Effects of Group Synchronization Control over Haptic Media in Collaborative Work

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Abstract

This paper investigates the effects of group (or inter-destination) synchronization control over haptic media in collaborative work where two clients manipulate a CG object in a virtual space by using haptic interface devices. The group synchronization control adjusts the output timing of haptic media among different clients. By experiment, we subjectively assess the haptic media output quality so as to demonstrate the effectiveness of the control. We also clarify the relations between subjective and objective assessment results.

Key words: Collaborative virtual environments, Haptic media, Group synchronization, Objective assessment, Subjective assessment, Experiment

1. Introduction

In networked 3-D virtual environments, we can largely improve the efficiency of collaborative work such as remote surgery simulation and design by using haptic interface devices [1]. However, network delay jitter disturbs the temporal relations among multiple haptic media streams. To solve the problem, we need to carry out media synchronization control [2] for haptic media.

Media synchronization control falls into three types: *intra-stream*, *inter-stream*, and *group* (or *inter-destination*) synchronization control. The intra-stream synchronization control is necessary for the preservation of the timing relation between *media units* (*MUs*), each of which is the information unit for media synchronization, in a single media stream. The inter-stream synchronization control is required for keeping the temporal relation among MUs in multiple media streams. Group synchronization control as well as the first two types of control is needed in multicast communications [3], [4]. The purpose of the group synchronization control is to output each MU of media streams simultaneously at different destinations for the fairness among the destinations. This paper focuses on the group synchronization control.

There are few papers which address the group synchronization issue for haptic media [5]. In [5], the authors enhance the *synchronization maestro scheme* [3], which they previously proposed for voice and video. In the scheme, the *synchronization maestro* gathers the information about the output timing of haptic MUs from each client, and it determines the *reference output timing* and transmits the information about the reference output timing to all the clients. Each client gradually adjusts its output timing to the reference output timing. In [5], by carrying out an experiment in which two clients manipulate a CG object collaboratively with haptic interface devices, the authors try to demonstrate the effectiveness of the group synchronization control objectively. They deal with two methods depending on which client's output timing is selected as the reference output timing (*Methods 1* and *2*). Method 1 selects the later output timing, and Method 2 the earlier. As a result, they show that Method 2 is better than Method 1; this result is different from the result shown in [4], where Method 1 outperforms Method 2 for voice and video. This is because haptic media have severer requirements for the interactivity than voice and video. However, they do not sufficiently clarify how Method 2 is superior to a scheme (referred to as *No group-sync* in this paper) which does not perform the group synchronization control in Method 2; the difference in the quality of haptic media output between Method 2 and No group-sync is not large objectively [5].

Which method is better than the other may depend on the type of work. This paper handles only collaborative work. We also need to deal with competitive work (e.g., networked games). This is for further study.

To investigate the effectiveness of the group synchronization control in collaborative work in further detail, we need to carry out subjective assessment of haptic media output quality in a systematic way. However, to the best of the authors' knowledge, there are no papers that address the effects of the group synchronization control on the haptic media output quality subjectively.

In subjective assessment, MOS (mean opinion score) [6] is often used as a quality measure. However, it is more difficult to obtain MOS for the quality of collaborative work using haptic media than for the voice or video quality. This is because the collaborative work using haptic media is more complicated; that is, the quality is related to both visual and tactile sensations. Also, since MOS is an ordinal scale, it is not always appropriate to quantitative discussions [7]. In this paper, we investigate the relations between subjective and objective assessment results by the principal component analysis and multiple regression analysis. From the relations, we can clarify which objective quality measures are more important than the others. The clarification is important since systematic subjective assessment requires a number of human resources and it is time-consuming.

We can solve the problems of MOS by using an interval scale [7] obtained by the pair comparison method [8], [9] and Thurstone's law of comparative judgment [10]. In the interval scale, the size of the difference between numbers measured, as well as their ordinal relation, has meaning [7].

This paper carries out subjective assessment of haptic media output quality in collaborative work under the group synchronization control. We obtain an interval scale in the subjective assessment. By making a quality comparison between Method 2 and No group-sync, the paper demonstrates the effectiveness of Method 2. It also clarifies the relations between subjective and objective assessment results.

