Enhancing the Transparency by Onomatopoeia for Passivity-Based Time-Delayed Teleoperation

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***Abstract*—Robotic teleoperation with force feedback has been studied extensively since it was first developed in the 1940s. Time delay is a common problem of bilateral teleoperation systems. Although many efforts on optimizing the control architectures have been made, there is always a trade-off between transparency and stability for bilateral systems, and the perfect transparency and stability can only be achieved simultaneously in ideal situations. In this paper, we propose a novel approach to compensate for the degraded transparency while using the conventional passivity-based approach to maintain system stability under time-delay. The proposed approach is based on visual feedback and enhances the transparency by displaying different kinds of onomatopoeia according to contact force detected on the slave side. The basic performance is evaluated by conducting a stiffness classification task under constant round trip time delays (0 ms, 500 ms and 1000 ms). The preliminary results indicate that the subjects have higher accuracy for classifying the stiffness of a remote object by using onomatopoeia enhanced force feedback compared with the conventional passivity-based position-force feedback.**

***Index Terms*—Haptics and Haptic Interfaces, Telerobotics and Teleoperation, Human-Centered Robotics, Onomatopoeia, Wave Variable Control**

I. INTRODUCTION

ROBOTIC teleoperation or telerobotics, a technology that acts as a bridge between human control and autonomous machines has been actively developed since the first pure mechanical master-slave system was introduced by Goertz [1]. The original idea behind the development of the remote manipulator was to enable the human operators to do manipulations even in hazardous environments. The technology was widely applied to space operations, hazardous material handling and deep-sea operations. Recently, as the technologies of internet communication, computer science, artificial intelligence, and robot control advance, the applications are not regulated to the traditional areas. As a result, new applications such as telesurgery, domestic nursing care and even travelling to a remote location through a teleoperated robot are becoming possible [2], [3], [4].

Haptic feedback, especially the force feedback is reported to be able to improve the overall task performance of the teleoperated system [5]. This kind of force feedback can be provided by bilateral control. The architectures of a typical bilateral control can be represented as position-position, position-force, or even more sophisticated 4 channel control [6]. However, a time delay is a commonly existing factor that affects the stability of a bilateral control system that involves a real robot and an environment.

The promising solution for stabilizing the bilateral system under network time delay is to make the system passive. Passivity is an important component of non-linear control theory, has been widely applied to the designing of stable controllers for robotic manipulators [7], [8]. The concept of passivity-based control is to modify the system's natural energy input and output to meet the passivity condition while in the meantime achieving the control objectives. The passivity condition states that the energy transfer to the system is lower bounded by the negative initial energy [9].

Applying passivity-based control for bilateral teleoperation is extensively researched. Typically, a teleoperation system can be represented as a two-port network system, the controller design is mainly focused on its stabilization. Wave variable transformation [10] and Time Domain Passivity Approach (TDPA) [11] are two states of the art algorithms that are widely used to stabilize the teleoperation systems under time delay. However, one of the issues for passivity-based control is that stability and transparency become conflicting objectives. The passivity controller will guarantee the stability at the cost of transparency and this becomes critical with increased network delay. In this situation, hard objects are displayed softer than they are [12]. Hence, it is important to provide a solution to compensate for degraded transparency.

The solution could be providing additional visual assistance or visual feedback for the operator. In recent years many researchers have tried to use various visual assistance to improve teleoperation experience. Lipton et al. proposed a teleoperation system with visual assistance by introducing a virtual reality control room [13]. Moreover, an augmented teleoperation system that combines haptic feedback and AR display were proposed by Lee et al [14].

In order to use the additional visual feedback to enhance the degraded transparency of the passivity control, the haptic sensation could be displayed visually. We consider using onomatopoeias for visual feedback is a solution, since it can intrinsically regenerate haptic sensations. Onomatopoeias are words that imitate sounds [15] are commonly used in one's daily life, and are actively used by media and comics to reproduce a certain scene. Moreover, onomatopoeias can be translated into other languages. Onomatopoeia can verbally reproduce one's sensations including visual, auditory and

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tactile. As an example, Doizaki et al. tried to use onomatopoeia to represent texture information and successfully applied it to a product recommendation system [16]. From this perspective, we consider it is able to provide haptic information visually for teleoperation systems.

