Human Perception of Force in Cooperation between Remote Robot Systems with Force Feedback

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***Abstract*—In this paper, we clarify human perception of force by carrying out quality of experience (QoE) assessment in cooperation between two remote robot systems with force feedback. In the cooperation, robot arms of the two remote robot systems grasp both ends of each wooden stick, and then one side of the stick is moved only in one direction of front and back, left and right, and up and down. A user can perceive force sensed by a force sensor attached to the tip of the robot arm via a haptic interface device. Then, we investigate to what extent humans can accurately perceive the force direction via the haptic interface device. We also examine the influence of the length of the wooden stick on the human perception of force direction.**

***Index Terms*—remote robot system, force feedback, human perception, QoE assessment**

I. Introduction

Recently, a number of researchers focus on remote robot systems with force feedback [1]-[4] in each of which a user at the master terminal remotely controls an industrial robot arm at the slave terminal by operating a haptic interface device while watching video [5]-[7]. The user can perceive the shape, weight, and softness of a remote object via the haptic interface device during the operation. Thus, the efficiency and accuracy of work can greatly be improved. However, when the information about haptic sense is transmitted over a network such as the Internet, which does not guarantee the quality of service (QoS) [8], the quality of experience (QoE) [9] such as the operability of the haptic interface device may seriously be degraded owing to the network delay, delay jitter, and packet loss. To solve the problem, we need to exert QoS control. Moreover, to carry out QoS control efficiently, human perception of the force (i.e., the shape, weight, and softness of a remote object) should be clarified [10].

In [10], the authors investigate the influences of weight change on human perception of weight by using a haptic interface device in a networked virtual environment by QoE assessment. Assessment results show that humans can hardly perceive absolute weight changes lighter than or equal to about 10 gf, and they start to perceive absolute weight changes heavier than about 20 gf. However, it is necessary to investigate human perception in a real environment as well as in a virtual environment. Especially, human perception of force by force feedback has not sufficiently been clarified so far.

In this paper, therefore, we carry out QoE assessment of human perception of force in cooperation between two remote robot systems with force feedback. In the assessment, ends of a wooden stick are grasped with two industrial robot arms of the systems. We move one side of the stick in one direction of front and back, left and right, and up and down at one industrial robot arm, and then we investigate to what extent each subject can accurately perceive the force direction via a haptic interface device on the other industrial robot arm side. We also investigate the influence of the length of the wooden stick on the human perception of force direction.

The rest of this report is organized as follows. Section II describes the remote robot system with force feedback. Then, the QoE assessment method is explained in section III, and assessment results are presented in section IV. Finally, we conclude the paper in section V.

II. Remote Robot System with Force Feedback

A. System Configuration

Fig. 1 shows the configuration of the two remote robot systems with force feedback (called *systems 1 and 2* here) which are used in our QoE assessment. In each system, PC for a haptic interface device at the master terminal and PC for an industrial robot at the slave terminal are connected to each other by switching hubs over a network. The haptic interface device called Geomagic Touch [11] is connected to the PC for the haptic interface device. PC for the industrial robot is directly connected to the industrial robot via an Ethernet (100 BASE-TX) cable. The industrial robot consists of a robot arm (RV-2F-D [12], RV-2FB-Q [13] by Mitsubishi Electric Corp.), a robot controller (CR750-Q [12], [13]), a force interface unit (2F-TZ561 [14]), and a force sensor (1F-FS001-W200 [14]) which is attached to the surface of the flange of the robot arm.

