Influences of Network Delays on Dual-User Operation in Remote Robot Systems with Force Feedback

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Outline

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Background (1/2)

- Many researchers have focused on remote robot systems with force feedback.

Users can touch remote objects and feel the reaction force from the objects

- By using a remote robot system with force feedback, various tasks can be performed efficiently.

It is important to take account of that network delays between the remote robot and users may vary.

Background (2/2)

When force information is transmitted over the Internet, which does not guarantee the QoS (Quality of Service)

↓ Network delay, delay jitter and packet loss

QoE (Quality of Experience) degradation

↓

To develop effective QoS control solutions for the issues, it is essential to investigate influences of network factors.

Previous Work (1/2)

*1 T. Hagiwara *et al.,* iScience, Nov. 2020.
*2 R. Ye *et al.*, in Proc. IEEE ICCE-TW, July 2023.

- **Carried out tasks by controlling an avatar together in a virtual environment and found that two users performed better than one user.**[*1]
- **Demonstrated that in a networked haptic game, a player with the smaller delay can help the other player (i.e., a teammate) with the higher delay**[*1]
- **In the remote robot system with force feedback, dual-user operation may be more effective than single-user operation.**[*2]

Previous Work(2/2)

*2 R. Ye *et al*., in Proc. IEEE ICCE-TW, July 2023.

In the remote robot system with force feedback

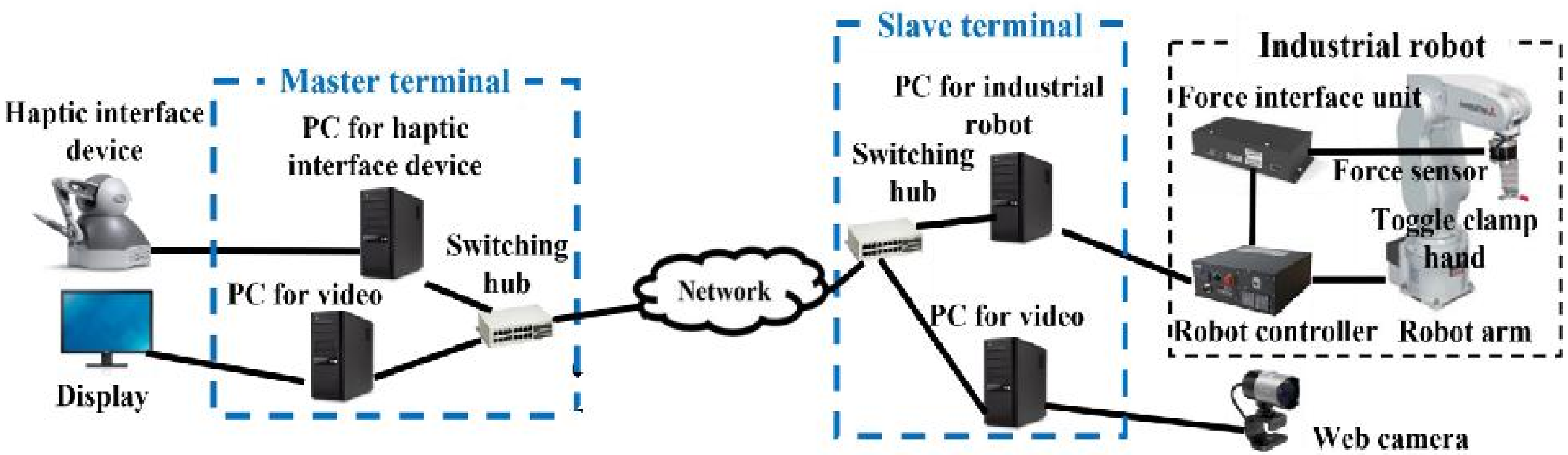
- **the performance of dual-user operation under varying network delay conditions is still unclear.**
- **The user with the smaller delay assists the other user, but it has not been evaluated.[*2]**

Purpose

This work

- **In the remote robot system with force feedback，Explore dual-user performance in diverse network delays.**
- **Assess if users with shorter delays assist others effectively.**

Remote Robot Systems with Force Feedback



System configuration of single-user operation

Calculation of Force

*3 R. Ye *et al*., ITE-ME Technical Report, Dec. 2022.