The remainder of the paper is organized as follows. Section 2 describes a system model for haptic media. Section 3 explains the group synchronization control scheme. Section 4 illustrates the experimental system and the assessment method, and the experimental results are presented in Section 5. Section 6 concludes the paper.

2. System Model

We suppose a situation in which N ($N \geq 2$) clients manipulate CG objects collaboratively by using haptic interface devices in a networked 3-D virtual space (see Fig. 1). Each client has the PHANToM DESKTOP [11] as a haptic interface device. Since the client performs haptic simulation by repeating the servo loop at a rate of 1 kHz [12], it inputs/outputs a stream of haptic MUs at the rate; that is, an MU is input/output every millisecond. Each MU contains the identification (ID) number of the client, the positional information of the cursor of the PHANToM, and the sequence number of the servo loop, which we use instead of the timestamp of the MU. MUs input at each client are transmitted to a single server.

The server carries out causality (i.e., ordinal relation in this paper) control [13] over received MUs. The causality control is required to maintain the temporal order of manipulation events. For the control, each haptic MU has a time limit which is equal to the generation time of the MU plus Δ milliseconds. If the MU is received by the server before the time limit, it is held in the buffer by the time limit, and it arranges them according to their timestamps (i.e., the sequence numbers). Then, the server calculates the positions of CG objects every millisecond by using the information about the position of the cursor of the PHANToM included in the MU. Otherwise, the MU is immediately used for the calculation.

The server judges whether the PHANToM cursor touches each CG object. Then, the server calculates the positions of CG objects by using a spring-damper model [12] and multicasts the positional information as an MU to all the clients. The MU also includes the positional information of the cursors at all the clients.

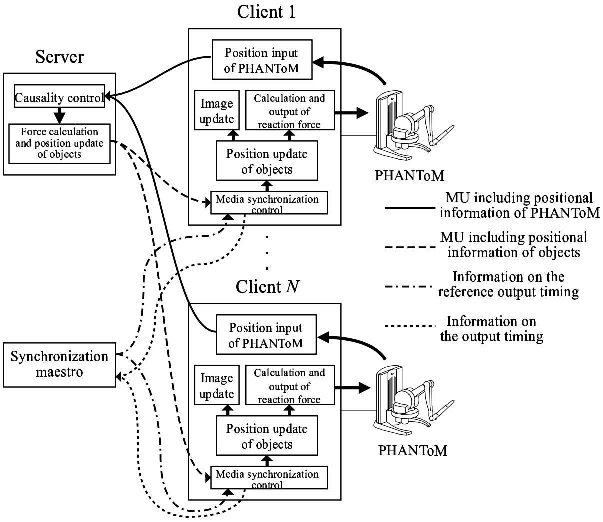

Fig. 1. A system model.

When each client receives the MU, it updates the positions of CG objects and calculates the reaction force applied to the user by using GHOST (General Haptic Open Software Toolkit) [12]. The rendering rate of the virtual space is 30 Hz at the client.

In order to adjust the output timing of haptic MUs among all the clients, we enhance the *virtual-time rendering* (*VTR*) algorithm [14] which employs the synchronization maestro scheme (see Section 3). The scheme uses the synchronization maestro as shown in Fig. 1. The synchronization maestro gathers the information about the output timing of haptic MUs from each client, and it determines the reference output timing and multicasts the information about the reference output timing to all the clients. Each client gradually adjusts its output timing to the reference output timing.

Figure 1 also shows what kinds of functions the server and clients have. As shown in this figure, the media synchronization control is carried out at each client, and the server performs the causality control.

3. Group Synchronization Control Scheme

For group synchronization, as described earlier, we enhance the VTR algorithm which employs the synchronization maestro scheme [5]. The reason why we enhance the algorithm is that we make use of the servo loop of 1 kHz instead of the timer as described earlier. That is, the time is discrete in milliseconds in this paper. Note that an MU should be output every millisecond and the time resolution is 1 ms here. Therefore, we cannot exert the *shortening of output duration* or the *virtual-time contraction* [15], which is employed in the VTR algorithm; the shortening of output duration and the virtual-time contraction bring discarding MUs.

