1. Introduction

Recently, a number of researchers have been paying their attentions to networked virtual environments with haptic sense [1]-[11]. By using a haptic interface device, each user can feel the shape, softness, and weight of an object in a three-dimensional (3D) virtual space. When such a environment is constructed over a network like the Internet, which does not guarantee Quality of Service (QoS) [12], the consistency (e.g., the positions of an object at different terminals are the same) [13] among users and the operability of haptic interface device [14] may seriously deteriorate owing to the network delay, delay jitter, and packet loss. This means degradation of Quality of Experience (QoE) [15]. The reason is mainly that the features of objects may change in different ways; for example, they may become harder and/or heavier as the network delay increases [17]-[21]. To avoid the deterioration, we need to carry out QoS control such as the local lag control [13], the dynamic local lag control [22], the adaptive ∆-causality control [23], which also utilizes the local lag control, and adaptive viscoelasticity control [24]. However, the control may have side effects. For example, the local lag control, which we handle in this paper, may make the interactivity and operability worse by producing the local lag larger than or equal to the network delay to achieve a high-level of consistency; a longer local lag improves the consistency but degrades the interactivity and operability. That is, there is a trade-off relationship under the control. Thus, for effective QoS control, we should clarify human perception of features such as the shape, softness, and weight of an object [17]-[21]. However, human perception of the features has not clarified sufficiently so far.

In [17], the authors investigate the influence of network delay on QoE such as the operability of haptic interface device and fairness between players for soft objects in a networked real-time game subjectively and objectively. They handle a networked balloon bursting game in which two players burst balloons (i.e., soft objects) in a 3D virtual space by using haptic interface devices, and the players compete for the number of burst balloons. As a result, they find that the operability of haptic interface device depends on the local lag, which is set to a certain value. Each subject bursts the two balloons by using a haptic interface device and answers which balloon is harder or not. As a result, we clarify how largely the local lag makes the softness harder.
manipulates a haptic interface device, and the users collaboratively lift up a stick by holding two ends of the stick in a 3D virtual space. As a result, they illustrate that the local lag control can improve the efficiency of the collaborative work. Also, without carrying out the local lag control, keeping the ball placing at the center of stick becomes more difficult as the network delay increases. When the network delay is smaller than approximately 25 milliseconds (ms), it is possible to keep the ball around at the center. However, they only clarify the influence of local lag on the human perception of only weight.

In [19], the influence of weight change on human perception of weight is investigated in a networked haptic virtual environment. In their QoE assessment, each subject has one end of a bar with a certain weight in a 3D virtual space by using a haptic interface device, and the subject answers whether the weight has been changed or not when the weight is changed. Assessment results demonstrate that subjects can hardly perceive weight changes less than or equal to about 10 gf. However, they only investigate human perception of weight.

In [20], the authors handle a remote robot system with force feedback in which a user can operate a remote industrial robot by using a haptic interface device to assess the influence of weight change on human perception of weight by QoE assessment. As a result, they clarify that subjects can hardly perceive the weight change within about 10 gf, and when the absolute difference exceeds about 20 gf, the subjects start to perceive the change of weight. However, they only examine the influence of weight change on the weight perception.

In [21], we clarify influences of the network delay and moving velocity of a ball on haptic virtual cooperative work by experiment. In the work, each of two users operates a haptic interface device, and the two users collaboratively raise a stick in a 3D virtual space while keeping the ball at the center of the stick. Experimental results demonstrate that it is possible to keep the ball around at the center when the network delay is small and there exists the optimal moving velocity of the ball depending on the network delay. However, they do not examine the human perception of features of objects.

In this paper, we investigate the influence of local lag on human perception of softness in a networked virtual environment with haptic sense by QoE assessment. In the assessment, we employ only one terminal in the networked haptic balloon bursting game [17] where there are two balloons in a 3D virtual space; one balloon has a standard value of softness and the local lag is set to 0 ms, and the other has a different value of softness and the local lag is set to a certain value. Then, each subject bursts two balloons by using a haptic interface and answers which balloon is harder or not.