In this paper, we propose a novel approach that uses onomatopoeias to visually provide haptic information and thus enhancing the degraded transparency of the conventional wave variable based passivity control. A basic onomatopoeia display is implemented based on the contact force detected on the slave side. We evaluated its performance by conducting a stiffness classification experiment, where the subjects need to classify three objects with different stiffness (a hard box, a sponge, and a soft towel). In the experiment, three conditions are given: (1) pure force feedback based on wave variable transformation, (2) pure visual feedback using onomatopoeia and (3) force feedback enhanced by onomatopoeia. The reaction time of the subjects and classification accuracy are evaluated under the conditions of distinctly given constant round trip time delays (0 ms, 500 ms, and 1000 ms).

This paper is organized as follows. In Section II, the implemented passivity-based teleoperation system is introduced. Subsequent Section III presents our onomatopoeia haptic display. Experimental set up and discussions are described in Section IV. Section V provides the conclusions and future works.

II. Passivity-based Teleoperation System

A. System hardware setup

The system hardware setup is shown in Fig. 1. The implemented system is composed of two collaborative robot manipulators (UR5e and UR3e), one Ovrvision Pro stereo camera, one Omega 7 haptic device, one Robotiq gripper, one LCD screen that displays camera image, one Windows PC running Oculus driver and stereo camera driver, and another Linux PC running ROS (Robot Operating System, [17]). Ovrvision Pro is attached to the tool tip of UR3e. Robotiq gripper is attached to the tool tip of UR5e and connected to the computer running ROS directly. The Robotiq gripper can be controlled using ROS packages. UR5e and UR3e both have 6 DOF and Omega 7 haptic device has 7 DOF (6 DOF plus gripper). The partition is used to hide objects from operators during the experiment.

B. Wave variable transformation

The wave variable transformation, also known as scattering transformation is a promising approach to guarantee the passivity of a bilateral teleoperation system with constant time delay [10]. Instead of directly transmitting the power variables (force and velocity) through the network, power variables are first transformed to the wave variables then transmitted through the network. In this way, the output wave amplitude is bounded by the amplitude of the possibly delayed input wave, and thus satisfies the passivity condition which the energy provided by the output waves is limited to the energy received by the input waves.

The architecture of a typical wave variable control is shown in Fig. 2. The vectors u_m and u_s provides the power flow into the system and can be interpreted as input waves. On contrast, v_m and v_s decreases the power flow and can be interpreted as output waves. Those vectors are the linear combination of the force and velocity signals, and defined as:

$$\begin{aligned} u_m &= \frac{1}{\sqrt{2b}}(f_m + b\dot{x}_m) \quad & u_s &= \frac{1}{\sqrt{2b}}(f_s - b\dot{x}_s) \\ v_m &= \frac{1}{\sqrt{2b}}(f_m - b\dot{x}_m) \quad & v_s &= \frac{1}{\sqrt{2b}}(f_s + b\dot{x}_s) \end{aligned} \tag{1}$$

where f_m, f_s, $\dot{x}_m$, $\dot{x}_s$ and b denote for master side force, slave side force, master side velocity, slave side velocity and wave impedance, respectively.

