Controller Design for Reproduction of Grasping/Manipulation Motion of Grasping Objects with Different Diameters

Shunsuke Yajima∗ Student Member, Eiichi Saito∗ Student Member
Seiichiro Katsura∗ Senior Member

(Manuscript received April 16, 2012, revised Oct. 7, 2012)

This paper proposes a controller design method for the reproduction of multi-degree-of-freedom (DOF) motion. For the storage and reproduction of haptic information, a motion-copying system was proposed. In the conventional method, however, it is difficult to reproduce the saved motion when the environmental configuration in the motion-loading phase is different from that in the motion-saving phase. This problem can be solved by the proposed method. The proposed design procedures are divided into two steps. First, a control structure with a different environmental configuration is proposed, and it is shown that the difference in the environmental configuration influences the reproduction of force information. Second, a novel controller that is based on the abovementioned analysis is proposed. By using the proposal, we can reproduce the saved motion even though the environmental configuration is changed. In this study, the grasping/manipulation motion is considered to be a multi-DOF motion, and the validity of the proposal is confirmed via experiments.

Keywords: haptics, bilateral control, motion-copying system, acceleration control, disturbance observer, motion control

1. Introduction

Recently, the storage and reproduction of advanced techniques of experts have been required for improving the work efficiency of robots or passing their skills on to the next generation. One of the conventional methods which acquire human motion is motion capture (1)–(3). However, this approach can just acquire the trajectory of human motion, and can not acquire force information of human motion. By using this method, therefore, it is difficult to store and reproduce the motion which contains the contact motion with an unknown environment. In response to this reason, a motion-copying system was proposed (4)–(5). The motion-copying system is based on the bilateral control. The bilateral control can transmit haptic information which is acquired at the remote place (6)–(10). Although considerable study has been proposed for the bilateral control, a bilateral control based on an acceleration control (11) has realized transmission of haptic information with high transparency (12). It is possible to acquire human motion information and unknown environmental information simultaneously by the bilateral control, therefore, various applications based on the bilateral control have been proposed for human support system (11)(12).

The motion-copying system is one of these applications, and can store and reproduce not only trajectory information but also force information which are acquired by the bilateral control. Because storing and reproducing of force information can be realized, the advanced techniques of experts which are required exquisite force information are able to be reproduced. As the applications, the motion-copying system is expected to be utilized in various fields such as industrial applications, training system, medical and welfare human assist, and so on. In the industrial field, for example, techniques of experts can be stored and reproduced by robots to improve work efficiency.

The motion-copying system is composed of two systems: a motion-saving system and a motion-loading system. In the conventional motion-copying system (13), it is difficult to reproduce the saved motion perfectly when the environmental configuration in the motion-loading system is different from that in the motion-saving system. In order to solve this problem, some methods have been proposed in the past (13)–(15). Tsunashima et al. proposed an acceleration information based method (16). Sato et al. proposed a novel motion reproduction method (17). Tsunashima et al. also proposed a motion-loading system with coordinate modification (18). In these conventional methods, however, it is difficult or ambiguous to design the control systems, and these methods have been applied to 1-degree-of-freedom (DOF) master-slave system. Therefore, the validity of application to the multi-DOF master-slave systems by these methods has not been verified yet.

This paper proposes a controller design method for reproduction of multi-DOF motion. The grasping/manipulation motion is treated as multi-DOF motion in this paper. The proposed design procedures are divided into two steps. At first, a control structure of the motion-loading system with different environmental configuration is proposed and analyzed, and it is shown that the difference in the environmental configuration influences the reproduction of force information. Second, a novel controller that is based on the abovementioned

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

© 2013 The Institute of Electrical Engineers of Japan.
analysis is proposed, and it is shown that this controller is equivalent to a velocity based motion-copying system, which we proposed previously\(^{(16)}\)\(^{(17)}\). In the proposed method, proportional force controller and proportional velocity controller are used. Therefore, the proposed method is easier to design than the conventional methods. In addition, design procedures of the proposed system are simpler than the conventional methods even when the number of DOF is increased. By using the proposed design procedures, position responses do not correspond between the motion data memory and the slave. On the other hand, the summation of the force between the motion data memory and the slave is zero once the slave contacts with the environment. In other words, the proposed method gives preference to reproduction of force information over reproduction of position information.