In the rest of this paper is organized as follows. We explain the networked haptic balloon bursting game in Section 2. Section 3 outlines the local lag control, and Section 4 describes the assessment method. Then, we present assessment results and discuss them in Section 5. Finally, we conclude the paper in Section 6.

2. Networked Haptic Balloon Bursting Game

2.1 System Configuration

The system configuration of the networked haptic balloon bursting game is shown in Fig. 1, where each of two players bursts balloons with his/her haptic interface device in a 3D virtual space. The two players compete with each other for the number of burst balloons. We here employ two balloons for simplicity in the virtual space. The system consists of two terminals (called terminals 1 and 2 here), each of which has a PC with a display, a haptic interface device (3D Systems Touch [25]), and a headset. Each player employs his/her haptic interface device to move the virtual stylus in the virtual space. The tip of the stylus corresponds to the cursor (i.e., the contact point to an object) of the haptic interface device. When the player touches the balloon with the tip of the stylus, the reaction force is perceived through the haptic interface device; he/she can feel the softness of the balloon. The balloon is distorted when the player pushes the balloon with the stylus. If he/she pushes it strongly, the balloon is largely distorted. When the force applied to the balloon exceeds a threshold value, the balloon is burst and disappeared. Then, he/she hears a sound of bursting it via the headset. It should be noted that in [14] and [17], a balloon is burst when the volume of the balloon becomes less than a threshold value; this is not real because the volume is not changed actually if the air does not come out of the balloon. Thus, we assume that a balloon is burst when the force applied to the balloon exceeds a threshold value in this paper.

In the game, we can change the number of players, the softness of the balloon, and so on. We set the number of players to one as shown in Fig. 2 in this paper. This is
because we just investigate the influence of local lag on human perception of the balloon softness by using the system.

2.2 Calculation of Reaction Force

The reaction force applied to a balloon by the haptic interface device is generated by the haptic rendering engine [26], which uses the object shape and material properties such as stiffness and friction for calculation of the reaction force. The force applied to the balloon when the player pushes the balloon with the stylus is equal to the reaction force against the player; note that the direction of the force is reverse. He/she feels harder as the penetration depth of the stylus becomes larger [14]. The penetration depth of the stylus is the distance from the surface of the balloon to the tip of the stylus as shown in Fig. 3. We assume that the reaction force applied to the haptic interface device is proportional to the penetration depth as in the following equation:

\[ F_t = K_S \cdot p_t \]  

where \( F_t \) denotes the reaction force at time \( t \) (> 0), \( p_t \) is the penetration vector at time \( t \), and \( K_S \) is the elastic (or
spring) coefficient of the balloon.

3. Local Lag Control

In order to keep the consistency high, we can use the local lag control, which buffers local information at a local terminal for a constant time called the local lag according to the network delay from the local terminal to the other terminal before transmitting the information [13]. The local lag is set to a value larger than the network delay to absorb the delay jitter to some extent; if there is no delay jitter, we can set the local lag to the same as the network delay. Therefore, when the network delay is large, the control degrades the interactivity and operability [17].

When we apply the local lag to the networked haptic balloon bursting game, it may change the softness of balloon according to the network delay because the local lag is determined depending on the network delay. That is, the local lag may make a balloon harder. When there exists a network delay, only the haptic interface device moves first, and the changes in the virtual space occur later (delayed by the local lag; note that the sound is outputted when the balloon is burst).

Therefore, in this paper, we investigate the influence of local lag on the human perception of softness. Since the local lag control is utilized under several types of QoS control such as the dynamic local lag control and the adaptive Δ-causality control as described earlier, it is important to clarify the influence of local lag.

4. Assessment Method

In our assessment system, as shown in Fig. 2, we used only one terminal in the networked haptic balloon bursting game [17] where there are two balloons in a 3D virtual space; one balloon has a standard value of softness (called the standard softness here) and the local lag is set to 0 ms, and the other has a different value of softness (called the other softness) and the local lag is set to a certain value. Then, each subject burst both of balloons alternatively by using a stylus of the haptic interface device and answered which balloon is harder or softer. We presented the following three different values as the standard softness in random order for each subject: 1.2 N, 2.0 N, and 2.8 N [21] (note that the softness is expressed in force (newton) in this paper, and the maximum reaction force of the haptic interface device is 3.3 N [25]); we changed the threshold value of force which is used for judgement of bursting. For each standard softness, we changed the other softness from the standard softness minus 0.5 N to the standard softness at intervals of 0.1 N; for example, from 0.7 N to 1.2 N for the standard softness of 1.2 N. We also changed the local lag from 0 ms to 250 ms at intervals of 25 ms. We presented combinations of the other softness and local lag in random order for each standard softness.