In physical systems, waves are reflected at points where the impedance of the wave carrier changes. This reflection may happen at both slave sites and master sites, and causing oscillatory behavior of the system. Wave impedance matching will terminate this kind of reflection. However, matching the impedance on the master site will modify the system response and introduces scaling for the slave position command, and thus creates positional drift between master and slave. Since strict kinematic accuracy is required for teleoperation systems, this kind of positional drift is not acceptable and should be avoided. Thus, in our implemented system, to avoid wave reflection, wave impedance matching is only implemented on the slave site. The control architecture of the implemented teleoperation system is shown in Fig. 3. Here, f_s is defined as:

$$f_s = f_s' + b\dot{x}_s \tag{2}$$

where f_s' is independent of $\dot{x}_s$, and substitute equation (2) into equation (1) we can obtain the new wave variable transformation as follows:

$$\begin{aligned} u_m &= \frac{1}{\sqrt{2b}}(f_m + b\dot{x}_m) \quad & u_s &= \frac{1}{\sqrt{2b}}f_s' \\ f_m &= b\dot{x}_m + \sqrt{2b}v_m \quad & \dot{x}_s &= -\frac{1}{2b}f_s' + \frac{1}{\sqrt{2b}}v_s \end{aligned} \tag{3}$$

note that, due to the time delay, v_m and v_s, are defined as:

$$v_m = u_s(t-T) \quad v_s = u_m(t-T) \tag{4}$$

By only implementing the impedance matching on the slave side, the position drift is reduced to:

$$x_m(t-T) - x_s(t) = \frac{1}{2b}\int_{t-2T}^{t} f_s'(\tau)d\tau \tag{5}$$

where, x_m and x_s are master position and slave position, respectively [18]. Anderson and Spong stated that the teleoperation system is passive and stable if and only if its scattering operator is no larger than one [19]. The scattering matrix has the form of:

$$S(s) = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \left[H(s) - I\right] \left[H(s) + I\right]^{-1} \tag{6}$$

where $H(s)$ is the hybrid matrix that relates the force and velocities of a teleoperation system. The implemented wave-based control system is stable since its norm of the scattering operator is no larger than one. Note that, the implemented wave-based control architecture is first proposed by [10] and further investigated by [20].

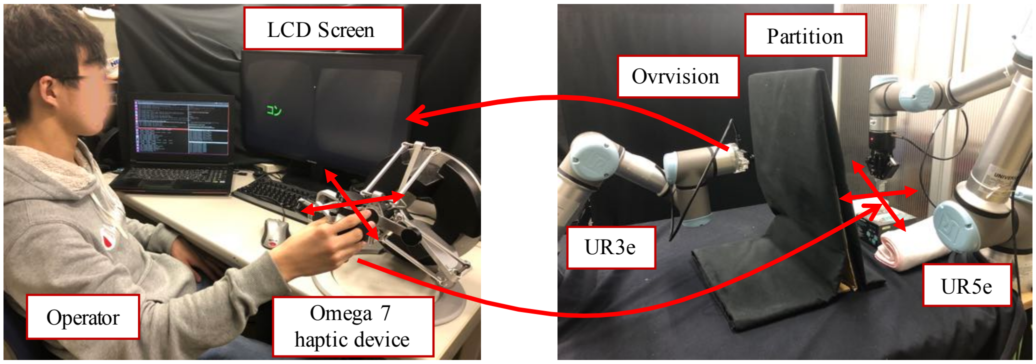

Fig. 1. System hardware setup

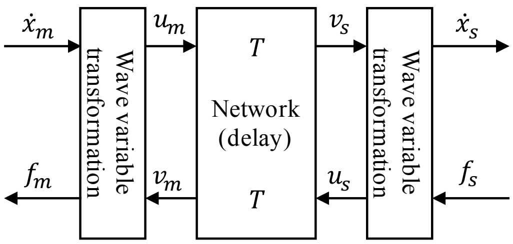

Fig. 2. Wave variable transformation for time delayed teleoperation

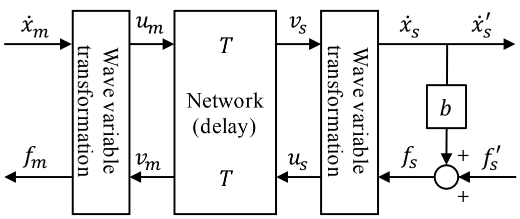

Fig. 3. Wave-based controller with impedance matching on the slave side

(a) Kon (Knock) (b) Fuwa (Fluffy)