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

- $\boldsymbol{F}_t^{(\mathrm{m})}$: **Force outputted at master terminal at time t ($t \geq 1$)**
- $\boldsymbol{F}_t^{(\mathrm{s})}$: **Force received from slave terminal at time t**
- $\boldsymbol{K}_{\mathrm{scale}}^{(\mathrm{F})}$: **Mapping scale about force between industrial robot and haptic interface device ($\boldsymbol{K}_{\mathrm{scale}}^{(\mathrm{F})}$=0.33[*3])**

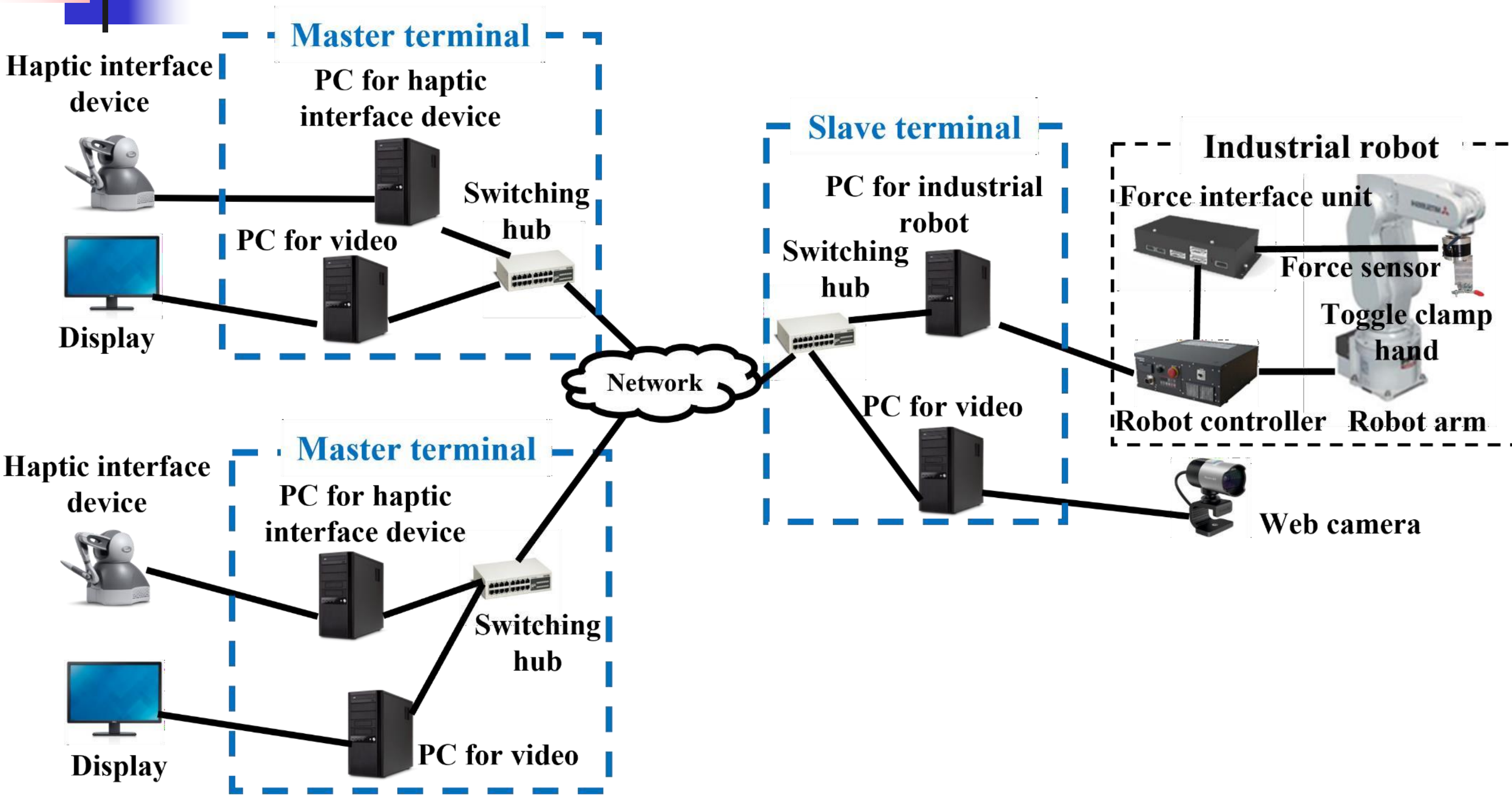
Calculation of Position

*3 R. Ye *et al*., ITE-ME Technical Report, Dec. 2022.

