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QoS Control and QoE Assessment in Multi-Sensory Communications with Haptics

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SUMMARY Multi-sensory communications with haptics attract a number of researchers in recent years. To provide services of the communications with high realistic sensations, the researchers focus on the quality of service (QoS) control, which keeps as high quality as possible, and the quality of experience (QoE) assessment, which is carried out to investigate the influence on user perception and to verify the effectiveness of QoS control. In this paper, we report the present status of studies on multi-sensory communications with haptics. Then, we divide applications of the communications into applications in virtual environments and those in real environments, and we mainly describe collaborative work and competitive work in each of the virtual and real environments. We also explain QoS control which is applied to the applications and QoE assessment carried out in them. Furthermore, we discuss the future directions of studies on multi-sensory communications.
key words: *multi-sensory communications, haptics, application, QoS control, QoE assessment*

1. Introduction

In recent years, haptic and olfactory sensations as well as auditory and visual sensations are becoming utilizable over a network [1], [2]. Among these sensations, in particular, haptic sensation attracts attention as the third media that rank next to auditory and visual sensations. By using haptic sensation, a user can feel as if the user were touching an object at a remote location, and he/she can also perceive the reaction force and the gravity of the object by lifting it. Since we can get high realistic sensations by using haptic sensation together with other sensations such as auditory, visual, and olfactory sensations [3], it is expected to improve the quality of life. Thus, this paper deals with multi-sensory communications with haptics.

Multi-sensory communications with haptics are utilized for various applications such as remote education, remote surgery, networked games, and distributed museums [4]–[60]. However, when multiple media streams are transmitted over a network which does not guarantee the quality of service (QoS) [61], the network delay, delay jitter, and packet loss may seriously degrade the output quality of the streams. To solve this problem, we need to carry out QoS control, and there are many studies on QoS control for the communications.

In order to perform QoS control efficiently, we need to investigate the influences of network delay, delay jitter, and packet loss on human perception. Also, it is necessary to verify the effects of QoS control. Since services of multi-sensory communications are provided for end-users, it is important to carry out the assessment of the quality of experience (QoE) [62], and several QoE assessment methods have been used so far.

In this paper, we report the current status of studies on multi-sensory communications with haptics. In what follows, Sect. 2 explains what haptics is. Section 3 presents applications utilizing the communications. Then, we divide the applications into applications in virtual environments and those in real environments, and we mainly describe collaborative work and competitive work in each of the virtual and real environments. In Sects. 4 and 5, we explain QoS control and QoE assessment, respectively, for the applications. Finally, we discuss the future directions of studies on multi-sensory communications in Sect. 6, and Sect. 7 concludes the paper.

2. Haptics

Haptic sensation is input and output via a haptic interface device [63]. Currently, there are a number of commercially-available haptic interface devices [64]–[72]. In this section, we present a brief description of the devices and then explain haptic media.

2.1 Haptic Interface Devices

Haptic sensation is generally different from auditory and visual sensations in that the input and output of haptic sensation are done via a single device. In order to display the haptic sense to a user naturally, the frequency of input/output for the haptic interface device is 1 kHz or more [73]. That is, the haptic interface device has a high update rate.

Haptic interface devices can be grouped into 1-DoF (Degree-of-Freedom), 2-DoF, and 3-DoF or more by the number of DoF [63]. A user can move the interaction point of a 1-DoF device in a straight line, and the user can move that of a 2-DoF device on a plane surface like a mouse of PC. He/she can move the interaction point(s) of a 3-DoF or more device in a 3-D space. As the number of DoF increases, the device becomes more complex (that is, the number of haptic sensors and the amount of transmitted data increase), and manipulation of the device becomes more natural and more intuitive [74]. Therefore, we handle 3-DoF or more

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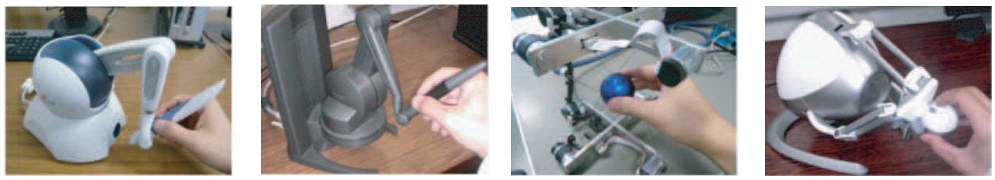


(a) PHANToM Omni (b) PHANToM Desktop (c) SPIDAR-G AHS (d) Falcon

Fig. 1 Examples of haptic interface devices.

devices in this paper. As the 3-DoF or more devices, we have PHANToM Omni (see Fig. 1(a)), PHANToM Desktop (Fig. 1(b)), PHANToM Premium 1.5 [64], SPIDAR-G AHS (Fig. 1(c)) [65], Falcon (Fig. 1(d)) [66], Omega [67], Virtuose [68], HapticMaster [71], CyberGrasp, CyberForce [72], and so on. These devices excluding the last two ones are mainly manipulated by a single interaction point (called the cursor here), which a user operates to touch an object.

2.2 Haptic Media

Haptic media are transmitted as media units [75] (MUs, which are information units for media synchronization), each of which includes the position information of cursor or information about reaction force, timestamp which represents the input time, and sequence number. There are at least two control schemes for haptic media transmission [18], [55]. One is the position-position control scheme [76], and the other is the position-force control scheme [77].

In the position-position control scheme, a terminal (say terminal 1) transmits MUs which include the position information of its haptic interface device to another terminal (say terminal 2). When terminal 2 receives the MUs, it calculates the reaction force applied to its haptic interface device or an object based on the received position information and the position information of the device. Then, terminal 2 returns MUs which include the position information of its device or the object. Terminal 1 also calculates the reaction force applied to its device or an object based on the received position information and the position information of the device.

The main difference between the position-force and position-position control schemes is in that terminal 2 of the position-force control scheme returns MUs including the information about the reaction force. Terminal 1 calculates the reaction force applied to its haptic interface device by multiplying the force received from terminal 2 by the gain coefficient.

3. Applications

We group applications using multi-sensory communications with haptics into those in virtual and real environments, and mainly explain collaborative work and competitive work in each of the virtual and real environments.

3.1 Virtual Environments

Here we present collaborative work, competitive work, and other work. All the types of work described here are done in 3-D virtual spaces created by Computer Graphics (CG). That is, CG is mainly used for visual sensation in this case.

3.1.1 Collaborative Work

(1) Collaborative movement of objects [4]–[20]

In these types of work, multiple users collaboratively move an object(s) from one place to another place by using haptic interface devices. For example, in [11] and [12], two users pile up building blocks as objects collaboratively to build a dollhouse by manipulating PHANToM Omnis (see Fig. 2(a)). In [17] and [18], Sung et al. deal with a basketball game in which two users lift and move a basketball collaboratively to a basket. In [20], two users move a rigid cube collaboratively while having a conversation by putting the cube between two cursors of PHANToM Desktops so that the cube contains a target which revolves along a circular orbit at a constant velocity.