In order to explain the group synchronization control, let us focus on a client. We first define the *ideal target output time* [16] x_n of the n-th MU ($n = 1, 2, \cdots$) as the time at which the MU should be output in the case where there is no network delay jitter. Let T_n, A_n, and D_n denote the generation time, arrival time, and output time, respectively, of the n-th MU. It should be noted that the values of these variables are integers represented in milliseconds.

The ideal target output time x_n is calculated as follows:

$$x_1 = T_1 + \delta, \tag{1}$$

$$x_n = x_1 + (T_n - T_1) \quad (n \geq 2), \tag{2}$$

where δ denotes the *target delay time* [13], which is defined as the time from the moment an MU is generated until the instant the MU should be output, and $\delta \leq \Delta_{\mathrm{al}}$. We employ the *maximum allowable delay* Δ_{al} [16] in order to preserve the interactivity of haptic media.

We cannot always output each MU at its ideal target output time since there exists network delay jitter. Therefore, we next introduce the *target output time* [14] t_n of the n-th MU, which is calculated by adding some amount of time (called the *total slide time* [16]) to the ideal target output time.

Let us define the *slide time* [16] of the n-th MU, which is denoted by ΔS_n, as the difference between the *modified target output time* [14] t_n^* and the original target output time t_n. We also define the total slide time S_n as follows:

$$S_0 = 0, \tag{3}$$

$$S_n = S_{n-1} + \Delta S_n \quad (n \geq 1), \tag{4}$$

where $\Delta S_1 = 0$. Then, t_n and t_n^* are expressed by

$$t_1 = x_1, \tag{5}$$

$$t_n = x_n + S_{n-1} \quad (n \geq 2), \tag{6}$$

$$t_n^* = t_n + \Delta S_n \quad (n \geq 1). \tag{7}$$

When the client receives the first MU, it determines the output time D_1 of the MU as follows: $D_1 = \max(t_1, A_1)$. Then, it inquires of the synchronization maestro whether the target output time should be modified or not, by sending the information about the output timing to the maestro. The purpose is to adjust the output timing of the succeeding MUs among all the clients. In this paper, we represent the output timing in terms of the total slide time. Therefore, the client sends a recommended value of the total slide time, which is referred to as the *recommended total slide time* [13] in this paper, to the maestro.

After the beginning of the output, when the client receives a constant number of consecutive MUs each of which has arrived earlier (or later) than its target output time, it notifies the maestro of the recommended total slide time if it has not transmitted any information to the maestro for those MUs at all. The recommended total slide time is different from the total slide time in that the latter is the accumulation of the slide times, while the former is employed for inquiry about the modification of the target output time in advance. The amount by which the target output time should be modified is called the *recommended slide time* [13] here. Let us denote the recommended total slide time and recommended slide time for the n-th MU by s_n and Δs_n, respectively. These times are given by

$$s_1 = \Delta s_1 = D_1 - x_1, \tag{8}$$

$$s_n = S_{n-1} + \Delta s_n \quad (n \geq 2). \tag{9}$$

We will explain how to obtain the value of Δs_n ($n \geq 2$) later in this section.

In addition, the client notifies the synchronization maestro of the total slide time S_n whenever the target output time is modified [14] at the n-th MU (that is, in the case of the *virtual-time expansion* [15]).

When the synchronization maestro receives the total slide time or the recommended total slide time from each client, it determines the reference value S of the total slide time as the reference output timing. Then, the maestro multicasts the information about S to all the clients at regular intervals (every 5 seconds in our experiment in Section 4) [13].

The client gradually adjusts its own total slide time to the reference one S when it receives the information about S. Until the client receives the information about S for the first time, it sets the initial value of S to $S_1 (= 0)$. For the adjustment, it compares S_{n-1} with S at the n-th MU. The control in the case of $S = S_{n-1}$ is the same as that in [13], while we enhance the control in the other case for haptic media. The reason why we enhance the control is as follows. If we change the total slide time to be adjusted to the reference one whenever the client receives an MU, the output quality of haptic media may deteriorate seriously. This is because the output duration of each MU is 1 ms and we output only one MU every millisecond; therefore, the increase and decrease of the total slide time (i.e., the virtual-time expansion and contraction) bring pausing and skipping MUs, respectively [17].

