Effect of Prediction Control in Remote Haptic Control System

Wyne Lei Lei
University of Computer Studies, Yangon
Yangon, Myanmar
wynelei@ucsy.edu.mm

Yutaka Ishibashi
Nagoya Institute of Technology
Nagoya, Japan
ishibasi@nitech.ac.jp

Khin Than Mya
University of Computer Studies, Yangon
Yangon, Myanmar
khinthanmya@ucsy.edu.mm

***Abstract*—In this paper, we examine the effect of prediction control in a remote haptic control system by Quality of Experience (QoE) assessment. In the system, a user operates a haptic interface device (just called a haptic device here) at a remote place by using one more haptic device while monitoring the operation by a video camera. The prediction control predicts the position of a haptic device a constant time (called the prediction time) earlier than the current time. Assessment results demonstrate that the optimum prediction time exists according to the network latency. We also clarify the relation between the optimum prediction time and the network latency by carrying out regression analysis. We further illustrate how largely the prediction control mitigates the influence of network latency.**

Keywords—Remote control system, Haptics, Prediction control, Network latency, QoE, Assessment

I. INTRODUCTION

Haptic communications recreate the haptic sense (i.e., the sense of touch) by applying a series of forces, vibrations, or motions to remote users [1]-[4]. Therefore, there are a number of challenges to the underlying networks to support their interactions [5], [6]. Many papers have actively dealt with remote haptic control systems [7], [8]. In such a remote haptic control system, a user operates a haptic interface device (just called a haptic device here) at a remote location with one more haptic device while monitoring the operation by a video camera. We can conduct a variety of work efficiently by using the system.

However, when we transmit haptic information through a network like the Internet, which does not guarantee Quality of Service (QoS) [9], Quality of Experience (QoE) [10] may be degraded seriously because of the network latency, latency jitter, and packet loss. To solve the problem, QoS control needs to be carried out.

Various kinds of QoS control have been studied so far [11]-[25]. For example, in [18], the authors propose the dynamic local lag control with dynamic prediction control for the networked haptic drum performance. The proposed control dynamically changes the local lag according to the network latency to achieve high synchronization quality of sound and outputs the position information by predicting the future position to maintain the interactivity at a high level. The effect of the proposed control is investigated by QoE assessment. Assessment results show that the optimum prediction time exists according to the network latency.

In [19], group synchronization control with prediction is proposed to attain high quality of interactivity for the following two types of work: The remote haptic drawing instruction [20] and collaborative haptic play with building blocks [21]. The control adjusts the output timing among multiple terminals. The position information is outputted by predicting the future position later than the position included in the latest received *media unit* (*MU*), which is an information unit (e.g., a video frame and a voice packet) for media synchronization [22], by a fixed amount of time. The effect of the control is investigated by QoE assessment subjectively and objectively. The assessment results illustrate that we have the optimum prediction time depending on the network latency.

In [23], to improve the interactivity of the air hockey game with haptics, the authors propose the adaptive Δ-causality control with prediction, which maintains the consistency and causality at a high level. Under the proposed control, position information is outputted by predicting the future position based on the previously received position after a constant time. They also investigate the effect of the proposed control by QoE assessment. As a result, they illustrate that the proposed control is effective and there exists the optimum prediction time.

The above three papers handle the prediction control with other types of QoS control in networked haptic virtual environments. The prediction control may be effective in networked real environments. Because the calculation of reaction force is different between real and virtual environments [24], we need to confirm the effectiveness of the control in the real environments.

Therefore, this paper uses the prediction control to enhance the operability of haptic devices in the remote haptic control system as one of the networked real environments. We also investigate the effect of the prediction control by QoE assessment. Then, we show that there exists the optimum prediction time according to the network latency. We further get the relation between the optimum prediction time and the network latency by regression analysis.

The remainder of this paper is structured as follows. We introduce the remote haptic control system in Section II. Section III also explains the prediction control. Then, the assessment method is described in Section IV, and assessment results are discussed in Section V. Finally, Section VI is the conclusion.