This paper is organized as follows. Next section explains modeling and modal transformation for the grasping/motion control. In section 3, the motion-copying system is introduced. The proposed controller design method is shown in section 4. The validity of the proposal is verified via experiments in section 5. Finally, this paper is concluded in the last section.

2. Modeling and Modal Transformation

In this paper, a grasping/motion control is treated as the multi-DOF motion. Thus, this section introduces a grasping/motion bilateral control.

Model of the grasping/motion bilateral control is shown in Fig. 1. In Fig. 1, \(x_i\) and \(f_i\) are position and force of \(i\)-th linear motor. In this paper, the masses of each motor are the same. Then, the targets of the grasping/motion bilateral control are expressed as follows:

- Grasping and manipulation positions between the master and the slave are corresponded.
- Grasping and manipulation reaction force feedbacks between the master and the slave are realized.

In order to realize above targets, position and force information of the master and the slave are transformed into a modal space. In the modal space, these targets are divided into four modes which are based on common mode, differential mode, grasping mode, and manipulation mode. The common mode and the differential mode are tasks of the bilateral control, and the grasping mode and manipulation mode are tasks of grasping/motion control. The grasping mode and the manipulation mode with respect to position information are expressed as

\[
\begin{bmatrix}
X_{gM} \\
X_{mM}
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
x_1 + x_2 \\
x_1 - x_2
\end{bmatrix}
\]

where \(X_{gM}\) and \(X_{mM}\) denote master, slave, grasping, and manipulation, respectively. Fig. 2 shows the concept of modal decomposition for grasping/motion modes. The common mode and differential mode in the grasping and manipulation modes are expressed as

\[
\begin{bmatrix}
X_{gC} \\
X_{mC} \\
X_{gD} \\
X_{mD}
\end{bmatrix} = \begin{bmatrix}
X_{gM} + X_{gS} \\
X_{gM} - X_{gS} \\
X_{mM} + X_{mS} \\
X_{mM} - X_{mS}
\end{bmatrix}
\]

where subscripts \(C\) and \(D\) denote common mode and differential mode, respectively. Here, (1) to (4) are rewritten as

\[
\begin{bmatrix}
X_{gC} \\
X_{mC} \\
X_{gD} \\
X_{mD}
\end{bmatrix} = \begin{bmatrix}
1 & 1 & 1 & 1 \\
1 & -1 & 1 & -1 \\
1 & 1 & -1 & -1 \\
1 & -1 & -1 & 1
\end{bmatrix}
\]

To satisfy (5), a transformation matrix \(T\) is introduced

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

By using \(T\), (5) is expressed as

\[
\begin{bmatrix}
X_C \\
X_D
\end{bmatrix} = T \begin{bmatrix}
X_M \\
X_S
\end{bmatrix}
\]

where \(x\) and \(X\) denote position vectors of the actuator space and the modal space, respectively. As well as position information, force transformation is derived as

\[
\begin{bmatrix}
F_C \\
F_D
\end{bmatrix} = T \begin{bmatrix}
F_M \\
F_S
\end{bmatrix}
\]

where \(f\) and \(F\) denote force vectors of the actuator space and the modal space, respectively.
3. Motion-Copying System

In this section, the motion-copying system is explained.

3.1 Concept

Overview of the motion-copying system is shown in Fig. 3. The motion-copying system is composed of two systems: a motion-saving system and a motion-loading system. In the motion-saving system, a bilateral control is implemented between the master and the slave. The motion-saving system stores the force and position information at the master into the motion data memory. As a result, the motion of the operator is stored, and the saved motion is reproduced by the motion-loading system.

Accordingly, the bilateral control with high transparency between the master and slave systems is achieved.