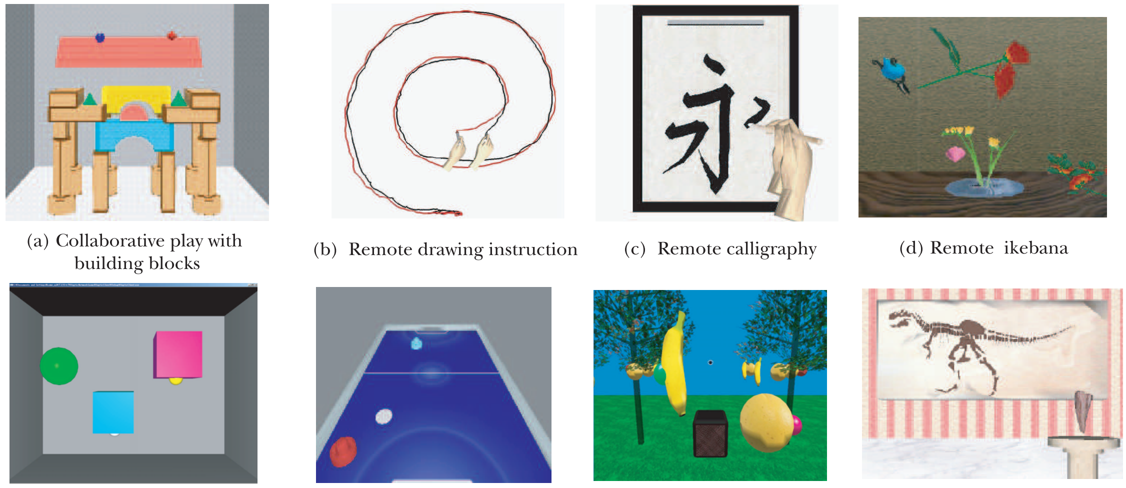
(2) Remote education

In [12] and [21] through [24], a teacher can instruct a student at a remote place how to write characters or draw figures with a brush while feeling the sense of force interactively by using PHANToM Desktops or Omnis (see Fig. 2(b) for remote drawing instruction in [12], [23], and [24]). In remote calligraphy [24]–[26], a teacher can instruct a student at a remote place how to write characters (see Fig. 2(c)) by using PHANToM Omnis, and the student can feel as if his/her calligraphy brush were held and navigated by the teacher. In [26], a teacher can also instruct multiple students by multicast communications.

In remote ikebana [27], [28], a teacher can teach a student how to arrange flowers (see Fig. 2(d)). By manipulating PHANToM Omni, the teacher or student can hold a flower, adjust the length of the held flower's stem with a pair of scissors, and impale the flower on a flower pinholder. The teacher is also able to change the arrangement designed by the student. The teacher or student can further perceive the fragrance of a flower by using an olfactory display SyP@D2 [78] when the flower approaches his/her viewpoint.

(3) Remote surgery

Remote surgery training is dealt with in [29] through [32].



(a) Collaborative play with building blocks (b) Remote drawing instruction (c) Remote calligraphy (d) Remote ikebana

(e) Competitive elimination of target (f) Networked air hockey (g) Networked fruit harvesting (h) Distributed museum

Fig. 2 Displayed images of virtual space.

For instance, in [30], a teacher can instruct a student how to perform an operation (e.g., a surgery for cholecystectomy) by using PHANToM Premiums 1.5. In [32], a teacher guides a student how to go through a bifurcation of artery to the correct direction by employing PHANToM Omnis.

3.1.2 Competitive Work

As examples of competitive work, we describe networked fighting games.

(1) Competitive elimination of target

In [33] and [34], each of two users lifts and moves his/her own cube from underneath to eliminate a target sphere (see Fig. 2(e)) by using PHANToM Desktop or PHANToM Omni, and the users compete on the number of eliminated targets. When the target is contained by either of the two users' objects, it disappears and then appears at a randomly-selected position.

(2) Networked ball games

Morris et al. handle Haptic Battle Pong [35], in which each of two users employs a haptic interface device (PHANToM Omni, PHANToM Desktop, or PHANToM Premium 1.5) in order to operate a paddle and to hit a ball with the paddle toward the opponent's court. If the ball falls down in a user's court, the user loses one point. A networked air hockey game (see Fig. 2(f)) is dealt with in [36] through [38], where each of two users manipulates PHANToM Omni to operate his/her mallet and hits a puck toward his/her opponent's goal.

(3) Networked fruit harvesting game

A networked fruit harvesting game (see Fig. 2(g)) is handled in [39], where the smell of fruit is selected randomly. A harvester picks fruit and moves the fruit toward his/her viewpoint by using PHANToM Omni to perceive the fragrance of the fruit output by SyP@D2. The harvester judges whether the fragrance is in agreement with appearance or not. If the fragrance is agreement with the appearance, he/she harvests the fruit. Otherwise, he/she discards the fruit. An impeder makes the harvester perceive the fragrance of another fruit by picking the fruit and moving it toward the harvester's viewpoint to interfere with the judgment of the harvester.

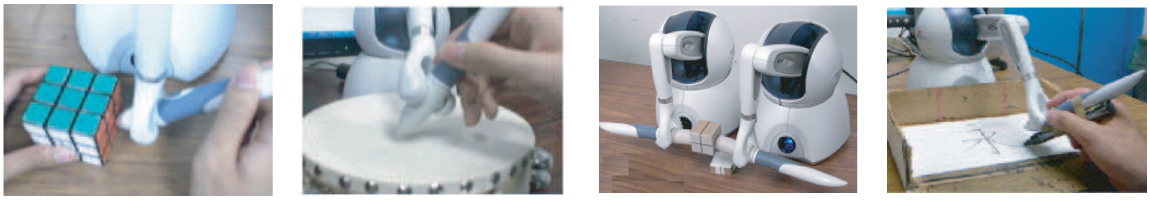
In addition to the above collaborative and competitive work, there are studies which deal with competitive work with collaboration [40], [41]. In [40] and [41], four users are divided into two groups each of which consists of two users. In each group, two users employ PHANToM Omnis to lift and move a cube collaboratively. The two groups are asked to play the competitive elimination of target (see (1) in this subsection).

3.1.3 Other Work

As other types of work, we here introduce distributed exhibitions [42]–[45] and home shopping [46].

(1) Distributed exhibitions

Distributed exhibitions are dealt with in [42] through [45]. In a distributed museum (see Fig. 2(h)) [42]–[44], each user can touch exhibits (an Egyptian mummy sculpture, a dinosaur skeleton and one of its fangs, and a painting of sunflowers by Vincent Van Gogh) by using PHANToM Desktop, and the user can get guidance services with voice and video which are activated by touching a specific and interesting portion of an exhibit. He/she can also lift and move an exhibit, and he/she can feel the weight of the exhibit when he/she lifts it. Nishino et al. [45] handle Heritage Alive, which reproduces the ancient Gyeongju area in Silla King-



(a) Remote touch (b) Remote music performance (c) Collaborative movement of object (d) Remote penmanship

(e) Networked ensemble (f) Networked penatly shootout game (g) Remote writing/drawing

Fig. 3 Displayed images of video.

dong. Each user can touch and lift objects by manipulating PHANToM Omni.