First, let us describe the control in the case of $S = S_{n-1}$. Next, we explain the control when $S > S_{n-1}$ and then that when $S < S_{n-1}$.

(a) Case of $S = S_{n-1}$

In this case, if $t_n \geq A_n$, the client sets the scheduled output time d_n of the n-th MU as follows: $d_n = t_n$

(in this paper, since the server multicasts a single haptic media stream to each client, we do not need to perform inter-stream synchronization control. Thus, the output time of the n-th MU is set to $D_n = d_n$). Otherwise, it sets $d_n = A_n$. If the MU arrives more than T_{h2} milliseconds later than its target output time (that is, if $A_n - t_n > T_{h2}$)[†] , we set the slide time as follows: $\Delta S_n = \min(r_1, T_n + \Delta_{\rm al} - t_n)$. In this equation, r_1 ($r_1 \geq 1$ ms) is the maximum value of the slide time in the case where the total slide time is increased under the intra-stream synchronization control, and the smaller value between the two is selected so that the modified target output time does not exceed the generation time T_n of the MU plus $\Delta_{\rm al}$.

Also, let us assume that when the client receives the n-th MU, it observes that $N_{\rm c}$ ($N_{\rm c} \geq 1$) consecutive MUs each have arrived later than their target output times. We further assume that for all the $N_{\rm c}$ MUs the client has sent information about neither the total slide time nor the recommended total slide time to the maestro. Then, the client sets $\Delta s_n = \min(r_2, T_n + \Delta_{\rm al} - t_n)$ and notifies the maestro of the recommended total slide time s_n, where r_2 ($r_2 \geq 1$ ms) is the maximum value of the recommended slide time for increment of the recommended total slide time. On the other hand, when the client observes that $N_{\rm d}$ ($N_{\rm d} \geq 1$) successive MUs each have arrived earlier than their target output times, it sets $\Delta s_n = -\min(r_3, S_{n-1})$ so that the modified target output time does not become less than the ideal target output time, where r_3 ($r_3 \geq 1$ ms) is the maximum absolute value of the recommended slide time for decrement of the recommended total slide time. The client also transmits the information about the value of s_n to the maestro.

(b) Case of $S > S_{n-1}$

When $S > S_{n-1}$, the client sets $\Delta S_n = \min(r_4, S - S_{n-1})$ so as to adjust its total slide time to the reference one (i.e., the virtual-time expansion), where r_4 ($r_4 \geq 1$ ms) is the maximum value of the slide time by which the total slide time is increased under the group synchronization control [13]. However, as described earlier, if we change the total slide time to be adjusted to the reference one whenever the client receives an MU, the output quality of haptic media may deteriorate seriously. Therefore, we adjust the total slide time every $N_{\rm e}$ MUs for each of which the total slide time is larger than the reference one. In this case, if $t_n^* \geq A_n$, the client sets $d_n = t_n^*$; otherwise, it sets $d_n = A_n$.

(c) Case of $S < S_{n-1}$

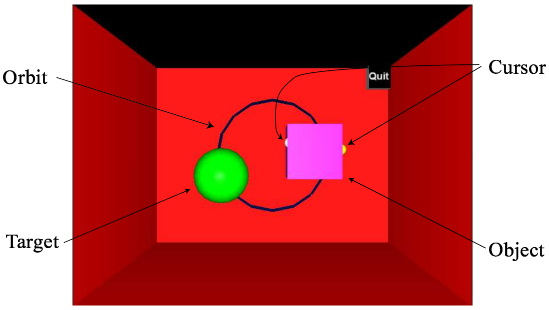

Fig. 2. A displayed image of the virtual space.