II. REMOTE HAPTIC CONTROL SYSTEM

A. System Design

Figure 1 shows the design of the remote haptic control system, which consists of two PCs (OS: Windows 10). One is a master PC, and the other is a slave PC. Each PC has 3D Systems Touch [26] as a haptic device. The degree of freedom (DOF) of the haptic device is 3. In remote haptic

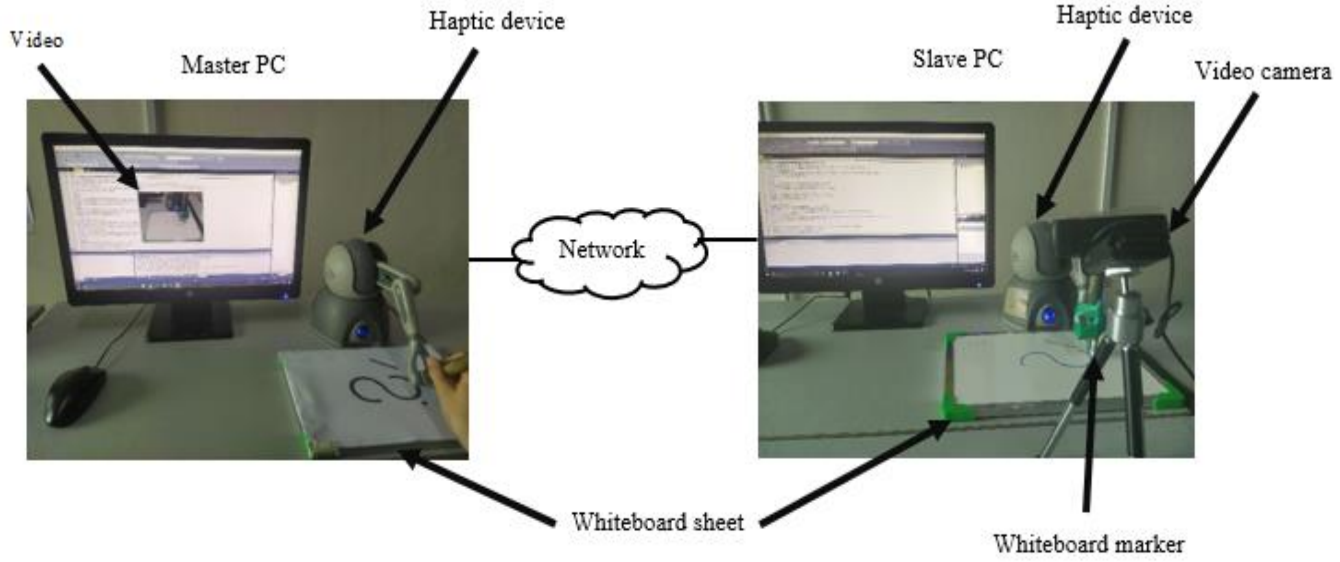


Fig. 1. Design of remote haptic control system.

control system, a user of the master PC operates the haptic device of the slave PC by using the haptic device of the master PC while monitoring the operation by a video camera. There is a wihiteboard sheet in front of each haptic device. A whiteboard marker is attached to the haptic device of the slave PC (see Fig. 1). At the slave PC, moving parts of the haptic device that are unrelated to the position information are secured with tape [8]. This makes it possible for the user to write characters and draw figures without holding the stylus of the device by hand. Note that a user holds the stylus of the haptic device at the master PC as shown in Fig. 1.