Before the assessment, each subject practiced how to burst a balloon by using the haptic interface device for about two minutes. In the assessment, each subject firstly burst the pink balloon which has the standard softness and the local lag of 0 ms by pushing the top of the balloon with the stylus (see Fig. 2). Next, the subject burst the green balloon which has a different value or the same value of softness from/as the pink balloon and the local lag of certain value. Then, he/she selected one from among the following three answers: "Softer," "same," and "harder" compared with the pink balloon in terms of softness when the balloons were burst. We carried out the assessment with 20 subjects (1 male and 19 females) whose ages were between 25 and 35. The total assessment time including break time was about 1 hour per subject.

5. Assessment Results

We show the noticed difference rates versus the local lag for the three values of the standard softness (1.2 N, 2.0 N, and 2.8 N) in Fig. 4. The noticed difference rate is here defined as the ratio of the number of answers that there exists a difference between the standard softness (the pink balloon with the local lag of 0 ms) and the other softness (the green balloon with the local lag of a certain value) to the number of all the answers. In the figure, the noticed difference rate of 0% means that all the subjects answered "same." Also, the noticed difference rate on the left hand side of the noticed difference rate of 0% shows the ratio of the number of answers that the other softness is softer than the standard softness to the number of all the answers; on the right hand side, the rate represents the ratio of the number of answers that the other softness is harder.

In Fig. 4, we can confirm that when the difference between the standard softness and other softness is zero and the local lag is 0 ms, the noticed difference rate is 0%; all the subjects cannot perceive any difference. We also see that when the other softness is the same as the standard softness, the noticed difference rate becomes larger as the local lag increases up to around 125 ms. When the other softness is not equal to the standard softness, the noticed difference rate first decreases down
Fig. 4 Noticed difference rate versus local lag
to almost zero and then increases as the local lag becomes larger. Furthermore, we observe that as the other softness becomes larger, the noticed difference rate tends to start to increase at a smaller local lag; the rate has a tendency to reach 100% more earlier. From these considerations, we can conclude that the local lag makes the balloon harder.

To clarify how largely the local lag increases the softness, we show the hardening with local lag, which is here defined as the force which is increased when the local lag is changed, in Table 1. We calculated the hardening with local lag as follows. According to [27], humans can hardly perceive the difference in softness when the other softness is almost the same as the standard softness; they start to perceive the absolute differences larger than or equal to about 0.1 N. Also, when the other softness is larger than the standard softness by around 0.4 N, most of humans can perceive the difference. In Fig. 4 (a), we notice that for example, when the other softness is 0.7 N and the local lag is between about 100 ms and 125 ms, the noticed difference rate is 0%; then, the perceived softness should be between about 1.1 N and 1.3 N (= the standard softness (1.2 N) ± 0.1 N). This means that the hardening with local lag is about 0.4 (= 1.1 N – 0.7 N) to 0.6 (= 1.3 N – 0.7 N). In the same way, we can fill out the yellow range, in which the noticed difference rate is 0%, in Table 1. On the other hand, in Fig. 4 (a), we find that for instance, when the other softness is 0.7 N and the local lag is larger than or equal to about 200 ms, the noticed difference rate is 100%; then, the perceived softness is larger than about 1.6 N (= the standard softness (1.2 N) + 0.4 N); this indicates that the hardening with local lag is larger than or equal to about 0.9 N (= 1.6 N – 0.7 N). Similarly, we can fill out the pink range, in which the noticed difference rate is 100%, in Table 1. The hardening with local lag of the other (white) range on the left hand side of the yellow range in