When $S < S_{n-1}$, the client sets $\Delta S_n = -\min(r_5, S_{n-1} - S)$ every $N_{\rm f}$ MUs for each of which the total slide time is smaller than the reference one as in case (b), where r_5 ($r_5 \geq 1$ ms) is the maximum absolute value of the slide time by which the total slide time is decreased for group synchronization [13]; that is, the virtual-time contraction occurs. The client determines d_n in the same way as in case (b).

We have a possibility that $d_n \leq D_m$ ($m < n$) in the case of the virtual-time contraction, where m is the sequence number of the last output MU. In this case, we skip the n-th MU.

4. Experimental System

We have carried out an experiment in which two clients ($N = 2$) move a rigid cube as a CG object by putting the cube between the two cursors of the PHANToMs in a networked 3-D virtual space (height: 89.7 mm, width: 129.7 mm, depth: 89.7 mm) (see Fig. 2). The cursor of each PHANToM moves in the space when the client manipulates the stylus of the PHANToM with the user's hand. The two clients lift and move the cube collaboratively so that the cube contains a target object (a sphere in Fig. 2), which revolves along a circular orbit at a constant velocity (it takes 10 seconds to revolve once). Each side of the cube is a quarter of the virtual space's height, and the radius of the sphere is half of the cube's side. The target and the orbit do not collide with the cube or the cursors.

4.1 System Configuration

As shown in Fig. 3, the experimental system consists of the server (CPU: Pentium4 processor at 2.26 GHz, OS: FreeBSD 4.7), client 1 (CPU: Xeon processor at 2.00 GHz, OS: Windows2000, graphic board: 3Dlabs Wildcat II), client 2 (CPU: Pentium4 processor at 2.26 GHz, OS: Windows2000, graphic board: 3Dlabs OXYGEN VX1), and four PCs (PC1 through PC4). They are connected to an Ethernet switching hub and two Ethernet shared hubs (10BASE-T). For simplicity, client 1 has a function of the synchronization maestro.

[†] This means that the virtual-time expansion occurs. Note that T_{h2} is a threshold value which we use so as to judge whether the target output time should be delayed or not [14].

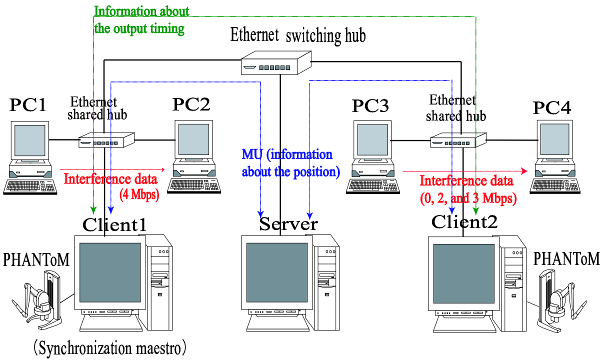

Fig. 3. Configuration of the experimental system.

The size of an MU from the server to each client is 61 bytes, and that in the opposite direction is 33 bytes (see Section 2 for the difference in the MU size). MUs and the information about the output timing for the group synchronization control are transmitted by UDP. The size of the information from the synchronization maestro to each client is 3 bytes, and that from each client to the synchronization maestro is 5 bytes (the difference of 2 bytes corresponds to the number of bytes representing the client's ID).

In order to generate traffic flows of interference, PC1 (PC3) sends fixed-size data messages of 1472 bytes each to PC2 (PC4) at exponentially distributed intervals (see Fig. 3). For transmission of interference data, we also use the UDP protocol. The switching hub is employed so that the traffic flow of interference in one of the shared hubs does not affect the other.

As described earlier, we deal with Method 2 and No group-sync. In No group-sync, each client exerts only the intra-stream synchronization control, which is also carried out in Method 2. The server performs the same causality control in Method 2 and No group-sync.

The values of the parameters and thresholds in the proposed scheme were determined by a preliminary experiment as follows[†] : $\delta = 10$ ms, $\Delta_{\mathrm{al}} = 30$ ms, $T_{\mathrm{h2}} = 20$ ms, $r_1 = 5$ ms, $r_2 = r_3 = 3$ ms, $r_4 = r_5 = 1$ ms, $N_{\mathrm{c}} = N_{\mathrm{d}} = 1000$, and $N_{\mathrm{e}} = N_{\mathrm{f}} = 20$. The value of J_{max} in No group-sync was set to 10 ms ($= \delta$). Also, we set the buffering time Δ of the causality control at the server to 5 ms. Parameter values which are related to the virtual space and the spring-damper model were set to the same as those in [17].