(2) Home shopping

In home shopping [46], each user can touch a CG product by using PHANToM Premium 1.5 while hearing a voice guidance explaining how to manipulate the product.

3.2 Real Environments

Collaborative work, competitive work, and other work in real environments are presented as in Sect. 3.1. We employ video for visual sensation in this case.

3.2.1 Collaborative Work

(1) Remote control [47]–[53]

In [47] and [49], a user controls PHANToM Omni at a remote location to touch an real object at the remote location with PHANToM Omni at a local location while watching normal video or stereoscopic video, and the user perceives the texture of the object when he/she touches it (see Fig. 3(a)). In [50] and [51], sound is added to the system in [47], and the sound is generated by hitting a tambourine with PHANToM Omni (see Fig. 3(b)).

The two systems in [47] are employed independently in [53], where the authors fix moving parts of the styli of two PHANToM Omnis at a remote place which are irrelevant to the positional information of the PHANToM Omni cursor. The purpose of fixing the moving parts is to hold the PHANToM Omni styli at the remote place without using hands. One or two users manipulate the PHANToM Omnis at a local location to control the PHANToM Omnis at the remote place, and lift and move a real object (a cube which is made of cardboard) and put the object on a stand at the remote place (see Fig. 3(c)).

(2) Remote education

In remote penmanship [54], a teacher instructs a student how to write characters or draw figures (see Fig. 3(d)) while watching video by using the remote control system in [47]. A whiteboard marker is attached to the stylus of the student's PHANToM Omni, and the teacher can control the student's PHANToM Omni by using his/her PHANToM Omni. In [54] and [55], a whiteboard marker is attached to the stylus of the teacher's PHANToM Omni as well as that of the student's PHANToM Omni, and the teacher instructs a student how to write characters or draw figures while both teacher and student are watching videos.

(3) Networked ensemble

In [56], a user controls a remote PHANToM Omni by using a local PHANToM Omni to hit a tambourine according to the sound of a keyboard harmonica played by another user at the remote place (see Fig. 3(e)). The moving parts of the stylus of the remote PHANToM Omni are fixed as in [53] (see (1) in this subsection).

3.2.2 Competitive Work

There are few researches on competitive work in real environments. A networked penalty shootout game (see Fig. 3(f)) is handled in [57]. In the game, two users play as one keeper and one shooter. Each user employs PHANToM Omni at a local terminal to control PHANToM Omni at a remote terminal to play penalty shootout in a remote field while watching video of the field. The shooter shoots a marble which is set at a penalty mark toward a goal several times, and the keeper tries to block shots so as to prevent the shots from entering the goal.

3.2.3 Other Work

As examples of other work, we have remote writing/drawing

[58], [59] in which the remote control system in [47] is used and video streaming [46], [60]. In the remote writing/drawing, a user employs a local PHANToM Omni to control a remote PHANToM Omni for writing characters or drawing figures (see Fig 3(g)). A whiteboard marker or a writing brush is attached to the stylus of the remote PHANToM Omni, the moving parts of the stylus of which are fixed.

In [46] and [60], each user can get haptic sensation passively by using a haptic interface device while watching a streaming video. For example, in [60], while watching a boxing video, each user can feel the reaction force in his/her left hand by wearing Haptic Jacket [79], [80] when a boxer hits the other one by his/her left fist.

4. QoS Control

There are various types of QoS control such as traffic management and control, error control, media synchronization control, causality control, and consistency control for multi-sensory communications with haptics. In this section, we explain each control.

4.1 Traffic Management and Control

By managing data transmitted over a network, traffic management and control alleviate the network delay and delay jitter, and decrease the frequency of packet loss [14], [16], [36], [81]–[83].

In [16], haptic media are transmitted in a DiffServ network and a best effort network which are compared for work like the collaborative movement of objects in Sect. 3.1.1 (1). As a result, they demonstrate that the DiffServ network is superior to the best effort network.

Eid et al. [81] propose an adaptive and intelligent multiplexer for multiple media transmission according to the application requirements and network delay. The multiplexer guarantees the allocation of minimum bandwidth that is sufficient to keep the interactivity of haptic interface device high.

The adaptive dead reckoning, which is applied to the networked air hockey game in Sect. 3.1.2 (2) [36], dynamically changes a threshold value of dead reckoning [84] according to the network delay. The dead reckoning consists of prediction and convergence [14], [85], [86]. In the prediction, the current position of an object (or the cursor of a haptic interface device) is predicted by using the positional information of the object (or the cursor) included in transmitted (or received) MUs. In the convergence, when an MU is received (or transmitted), we correct the position gradually. At the transmitting terminal, if the prediction error (i.e., the difference between the predicted current position and the actual current position) is larger than the threshold value, the information about the actual current position is transmitted as an MU. The receiving terminal carries out the same prediction as the transmitting terminal, and it also performs the same convergence after receiving an MU.

In [82], the packet transmission rate of haptic media is dynamically changed according to the network load. Lee et al. [14] propose network-adaptive haptic event aggregation control for work like the collaborative movement of object in Sect. 3.1.1 (1). The control dynamically changes the packetization interval according to the network load. Lee and Kim [83] control the transmission rate based on the number of MUs in the receiving buffer.

4.2 Error Control

Error control recovers from packet error, packet loss, duplication, and order error [6], [7], [16], [24]–[26]. In [16], Yap and Marshall employ interleaving to spread bursts of errors for haptic transmission. The interleaving converts burst errors into random errors. After the interleaving, they also use error correction codes. Under prediction control in [6], [7], and [25], each lost position is predicted by using the positions in the last output two MUs for the collaborative movement of object and the remote calligraphy in Sect. 3.1.1.

In [24] and [26], error control which is based on the degree of importance is proposed for the remote calligraphy in Sect. 3.1.1 (2). The control transmits important MUs twice which include the positional information in the case where the speed of the teacher's brush stroke is faster than a threshold value and in the case where the direction of the teacher's brush stroke is largely changed. Prediction is also employed for losses and late arrivals of MUs. The control is compared with Forward Error Correction (FEC) with XOR calculation, FEC with Reed-Solomon Coding, and so on to demonstrate its effectiveness.

4.3 Media Synchronization Control

Media synchronization control compensates for network delays and network delay jitter, and the control is grouped into intra-stream synchronization control, inter-stream synchronization control, and inter-destination (or group) synchronization control [87]. Intra-stream synchronization control is required for preservation of the timing relation between MUs in a single media stream. Inter-stream synchronization control is required for keeping the temporal relationship among media streams. Inter-destination synchronization control is necessary to output each MU simultaneously at different destinations.

4.3.1 Intra-Stream Synchronization Control

There are several types of intra-stream synchronization control such as Skipping [75], Buffering [75], Adaptive Buffer Control (ABC) [29], Queue Monitoring (QM) [86], Virtual-Time Rendering (VTR) [75], [88], and media adaptive buffering [52].