B. *Calculation Method of Reaction Force*

We compute the reaction force at the slave PC as follows:

$$\boldsymbol{F}_t^{(s)} = K_s \left(\boldsymbol{M}_t^{(s)} - \boldsymbol{S}_t^{(s)}\right) \tag{1}$$

where $\boldsymbol{F}_t^{(s)}$ is the reaction force at the slave PC at time t (ms), K_s is the elasticity coefficient (K_s = 0.1 [8]), $\boldsymbol{M}_t^{(s)}$ is the position vector of the master PC which is received from the master PC at time t, and $\boldsymbol{S}_t^{(s)}$ is the position vector of the slave PC. The reaction force at the master PC is calculated by

$$\boldsymbol{F}_t^{(m)} = K_s \left(\boldsymbol{S}_t^{(m)} - \boldsymbol{M}_t^{(m)}\right) \tag{2}$$

where $\boldsymbol{F}_t^{(m)}$ is the reaction force at the master PC at time t, $\boldsymbol{S}_t^{(m)}$ is the position vector of the slave PC which is received from the slave PC, and $\boldsymbol{M}_t^{(m)}$ is the position vector of the master PC.

The above method differs from that in [8] and [17], where the reaction force consists of the elasticity and viscosity; note that only the elasticity is handled for simplicity in this paper. The method is also different from that in networked haptic virtual environments [18], [23] where the reaction force is calculated from the penetration depth from the surface to the cursor (that is, the tip of stylus) of the haptic device in an object (i.e., the elasticity) and the relative velocity of the cursor to the object (the viscosity).

III. PREDICTION CONTROL

In the remote haptic control system, each PC sends information about the cursor position of haptic device to the other PC every millisecond. Thus, we can predict the future position based on the current and previous positions. In this paper, we adopt the first-order prediction for simplicity. The predicted positions $\hat{\boldsymbol{M}}_t^{(m)}$ and $\hat{\boldsymbol{S}}_t^{(s)}$ at the master and slave PCs, respectively, are calculated as follows:

$$\hat{\boldsymbol{M}}_t^{(m)} = \boldsymbol{M}_t^{(m)} + \delta \left(\boldsymbol{M}_t^{(m)} - \boldsymbol{M}_{t-1}^{(m)}\right) \tag{3}$$

$$\hat{\boldsymbol{S}}_t^{(s)} = \boldsymbol{S}_t^{(s)} + \delta \left(\boldsymbol{S}_t^{(s)} - \boldsymbol{S}_{t-1}^{(s)}\right) \tag{4}$$

where δ (ms) denotes the prediction time. Note that $\boldsymbol{M}_t^{(m)} - \boldsymbol{M}_{t-1}^{(m)}$ and $\boldsymbol{S}_t^{(s)} - \boldsymbol{S}_{t-1}^{(s)}$ denote the velocity vectors at the master and slave PCs, respectively. $\hat{\boldsymbol{M}}_t^{(m)}$ and $\hat{\boldsymbol{S}}_t^{(s)}$ are used instead of $\boldsymbol{M}_t^{(m)}$ and $\boldsymbol{S}_t^{(s)}$, respectively, in Eqs. (1) and (2) to calculate the force. Each PC transmits the information about the predicted position to the other PC.

IV. ASSESSMENT METHOD

We performed QoE assessment subjectively with 15 subjects (9 males and 6 females) whose ages were 20 and 25. In the assessment, the two PCs are connected to each other by using a network emulator (NetEm [27]) to produce the constant latency for each packet transmitted between the both PCs. The constant latency is called the *additional latency* here. The additional latency was changed from 0 ms to 100 ms at intervals of 25 ms, and the prediction time is changed from 0 ms to 45 ms at intervals of 5 ms.

Before the assessment, each subject practiced writing Myanmar characters (see Fig. 2) when the additional latency is 0 ms and the prediction time is 0 ms for about two minutes and then regarded the operability of haptic device at that time as the *standard quality*. An example of written characters for practice is shown in Fig. 3, where we can confirm that written characters have almost the same shapes as Fig. 2.