4.2 Assessment Method

For subjective assessment, we adopt the pair comparison method, in which each subject judges which is better for each pair of stimuli. The method gives us an ordinal scale, from which we can calculate an interval scale by using Thurstone's law of comparative judgment [18]. The interval scale is referred to as the *psychological scale* in this paper as in [7] and [18]. The scale is more appropriate to statistical analyses such as the multiple regression analysis than the ordinal scale.

In Fig. 3, we set the data load (i.e., the average number of interference data bits transmitted in a second) at PC1 to 4 Mbps, and we select the data load at PC3 from among 0, 2, and 3 Mbps.

The number of subjects is 30. Their ages are between 19 and 24. Each subject used client 1, and one of the authors always did client 2. The work was done for 30 seconds from 5 seconds after the beginning of each stimulus; the subjects lifted and moved the cube from the floor to the target within the 5 seconds. The stimuli consist of a combination of the two schemes (Method 2 and No group-sync) and the three data loads (i.e., 0, 2, and 3 Mbps). Table 1 shows the pairs of stimuli, which are denoted by the cross symbols, employed in the experiment. The blanks in the table denote pairs of stimuli which were not employed since we found that which stimulus was better than the other stimulus in terms of the subjective quality of haptic media output was clear in a preliminary experiment; the purpose is to reduce the burden on each subject [19]. We provided each subject with stimuli randomly. The total assessment time per subject was about 30 minutes.

For objective assessment, we have measured the quality in each test of the subjective assessment in terms of the following measures:

- *Average distance between the cube and the target* (d): This measure is defined as the mean distance between the center of the cube and that of the target object. The measure is related to the accuracy of the work.
- *Coefficient of variation of velocity* (C_{velocity}): The coefficient of variation is the standard deviation divided by the mean. The coefficient of variation of velocity denotes the smoothness of movement of the cube.
- *Average MU delay* (D): The average MU delay is the average time in milliseconds from the moment an MU is generated until the instant the MU is output. This measure represents the interactivity.
- *Average MU rate* (R): The average MU rate is defined as the average number of MUs output in a second.
- *Coefficient of variation of output interval* (C_{output}): This measure denotes the smoothness of MU output.
- *Average reaction force* (f): The average reaction force is the mean of the reaction force applied to each subject through the PHANToM.
- *Coefficient of variation of reaction force* (C_{force}): This measure denotes the smoothness of the reac-

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[†] The optimum selection of the values is for further study.

Table 1
Pairs of stimuli employed in the experiment.

Scheme		No group-sync			Method 2		
	Data load (Mbps)	3	2	0	3	2	0
Method 2	0		×	×		×	
	2	×	×	×	×		
	3	×	×				
No group-sync	0		×				
	2	×					
	3						

tion force.

- *Mean square error of group synchronization* (E_{group}): This measure is the mean square of the difference between the output time of each MU at client 1 and that of the MU at client 2. As for group synchronization, how large time difference between the two clients is allowable is not clear; this is for further study.

5. Experimental Results

In this section, we make a quality comparison between Method 2 and No group-sync subjectively and objectively. We also investigate the relations between subjective and objective assessment results.

5.1 Subjective Assessment Results

We show the psychological scale as a function of the data load at PC3 in Fig. 4, where closed symbols denote the values of the psychological scale obtained by experiment.

In Fig. 4, we see that the psychological scale of Method 2 is higher than that of No group-sync in the whole range of the data load considered here. Therefore, Method 2 makes users manipulate the object more easily than No group-sync. This is because the interactivity of haptic media is important; since Method 2 selects the earlier output timing, we can keep the interactivity higher in Method 2 than in No group-sync.

We also confirm in Fig. 4 that as the data load becomes heavier, the psychological scales of Method 2 and No group-sync decrease. Especially, when the data load exceeds around 2 Mbps, the psychological scales largely decrease.