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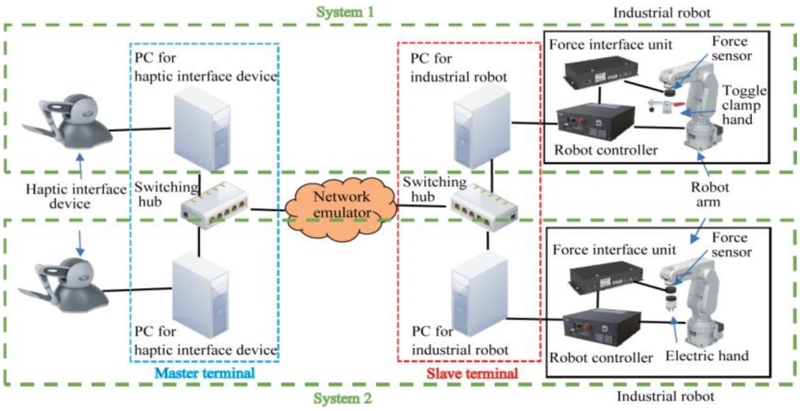


Figure 1. Configuration of two remote robot systems with force feedback in assessment.

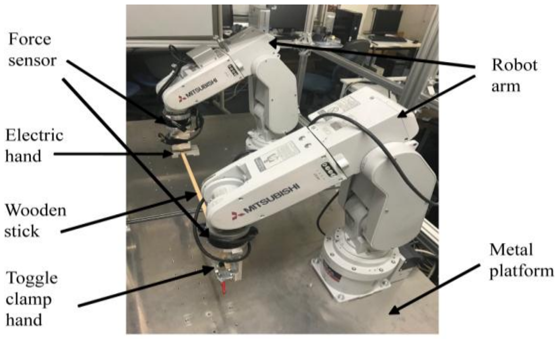


Figure 2. Appearance of two robot arms.

In the assessment, a network emulator is used to connect the two switching hubs [15]. A toggle clamp hand [16] is fixed to the tip of one force sensor, and an electric hand [17] is installed to the tip of the other force sensor. As shown in Fig. 2, the two robot arms are set on a metal platform.

B. Remote Operation

In each system of Fig. 1, a user can operate the robot arm remotely by using the haptic interface device. The initial position about the stylus of the haptic interface device is the original position which corresponds to the initial position of the industrial robot (i.e., the hand attached to the tip of the robot arm). The master terminal acquires the position information from the haptic interface device every millisecond, calculates the reaction force, and outputs it via the device. Then, the position information is transmitted to the slave terminal by UDP. The slave terminal employs the real-time control function [18] to obtain the information about the position of the industrial robot and to send instruction to the robot, and the terminal uses the real-time monitor function [18] to get the information about the force sensor from the robot controller every 3.5 milliseconds. The two types of information are transmitted as different packets between the robot controller and PC for the industrial robot by UDP. Then, PC for the industrial robot sends the position information of the robot arm and force information to the master terminal.

At the master terminal, the reaction force $\boldsymbol{F}_t^{(\mathrm{m})}$ outputted at time t (ms) ($t \geq 1$) against the haptic interface device is calculated as follows:

$$\boldsymbol{F}_t^{(\mathrm{m})} = K_{\mathrm{scale}} \boldsymbol{F}_{t-1}^{(\mathrm{s})} \tag{1}$$

where $\boldsymbol{F}_t^{(\mathrm{s})}$ is the force received from the slave terminal at time t. To obtain $\boldsymbol{F}_t^{(\mathrm{m})}$, $\boldsymbol{F}_{t-1}^{(\mathrm{s})}$ is multiplied by K_{scale} which is the mapping ratio about the force between the industrial robot and the haptic interface device (K_{scale} = 1.0 [4] in this paper). Moreover, if the absolute value of reaction force exceeds the maximum allowable reaction force of 3.3 N, 3.3 N is outputted.

At the slave terminal, the industrial robot arm is operated on the basis of the position information transmitted from the master terminal. In this paper, we control the robot arm directly by key input. Therefore, the position vector about the tip of the industrial robot arm $\boldsymbol{S}_t$ ($t \geq 1$) is calculated as follows:

$$\boldsymbol{S}_t = \begin{cases} \boldsymbol{M}_{t-1} & (|\boldsymbol{V}_{t-1}| \leq V_{\max}) \\ \boldsymbol{M}_{t-1} + V_{\max} \frac{\boldsymbol{V}_{t-1}}{|\boldsymbol{V}_{t-1}|} & (\text{otherwise}) \end{cases} \tag{2}$$

where $\boldsymbol{M}_t$ is the position vector about the stylus of the haptic interface device that is received from the master terminal at time t. $\boldsymbol{V}_t$ is the velocity of the industrial robot arm at time t. The moving velocity is limited to the maximum velocity $V_{\max}$ which is set to 5 mm/s in this paper.