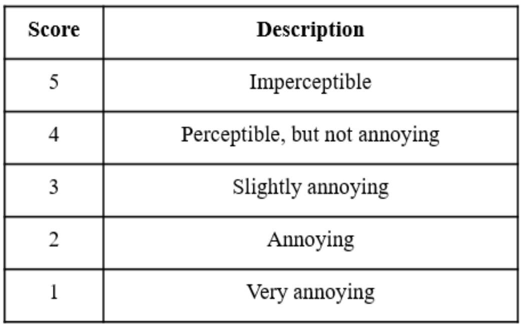
The reason why we handled writing characters in the assessment is as follows. We can easily confirm how accurately the force information is transmitted just by looking at the shapes of written characters. Also, the characters shown in Fig. 2 were selected since they have several basic elements (i.e., circle, straight line, and dot), sudden changes in writing direction, and several strokes (i.e., lifting the whiteboard marker from the sheet several times).

After the practice, we changed the prediction time for each value of the additional latency in the assessment. The order of stimuli (combinations of the additional latency and prediction time) were selected in random order for each subject.

A paper including printed characters (Fig. 2) was set on the whiteboard sheet at the master PC because every subject needs to write the characters several times with the same shape, the same stroke, and the same size at almost the same speed for 30 seconds (repeated about six times). The subject just moved the stylus of the haptic device along the characters on the paper. For each stimulus, by comparing with the standard quality, the subject gave a score as shown in Table I. We obtained MOS (Mean Opinion Score) [28] as one of QoE parameters by calculating the average scores of all the subjects.

Fig. 2. Example of Myanmar characters.

TABLE I. Five-grade impairment scale.



Score	Description
5	Imperceptible
4	Perceptible, but not annoying
3	Slightly annoying
2	Annoying
1	Very annoying

V. ASSESSMENT RESULTS AND DISCUSSIONS

A. Subjective Assessment Results

We show the MOS of the operability versus the prediction time for the five values of additional latency in Fig. 4. The 95% confidence intervals of the means are also plotted in the figure.

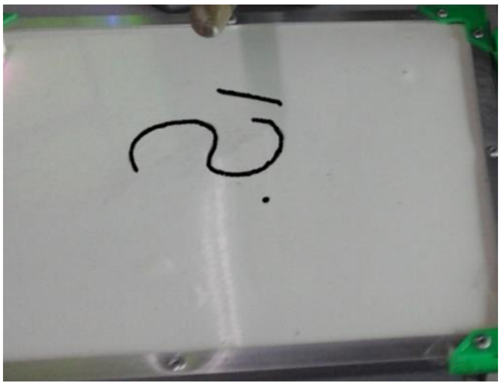


Fig. 3. Example of written characters for practice.

In Fig. 4, we see that the MOS values are the largest at the prediction time of about 0 ms,10 ms, 20 ms, 25 ms, and 30 ms when the addition latency is 0 ms, 25 ms, 50 ms, 75 ms, and 100 ms, respectively. Thus, there exists the optimum prediction time depending on the additional latency. This is because as the prediction time becomes larger, we can reduce the force more largely; we can operate the haptic device more easily (see Fig. 5(a), in which we find that the shapes of written characters are similar to those in Fig. 3). However, when the prediction time exceeds the optimum value, the prediction error is too large; it is very difficult to write characters (see Fig. 5(b)). In Fig. 5(b), we confirm that the shapes of written characters are largely damaged. From Fig. 4, we also observe that as the additional latency becomes larger, the optimum prediction time increases. In the assessment, we found that as the additional latency increases, the reaction force becomes stronger and vibration occurs more frequently. To solve the problems, we need to carry out other types of QoS control such as the adaptive reaction force control [29]. This is for further study.

To examine the relationship between the optimum prediction time and additional latency more clearly, we plot the optimum prediction time versus the additional latency in Fig. 6. From the figure, we see that the relationship is almost linear. Then, we carried out regression analysis [30]. As a result, we obtained the following equation:

$$\delta_{\mathrm{opt}} = 0.3\,L \qquad (5)$$

where δ_{opt} is the estimated optimum prediction time, and L is the additional latency. The contribution rate [31], which shows goodness of fit with the estimated equation, was 0.96. Therefore, the equation can express the relationship between δ_{opt} and L well.