5.2 Objective Assessment Results

For simplicity, we here show only the average distance between the cube and the target, the coefficient of variation of output interval, and the mean square error of group synchronization versus the data load at PC3 in Figs. 5 through 7, respectively. In the figures, we plot the 95 % confidence intervals of the quality measures. However, when the interval is smaller than the size of the corresponding symbol representing the experimental result, we do not show it in the figures.

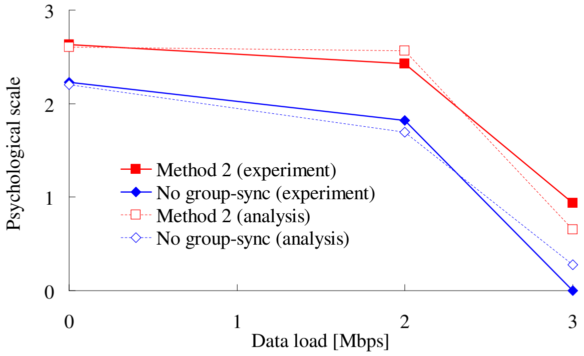

Fig. 4. Psychological scale versus data load.

In Fig. 5, we observe that the average distance of Method 2 is somewhat smaller than that of No group-sync in the whole range of the data load considered here. This is because Method 2 can preserve the interactivity higher than No group-sync as described in Subsection 5.1.

Figure 6 reveals that when the data load is lighter than around 2 Mbps, Method 2 has larger coefficients of variation of output interval than No group-sync. The reason is as follows. The data load in the sub-network (i.e., the Ethernet shared hub) to which client 1 is connected is 4 Mbps and heavier than that in the sub-network to which client 2 is connected. As the data load becomes heavier, the group synchronization control increases the frequency of modifications of the target output time. In Fig. 6, we also note that as the data load increases, the coefficient of variation of Method 2 decreases. The reason is that the data load in the sub-network to which client 2 is connected approaches that in the sub-network to which client 1 is connected; that is, in this case, the target output time is rarely changed at client 1 by the group synchronization control. We further notice in the figure that the coefficient of variation of No group-sync hardly depends on the data load. This is because the data load in the sub-network to which client 2 is connected does not affect client 1 in No group-sync.

From Fig. 7, we find that Method 2 has smaller mean square errors of group synchronization than No group-sync. This is the effect of the group synchronization control. Thus, we can say that Method 2 attains higher quality of group synchronization than No group-sync.

5.3 Relations between Subjective and Objective Assessment Results

By using the principal component analysis and multiple regression analysis, we have examined the relations between the subjective and objective assessment results. First, we extracted the principal components from the objective quality measures defined in Subsection 5.2 by the principal component analysis. As a result, since the

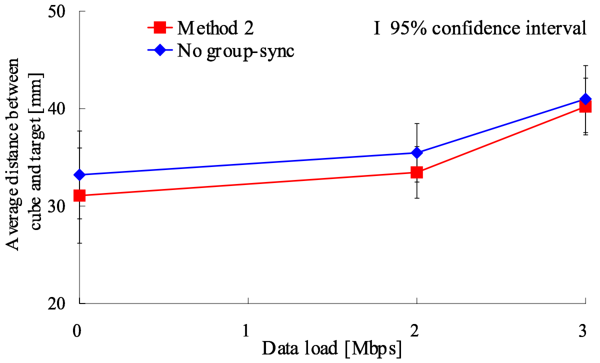

Fig. 5. Average distance between the cube and the target versus data load.