III. Assessment Method

In our assessment, as shown in Fig. 2, the two robot arms grasp both ends of a wooden stick with a toggle clamp hand and a electric hand. We call the robot arm with the toggle clamp hand as *robot arm 1* and the robot arm with the electric hand as *robot arm 2* in this paper.

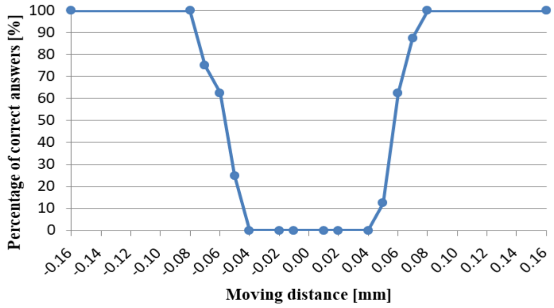
In the assessment, we moved only one side of the wooden stick at robot arm 1 in one direction of front and back, left and right, and up and down with key input. Then, each subject tried to perceive force at the master terminal through the haptic interface device which is connected to robot arm 2 (i.e., system 2) and answered in which direction the wooden stick was moved. In each assessment, the subject just held the stylus of the device to perceive the force. It should be noted that the haptic interface device in system 1 was not used in the assessment.

To investigate the influence of the length of wooden stick on the human perception of the force direction, we use wooden sticks with two different lengths (width 10 mm × height 10 mm × lengths 300 mm and 600 mm) in the assessment. When the length of the wood stick is 300 mm (called the 300 mm case), the absolute moving distance is changed from 0.01 mm to 0.16 mm. In the 600 mm case, the absolute moving distance in the front-back direction is from 0.06 mm to 0.48 mm, that in the left-right direction is from 0.01 mm to 0.16 mm, and that in the up-down direction is from 0.06 mm to 0.66 mm.

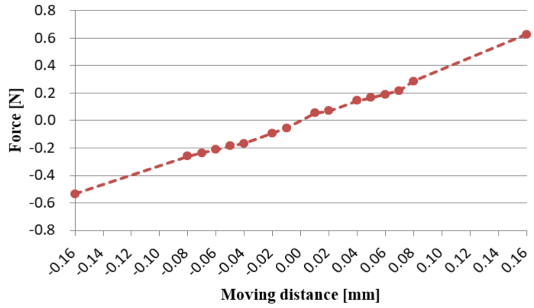
Each subject was asked to select one answer from among the following three answers: “I can perceive the force and know the moving direction,” “I can perceive the force but do not know the moving direction,” “I cannot perceive any force.” If the subject knew the moving direction, he/she was asked to say the moving direction. There were 15 subjects in the assessment, and the moving distance and moving direction were selected in random order per subject. We calculated the percentage of correct answers (i.e., each subject perceived the force and answered the correct moving direction).

IV. Assessment Results

Assessment results in the 300 mm and 600 mm cases are shown in Figs. 3 through 5 and Fig. 6, respectively. Due to space limitation of the paper, we only show results in the front-back direction in the 600 mm case. This is because we observed that quantitative relations among assessment results of the three directions in the 600 mm case are similar to those in the 300 mm case. Fig. (a) in each figure shows the percentage of correct answers versus the moving distance in direction of front-back, left-right, and up-down (negative values indicate back, right, and down). The average of average reaction force is shown in Fig. (b).

