Collaborative Work between Heterogeneous Haptic Interface Devices: Influence of Network Latency

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Abstract

By subjective and objective assessment, this paper investigates the influence of network latency on collaborative work between haptic interface devices which have different specifications from each other. In the collaborative work, two users lift and move an object by holding the object between two cursors of their haptic interface devices in a virtual space. As heterogeneous haptic interface devices, we employ PHANToM Desktop, PHANToM Omni, SPIDAR-G AHS, and Falcon. We also investigate the relations between subjective and objective assessment results.

1. Introduction

In networked haptic environments, users can touch and move objects by manipulating haptic interface devices [1]. Making use of the haptic interface devices, we can largely improve the efficiency of collaborative work such as remote surgery simulation and remote design. However, network latency deteriorates the efficiency of the collaborative work.

On the other hand, a variety of haptic interface devices have been developed so far. Since the haptic interface devices have different specifications such as shape, position resolution, and exertable force from each other [2], the devices have different operability from each other. Also, the influence of network latency on the operability of the devices is different from device to device. We need to realize collaborative work between heterogenous haptic interface devices, which have different specifications from each other. However, the quantitative relationships of the operability among the heterogeneous haptic interface devices in the collaborative work have not been clarified. It is necessary to investigate the influence of network latency on the collaborative work.

In this paper, we deal with collaborative work between heterogeneous haptic interface devices. In the collaborative work, two users lift and move a virtual object by holding the object between the two cursors (i.e., positions which the two users try to touch or are touching with their haptic interface devices). We employ PHANToM Desktop [3] (just called Desktop here), PHANToM Omni [3] (called Omni), SPIDAR-G AHS [4] (called SPIDAR), and Falcon [5] as the heterogeneous haptic interface devices. By subjective and objective assessment, we investigate the influence of network latency on the collaborative work.

The rest of this paper is organized as follows. Section 2 explains the collaborative work. Section 3 describes a system model of the work. Section 4 explains the method of experiment. We present experimental results in Section 5. Section 6 concludes the paper.

2. Collaborative Work

Each of two users operates a haptic interface device, and the two users move a rigid cube (the length of each side is 25 mm) as an object collaboratively by holding the cube between the two cursors of the devices in a 3-D virtual space surrounded by walls, a floor, and a ceiling (see Fig. 1). The width of the 3-D virtual space is set to 75 mm, the hight is 75 mm, and the depth is 70 mm so that the cursors of all the devices can reach the whole area in the virtual space.

The gravitational acceleration in the virtual space is assumed to be 2.0 m/s^2. If the object is not pushed from both sides strongly to some extent, it drops on the floor. The cursor of each haptic interface device moves in the virtual space when a user manipulates the stylus or grip of the device with his/her hand. The two users lift and move the cube collaboratively so that the cube contains a target (a sphere in Fig. 1) which revolves along a circular orbit at a constant velocity. The orbit is a circle with a radius of 25 mm. The plane on which the orbit exists is perpendicular to the *z*-*x* plane and forms an angle of 45 degrees with the *x*-*y* plane. We do not carry out collision detection among the target, the orbit, and the object or cursors.

3. System Model

A system model of the collaborative work is shown in Fig. 2. The system model is based on a client-server model which consists of a single server and two clients (clients 1 and 2). As a haptic interface device, we employ Desktop, Omni, or Falcon at client 1, and we use Desktop, Omni, SPIDAR, or Falcon at client 2.

When the server receives media units (MUs), each of which is the information unit for intra-stream synchronization, from the two clients, it calculates the position of the

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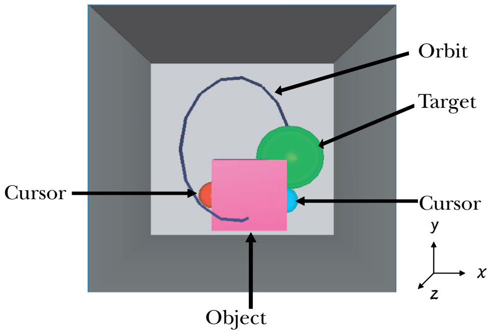

Figure 1. 3-D virtual space.

object based on the spring-damper model [6]. Then, it transmits the positional information of the object and cursor as an MU to the two clients. When each client receives an MU, the client updates the position of the object after carrying out intra-stream synchronization control and calculates the reaction force applied to a user of the client. We employ Skipping [7] for the intra-stream synchronization control at the clients. Skipping outputs MUs on receiving the MUs.