Skipping outputs MUs on receiving the MUs. Also, when the sequence number of a received MU is smaller than that of the last-output MU, Skipping discards the received MU. In Buffering, the first MU is output after exerting a constant-time buffering, and when an MU arrives late, the MU is output on receiving it. QM deletes the oldest MU in the receiving buffer if the value of counter (a counter is set for each MU in the buffer, and the counter is incremented by one whenever an MU is output) exceeds a threshold value, and then the value of counter is reset to zero. ABC dynamically extends the buffering time of MUs according to the network delay under the adaptive buffer approach, which determines the buffering time by observing the network delay, and the time adjustment mechanism, which determines the output time of each MU by adding the buffering time to the generation time. VTR has a virtual-time axis which can be contracted or expanded dynamically according to the network delay jitter. MUs are output along the virtual-time axis. These five types of control (Skipping, Buffering, ABC, QM, and VTR) are compared for the remote drawing instruction and remote calligraphy in Sect. 3.1.1 (2), and work in which a user lifts and moves an object (a rigid cube) from underneath to contain a target as in the collaborative movement of objects (see Sect. 3.1.1 (1)) [89]. As a result, it is illustrated that VTR is the most effective.

Isomura et al. [52] propose the media adaptive buffering, which sets the proper playout buffering time depending on the media type. In [83], Lee and Kim propose adaptive control which dynamically changes the buffering time according to the maximum and minimum network delays.

4.3.2 Inter-Stream Synchronization Control

VTR and the control in [20] are two examples of inter-stream synchronization control. They define one media stream as the master stream and the others as slave streams.

VTR carries out only the intra-stream synchronization control for the master stream. For the slave streams, it exerts the inter-stream synchronization control in [88] after carrying out the intra-stream synchronization control. The output time of an MU is determined by using the target output time [88] determined under the intra-stream synchronization control for the MU and the scheduled output time [88] determined from the output time of the corresponding master MU.

Under the inter-stream synchronization control in [20], if the synchronization error is outside the allowable range, in which users consider that the error is allowable, the error is reduced gradually until the error enters the imperceptible range, in which users cannot perceive the error.

4.3.3 Inter-Destination Synchronization Control

For inter-destination synchronization control, three schemes have been proposed. One is the master-slave destination scheme [87], another is the synchronization maestro scheme [90], and the other is the distributed control scheme [91]. Here we explain the last two schemes since they are used for applications in Sect. 3.

(1) Synchronization maestro scheme

In the synchronization maestro scheme, each terminal notifies the synchronization maestro of the information about its output timing. When the synchronization maestro receives the information about the output timing from each terminal, it determines the reference output timing [91] and multicasts the information about the reference output timing to all the terminals. Each terminal gradually adjusts its output timing to the reference output timing. This scheme is used for work like the collaborative movement of object in Sect. 3.1.1 (1) [9] and the competitive elimination of target [34] and the competitive work with collaboration [40] in Sect. 3.1.2.

(2) Distributed control scheme

The main difference between the distributed control scheme and the synchronization maestro scheme is in how to determine the reference output timing. In the distributed control scheme, each terminal notifies the other terminals of the information about its output timing. The terminal determines the reference output timing from among the notifications and gradually adjusts its output timing to the reference output timing. The scheme is employed for the competitive work with collaboration [41] in Sect. 3.1.2.

To improve the interactivity of the inter-destination synchronization control, the authors propose inter-destination synchronization control with prediction in [12]. The control outputs position information by predicting the future position later than the position included in the last-received MU by a fixed amount of time. It also advances the output time of position information at each local terminal by the same amount of time. It is applied to the synchronization maestro scheme and the distributed control scheme for the collaborative play with building blocks in Sect. 3.1.1 (1) and to the distributed control scheme for the remote drawing instruction in Sect. 3.1.1 (2).

4.4 Causality Control

In networked real-time games, it is necessary to keep the causal (i.e., temporal order) relationships among events. The Δ-causality control [92] and adaptive Δ-causality control [93] are typical examples of causality control.

In the Δ-causality control, each MU has a time limit which is equal to the generation time of the MU plus Δ seconds for preservation of the real-time property. If the MU is received after the time limit, it is discarded since it is considered useless. Otherwise, it is output at the time limit. The adaptive Δ-causality control dynamically changes the value of Δ in the Δ-causality control according to the network load. The control does not discard an MU received after the time limit and uses the MU for prediction. The control is employed together with the adaptive dead reckoning (see Sect. 4.1) for the networked air hockey game [36] in Sect. 3.1.2 (2). In [38], it is also used together with dynamic control of prediction time so as to keep both interactivity and media output quality high for the game.

4.5 Consistency Control

Consistency control maintains the state consistency among players in a networked game. A combined method of AtoZ (Allocated Topographical Zone) [94] and CDP (Count Down Protocol) [95] is employed for competition avoidance of management of a shared object (a puck) in the networked air hockey game (see Sect. 3.1.2 (2)) [37]. AtoZ is used to determine which terminal can access to the puck most quickly by taking account of the positions and velocities of the mallets. CDP is a protocol used when the puck exists in a field where the owner of the puck cannot be uniquely determined.

For work like the collaborative movement of objects in Sect. 3.1.1 (1), Cheong et al. [8] propose a feedback based synchronization controller to achieve the consistency. The controller compensates for the state error between terminals.

4.6 Other Control

As other QoS control, we have the adaptive control of reaction force [58], [59], [96], dynamic control of fragrance output timing [28], adaptive display control of exhibits [42], proactive file transfer control [44], and so on. We here explain the first two.

(1) Adaptive control of reaction force

As the network delay increases, the reaction force applied to a haptic interface device becomes larger; that is, more serious deterioration in output quality of haptic media occurs. In order to solve this problem, the adaptive control of reaction force is proposed for the remote writing/drawing (see Sect. 3.2.3) [58], [59] and work in which a user moves a cube as in the collaborative movement of objects (see Sect. 3.1.1 (1)) [96]. The control dynamically changes the elastic modulus used to calculate the reaction force so that the reaction force does not change largely owing to network delay variations.

(2) Dynamic control of fragrance output timing

In [28], the authors propose the dynamic control of output timing of fragrance in the remote ikebana (see Sect. 3.1.1 (2)). The control changes the output timing of fragrance dynamically according to the movement speed and direction of an object (i.e., a flower) which is a fragrance source.

5. QoE Assessment

For QoE assessment, we carry out subjective assessment and objective assessment [97].

5.1 Subjective Assessment

Subjective assessment obtains user opinions about QoE (for example, the operability of haptic interface device, prettiness of video, and smoothness of object moving). As subjective assessment methods, there are the rating scale method [98], SD (Semantic Differential) method [99], method of successive categories [100], pair comparison method [98], constant method [101], questionnaire survey [97], and so on.

Since we handle multiple media in multi-sensory communications, the QoE assessment is carried out multidimensionally. For example, the output quality of video, haptic media, and audio, and inter-stream synchronization quality between video and haptic media, overall quality, and so on are assessed at the same time in [49] through [52] and [56].

(1) Rating scale method

In the rating scale method, subjects are asked to make an assessment based on a category scale. There are two main categories: DCR (Degradation Category Rating) and ACR (Absolute Category Rating). A typical example of the rating scale method uses the five-grade scale, and subjects are asked to give a score from 1 to 5 for each stimulus. MOS (Mean Opinion Score) [102] is obtained by averaging scores given by multiple subjects. In the method, users are asked to assess, for example, the fairness [33], [37], [39], inter-stream synchronization quality [48]–[53], [56], and operability of haptic interface device [6], [11], [12], [14], [21]–[25], [36], [49]–[51], [53]–[57], [103], [104].