3.2 Motion-Saving System

The control targets of the bilateral control are expressed as

\[ F_{\text{ext}} = 0 \]  \hspace{1cm}  (13)
\[ X_{\text{res}} = 0 \]  \hspace{1cm}  (14)

where superscripts ext and res mean external and response. The block diagram of the motion-saving system is shown in Fig. 4. In order to realize the robust acceleration control, the disturbance observer (DOB) is implemented in each motor, and the external force is estimated by the reaction force observer (RFOB).

In Fig. 4, superscript ref denotes reference, and \( C_f \) and \( C_p \) mean force controller matrix and position controller matrix, which are expressed as

\[ C_f = \text{diag} \left[ K_f, K_f \right] \]  \hspace{1cm}  (15)
\[ C_p = \text{diag} \left[ K_p + K_s, K_p + K_s \right] \]  \hspace{1cm}  (16)

where \( K_f, K_p, \) and \( K_s \) are force gain, position gain, and velocity gain. Here, acceleration references in the modal space are calculated as

\[ s^2 X_{\text{ref}}^C = -C_f F_{\text{ext}} \]  \hspace{1cm}  (17)
\[ s^2 X_{\text{ref}}^D = -C_p X_{\text{res}} \]  \hspace{1cm}  (18)

In addition, acceleration references in the actuator space are calculated from (7) as

\[ \begin{bmatrix} s^2 X_{\text{ref}}^f \\ s^2 X_{\text{ref}}^s \end{bmatrix} = T^{-1} \begin{bmatrix} s^2 X_{\text{ref}}^C \\ s^2 X_{\text{ref}}^D \end{bmatrix} \]  \hspace{1cm}  (19)

4. Controller Design

This section analyzes the motion-copying system with different environmental configuration. A diameter of a grasping object is focused on as different environmental configuration because the grasping/manipulation motion reproduction is treated in this paper. An overview of different environmental configuration is shown in Fig. 6. Here, \( d^w \) and \( d^l \) mean diameters in the motion-saving phase and the motion-loading phase, respectively. \( x_{\text{ref}} \) is the difference between \( d^w \) and \( d^l \), which is represented as

\[ x_{\text{ref}} = d^w - d^l \]  \hspace{1cm}  (20)

Fig. 6 shows the case of \( d^w > d^l \).

The influence of \( x_{\text{ref}} \) for the reproduction of the stored motion is analyzed. This section has some assumptions that the initial center position and the mechanical impedance of the object in the motion-loading system are not varied from those in the motion-saving system. Because the initial center position of the grasping object is the same between the
Controller Design for Reproduction of Grasping/Manipulation Motion (Shunsuke Yajima et al.)

motion-saving system and the motion-loading system, the grasping mode is only considered. An equivalent block diagram of the motion-loading system in the grasping mode with different environmental configuration is shown in Fig. 7. In Fig. 7, $M_n$, $K_e$, $D_l$, $g_{dis}$, and $g_{rea}$ denote nominal equivalent mass in the grasping mode, elastic coefficient of the environment, viscous coefficient of the environment, cut-off frequency of the disturbance observer, and cut-off frequency of the reaction force observer, respectively. In order to examine the influence of $x^{em}$, a transfer function of the force in the common mode $F^{ext}_{gC}$ from $x^{em}$ is derived as

$$G = \frac{F^{ext}_{gC}}{x^{em}}$$

$$= \frac{a_2 s^2 + a_1 s + a_0}{b_2 s^2 + b_1 s + b_0}$$

(21)

where the coefficients in the numerator are expressed by

$$a_2 = M_n g_{dis}$$

(22)

$$a_1 = K_e M_n g_{dis}$$

(23)

$$a_0 = K_e M_n g_{dis}$$

(24)

Additionally, the coefficients in the denominator are represented as

$$b_2 = D_e$$

(25)

$$b_1 = D_e K_e M_n + 1$$

(26)

$$b_0 = (K_e K_f M_n + 1) g_{dis}$$

(27)