Fig. 4. Illustration of displayed onomatopoeias

TABLE I
CONDITIONS FOR SELECTING ONOMATOPOEIAS

Onomatopoeia	K_k (N/m)	Δf_k (N/ms)	$\lvert f_k\rvert$ (N)
Gon	$K_k \geq 10.00$	$\Delta f_k > 0.07$	$\lvert f_k\rvert \geq 5.00$
Kon	$K_k \geq 10.00$	$0.07 \geq \Delta f_k > 0.02$	$\lvert f_k\rvert \leq 3.00$
Fuwa	$0.80 \geq K_k > 0.30$	$0.02 \geq \Delta f_k > 0.01$	$\lvert f_k\rvert \leq 3.00$
Gu	$10.00 \geq K_k > 0.80$	$0.05 \geq \Delta f_k > 0.01$	$\lvert f_k\rvert \leq 3.00$

III. ONOMATOPOEIA HAPTIC DISPLAY

Four kinds of onomatopoeias in Japanese are implemented to represent the haptic sensation related to physical interaction. Those onomatopoeias are *Fuwa*, *Kon*, *Gon* and *Gu*. The word *Fuwa* would represent a state of touching a soft object. *Kon* would describe relatively light contact with a hard object and *Gon* would describe contact with a hard object which involves a larger magnitude of the force. In addition to the basic three onomatopoeias (*Fuwa*, *Kon* and *Gon*), the fourth onomatopoeia is prepared to represent the stiffness which is softer than *Kon* but stiffer than *Fuwa*. The fourth onomatopoeia is called *Gu*, which represents the state of contacting and pressing an object that has moderately stiff characteristics (such as the given sponge in the experiment). Fig. 4 illustrates some onomatopoeias which are projected on an uniform background and displayed on an LCD screen.

Desirable onomatopoeias for display are selected in real-time by considering the contact force measured by the force/torque sensor mounted on the slave side robot. Three parameters are chosen to represent the contact state of the robot end-effector and the environment. Those parameters are $|f_k|$, Δf_k and K_k, which are the norm of the translational force vector, the estimated time derivative of the norm of the translational force vector and the estimated stiffness based on Euler discretization, respectively. Here, k represents the current time. The estimated time derivative of translational force Δf_k is given by

$$\Delta f_k = \frac{|f_k| - |f_{k-1}|}{\Delta T} \tag{7}$$

where ΔT is the sampling time and $|f_k|$ is the norm of the translational force vector. The estimated stiffness K_k is then given by

$$K_k = \frac{|f_k| - |f_{k-1}|}{|v_k|\Delta T} = \frac{\Delta f_k}{|v_k|} \tag{8}$$

where $|v_k|$ denotes the norm of the end-effector velocity.

The thresholds of the parameters are empirically determined through an object-contact experiment. We used the manipulator to touch each object 10 times, and recorded the value of the three parameters. By referencing the recorded data, we determined the appropriate thresholds of the parameters that can distinguish the three objects. The appropriate onomatopoeia to display is selected by referencing to the threshold of the parameters in Table I.

IV. Experiment and Discussion

The experiment is carried out to evaluate the effect of onomatopoeia haptic display on enhancing the degraded transparency of passivity control which is caused by communicational time delay. The experiment is performed by 3 healthy men subjects. The age of the subjects is 30, 30 and 22, respectively.

A. Experimental setup

1) Robot setup: In the experiment, the DOF of the slave side robot is regulated to 1, this one DOF only allows the robot to move along the z-axis (up and down). The wave impedance b is set to 40 Ns/m.

2) Experimental conditions: Three ways to display the remote force are prepared for the operators: (1) by purely using the force feedback provided by the system, (2) by purely using the onomatopoeia haptic display, the system force feedback is turned off, and (3) by using the force feedback provided by the system simultaneously with the onomatopoeia haptic display. Note that onomatopoeia haptic display uses four onomatopoeias (*Fuwa*, *Kon*, *Gon* and *Gu*).