B. Relationalship between Subjective and Objective Measures

In order to clarify the effect of the prediction control quantitatively, we replot the MOS value versus and the additional latency in Fig. 7 when the prediction time is 0 ms. In Fig. 7, we see that MOS value of the prediction control decreases almost linearly as the additional latency becomes larger. As a result of regression analysis, we obtained Eq. (6).

$$O_{\mathrm{MOS}} = -0.04\,L + 4.58 \qquad (6)$$

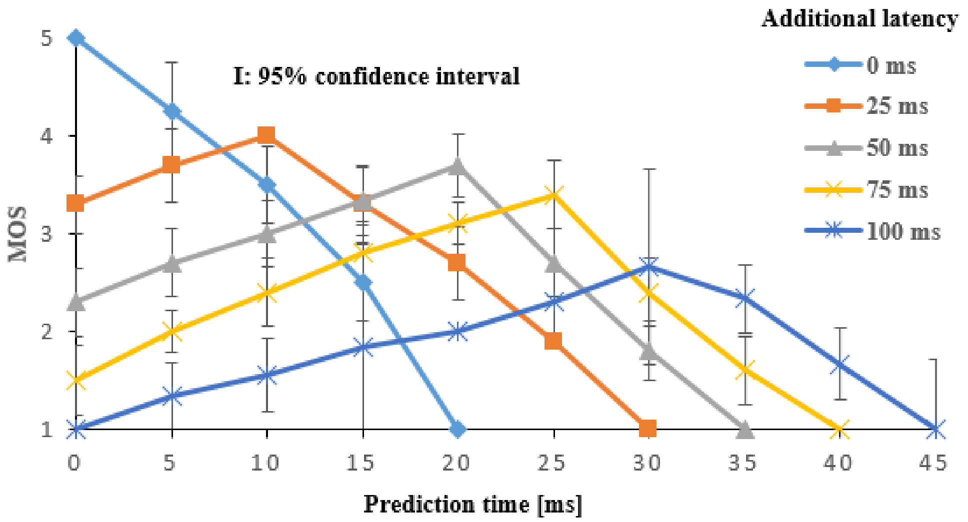
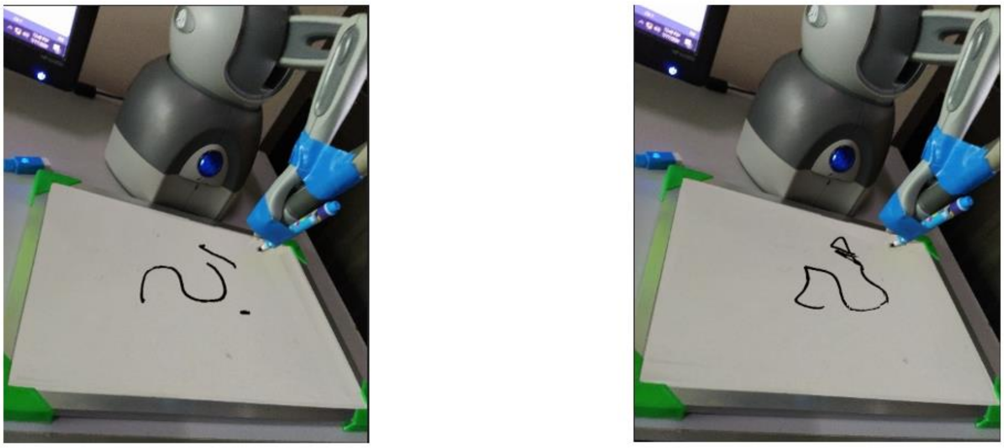


Fig. 4. MOS versus prediction time.