### Table 1 Hardening with local lag (N) for each other softness

#### (a) Standard softness: 1.2 N

| Other softness (N) | 0  | 25 | 50 | 75 | 100 | 125 | 150 | 175 | 200 | 225 | 250 |
|-------------------|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|
| 0.7               | 0.4-0.6 | 0.4-0.6 | ≥0.9 | ≥0.9 | ≥0.9 |
| 0.8               | 0.3-0.5 | 0.3-0.5 | ≥0.8 | ≥0.8 | ≥0.8 |
| 0.9               | 0.2-0.4 | 0.2-0.4 | 0.2-0.4 | ≥0.7 | ≥0.7 | ≥0.7 |
| 1.0               | 0.1-0.3 | 0.1-0.3 | ≥0.6 | ≥0.6 | ≥0.6 |
| 1.1               | 0-0.2   | 0-0.2   | ≥0.5 | ≥0.5 | ≥0.5 | ≥0.5 |
| 1.2               | 0-0.1-0.1 | ≥0.4 | ≥0.4 | ≥0.4 | ≥0.4 | ≥0.4 |

#### (b) Standard softness: 2.0 N

| Other softness (N) | 0  | 25 | 50 | 75 | 100 | 125 | 150 | 175 | 200 | 225 | 250 |
|-------------------|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|
| 1.5               | 0.4-0.6 | 0.4-0.6 | ≥1.0 | ≥1.0 | ≥1.0 | ≥1.0 |
| 1.6               | 0.3-0.5 | 0.3-0.5 | ≥0.9 | ≥0.9 | ≥0.9 | ≥0.9 |
| 1.7               | 0.2-0.4 | 0.2-0.4 | 0.2-0.4 | ≥0.8 | ≥0.8 | ≥0.8 |
| 1.8               | 0.1-0.3 | 0.1-0.3 | ≥0.7 | ≥0.7 | ≥0.7 |
| 1.9               | 0-0.2   | ≥0.6   | ≥0.6 | ≥0.6 | ≥0.6 | ≥0.6 |
| 2.0               | 0-0.1-0.1 | ≥0.5 | ≥0.5 | ≥0.5 | ≥0.5 | ≥0.5 |

#### (c) Standard softness: 2.8 N

| Other softness (N) | 0  | 25 | 50 | 75 | 100 | 125 | 150 | 175 | 200 | 225 | 250 |
|-------------------|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|
| 2.3               | 0.5 | ≥0.9 | ≥0.9 | ≥0.9 | ≥0.9 |
| 2.4               | 0.4 | ≥0.8 | ≥0.8 | ≥0.8 | ≥0.8 |
| 2.5               | 0.3 | ≥0.7 | ≥0.7 | ≥0.7 | ≥0.7 |
| 2.6               | 0.2 | ≥0.6 | ≥0.6 | ≥0.6 | ≥0.6 |
| 2.7               | 0.1 | ≥0.5 | ≥0.5 | ≥0.5 | ≥0.5 | ≥0.5 |
| 2.8               | 0  | 0  | ≥0.4 | ≥0.4 | ≥0.4 | ≥0.4 | ≥0.4 |
Table 1 is smaller than about that of the yellow range, and that of the white range on the right hand side is larger than around that of the yellow range and smaller than approximately that of the pink range. For visibility, we do not write the hardening with local lag in the white range.

In each of Tables 1 (a), (b), and (c), we see that the pink range tends to become wider as the other softness increases; the local lag in this range increases the softness by at least 0.4 N. Also, the yellow range tends to shift left. This means that humans can feel the difference in softness by the local lag more easily the difference becomes smaller. From Tables 1 (a), (b), and (c), we find that the pink range becomes wider as the standard softness increases. Also, the yellow range tends to become narrower as the standard softness increases; the range has a tendency to shift left. This indicates that humans perceive the difference in softness by the local lag more easily as the standard softness become larger.

6. Conclusion

In this paper, we investigated the influence of local lag on human perception of softness in a networked virtual environment with haptic sense by QoE assessment. We handled a networked haptic balloon bursting game which included two balloons with different values of softness. In the assessment, subjects judged whether the two balloons have the same softness or not. As a result, we found that the human perception of softness is dependent on the local lag. We also clarified how largely the local lag makes the softness harder; for example, the softness of 1.2 N is increased by at least about 0.2 N when the local lag is larger than or equal to around 100 ms.