Then, three kinds of constant round trip time delays are prepared: (1) 0 ms, (2) 500 ms and (3) 1000 ms. Each experimental set consists of one kind of time delay and one kind of force display method. And in each experimental set, 15 trials are included. Among the 15 trials, 5 trials are given for each object (in total, 3 objects for classification). The operators do not know the experimental outcomes before and during the experiment.

3) Experimental task: The experimental task for the operators are to classify three objects with different stiffness. To focus on the effect of onomatopoeia based visual assistance, the objects are completely hidden from the operators and are randomly given on each trial. And the onomatopoeia is displayed on a simple LCD screen with uniformed background. In each trial, only one object is given, the operators need to control the slave robot to approach the object, and to classify the given object through perceived impedance reflected by the master interface. The experimental setup and given three objects are illustrated in Fig. 5. Three objects are a hard box, a sponge and a folded towel. The stiffness of the given sponge is the intermediate of the hard box and the towel.

The three objects appear commonly in one's daily life, and before the experiment, the operators are allowed to touch the three objects. The operators are asked to answer instantly the object's name when they know what the given object is.

4) Experimental measurement: During the experiment, two parameters are measured: (1) reaction time for the operators to give an answer and (2) the accuracy of the given answer. Reaction time is defined as when the end effector of the robot touches the objects until the operators give an answer.

B. Preliminary experimental results and discussion

The preliminary experimental results are given in this section. Note that in Fig. 6, Fig. 7 and Fig. 8 "**" denotes for $p < 0.01$, and "*" denotes for $p < 0.05$. Here p is defined as the probability value in statistical hypothesis testing.

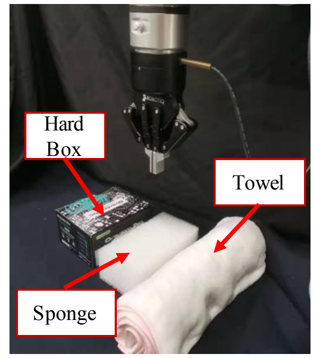

Fig. 5. Experimental setup and given objects for classification

1) Reaction time: Fig. 6 is the box plots of the operators' reaction times when the given object is the hard box. When the time delay is set to 0 ms, the mean value of the reaction time using pure force feedback is less than that of pure onomatopoeia haptic display. The mean value of reaction time using onomatopoeia enhanced force feedback is the highest among three conditions when there is no time delay. As the time delay increases, the mean reaction times for pure force feedback methods and pure onomatopoeia increase slightly. In every set of increased time delay, onomatopoeia enhanced force feedback keeps the least mean reaction time. When the time delay is increased to 1000 ms, the reaction time of pure force feedback shows more distribution. When the delay is 1000 ms, a significant difference is observed between pure force feedback and pure onomatopoeia feedback. This may imply that pure onomatopoeia feedback helps the operators to perceive the stiffness without much divergence from the mean reaction time as compared to pure force feedback.

Fig. 7 is the box plots of the operators' reaction times when the given object is the sponge. As time delay increases the mean reaction time for each feedback method increases. In every set of time delay, the mean reaction time of onomatopoeia enhanced force feedback remains the least. This may imply that the onomatopoeia enhanced force feedback provides additional information which improves the stiffness perception and helps the subjects to classify the object.

Fig. 8 is the box plots of the operators' reaction times when the given object is the towel. When time delay is no greater than 500 ms, the mean reaction time of pure force feedback is less than pure onomatopoeia feedback. When time delay reaches to 1000 ms, the mean reaction time of pure onomatopoeia feedback is less than pure force feedback. In every sets of time delay, the mean value of reaction time using onomatopoeia enhanced force feedback is the least among three conditions.