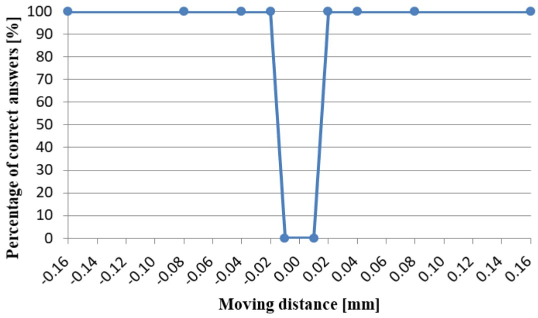


(a) Percentage of correct answers

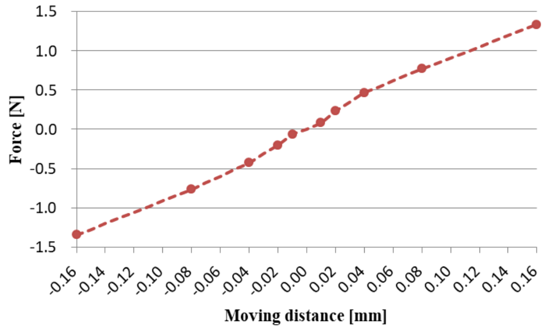


(b) Average of average reaction force

Figure 3. Assessment results of front-back direction in 300 mm case.

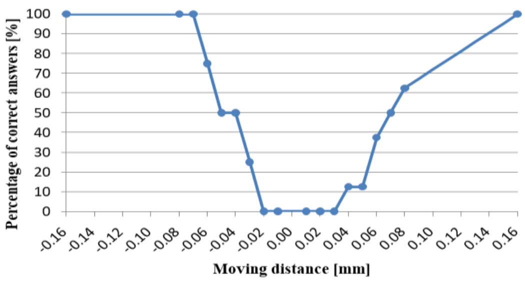


(a) Percentage of correct answers

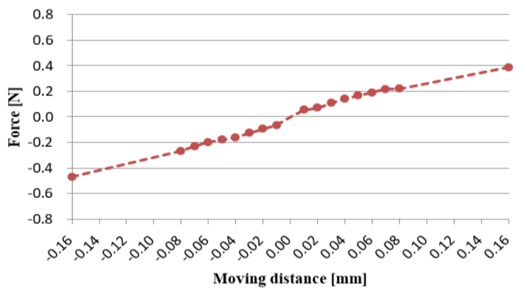


(b) Average of average reaction force

Figure 4. Assessment results of left-right direction in 300 mm case.