$$\boldsymbol{S}_t = K_{\text{scale}}^{(\text{P})} \boldsymbol{M}_{t-1} + \boldsymbol{V}_{t-1}$$

- $\boldsymbol{S}_t$ **: Position vector of industrial robot at time *t* (*t* ≥ 1)**
- $\boldsymbol{M}_t$ **: Position vector of haptic interface device at time *t***
- $\boldsymbol{V}_t$**: Moving velocity of industrial robot at time *t***
- $K_{\text{scale}}^{(\text{P})}$ **: Mapping scale about position between industrial robot and haptic interface device** ($K_{\text{scale}}^{(\text{P})} = 0.5$ [*3])

Dual-user Operation (1/2)



System configuration of dual-user operation

Dual-user Operation (2/2)

*3 R. Ye *et al.*, ITE-ME Technical Report, Dec. 2022.

Calculation of Force

$$\boldsymbol{F}_t^{(1)} = \boldsymbol{F}_t^{(2)} = K_{\text{scale}}^{(\text{F})} \boldsymbol{F}_{t-1}^{(\text{s})}$$

- $\boldsymbol{F}_t^{(i)}$ **: Force outputted at master terminal *i* (*i* = 1 or 2) at time *t* (*t* ≥ 1)**
- $K_{\text{scale}}^{(\text{F})} = 0.142$ *3

Calculation of Position

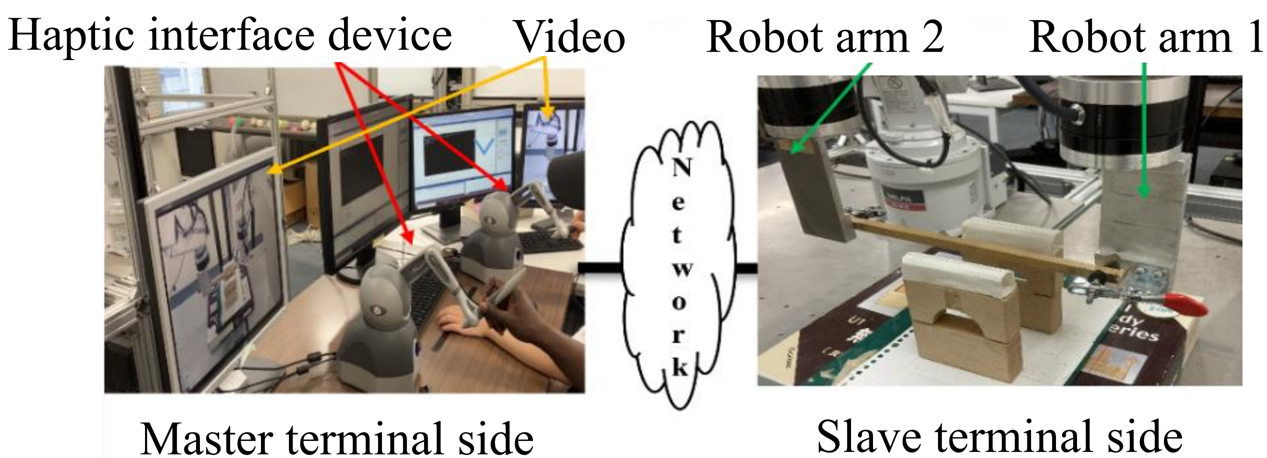
$$\boldsymbol{S}_t = K_{\text{scale}}^{(\text{P})} \left\{ \left(\boldsymbol{M}_{t-1}^{(1)} + \boldsymbol{M}_{t-1}^{(2)} \right) /2 \right\} + \boldsymbol{V}_{t-1}$$