2) Classification accuracy: Fig. 9 shows the average of the classification accuracies in the three time delays of each feedback method. When the time delay is 0 ms, Onomatopoeia enhanced force feedback has the highest accuracy, the pure onomatopoeia visual feedback has the second-highest accuracy and the pure force feedback the third. This would imply that even without time delay, using onomatopoeia to enhance the force feedback could still bring positive effects on the

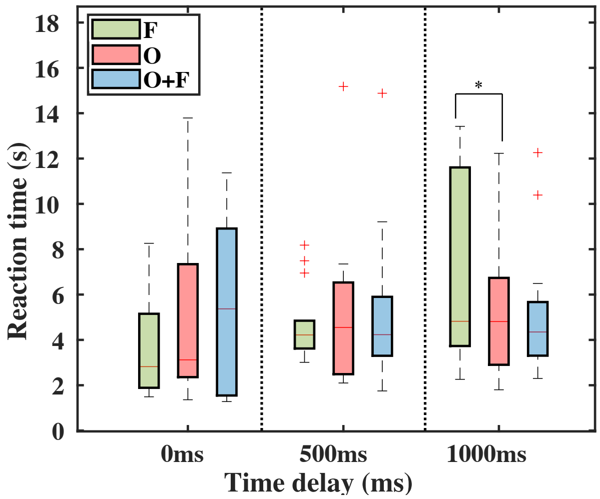

Fig. 6. Reaction time for classification of the hard box.

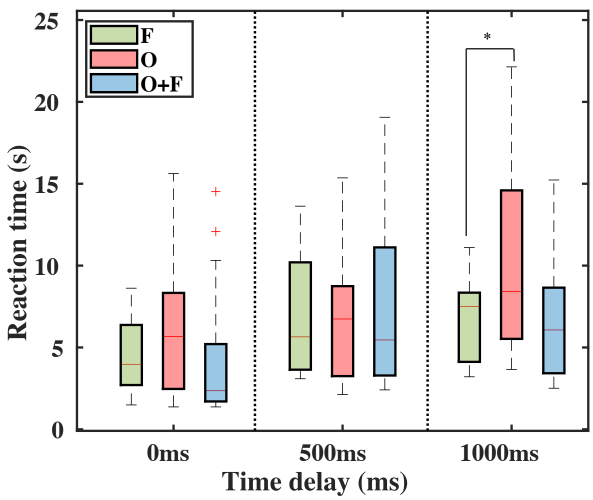

Fig. 7. Reaction time for classification of the sponge.

perception of remote stiffness. When time delay is increased to 500ms, the result indicates that the operators are still able to perceive the remote stiffness using pure force feedback. However, when the delay is increased to 1000 ms, the accuracy of pure force feedback decreases and pure onomatopoeia feedback and onomatopoeia enhanced force feedback remain the higher accuracy. From this point, the visually displayed haptic information becomes superior to the pure force feedback, even though the onomatopoeia enhanced force feedback has the highest accuracy. This result indicates that, when there is a large time delay the onomatopoeia could provide some additional haptic information for the passivity based force feedback that maintains its perception accuracy and thus enhancing the transparency.

Table II is a confusion matrix of the pure force feedback including all set of time delay. The accuracy of the box, sponge and towel are 0.87, 0.76 and 1.00, respectively. The data indicates that when using the pure force feedback, the operators are tend to confuse the classification of the box and

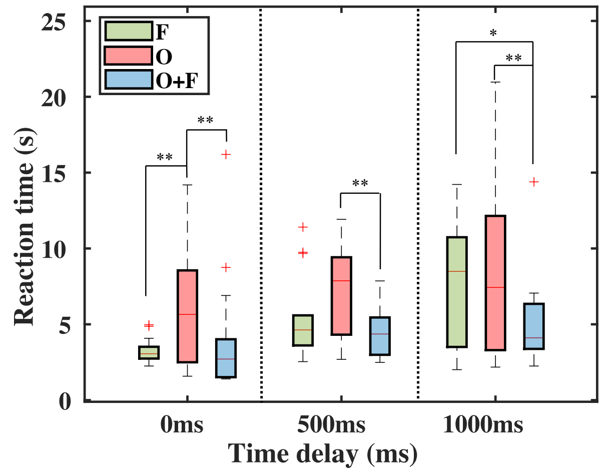

Fig. 8. Reaction time for classification of the towel.