In (21) to (27), it is assumed that $g_{rea}$ is the same value as $g_{dis}$. Here, $x^{em}$ is regarded as a step input in this system, therefore, the step response of $G$ is considered. The final value of the step response of $G$ is derived by using the final-value theorem as

$$\lim_{s \to 0} s \cdot G = \lim_{s \to 0} G$$

$$= \frac{K_p M_n}{K_e K_f M_n + 1}$$

(28)

Although $F^{ext}_{gC}$ should be always 0 in an ideal condition, (28) represents that $F^{ext}_{gC}$ can’t converge on 0 when $x^{em}$ is existing in the system. From (28), $K_p$ should be 0 in order to solve above problem. When $K_p$ is equal to 0, (28) is rewritten as

$$\lim_{s \to 0} s \cdot G = \frac{K_p M_n}{K_e K_f M_n + 1}$$

$$= 0 \ (K_p = 0)$$

(29)

Eq. (29) shows that $F^{ext}_{gC}$ can converge on 0 regardless of the presence of $x^{em}$. Considering the whole motion-loading system, therefore, the position controller matrix $C_p$ is redefined as

$$C_p = \text{diag}[K_s, K_p + K_x s]$$

(30)

This controller is equivalent to a velocity controller in the differential mode that we proposed in (16) (17).

In this section, the initial center position of the grasping object is set as the same between the motion-saving system and the motion-loading system for analyzing the influence of $x^{em}$ simply. However, the proposed method can reproduce the saved motion according to the object even when the initial center position is different between the motion-saving system and the motion-loading system. This is because the initial center position does not affect the proposed system. Furthermore, the proposed method can allow any different environmental configuration $x^{em}$ even when the velocity gain is designed any value because of (29). However, if $K_p = 0$, the saved motion may not be reproduced well because the system only has the force controller. The additional study about this point is needed to develop the proposed method theoretically.

Although $x^{em}$ is treated as the different environmental configuration in the grasping/ manipulation motion reproduction in this paper, this analysis method can be applied to the other motions. In 1-DOF motion, for example, $x^{em}$ can be treated as the different environmental location.

In this section, the static change between the motion-saving system and the motion-loading system as a step input is only considered. On the other hand, when the environmental configuration changes dynamically, the proposed method can’t always reproduce the saved force information. However, in the grasping manipulation motion, there are very few cases in which the environmental configurations are different dynamically in the motion-loading phase. Therefore, this paper only considers the static change of the environmental configuration between the motion-saving system and the motion-loading system.

5. Experiments

5.1 Experimental Setup

The proposed method is compared with the conventional method by experiments in this section. Overview of experimental setup is shown in Fig. 1. As the master and the slave systems, linear motors are utilized, and position responses of each motor are obtained by linear encoders which are attached to each motor. In these
Controller Design for Reproduction of Grasping/Manipulation Motion (Shunsuke Yajima et al.)

### Table 1. Experimental parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of motor</td>
<td>0.3 kg</td>
</tr>
<tr>
<td>$K_p$ (Position gain)</td>
<td>3600.0</td>
</tr>
<tr>
<td>$K_v$ (Velocity gain)</td>
<td>120.0</td>
</tr>
<tr>
<td>$K_f$ (Force gain)</td>
<td>3.0</td>
</tr>
<tr>
<td>$\omega_{DOB}$ (Cut-off frequency of DOB)</td>
<td>500.0 rad/s</td>
</tr>
<tr>
<td>$\omega_{RFOB}$ (Cut-off frequency of RFOB)</td>
<td>500.0 rad/s</td>
</tr>
<tr>
<td>$d_1$ (Diameter in first experiment)</td>
<td>0.06 m</td>
</tr>
<tr>
<td>$d_2$ (Diameter in second experiment)</td>
<td>0.05 m</td>
</tr>
</tbody>
</table>

Fig. 8. Experimental results of the motion-saving system

(a) Force response of the grasping mode

(b) Force response of the manipulation mode

(c) Position response of the grasping mode

(d) Position response of the manipulation mode

Fig. 9. Experimental results of the proposed motion-loading system (diameter of the object is the same)

5.2 Experimental Results

Fig. 8 shows the experimental results of the motion-saving system. In (a) and (b), force responses of the grasping mode and the manipulation mode are shown, and (c) and (d) also show position responses of each mode. Manipulation force was caused by the frictional force which was acting on between the object and the floor. From these results, reaction force feedbacks and position tracking between the master and the slave in each mode were well achieved. In addition, the responses of the master were stored into the motion data memory in this system.