When the haptic interface device at a client is Desktop, Omni, or Falcon, the client performs haptic simulation by repeating the servo loop at a rate of 1 kHz [5], [6]. And it inputs/outputs a stream of 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 partner device, and the sequence number of the servo loop, which we use instead of the timestamp of the MU [7].

When the haptic interface device at a client is SPIDAR, the client carries out haptic simulation at 1 kHz by using a timer and inputs/outputs a stream of MUs in the same way as the other haptic interface devices.

4. Method of Experiment

4.1. Experimental System

As shown in Fig. 3, the experimental system consists of a single server, two clients, a switching hub, and a network emulator (NIST Net [8]). The two clients are connected to NIST Net via the switching hub by Ethernet cables (100BASE-T). The server is also connected to NIST Net via an Ethernet cable. NIST Net generates a constant additional delay for each MU transmitted from the server to the two clients.

4.2. Performance Measures

In subjective assessment, each subject was asked to base his/her judgment about the operability of his/her haptic interface device in the collaborative work in terms of wording used to define the subjective scale (see Table 1). Each subject gave a score from 1 through 5 to each test to obtain the *mean opinion score (MOS)* [9]. The number of subjects (men and women) whose ages are between 21 and 25 is twenty.

In the experiment, two subjects simultaneously manipulate haptic interface devices at clients 1 and 2. We investigate the influence of the constant additional delay, which is changed from 0 ms to 60 ms at intervals of 10 ms, on the operability of the devices in the collaborative work. We select the constant additional delay in random order for each subject. The measurement time of each test is 30 seconds.

Table 1. Five-grade quality scale.

Score	Description
5	Excellent
4	Good
3	Fair
2	Poor
1	Bad

The objective assessment is carried out at the same time as the subjective assessment. We employ the *average distance between cube and target* [7] as a performance measure of the objective assessment. The average distance between cube and target is defined as the mean distance between the centers of them. This measure is related to the accuracy of the collaborative work.

5. Experimental Results

We show the MOS values as a function of the constant additional delay in Figs. 4 and 5, where we also display the 95% confidence intervals. Figure 4 shows the MOS values in the case where two subjects use the same type of haptic interface devices at the two clients. Figure 5 shows the MOS values in the case where two subjects employ different types of haptic interface devices. When a subject at client 1 uses Falcon and a subject at client 2 employs Omni, for example, the MOS value of the subject at client 1 is shown as “Falcon-Omni” in the figures; the MOS value of the subject at client 2 is shown as “Omni-Falcon.” Since the MOS values of the subject at client 2 were almost the same as those at client 1, we do not show the MOS values at client 2 in this paper.

From Figs. 4 and 5, we find that the MOS values of all the combinations of haptic interface devices become smaller as the constant additional delay increases. We also notice that the MOS values are smaller than two when the constant additional delay is larger than around 40 ms.

In Fig. 4, we see that when the constant additional delay is 0 ms and 60 ms, the MOS values are almost the same among Desktop-Desktop, Omni-Omni, and Falcon-Falcon. When the constant additional delay is larger than about 0 ms and smaller than around 60 ms, the MOS values of Desktop-Desktop and Omni-Omni are higher than that of Falcon-Falcon.

In Fig. 5, we observe that the MOS value of Falcon-SPIDAR is the worst when the constant additional delay is smaller than about 50 ms. The reason is that the operability of SPIDAR is more difficult than that of the other haptic interface devices, and when the constant additional delay is large, the operability of Falcon is worse than that of Desktop and Omni. Figure 5 also reveals that when the constant additional delay is between around 10 ms and about 40 ms, Omni-Desktop has the largest MOS value.

