the grasped object, in other words, only grasping motion is considered. Theoretical value in this experiment $\theta_f$ is −45°. This value means differential mode of force. At last, control of both the center of gravity position and internal force for the grasped object are considered. This motion is integration of the above two cases. Theoretical value in this experiment $\theta_x$ is 45° and $\theta_f$ is −45°. For each case, estimation value based
Functional Mode Estimation of Human Motion

(a) Force responses of phase plane.

(b) Position responses of phase plane.

(c) Functional mode of force.

(d) Functional mode of position.

Fig. 9. Experimental results of automated grasping/manipulating control.

Fig. 10. Experimental setup for human motion

Fig. 11. Grasped objects

on experimental result is compared to theoretical value.

By using two linear motors, aluminium block is grasped and manipulated automatically. As control functional mode, grasping mode of force $f_g$ and manipulating mode of position $x_m$ is used introduced in section 3. Grasping/manipulating control is implemented by realizing acceleration control system. In this experiment, control goals are represented as

\[
\begin{align*}
  f_g^{cmd} &= 2 + \sin(2\pi t) \ (0.0 \leq t \leq 10.0) \\
  x_m^{cmd} &= 0.01 \sin(2\pi t) \ (0.0 \leq t \leq 10.0)
\end{align*}
\]

where $t$ denotes time. Also, motion is started with the state system 1 and system 2 contact the grasped object.

4.1.2 Experimental Results

Fig. 9 shows the experimental results of the verification experiment. The responses of automated grasping/manipulating control and estimated functional mode are shown in the figure. Subpanels (a) and (b) show the force response and position response in the phase plane, respectively. Then, by using PCA, functional modes of the force $\theta_f$ and position $\theta_x$ are estimated from these results, respectively.

Subpanels (c) and (d) show estimated functional mode of the force and position abstracted by automated grasping/manipulating control. The theoretical value of proposed index $\theta_f$ and $\theta_x$ are $-45^\circ$ and $45^\circ$, and each theoretical value is plotted with dashed line in subpanels (c) and (d), respectively. In this paper, estimation error to theoretical value is evaluated by using root mean square error (RMSE), which is represented as

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum (x_i - x^*)^2}
\]

where $\ast$ denotes theoretical value. The RMSE of $\theta_x$ and $\theta_f$ are 0.03 and 3.53, respectively. $\theta_x$ is nearly completely the same of the theoretical value, while $\theta_f$ has a little error to the theoretical value. It is considered the effect of noise and the force of manipulating mode. However, the difference of theoretical value of each functional mode is $90^\circ$, then these errors are enough small in this situation. Therefore, the validity of the proposed indeces $\theta_f$ and $\theta_x$ for estimation of functional mode of motion are confirmed.

4.2 Experiment of Human Motion for Variable Grasped Objects

Secondly, functional modes for human motion with variable grasped objects are estimated.

4.2.1 Experimental Setup

In this experiment, by using four linear motors, two pairs of bilateral control are implemented as shown in Fig. 10. Then, each force and position information are abstracted in this system. Important difference with the verification experiment is that human grasps and manipulates the object using bilateral control systems. In
this experiment, grasping/manipulating control is not used. As grasped objects, aluminium block, rubber ball, sponge are used as shown in Fig. 11. For aluminium block, stiffness is substantially dominant characteristic. Also, for rubber ball, stiffness is more dominant than viscosity. Then, for sponge, dominant rate of viscosity is higher than that of rubber ball. These three environments have different characteristics. As seen above, difference of functional mode estimation with variable objects is investigated. The others experimental setup including parameters are the same for verification experiment. In this experiment, each motor in the slave system is not contacted with the grasped object.

4.2.2 Experimental Results

The experimental results are shown in Figs. 12–14. The experimental results of aluminium block, rubber ball and sponge are shown, respectively. In each result, subpanels (a) and (b) show the force and position response in phase plane. From these results, functional modes of the grasping/manipulating motion for each grasped object are estimated. Each subpanels (c) and (d) show functional mode of force $\theta_f$ and functional mode of position $\theta_x$. Also, in each subpanels (c) and (d) of Figs. 12–14, dash line is the theoretical value of the force of grasping mode and position of the manipulating mode, respectively. In the beginning of the motion by approximately 2.0 s, each motor in the slave system is not contacted. Therefore, the relation between the motors does not have the functional mode. Though the response of $\theta_x$ in the transient phase is influenced by the time-window width, it is not said nothing about the influence, which may be different from the point in this paper.

In Fig. 12 (d), functional mode of position $\theta_x$ is 45°. Stiffness of aluminium block is substantially large, then position of the grasping mode $x_g$ doesn’t change. Therefore, as the principal functional mode, position of the manipulating mode $x_m$ is estimated. Moreover, though stiffness of rubber ball and sponge are lower than aluminium block, functional mode of position $\theta_x$ has few error to the theoretical value 45° as shown in Figs. 13, 14. In this experiment, the RMSE is calculated by using the data between 4.0 s and 10.0 s for using useful motion data including the component of function. The RMSE in this experiment for each grasped object is summarized in Table 2. As previously explained, these errors are enough small in this situation.

For all the grasped object in this experiment, the principal
function for human motion are the force of the grasping mode \( f_g \) and position of the manipulating mode \( x_m \), which are estimated directly from position information and force information without considering the grasping mode and manipulating mode explained in Section 3. Consequently, it is possible to apply the proposed method to grasping/manipulating motion regardless of the shape, stiffness and viscosity of grasped object.