Fig. 9 shows the experimental results of the proposed motion-loading system with the same diameter. As well as the motion-saving system, reaction force feedbacks and position tracking between the saved data and the slave in each mode were achieved. In fact, it can be said that the saved motion is reproduced by the proposed motion-loading system improved when these gains are set higher value. In this paper, these values were designed for the constraint of the actual experimental setup. As well as position controller, P controller in the force control was designed for the constraint of the actual experimental setup. The velocity gain in the proposed controller was designed as the same value of the velocity gain in the conventional position controller for comparing fairly.
Controller Design for Reproduction of Grasping/Manipulation Motion (Shunsuke Yajima et al.)

Fig. 10. Experimental results of the conventional motion-loading system (diameter of the object is different).

Fig. 11. Experimental results of the proposed motion-loading system (diameter of the object is different).

When the diameter in the motion-loading phase is the same as that in the motion-saving phase, experimental results of the conventional motion-loading system with different diameter are shown in Fig. 10. From Fig. 10, slave position was well tracked to position of the saved data in free motion. In contacting motion, however, both reaction force feedbacks and position tracking were not achieved. In this case, the reproduction of the saved motion was not attained. On the other hand, Fig. 11 shows the experimental results of the proposed motion-loading system with different diameter. In Fig. 11, the reproduction of the grasping position information according to the environmental configuration was well achieved. At the same time, in (a) and (b), the control targets with respect to the force responses were realized once the slave contacts with the object. In these results, however, it is shown that position responses were disaccord subtly at some points between the saved data and the slave in the proposed method. This is because the velocity gain in the proposed controller was set the same value as that in the motion-saving system for comparing fairly. The tracking performance will be improved when the velocity gain in the proposed controller is set the higher value. However, large velocity gain leads to phase lag of the position response. That is, when large $x^{en}$ is input the system with large velocity gain in the proposed controller, the convergence speed of the responses may be slow.

From these results, the validity of the proposed method was verified.

6. Conclusions

In this paper, a controller design for reproduction of multi-DOF motion was proposed. The conventional method was not able to reproduce the saved motion when the environmental configuration in the motion-loading system was different from that in the motion-saving system. This paper analyzed the motion-loading system with different environmental configuration, and discussed why the saved motion was not reproduced well. Next, a controller was proposed based on this analysis, and this controller was shown to be equivalent the velocity controller that we proposed previously. By using the proposed method, the saved motion can be reproduced according to the environment. In fact, it can be said that the proposed method gives preference to reproduction of force information over reproduction of position information. The proposed method is expected to be applied to various applications because the configuration of the environment needs not
to be considered. Finally, the validity of the proposed method was verified by the experiments.

Acknowledgment

This research was partially supported by the JST Adaptable and Seamless Technology transfer Program A-STEP.

References


Shunsuke Yajima (Student Member) received the B.E. degree in system design engineering and the M.E. degree in integrated design engineering from Keio University, Yokohama, Japan, in 2011. He is currently working toward the M.E. degree at Keio University. His research interests include haptics, motion control, and human support system.

Eiichi Saito (Student Member) received the B.E. degree in system design engineering and the M.E. degree in integrated design engineering from Keio University, Yokohama, Japan, in 2011 and 2012, respectively. He is currently working toward the Ph.D. degree at Keio University. His research interests include vibration control, haptics, and time delay compensation. He received the IEEE Industrial Electronics Society Best Conference Paper Award in 2012.

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 (IEEE) 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 IEEE 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).