From Figs. 4 and 5, we find that when the constant additional delay is larger than about 0 ms and smaller than

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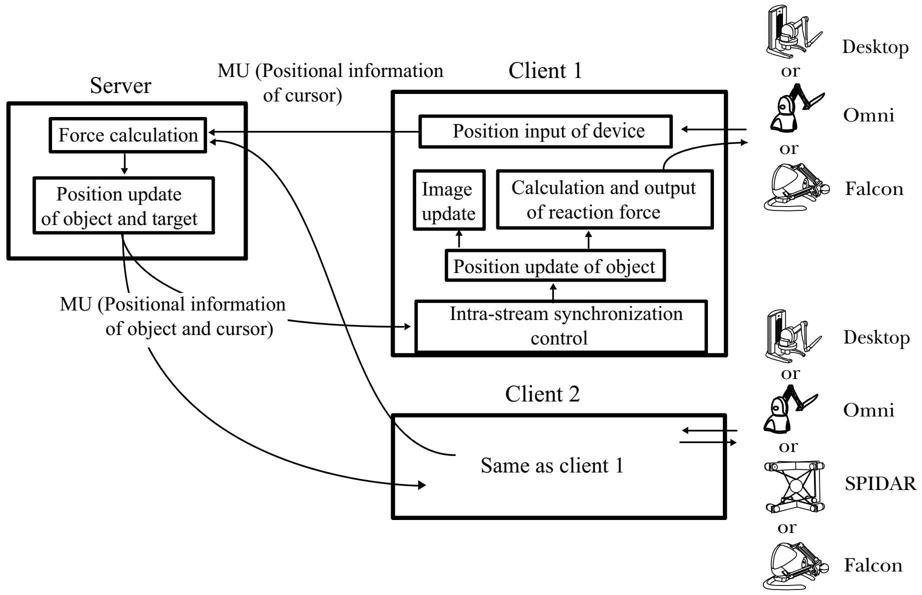

Figure 2. System model.

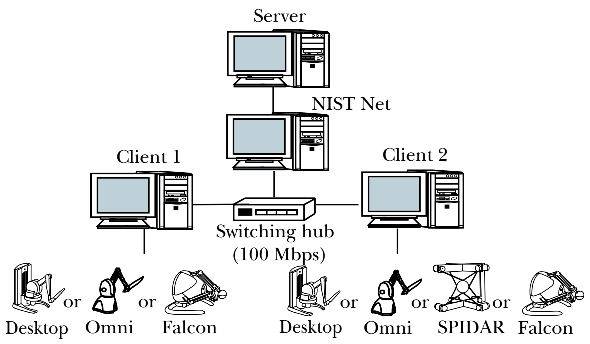

Figure 3. Configuration of experimental system.

around 50 ms, the MOS values of Falcon-SPIDAR and Falcon-Falcon are worse than those of the other combinations; the MOS values of Desktop-Desktop, Omni-Omni, and Omni-Desktop are larger than those of the other combinations. In Figs. 4 and 5, we also notice that the MOS values of Falcon-Desktop and Falcon-Omni are larger than that of Falcon-Falcon in the same area of the constant additional delay. This is because Falcon is assisted by Desktop or Omni, which has good operability, in the collaborative work.

In addition, we show the average distance between cube and target versus the constant additional delay in Figs. 6 and 7. We find in the figures that the average distance between cube and target is closely related to the MOS value. In order to investigate the relations between the distance and the MOS value, we have carried out multiple regression analysis. As a result, we have obtained the following equation:

$$V_{\mathrm{mos}} = 6.94 - 0.183d$$

where V_{mos} is an estimated value of the MOS, and d is the average distance between cube and target. The contribution rate adjusted for degrees of freedom is 0.876. Therefore, we can estimate the MOS value with high accuracy from the average distance between cube and target.

6. Conclusions

This paper dealt with collaborative work between heterogeneous haptic interface devices (Desktop, Omni, SPIDAR, and Falcon). We investigated the influence of network latency on the collaborative work by subjective and objective assessment. We found that the MOS values of all the combinations of haptic interface devices become smaller as the constant additional delay increases. When the constant additional delay is larger than about 40 ms, it is very difficult to do the collaborative work. We also saw that when the constant additional delay is larger than about 0 ms and smaller than around 50 ms, the MOS values of Desktop-Desktop, Omni-Omni, and Omni-Desktop are larger than those of the other combinations; the MOS values of Falcon-SPIDAR and Falcon-Falcon are worse than those of the other combinations.

As the next step of our research, we plan to investigate the influence of network latency between heterogeneous haptic interface devices on different types of work from the work in this paper. We also need to use other kinds of haptic interface devices.