(2) SD method

The SD method is often used in psychological experiments. The method assesses a stimulus from various points of view with many pairs of polar terms such as “heavy - light,” “natural - artificial,” and “satisfied - unsatisfied.” For example, each subject is asked to give a score from 1 to 5 for each pair of polar terms. Isomura et al. [52] employ the method by using the terms classified into six classes: Video, haptic media, audio, inter-stream synchronization, interaction, and overall satisfaction.

(3) Method of successive categories

The method of successive categories obtains the interval scale by applying the law of categorical judgment [100] to measurement results gotten by the rating scale method and SD method. In order to confirm the goodness of fit for the obtained scale, it is necessary to conduct Mosteller’s test [105]. If the goodness of fit is confirmed, the interval scale can be used as the psychological scale [100]. In [52], Isomura et al. also calculate the psychological scale from assessment results of the SD method.

(4) Pair comparison method

In the pair comparison method, each subject judges which is better for each pair of stimuli [9]. It is easy for subjects to make a judgment, but there are a large number of comparisons.

(5) Constant method

The constant method is a type of psychophysical procedure that repeatedly uses the same set of stimuli throughout an experiment. In the method, stimuli are presented numerous times in random order. Ohnishi and Mochizuki [101] use the method to measure the difference threshold (DL), which is the smallest change in stimulation that a person can detect, and Weber fraction, which is the fraction given by the difference threshold divided by the standard intensity, and so on for the perception of elastic force generated by a haptic interface device.

(6) Questionnaire survey

This method surveys user opinions via questionnaires [4], [5], [27], [31], [43]. A questionnaire consists of a number of questions which should be relevant, meaningful, and easy to understand.

5.2 Objective Assessment

Objective assessment does not depend on user opinions, and the assessment can be carried out objectively. However, assessment results also depend on user skills, reflexes, and so on.

We use assessment measures such as work efficiency and winning rate in the objective assessment, and which measures are used depends on applications.

(1) Work efficiency

As work efficiency, we use the following rate [12], [24] for the remote drawing instruction in Sect. 3.1.1 (2), the average operation time [12], [14], [19] for the collaborative movement of objects in Sect. 3.1.1 (1), where the average distance between the object and target [9], [10], [20] is also used, and the average number of eliminated targets [106] for work in which a user lifts and moves an object (cube) to eliminate a target as in Sect. 3.1.2 (1).

(2) Winning rate

As the winning rate, the authors use the number of eliminated targets [34], [40], [41] for the competitive elimination of target and the competitive work with collaboration in Sect. 3.1.2 and the number of correct judgments [39] for the networked fruit harvesting game in Sect. 3.1.2 (3).

Also, the relations between objective and subjective assessment results are investigated in [12], [24], [33], and [39]. As a result, it is shown that the subjective assessment results can be estimated from the objective assessment results with a high degree of accuracy.

6. Discussions

As described earlier, there are many applications of multi-sensory communications with haptics in which visual, auditory, and/or olfactory sensations are handled together. However, to the best of the authors' knowledge, there is no application which handles gustation together with haptic sensation. Therefore, it is expected to achieve higher realistic sensations than the current applications by adding gustation. On the other hand, multi-view video [107] and free-viewpoint video [108] are studied recently. Since the multi-view video and free-viewpoint video can improve realistic sensations by changing the viewpoint of a user, it is also important to use these kinds of video in the communications. However, since how much each sensation contributes to realistic sensations has not been clarified sufficiently, the authors are currently investigating each contribution quantitatively.

Also, various types of QoS control have been proposed, and many types of QoS control are carried out independently of each other. In multi-sensory communications, we may carry out several types of QoS control together. If we perform them independently, QoE may seriously deteriorate owing to excessive or insufficient effects of the control [109]. Hence, it is necessary to perform the adaptive QoS control [109], which carries out different kinds of QoS control in an integrated manner. Furthermore, it is confirmed that there is the mutually-compensatory property among multiple media in [100] and [110]. Therefore, it is necessary to take the property into account when we study QoS control in the communications.

Furthermore, several QoE assessment methods have been used. Since subjective assessment of QoE is based on user opinions, the reliability of the assessment is low. This is because it is difficult for users to give appropriate scores and subjective assessment results are also affected by users' psychological factors [97]. On the other hand, objective assessment of QoE does not depend on user opinions, and its reliability is high. Therefore, it is necessary to establish objective assessment methods such as brain activity imaging (fMRI: functional magnetic resonance imaging, MEG: magnetoencephalogram, EEG: electroencephalogram, NIRS: near-infrared spectroscopy, etc.), data analysis methods (heartbeat, breathing, pupils-palpebration, electrodermal activity (GSR), and so on), and behavioral measurement (activity of eyes, hands, body, etc.) [111]. Such objective assessment methods should be ones which can estimate subjective assessment results from objective assessment results with a high degree of accuracy. It is also important to carry out QoS mapping [9], [24], [49]–[51], which estimates QoE (also called the user-level QoS) from QoS parameters at the application-level or lower levels with a high degree of accuracy.

7. Conclusions

In this paper, we reported the present status of studies on applications, QoS control, and QoE assessment in multi-sensory communications with haptics. As a result, we found that a number of useful applications have been developed so far. We expect that more and more such applications will be widely used in the near future. Also, various types of QoS control have been proposed. However, many types of QoS control are carried out independently of each other. When we carry out different kinds of QoS control at the same time, it is necessary to perform them in an integrated manner. Furthermore, there is an urgent need to establish reliable objective assessment methods of QoE.

In this paper, we made a survey of studies using commercially-available haptic interface devices mainly. As the next step of our research, we need to investigate studies using other haptic interface devices and industrial robots with haptic sensors. Also, we plan to improve the accuracy of work in real environments by using the industrial robots.