### 4.3 Experiment of Human Motion for Different Examinees

Thirdly, functional modes for human motion with variable grasped objects are estimated.

#### 4.3.1 Experimental Setup

In this experiment, by using four linear motors, two pairs of bilateral control are implemented as shown in Fig. 10. Then, each force and position information are abstracted in this system. Important difference with the verification experiment is that human grasps and manipulates the object using bilateral control systems. In this experiment, grasping/manipulating control is not used. As grasped objects, aluminium block, rubber ball, sponge are used as shown in Fig. 11. For aluminium block, stiffness is substantially dominant characteristic. Also, for rubber ball, stiffness is more dominant than viscosity. Then, for sponge, dominant rate of viscosity is higher than that of rubber ball. These three environments have different characteristic. As seen above, difference of functional mode estimation with variable objects is investigated. The others experimental setup including parameters are the same for verification experiment. In this experiment, each motor in the slave system is not contacted with the grasped object.

#### 4.3.2 Experimental Results

The experimental results are shown in Fig. 15. In each result, subpanels (a) and (b) show the force and position response in phase plane. From these results, functional modes of the grasping/manipulating motion for each grasped object are estimated. Each subpanels (c) and (d) show functional mode of force \( \theta_f \) and functional mode of position \( \theta_x \). Also, in each subpanels (c) and (d) of Figs. 12–14, dash line is the theoretical value of the force of grasping mode and position of the
manipulating mode, respectively.

In Fig. 15(d), functional mode of position $\theta_x$ is 45°. Stiffness of aluminium block is substantially large, then position of the grasping mode $\theta_y$ doesn’t change. Therefore, as the principal functional mode, position of the manipulating mode $\lambda_m$ is estimated. Moreover, though stiffness of rubber ball and sponge are lower than aluminium block, functional mode of position $\theta_z$ has few error to the theoretical value 45°.

Even if motion information of the different examinee is used, most of the same function is estimated using the proposed method. For initial phase of the motion, each evaluation index has different value. This is the state which has no function. In this experiment, the RMSE is calculated by using the data between 4.0 s and 10.0 s for using useful motion data including the component of function. The RMSE in this experiment for each examinee is summarized in Table 3. As previously explained, these errors are enough small in this situation. In addition, for all results of examinees in this experiment, most of the same function is estimated using the proposed method.

In this section, validity of proposed index and method is confirmed using automated control of grasping/manipulating mode control at first. Secondly, for variable grasped object, common dominant functional mode of position and force are estimated. Lastly, for some examinees, the same function is estimated in each grasping and manipulating motion. Though grasping/manipulating motion treated as human motion in this paper is only 2 DOF motion on 1 axis, proposed estimation method for functional mode is apply to multi-DOF and multi-axis motion in the same way abstracted human motion information by structuring corresponding bilateral control systems.

5. Conclusions

In this paper, function estimation method using PCA has been proposed. The proposed method can estimate function from position and force information directly without pre-defining functional mode. The proposed method was applied to grasping/manipulating motion. In terms of the proposed method, two important knowledge have gotten. The proposed method is apply not depending on work or work object. To verify the effectiveness of the proposed method, two types of experiment are conducted. These experiments are conducted on the condition whose theoretical value is exist. By comparing functional mode estimated from the force and position information to the theoretical value, validity of the proposed method is confirmed quantitatively.

Acknowledgment

This research was partially supported by the Ministry of Internal Affairs and Communications, Strategic Information and Communications R&D Promotion Programme (SCOPE), 112103003, 2011.

<table>
<thead>
<tr>
<th>Object</th>
<th>RMSE of $\theta_x$</th>
<th>RMSE of $\theta_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examinee 1</td>
<td>0.06</td>
<td>3.21</td>
</tr>
<tr>
<td>Examinee 2</td>
<td>0.15</td>
<td>3.84</td>
</tr>
<tr>
<td>Examinee 3</td>
<td>0.14</td>
<td>4.79</td>
</tr>
</tbody>
</table>
Hiroki Nagashima (Student Member) received his B.E. degree in system design engineering from Keio University, Yokohama, Japan, in 2012. Since 2012, he has been Master’s course at Keio University, Yokohama, Japan. Since 2012, he has been a Research Assistant (RA) for the Leading Graduate School program for “Science for Development of Super Mature Society”. His research interests include real-world haptics, and human support space. He is a Student Member of IEEJ, as well as a Member of the IEEE, The Japan Society of Mechanical Engineers (JSME).

Seiichiro Katsura (Senior Member) received his B.E. degree in system design engineering and his 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 at Keio University, Yokohama, Japan. His research interests include real-world haptics, human support space, systems energy conversion, and electromechanical integration systems. Prof. Katsura received the Best Paper Award from the Institute of Electrical Engineers of Japan (IEEJ) in 2003, the Dr. Yasujiro Niwa Outstanding Paper Award in 2004, The European Power Electronics and Drives-Power Electronics and Motion Control Conference, EPE-PEMC’08 Best Paper Award in 2008, and the IEEJ Industrial Electronics Society Best Conference Paper Award in 2012. He is a Senior Member of IEEJ, as well as a Member of the IEEE, EPE, The Society of Instrument and Control Engineers (SICE), The Japan Society of Mechanical Engineers (JSME), The Japan Society for Precision Engineering (JSPE), Robotics Society of Japan (RSJ), The Institute of Electronics, Information and Communication Engineers (IEICE), and The Japan Society of Computer Aided Surgery (JSCAS).