As the next step of our research, we will study how to mitigate the influence of local lag and/or network delay on the softness by using QoS control. We also plan to examine influences of the network delay, delay jitter, and packet loss on other haptic features. In addition, we further need to investigate the influence of only haptic sense on the softness by eliminating the influences of the auditory and visual senses.

References

1) S. Andrews, J. Mora, J. Lang and W.S. Lee: "HaptiCast: A physically-based 3D game with haptic feedback," in Proc. Future Play Conference (Oct. 2006)
2) D. Morris, N. Joshi and K. Salisbury: "Haptic Battle Pong: High-degree-of-freedom haptics in a multiplayer gaming environment," in Proc. Experimental Gameplay Workshop, Game Developers Conference (Mar. 2004)
3) H. Liu, Z. Zhang, X. Xie, Y. Zhu, Y. Liu, Y. Wang and S. Zhu: "High-fidelity grasping in virtual reality using a glove-based system," in Proc. International Conference on Robotics and Automation (ICRA), pp.5180-5186 (May 2019)
4) H. Kerdegari, Y. Kim and T.J. Prescott: "Head-mounted sensory augmentation device: Designing a tactile language," IEEE Trans. on Haptics, vol. 9, no. 3, pp.376-386 (July-Sep. 2016)
5) J. Singh, A.R. Srinivasan, G. Neumann and A. Kucukyilmaz: "Haptic-guided teleoperation of a 7-DoF collaborative robot arm with an identical twin master", IEEE Trans. on Haptics, vol. 13, no. 1, pp.246-252 (Jan.-Mar. 2020)
6) J.L. Castellanos-Cruz, M.F. Gomez-Medina, M. Tavakoli, P.M. Pilarski and K. Adams: "Preliminary testing of a telerobotic haptic system and analysis of visual attention during a playful activity," in Proc. The 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob), pp.1280-1285 (Aug. 2018)
7) S. Kim and J. Park: "Robust haptic exploration of remote environments represented by streamed point cloud data," in Proc. IEEE World Haptics Conference (WHC), pp.358-363 (June 2017)
8) M. Esfandiari, S. Sadeghnejad, F. Farahmand and V. Gossoughi: "Robust nonlinear neural network-based control of a haptic interaction with an admittance type virtual environment," in Proc. The 5th RSI International Conference on Robotics and Mechatronics (ICRoM), pp.322-327 (2017)
9) S. Haddadin, L. Johannsmeier and F.D. Ledezma: "Tactile robots as a central embodiment of the tactile Internet," in Proc. the IEEE, vol. 107, no. 2, pp.471-487 (Feb. 2019)
10) M. Panzirsch, R. Balachandran, B. Weber, M. Ferre and J. Artigas: "Haptic augmentation for teleoperation through virtual grasping points," IEEE Trans. on Haptics, vol. 11, no. 3, pp.400-416 (July-Sep. 2018)
11) M. Fujimoto and Y. Ishibashi: "The effect of stereoscopic viewing of a virtual space on a networked game using haptic media," in Proc. ACM SIGCHI International Conference on Advances in Computer Entertainment Technology (ACE), pp.317-320 (June 2004)
12) ITU-T Rec. E. 800: "Definitions of terms related to quality of service," International Telecommunication Union (2008)
13) M. Mave, J. Vogel, V. Hilt and W. Eftelfberg: "Local-lag and timewarp: Providing consistency for replicated continuous applications," IEEE Trans. on Multimedia, vol. 6, no. 1, pp.47-57 (Feb. 2004)
14) M. Sithu, Y. Ishibashi, P. Huang and N. Fukushima: "QoE assessment of operability and fairness for soft objects in networked real-time game with haptic sense," in Proc. The 21st Asia-Pacific Conference on Communications (APCC), pp.570-574 (Oct. 2015)
15) A. Hamam, A.E. Saddik and J. Alja'am: "A quality of experience model for haptic virtual environments," ACM Trans. on Multimedia Computing, Communications and Applications, article 28, pp.1-23 (Apr. 2014)
16) Y. Ishibashi and K. Kaneko: "Fairness among game players in networked haptic environments: Influence of network latency," in Proc. IEEE International Conference on Multimedia and Expo (ICME) (July 2005)
17) M. Sithu, Y. Ishibashi, P. Huang and N. Fukushima: "Influences of network delay on quality of experience for soft objects in networked real-time game with haptic sense," Int. J. Communications, Network and System Sciences (IJCNSS), vol. 8, no. 11, pp.440-455 (Nov. 2015)
18) P. Huang, R. Arima and Y. Ishibashi: "Influence of network delay on human perception of weight in virtual environment," in Proc. The 3rd IEEE International Conference on Computer Communications and Applications (ICCCA), pp.1221-1225 (Dec. 2017)
19) D. Osada, Y. Ishibashi, P. Huang and Y. Tateiwa: "Assessment of weight perception with haptics in networked virtual environment," in Proc. The 3rd International Conference on Computer and Communication Systems (ICCCS), pp.158-162 (Apr. 2018)
20) L. Wen, Y. Ishibashi, P. Huang, Y. Tateiwa and H. Ohnishi: "QoE assessment of weight perception in remote robot system with force
feedback,” in Proc. The 2nd World Symposium on Communication Engineering (WSCE), pp.200-204 (Dec. 2019)
21) M.Z. Oo, Y. Ishibashi and K.T. Mya: “Influences of network delay and moving velocity on virtual cooperative work with haptic sense,” in Proc. The 10th International Conference on Future Computer and Communication (ICFCC), pp 108-113 (Feb. 2020)
22) M. Sithu, Y. Ishibashi and N. Fukushima: “Effects of dynamic local lag control on sound synchronization and interactivity in joint musical performance,” ITE Trans. Media Technology and Applications (MTA), Special Section on Multimedia Transmission System and Services, vol. 2, no. 4, pp.299-309 (Oct. 2014)
23) Y. Hara, Y. Ishibashi, N. Fukushima and S. Sugawara: "Adaptive delta-causality control scheme with dynamic control of prediction time in networked haptic game," in Proc. ACM The 11th Annual Workshop on Network and Systems Support for Games (NetGames) (Nov. 2012)
24) T. Abe, H. Ohnishi and Y. Ishibashi: "Adaptive viscoelasticity control in remote control system with haptics," IEICE Trans. Commun (Japanese Edition), vol. J103-B, no. 1, pp.38-46 (Jan. 2020)
25) 3D Systems, Inc.: Haptic Devices, https://www.3dsystems.com/haptics-devices/touc
26) SensAble Technologies, Inc.: "OpenHaptics toolkit programmer's guide," version 3.0 (2009)
27) M.Z. Oo, Y. Ishibashi and K.T. Mya: “QoE assessment of human perception of softness in networked haptic virtual environment,” to appear in Proc. The 3rd International Conference on Computer Communication and the Internet (ICCCI) (June 2021)