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References

[1] E. Steinbach, S. Hirche, M. Ernst, F. Brandi, R. Chaudhari, J. Kammerl, and I. Vittorias, "Haptic communications," Proc. IEEE, vol.100, no.4, pp.937–945, April 2012.
[2] T. Nakamoto, N. Cho, N. Nitikarn, B. Wyszynski, H. Takushima, and M. Kinoshita, "Experiment on teleolfaction using odor sensing system and olfactory display synchronous with visual information," Proc. ICAT, pp.85–92, Dec. 2008.
[3] T. Tanikawa and M. Hirose, "A study of multi-modal display system with visual feedback," Proc. ISUC, pp.285–292, Dec. 2008.
[4] J. Kim, H. Kim, B. Tay, M. Muniyandi, M. Srinivasan, J. Jordan, J. Mortensen, M. Oliveira, and M. Slater, "Transatlantic touch: A study of haptic collaboration over long distance," Presence, vol.13, no.3, pp.328–337, June 2004.
[5] G. Basdogan, C. Ho, and M.A. Srinivasan, "An experimental study on the role of touch in shared virtual environments," ACM Trans. Computer-Human Interaction, vol.7, no.4, pp.443–460, Dec. 2000.
[6] K. Hikichi, H. Morino, I. Fukuda, S. Matsumoto, Y. Yasuda, I. Arimoto, M. Iijima, and K. Sezaki, "Architecture of haptics communication system for adaptation to network environments," Proc. IEEE ICME, pp.563–566, Aug. 2001.
[7] A. Boukerche, S. Shirmohammadi, and A. Hossain, "A prediction algorithm for haptic collaboration," Proc. IEEE HAVE, Oct. 2005.
[8] J. Cheong, S. Niculescu, A. Annaswamy, and M.A. Srinivasan, "Motion synchronization in virtual environments with shared haptics and large time delays," Proc. World Haptics, pp.277–282, March 2005.
[9] H. Kaneoka and Y. Ishibashi, "Effects of group synchronization control over haptic media in collaborative work," Proc. ICAT, pp.138–145, Nov./Dec. 2004.
[10] A. Tatematsu and Y. Ishibashi, "Mapping workspaces to virtual space in work using heterogeneous haptic interface devices," IN-TECH, Advances in Haptics, Chapter 33, pp.621–636, April 2010.
[11] P. Huang, Y. Ishibashi, N. Fukushima, and S. Sugawara, "Collaborative haptic play with building blocks," Proc. ACM ACE, pp.277–280, Oct. 2009.
[12] P. Huang, Y. Ishibashi, N. Fukushima, and S. Sugawara, "QoE assessment of group synchronization control scheme with prediction in work using haptic media," International Journal of Communications, Network and System Sciences (IJCNS), vol.5, no.6, pp.321–331, June 2012.
[13] R. Iglesias, E. Prada, A. Uribe, A. Garcia-Alonso, S. Casado, and T. Gutierez, "Assembly simulation on collaborative haptic virtual environments," Proc. 15th International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision, pp.241–248, 2007.
[14] S. Lee, S. Moon, and J. Kim, "A network-adaptive transport scheme for haptic-based collaborative virtual environments," Proc. ACM NetGames, Oct. 2006.
[15] S. Son, S. Lee, and J. Kim, "A delay compensation scheme based on prediction for networked haptic collaborative system," Proc. SPIE Optics East, Multimedia Systems and Applications X, vol.6777, Sept. 2007.
[16] K. Yap and A. Marshall, "Investigating quality of service issues for distributed haptic virtual environments in IP networks," Proc. IEEE ICIE, pp.237–242, July 2010.
[17] M. Sung, Y. Yoo, K. Jun, N. Kim, and J. Chae, "Experiments for a collaborative haptic virtual reality," Proc. ICAT, pp.174–179, Nov./Dec. 2006.
[18] Y. Yoo, M. Sung, N. Kim and K. Jun, "An experimental study on the performance of haptic data transmission in networked haptic collaboration," Proc. ICAC, pp.657–662, Feb. 2007.
[19] H.A. Osman, M. Eid, and A.E. Saddik, "Evaluating ALPHAN: A communication protocol for haptic interaction," Proc. Haptics, pp.361–366, March 2008.
[20] Y. Ishibashi, T. Kanbara, and S. Tasaka, "Inter-stream synchronization between haptic media and voice in collaborative virtual environments," Proc. ACM Multimedia, pp.604–611, Oct. 2004.
[21] H. Nishino, S. Yamabiraki, Y. Kwon, Y. Okada, and K. Utsumiya, "A remote instruction system empowered by tightly shared haptic sensation," Proc. SPIE Optics East, Multimedia Systems and Applications X, vol.6777, Sept. 2007.
[22] K. Hikichi, Y. Yasuda, A. Fukuda, and K. Sezaki, "The effect of network delay on remote calligraphic teaching with haptic interfaces," Proc. ACM NetGames, Oct. 2006.
[23] T. Asano, Y. Ishibashi, and S. Kameyama, "Interactive haptic transmission for remote control systems," Proc. IEEE ICME, pp.2113–2116, July 2006.
[24] T. Fujiura, Y. Kurokawa, and Y. Ishibashi, "Application of communication schemes using error control based on importance to remote haptic instruction systems," Trans. VRSJ, vol.13, no.3, pp.401–408, Sept. 2008. (in Japanese)
[25] Y. Ishibashi and T. Asano, "Media synchronization control with prediction in a remote haptic calligraphy system," Proc. ACM ACE, pp.79–86, June 2007.
[26] Y. Ishibashi, Y. Kurokawa, and S. Sugawara, "Error control based on importance in a remote haptic calligraphy system," Proc. IEEE/ACM DS-RT, pp.269–274, Oct. 2008.
[27] P. Huang, Y. Ishibashi, N. Fukushima, and S. Sugawara, "Questionnaire survey of students and influence of smell space size in remote ikebana system using olfactory and haptic media," IEICE Technical Report, CQ2011-21, July 2011. (in Japanese)
[28] P. Huang, Y. Ishibashi, N. Fukushima, and S. Sugawara, "Effect of dynamic control of fragrance output timing in networked virtual environment," Proc. APCC, pp.104–109, Oct. 2012.
[29] O. Wongwirat and S. Ohara, "Haptic media synchronization for remote surgery through simulation," IEEE Multimedia, vol.13, no.3, pp.62–69, July 2006.