(a) Additional latency: 50 ms, prediction time: 20 ms (optimum value)

(b) Additional latency: 100 ms, prediction time: 45 ms

Fig. 5. Examples of written characters in assessment.

where O_{MOS} is the estimated value of MOS. The contribution rate of Eq. (6) was 0.96. Therefore, the equation can express the relation between MOS and L well. From Eq. (6), we got the following equation:

$$L = (O_{\mathrm{MOS}} - 4.58\,)\,/\,(-0.04\,) \qquad (7)$$

Then, we calculate the *effectively-reduced network latency*, which is defined as the additional latency with the optimum prediction time minus that with the prediction time of 0 ms under the condition that the MOS is the same, as follows. According to Fig. 4, for example, we can obtain the following results: when the additional latency is 50 ms and the optimum prediction time is 20 ms, the MOS is 3.7. In this case, we obtain the additional latency of 22 ms when the prediction time is 0 ms from Eq. (7). From this result, we find that we can effectively reduce the additional latency by 28 ms (=50 ms – 22 ms) by using the prediction control because the MOS is almost the same. This is the effectively-reduced network latency by prediction.

We show the effectively-reduced network latency versus the additional latency in Fig. 8. From Fig. 8, we see that as the additional latency increases, the effectively-reduced network latency becomes larger almost linearly for the additional latency considered here. We carried out regression analysis to obtain the following equation:

$$R_{\mathrm{latency}} = 0.58\,L - 1.50 \qquad (8)$$

where R_{latency} is the effectively-reduced network latency. The contribution rate of Eq. (8) was 0.97.

From the above discussions, we can effectively reduce the network latency by using the prediction control. The obtained values are the maximum for the additional latency. By using the effectively-reduced network latency, we can easily make a comparison among the different types of QoS control. This is further study.

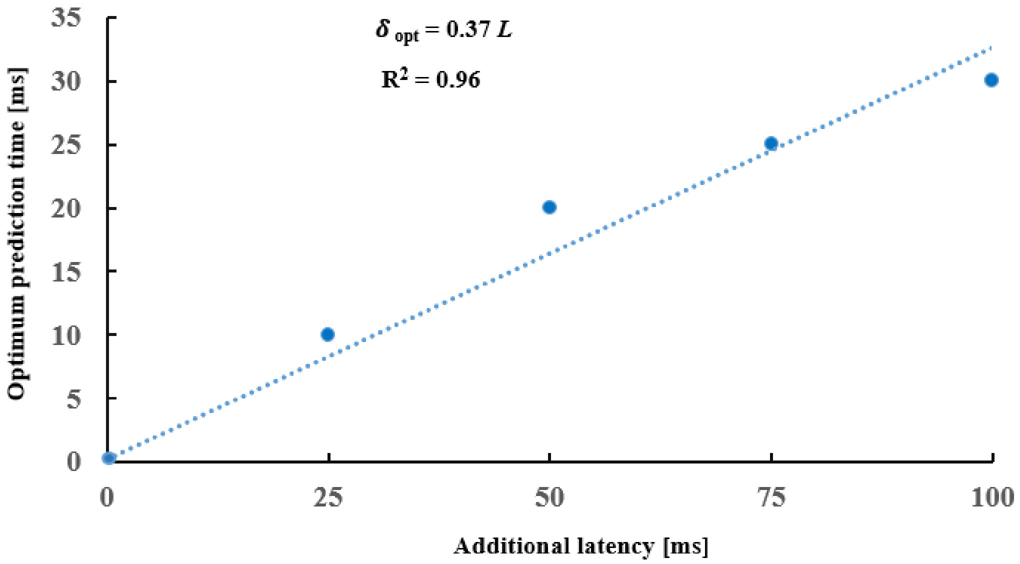


Fig. 6. Optimum prediction time versus additional latency.