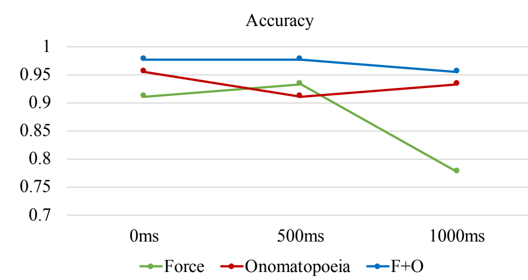

Fig. 9. Accuracy of the classification.

the sponge. While, the classification for the towel is accurate.

Table III is a confusion matrix of the pure onomatopoeia based visual feedback including all set of time delay. The accuracy of the box, sponge and, towel are 0.96, 0.91 and 0.93, respectively. The data indicates that when using the pure onomatopoeia based visual feedback, the operators have small confusion to classify the box and the sponge, and also the sponge and the towel.

Table IV is a confusion matrix of the onomatopoeia enhanced force feedback including all set of time delay. The accuracy of the box, sponge and, towel are 0.98, 0.96 and 0.98, respectively. The data indicates a high accuracy of the classification for the three objects.

By comparing Table II and Table III, it is observed that when the objects are relatively stiff (the box and the sponge), the onomatopoeia visual feedback has the advantage to tell the difference of the two object. However, when the object is soft (the towel), the pure force feedback has the advantage to differentiate the object from other relatively stiff objects. Table IV shows that the onomatopoeia enhanced force feedback improves the overall classification accuracy as compared to Table II and Table III.

V. Conclusions and Future Work

This paper proposes a novel approach to enhance the transparency of a passivity-based teleoperation system with communicational time-delay. The proposed approach is to use

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TABLE II
CONFUSION MATRIX OF THE PURE FORCE FEEDBACK.

		Perceived			
	Objects	Box	Sponge	Towel	Accuracy
Actual	Box	39	6	0	0.87
	Sponge	9	34	2	0.76
	Towel	0	0	45	1.00

TABLE III
CONFUSION MATRIX OF THE PURE ONOMATOPOEIA VISUAL FEEDBACK.

		Perceived			
	Objects	Box	Sponge	Towel	Accuracy
Actual	Box	43	2	0	0.96
	Sponge	3	41	0	0.91
	Towel	0	3	42	0.93

onomatopoeias to visually provide additional haptic information. It enhances transparency by displaying different kinds of onomatopoeia according to the slave side contact force. To evaluate the performance of the onomatopoeia based visual feedback, a stiffness classification experiment is conducted under distinctly given constant round trip time delays (0 ms, 500 ms, and 1000 ms). The preliminary results show that the operators have higher accuracy for classifying the stiffness of a remote object by using onomatopoeia enhanced force feedback compared with the conventional passivity-based position-force feedback method. The preliminary results verify the ability of onomatopoeia for enhancing the transparency of the passivity-based teleoperation system.

Future work will be investigating a way to numerically tune the parameters for onomatopoeia selection and improve its accuracy. This could lead to machine learning-based parameter selection and more sophisticated stiffness measurement algorithms could be implemented to increase the overall experience of the onomatopoeia based visual feedback. It could also be an interesting topic to research on how to extend the onomatopoeia to softer objects, such as by inducing the color change to displayed onomatopoeias to make it have a continuous characteristic.

In addition, onomatopoeias can be projected on Head Mounted Display which is widely used in Augmented Reality (AR) applications. In this way, the findings can be further extended to AR-enhanced teleoperations, such as the onomatopoeias can be displayed with direction indicators to intuitively indicate some potential collisions at the blind spot of a stereo camera, or it can act as a sensory substitution strategy that indicates force intensity for telemanipulation tasks.

TABLE IV
CONFUSION MATRIX OF THE ONOMATOPOEIA ENHANCED FORCE FEEDBACK.

		Perceived			
	Objects	Box	Sponge	Towel	Accuracy
Actual	Box	44	1	0	0.98
	Sponge	2	43	0	0.96
	Towel	0	1	44	0.98

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