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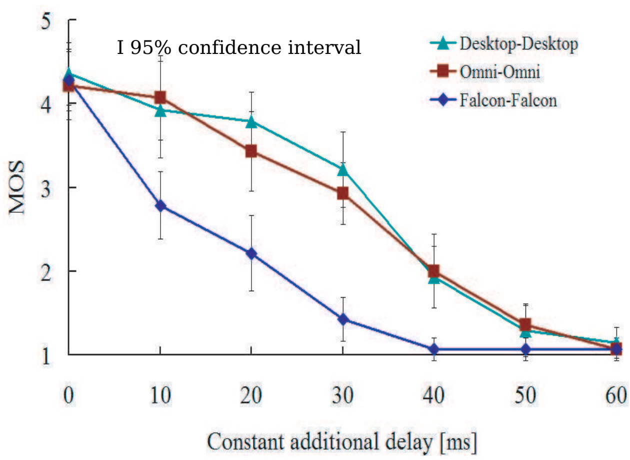

Figure 4. MOS in case where two subjects use same type of haptic interface devices.

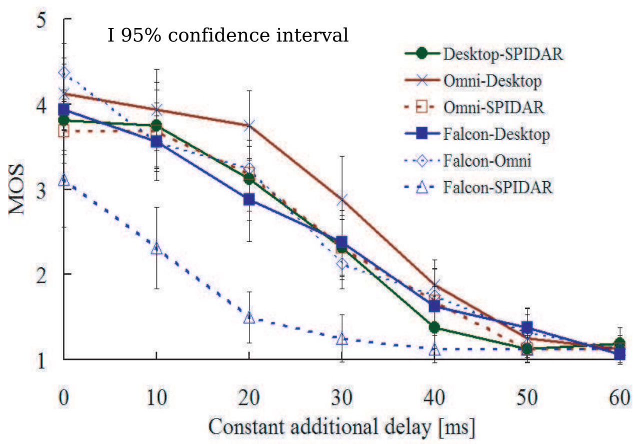

Figure 5. MOS in case where two subjects use different types of haptic interface devices.

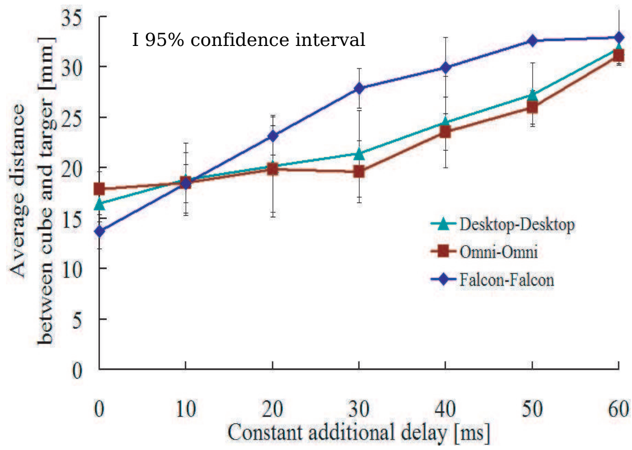

Figure 6. Average distance between cube and target in case where two subjects use same type of haptic interface devices.

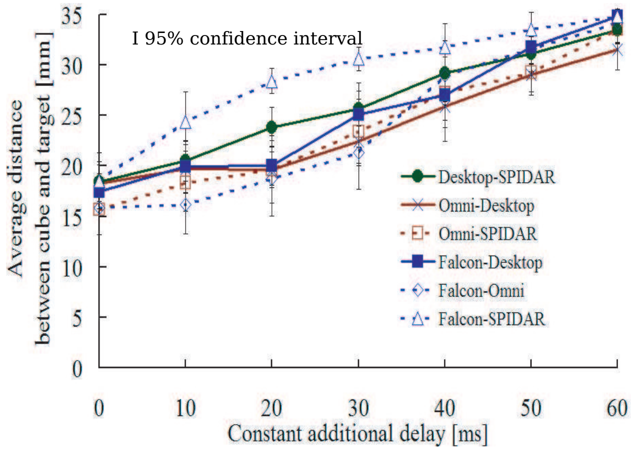

Figure 7. Average distance between cube and target in case where two subjects use different types of haptic interface devices.

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