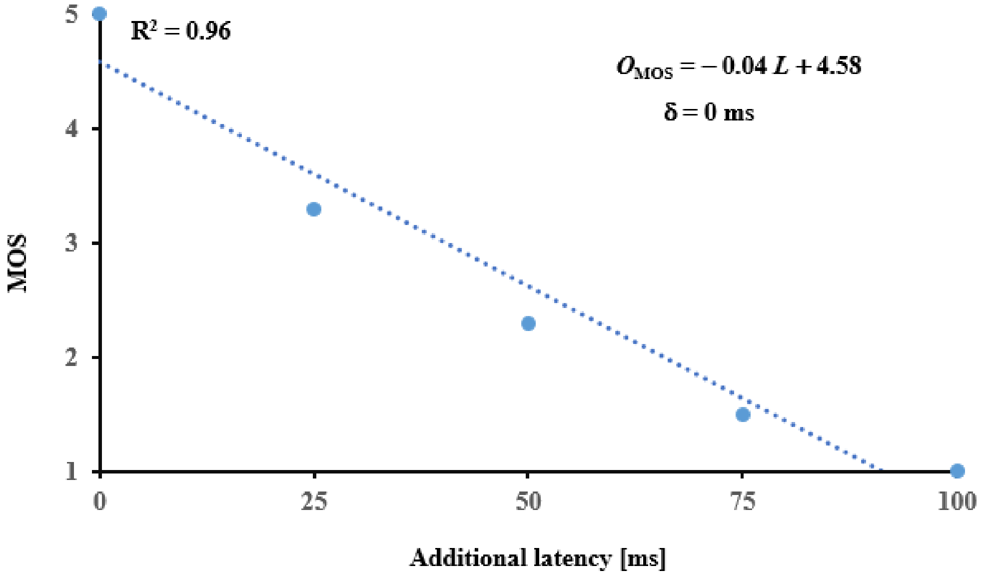


Fig. 7. MOS versus additional latency when prediction time is zero.

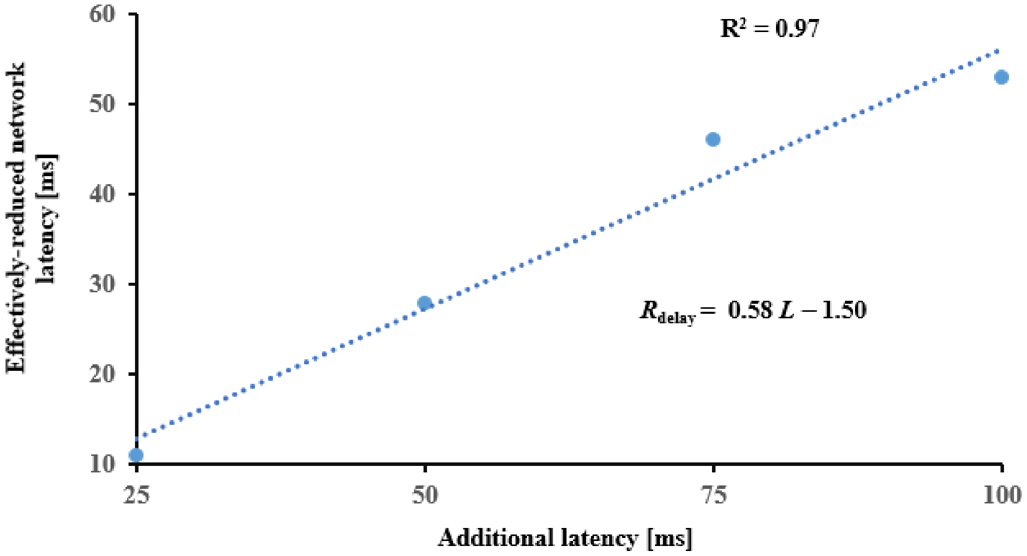


Fig. 8. Effectively-reduced network latency versus additional latency.

VI. CONCLUSIONS

In this paper, we examined the effect of the prediction control in the remote haptic control system by QoE assessment. As a result, we found that there exists the optimum prediction time depending on the network latency. We also investigated the relation between the optimum prediction time and the network latency by regression analysis.

In our future work, we plan to make a comparison between the prediction control and other types of QoS control such as the adaptive elasticity control by using effectively-reduced network latency for further enhancement of the operability of the haptic device.

ACKNOWLEDGMENT

This work was partly supported by JSPS KAKENHI Grant Number 18K11261.

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