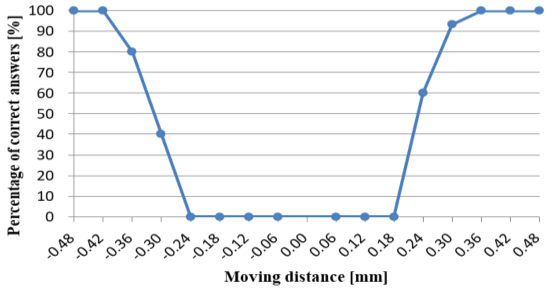


(a) Percentage of correct answers

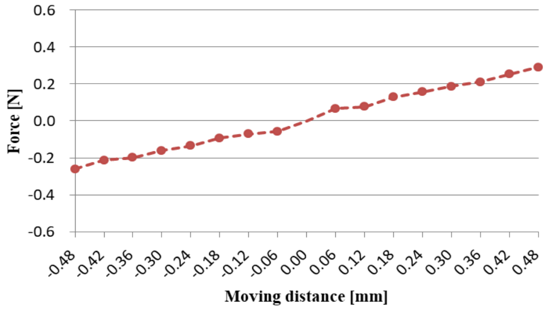


(b) Average of average reaction force

Figure 5. Assessment results of up-down direction in 300 mm case

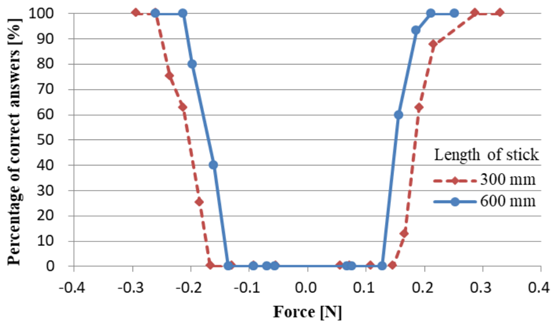


(a) Percentage of correct answers

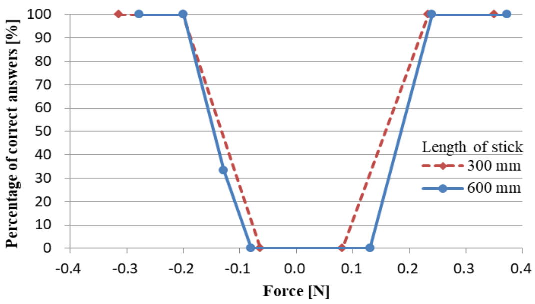


(b) Average of average reaction force

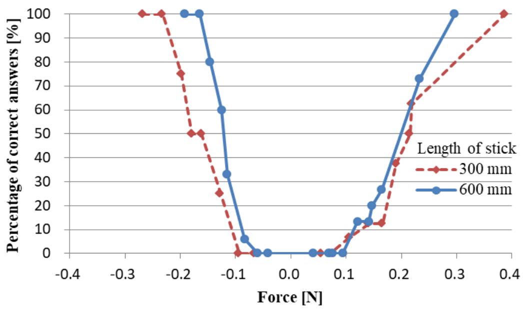
Figure 6. Assessment results of front-back direction in 600 mm case.



(a) Front-back direction



(b) Left-right direction



(c) Up-down direction

Figure 7. Percentage of correct answers versus force.

From Figs. 3(a), 4(a), and 5(a), we see that the percentage of correct answers in each direction increases as the absolute moving distance becomes larger. This means that more subjects can perceive the force and know the correct force direction as the moving distance increases. Also, in the figures, the percentages in the front-back and left-right directions (Figs. 3(a) and 4(a)) are almost symmetric with respect to a vertical line of the moving distance at 0.00 mm; we cannot see such symmetry in the up-down direction (Fig. 5(a)). In Figs. 3(b), 4(b), and 5(b), we find that the averages of average reaction force in each direction increase almost linearly as the moving distance becomes larger.

From Fig. 6, we observe that the absolute moving distances with a certain percentage in the front-back direction are larger and the corresponding forces are smaller than the results with the percentage in Fig. 3. This is because the wooden stick easily bends when the stick is long; thus, the force is easy to be absorbed.

To examine the relation between the percentage of correct answers and the force in further detail, we plot the percentages of correct answers versus the force in the 300 mm and 600 mm cases in Fig. 7 based on the above results. From the figure, we see that when the absolute value of the force in each direction is less than about 0.1 N, the percentages are almost 0% in both cases. This means that all the subjects could not perceive any force. We find in the figure that the percentages of correct answers increase as the absolute force becomes larger. Also, more than about 80% subjects can feel the force and answer the correct directions when the absolute value of force is stronger than about 0.2 N in each direction. The percentages are symmetric with respect to a vertical line of the force at 0.0 N in the front-back and left-right directions; we cannot see such symmetry in the up-down direction. This is because each subject holds the stylus of the haptic interface device in the assessment; it is difficult for the subjects to perceive the force in the up direction owing to the gravity. Furthermore, we note that the percentages in the 300 mm case are close to those in the 600 mm case. This means that the human perception of the force hardly depends on the length of the wood stick in our assessment.

Therefore, we can say that the human perception characteristics of the force do not heavily depend on the direction of force (excluding the up direction).

V. Conclusion

In this paper, we carried out QoE assessment to investigate to what extent humans can accurately perceive the force direction by using a haptic interface device in cooperation between the remote robot systems with force feedback. We also investigated the influence of the length of wooden stick on the human perception of the force direction. As a result, we found that humans can perceive the force correctly as the force is stronger than or equal to about 0.2 N. We also saw that the human perception of the force hardly depends on the length of the wood stick in the assessment.

As the next step of our research, we will carry out the assessment by using grasped sticks with different types of softness.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All the authors conducted the research; Qin Qian and Daiki Osada analyzed the data; Qin Qian wrote the paper, Yutaka Ishibashi revised the paper, and the others made some comments; all the authors had approved the final version.

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