May Zin Oo is currently a Ph.D. candidate of University of Computer Studies, Yangon, Myanmar. Her research interests include haptic communications.

Yutaka Ishibashi received the B.E., M.E., and Ph.D. degrees from Nagoya Institute of Technology, Nagoya, Japan, in 1981, 1983, and 1990, respectively. In 1983, he joined the Musashino Electrical Communication Laboratory of NTT. From 1993 to 2001, he served as an Associate Professor of Faculty of Engineering, Nagoya Institute of Technology. Currently, he is a Professor of Graduate School of Engineering, Professor of Department of Computer Science, Graduate School of Engineering, Nagoya Institute of Technology. His research interests include networked multimedia, QoS control, media synchronization, and remote robot control. He is a fellow of IEICE, a senior member of IEEE, and a member of ACM, IPSJ, VRSJ, and IEEJ.

Khin Than Mya received her M.Sc. (Physics) from University of Yangon in 1997 and M.A.Sc.(Computer Engineering) and Ph.D. (IT) degrees from University of Computer Studies, Myanmar in 2000 and 2007, respectively. She is now working as a Professor of Faculty of Computer Systems and Technologies, University of Computer Studies, Yangon. Her major research interests include embedded Systems, Internet of Thing (IoT), robotics and automation, Quality of Experience (QoE) assessment, multimedia communication, and smart agriculture. She is a Member of IEEE.