[30] C. Gunn, M. Hutchins, D. Stevenson, and M. Adcock, "Using collaborative haptics in remote surgical training," Proc. World Haptics, pp.481–482, March 2005.
[31] T. Kerwin, H. Shen, and D. Stredney, "Enhancing realism of wet surfaces in temporal bone surgical simulation," IEEE Trans. Vis. Comput. Graphics, vol.15, no.5, pp.747–758, Sept./Oct. 2009.
[32] D. Wang, L. Ni, M. Rossi, and K. Tuer, "Implementation issues for bilateral tele-mentoring applications," Proc. IEEE HAVE, pp.75–79, Oct. 2004.
[33] Y. Ishibashi and H. Kaneoka, "Fairness among game players in networked haptic environments: Influence of network latency," Proc. IEEE ICME, July 2005.
[34] Y. Ishibashi and H. Kaneoka, "Group synchronization for haptic media in a networked real-time game," IEICE Trans. Commun., vol.E89-B, no.2, pp.313–319, Feb. 2006.
[35] D. Morris, N. Hoshi, and K. Salisbury, "Haptic Battle Pong: High-degree-of-freedom haptics in a multiplayer gaming environment," Proc. Experimental Gameplay Workshop, Game Developers Conference, 2004.
[36] Y. Kusunose, Y. Ishibashi, N. Fukushima, and S. Sugawara, "QoE assessment in networked air hockey game with haptic media," Proc. ACM NetGames, Nov. 2010.
[37] Y. Kusunose, Y. Ishibashi, N. Fukushima, and S. Sugawara, "QoE comparison of competition avoidance methods for management of shared object in networked real-time game with haptic media," Proc. ICAT, Nov. 2011.
[38] Y. Hara, Y. Ishibashi, N. Fukushima, and S. Sugawara, "Adaptive delta-causality control scheme with dynamic control of prediction time in networked haptic game," Proc. ACM NetGames, Nov. 2012.
[39] Y. Ishibashi, S. Hoshino, Q. Zeng, N. Fukushima, and S. Sugawara, "QoE assessment of fairness between players in networked game with olfaction," Proc. ACM NetGames, Nov. 2012.
[40] T. Hashimoto and Y. Ishibashi, "Group synchronization control over haptic media in a networked real-time game with collaborative work," Proc. ACM NetGames, Oct. 2006.
[41] T. Hashimoto, Y. Ishibashi, and S. Sugawara, "Inter-destination synchronization control over haptic media in a P2P networked real-time game with collaborative work," IEICE Technical Report, CQ2007-25, July 2007. (in Japanese)
[42] T. Asano and Y. Ishibashi, "Adaptive display control of exhibits in a distributed haptic museum," Proc. IEEE HAVE'04, pp.19–23, Oct. 2004.
[43] T. Asano, Y. Ishibashi, S. Minezawa, and M. Fujimoto, "Surveys of exhibition planners and visitors about a distributed haptic museum," Proc. ACM ACE, pp.246–249, June 2005.
[44] T. Asano, M. Isamu, and Y. Ishibashi, "A proactive file transfer scheme in a distributed haptic museum," Proc. ACM ACE, June 2006.
[45] H. Nishino, S. Yamabiraki, Y. Kwon, Y. Okada, and K. Utsumiya, "A distributed virtual reality framework for Korea-Japan high-speed network testbed," Proc. IEEE AINA, April 2006.
[46] J. Cha, I. Oakley, Y. Ho, Y. Kim, and J. Ryu, "A framework for haptic broadcasting," IEEE Multimedia, vol.16, no.3, pp.16–27, July-Sept. 2009.
[47] S. Kameyama and Y. Ishibashi, "Dynamic video resolution control based on haptic media in haptic and visual communications," Proc. World Haptics, pp.280–285, March 2007.
[48] S. Kameyama and Y. Ishibashi, "Perception of synchronization errors in haptic and visual communications," Proc. SPIE Optics East, Multimedia Systems and Applications IX, vol.6391, no.8, Oct. 2006.
[49] A. Tatematsu, Y. Ishibashi, N. Fukushima, and S. Sugawara, "QoE assessment in tele-operation with 3D video and haptic media," Proc. IEEE ICME Workshop on Hot Topics in Multimedia, July 2011.
[50] A. Tatematsu, Y. Ishibashi, N. Fukushima, and S. Sugawara, "Influences of network latency and jitter in haptic media, sound and video transmission," J. Institute of Image Information and Television Engineers, vol.64, no.12, pp.873–1883, Dec. 2010. (in Japanese)
[51] K. Iwata, Y. Ishibashi, N. Fukushima, and S. Sugawara, "QoE assessment in haptic media, sound and video transmission: Effect of playout buffering control," ACM Computers in Entertainment, Special Issue on Advances in Computer Entertainment Technology, vol.8, no.2, pp.1–14, Dec. 2010.
[52] E. Isomura, S. Tasaka, and T. Nunome, "QoE enhancement in audiovisual and haptic interactive IP communications by media adaptive intra-stream synchronization," Proc. IEEE TENCON, pp.1085–1089, Nov. 2011.
[53] T. Fujimoto, Y. Ishibashi, and S. Sugawara, "Influences of inter-stream synchronization error on collaborative work in haptic and visual environments," Proc. Haptics, pp.113–119, March 2008.
[54] H. Mizuno, Y. Ishibashi, and S. Sugawara, "A comparison between transmission methods of sense of force in a remote haptic instruction system," Proc. IEEE ICME, pp.1202–1205, June/July 2009.
[55] J. Osada, Y. Ishibashi, N. Fukushima, and S. Sugawara, "QoE comparison of haptic control schemes in remote instruction system with haptic media, video, and voice," Proc. ITC-CSCC, July 2012.
[56] Q. Zeng, K. Iwata, Y. Ishibashi, N. Fukushima, and S. Sugawara, "Influence of network delay in networked ensemble with haptic media, sound, and video," National Convention of IPSJ, 3Y-5, March 2012. (in Japanese)
[57] T. Fujimoto, Y. Ishibashi, and S. Sugawara, "Networked penalty shootout with haptic media and video," Proc. ACM ACE, pp.76–82, Dec. 2008.
[58] Y. Ishibashi and H. Mizuno, "Switching of transmission of sense of force for remote haptic control systems," Proc. the 21st ITC Specialist Seminar on Multimedia Applications - Traffic, Performance and QoE, pp.1–6, March 2010.
[59] K. Matsunaga, Y. Ishibashi, N. Fukushima, and S. Sugawara, "Effect of adaptive reaction force control in remote control system with haptic media and video," Proc. ITC-CSCC, July 2012.
[60] M.A. Rahman, A. Alkhaldi, J. Cha, and A.E. Saddik, "Adding haptic feature to YouTube," Proc. ACM Multimedia, Oct. 2010.
[61] ITU-T Rec. I. 350, "General aspects of quality of service and network performance in digital networks, including ISDNs," March 1993.
[62] ITU-T Rec. P. 10/G. 100 Amendment 1, "New appendix I — Definition of quality of experience (QoE)," Jan. 2007.
[63] K. Salisbury, F. Conti, and F. Barbgli, "Haptic rendering: Introductory concepts," IEEE Comput. Graph. Appl., vol.24, no.2, pp.24–32, March 2004.
[64] SensAble, http://www.sensable.com/
[65] M. Sato, "Development of string-based force display: SPIDAR," Proc. VSMM, pp.1034–1039, Sept. 2002.
[66] Novint Technologies Inc., "Haptic device abstraction layer programmer's guide," Version 1. 1. 9 Beta, Sept. 2007.
[67] Force Dimension, http://www.forcedimension.com/
[68] F. Gosselin and A. Riwan, "Design of Virtuose 3D: A new haptic interface for teleoperation and virtual reality," Proc. ICAR, pp.205–212, Aug. 2001.
[69] Butterfly Haptics LLC, http://butterflyhaptics.com/
[70] Quarc Targets library, http://www.quarcservice.com/
[71] R.Q. Vanderlinde, P. Lammertse, E. Frederiksen, and B. Ruiter, "The HapticMaster, a new high-performance haptic interface," Proc. EuroHaptics, pp.1–5, 2002.
[72] CyberGlove Systems LLC, http://www.cyberglovesystems.com/
[73] M. Lin and K. Salisbury, "Haptic rendering: Beyond visual computing," IEEE Comput. Graph. Appl., vol.24, no.2, pp.22–23, March 2004.
[74] R. Weller and G. Zachmann, "User performance in complex bimanual haptic manipulation with 3 DoFs vs. 6 DoFs," Proc. IEEE

Haptics, March 2012.

[75] Y. Ishibashi, S. Tasaka, and T. Hasegawa, "The virtual-time rendering algorithm for haptic media synchronization in networked virtual environments," Proc. CQR, pp.213–217, May 2002.

[76] B. Khademian and K. Hashtrudi-Zaad, "Performance issues in collaborative haptic training," Proc. IEEE ICRA, pp.3257–3262, April 2007.