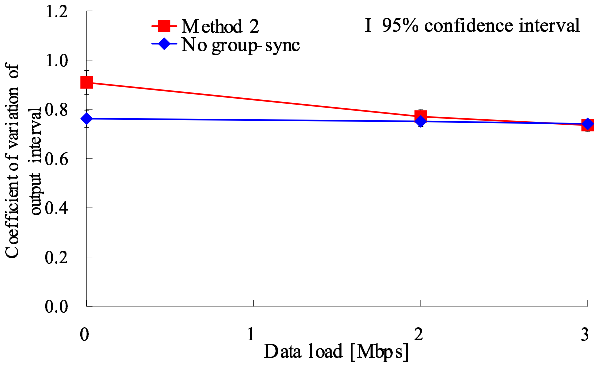

Fig. 6. Coefficient of variation of output interval versus data load.

cumulative contribution rate for the first three principal components was 97.8 % (see Fig. 8), we decided to use the three; that is, the first three principal components can present 97.8 % of information involved by the eight objective quality measures. In Table 2, we show the principal component loading, which represents the correlation between each objective quality measure and the principal components.

Next, we picked out one objective quality measure with the strongest correlation with each principal component from among the eight measures. We adopted the three objective quality measures (highlighted in boldface type in Table 2) as the predictor variables in the multiple regressive analysis. Then, we have obtained

$$\hat{S} = 16.771 - 0.309d - 5.021C_{\text{output}} - 0.002E_{\text{group}}, \quad (10)$$

where $\hat{S}$ is an estimated value of the psychological scale. The contribution rate adjusted for degrees of freedom is 0.908.

Figure 4 also plots the estimated value of the psychological scale (denoted by open symbols) versus the data load. In the figure, we confirm that agreement between the experimental value and the estimated value of the

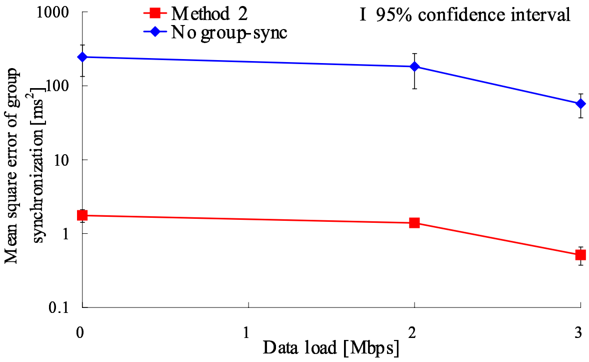

Fig. 7. Mean square error of group synchronization versus data load.

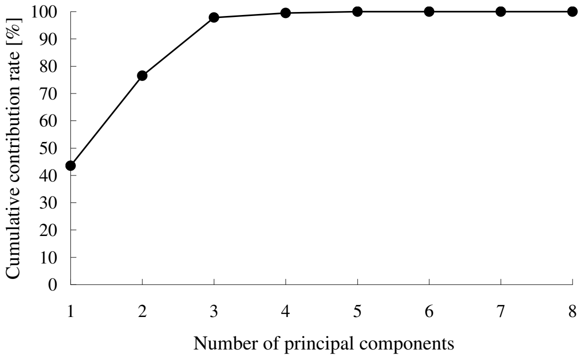

Fig. 8. Cumulative contribution rate versus the number of the principal components.

psychological scale is good. Therefore, we can roughly predict the psychological scale from the three objective quality measures in the experiment.

6. Conclusions

This paper subjectively assessed the haptic media output quality in collaborative work under group synchronization control by experiment. We also made a quality comparison between Method 2, which selects the earlier output timing as the reference output timing, and No group-sync, which does not carries out the control. We further investigated the relations between subjective and objective assessment results.

As a result, we saw that Method 2 is superior to No group-sync. We also found that the psychological scale can roughly be predicted from the following objective quality measures in the experiment: the average distance between the cube and the target, the coefficient of variation of output interval, and the mean square error of group synchronization control.

As the next step of our research, we plan to handle competitive work (e.g., networked games) and the case in which the number of clients is more than two.

Table 2

Principal component loading.

Objective quality measure	Principal component 1	2	3
$\boldsymbol{d}$	**0.923**	−0.380	0.047
C_{velocity}	−0.571	0.813	0.067
D	0.521	−0.572	0.577
R	−0.799	0.561	0.161
$\boldsymbol{C}_{\textbf{output}}$	−0.401	**0.818**	−0.398
f	0.580	−0.608	0.494
C_{force}	0.911	−0.384	−0.137
$\boldsymbol{E}_{\textbf{group}}$	−0.255	−0.044	**0.960**

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