[77] B. Willaert, B. Corteville, D. Reynaerts, H. Brussel, and E. Poorten, "Bounded environment passivity of the classical position-force teleoperation controller," Proc. IEEE/RSJ IROS, Oct. 2009.

[78] Exhalia, http://www.exhalia.com/

[79] J. Cha, M. Eid, L. Rahal, and A.E. Saddik, "HugMe: An interpersonal haptic communication system," Proc. IEEE HAVE, pp.99–102, Oct. 2008.

[80] A.S.M.M. Rahman, S.A. Hossain, and A.E. Saddik, "Bridging the gap between virtual and real world by bringing an interpersonal haptic communication system in second life," Proc. IEEE ISM, pp.228–235, Dec. 2010.

[81] M. Eid, J. Cha, and A.E. Saddik, "An adaptive multiplexer for multi-modal data communication," Proc. IEEE HAVE, Nov. 2009.

[82] Y. Ishibashi, T. Kanbara, T. Hasegawa, and S. Tasaka, "Traffic control of haptic media in networked virtual environments," Proc. IEEE KMN, pp.11–16, July 2002.

[83] S. Lee and J. Kim, "Intra-media synchronization scheme for haptic interactions in distributed virtual environments," Proc. SPIE IT-COM Multimedia Systems and Applications VIII, vol.6015, Oct. 2005.

[84] S.K. Singhal and M. Zyda, "Networked virtual environments: Design and implementation," ACM Press, SIGGRAPH Series, Sept. 1999.

[85] T. Kanbara, Y. Ishibashi, and S. Tasaka, "Haptic media synchronization control with dead-reckoning in networked virtual environments," Proc. SCI, vol.3, pp.158–163, July 2004.

[86] K. Hikichi, H. Morino, I. Arimoto, K. Sezaki, and Y. Yasuda, "The evaluation of delay jitter for haptic collaboration over the Internet," Conf. Rec. IEEE GLOBECOM, Nov. 2002.

[87] Y. Ishibashi, A. Tsuji, and S. Tasaka, "A group synchronization mechanism for stored media in multicast communications," Proc. IEEE INFOCOM, pp.693–701, April 1997.

[88] Y. Ishibashi and S. Tasaka, "A synchronization mechanism for continuous media in multimedia communications," Proc. IEEE INFOCOM, pp.1010–1019, April 1995.

[89] T. Fujiura, S. Sun, T. Fujimoto, and Y. Ishibashi, "An output quality comparison of intra-stream synchronization algorithms in haptic media communications," IEICE Trans. Commun. (Japanese Edition), vol.J92-B, no.7, pp.1193–1206, July 2009.

[90] Y. Ishibashi and S. Tasaka, "A group synchronization mechanism for live media in multicast communications," Conf. Rec. IEEE GLOBECOM, pp.746–752, Nov. 1997.

[91] Y. Ishibashi and S. Tasaka, "A distributed control scheme for group synchronization in multicast communications," Proc. ISCOM, pp.317–323, Nov. 1999.

[92] R. Yavatkar, "MCP: A protocol for coordination and temporal synchronization in multimedia collaborative applications," Proc. ICDCS, pp.606–613, June 1992.

[93] Y. Ishibashi and S. Tasaka, "Causality and media synchronization control for networked multimedia games: Centralized versus distributed," Proc. ACM NetGames, pp.34–43, May 2003.

[94] Y. Kawano, D. Hanawa, and T. Yonekura, "An approach to the P2P type real-time network virtual ball-game with the mutual prediction protocol and AtoZ," Trans. VRSJ, vol.9, no.2, pp.141–150, June 2004. (in Japanese)

[95] Y. Kawano and T. Yonekura, "Realization of avoidance of the critical cases in P2P type virtual ball game by count down protocol," IEICE Trans. Inf. & Syst. (Japanese Edition), vol.J89-D, no.10, pp.2219–2228, Oct. 2006.

[96] M. Fujimoto and Y. Ishibashi, "Adaptive control of reaction force in haptic media communications," IEICE Trans. Commun. (Japanese Edition), vol.J87-B, no.4, pp.589–592, April 2004.

[97] P. Brooks and B. Hestnes, "User measures of quality of experience: Why being objective and quantitative is important," IEEE Netw., vol.24, no.2, pp.8–13, March/April 2010.

[98] ITU-T Rec. P. 911, "Subjective audiovisual quality assessment methods for multimedia applications," Dec. 1998.

[99] C.E. Osgood, "The nature and measurement of meaning," Psychological Bulletin, vol.49, no.3, pp.197–237, May 1952.

[100] S. Tasaka and Y. Ito, "Psychometric analysis of the mutually compensatory property of multimedia QoS," Conf. Rec. IEEE ICC, pp.1880–1886, May 2003.

[101] H. Ohnishi and K. Mochizuki, "Effect of delay of feedback force on perception of elastic force: A psychophysical approach," IEICE Trans. Commun., vol.E90-B, no.1, pp.12–20, Jan. 2007.

[102] ITU-R Rec. BT. 500-12, "Methodology for the subjective assessment of the quality of television pictures," Sept. 2009.

[103] S. Matsumoto, I. Fukuda, H. Morino, K. Hikichi, K. Sezaki, and Y. Yasuda, "The influences of network issues on haptic collaboration in shared virtual environments," Proc. Fifth PHANToM Users Group Workshop, Oct. 2000.

[104] S. Lee, S. Moon, and J. Kim, "Performance evaluation of transport protocols for networked haptic collaboration," Proc. SPIE IT-COM Multimedia Systems and Applications IX, vol.6391, no.9, Oct. 2006.

[105] F. Mosteller, "Remarks on the method of paired comparisons: III. A test of significance for paired comparisons when equal standard deviations and equal correlations are assumed," Psychometrika, vol.16, no.2, pp.207–218, June 1951.

[106] M. Fujimoto and Y. Ishibashi, "The effect of stereoscopic viewing of a virtual space on a networked game using haptic media," Proc. ACM ACE, pp.317–320, June 2004.

[107] E.J. Rodriguez, T. Nunome, and S. Tasaka, "QoE assessment of multi-view video and audio IP transmission," IEICE Trans. Commun., vol.E93-B, no.6, pp.1373–1383, June 2010.

[108] A. Tatematsu, B. Liu, N. Fukushima, and Y. Ishibashi, "Influence of network delay on quality of experience in free-viewpoint video transmission," J. Institute of Image Information and Television Engineers, vol.65, no.12, pp.1742–1749, Dec. 2011. (in Japanese)

[109] Y. Ishibashi and M. Nagasaka, "An adaptive QoS control scheme of avatars in distributed virtual environments," J. Institute of Image Information and Television Engineers, vol.60, no.11, pp.1835–1839, Nov. 2006. (in Japanese)

[110] S. Tasaka and Y. Ishibashi, "Mutually compensatory property of multimedia QoS," Conf. Rec. IEEE ICC, pp.1105–1111, April/May 2002.

[111] H. Ando, A. Callan, N.E. Nawa, Y. Nishino, J. Liu, A. Wada, and Y. Sakano, "Perceptual and cognitive mechanisms of presence and its evaluation technology," J. National Institute of Information and Communications Technology, vol.57, no.1/2, pp.159–168, March/June 2010.

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