- $\boldsymbol{M}_t^{(i)}$**: Position vector of haptic interface device *i* (*i* = 1 or 2) at time *t* (*t* ≥ 1)**

Experiment Method (1/4)

- **Each user operated the haptic interface device with his/her hand while watching video.**

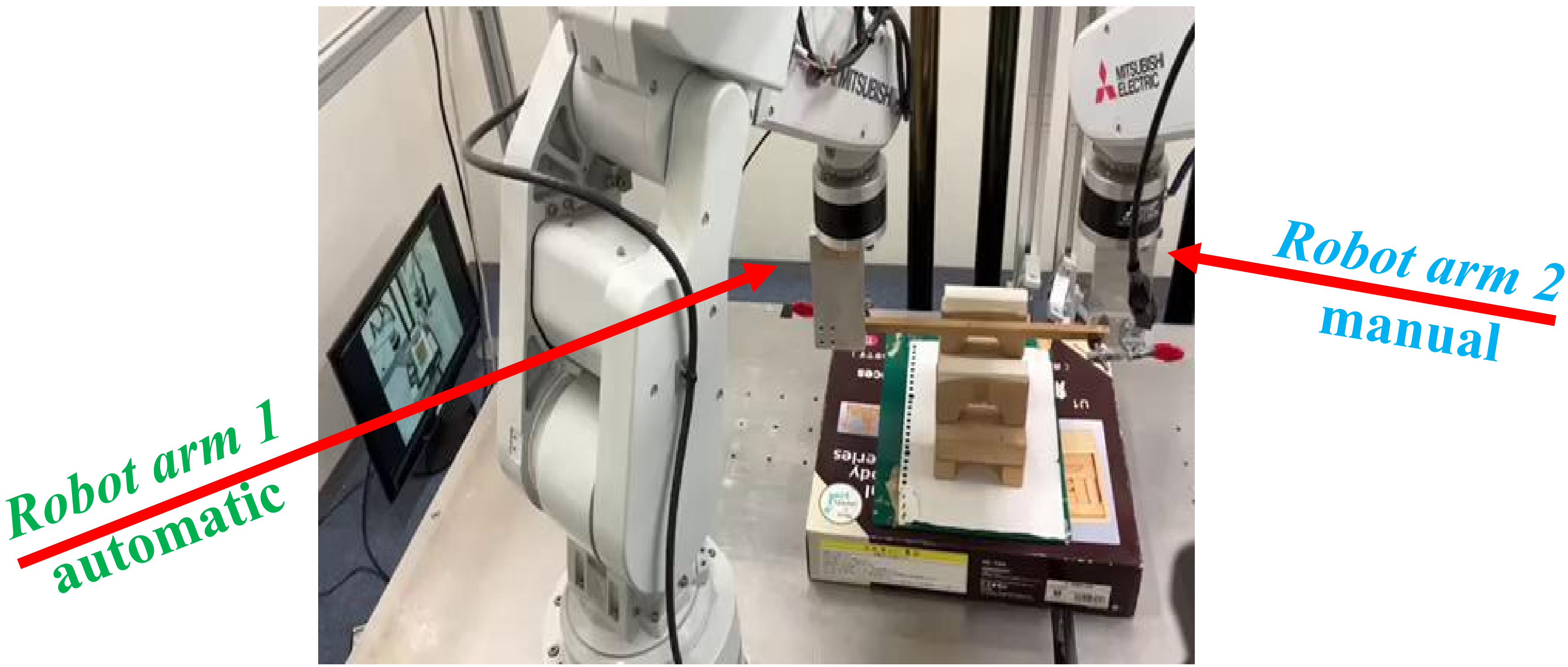
- **We conducted a cooperation work involving the movement of an object (a wooden stick) clamped by the two robot arms in the front-back direction.**



Appearance at master and slave terminals

Experiment Method (2/4)

- **One of the two robot arms (referred to as *robot arm 1*) moved automatically and the other robot arm (*robot arm 2*) was moved by two users in the same way as *robot arm 1*.**



Experiment Method (3/4)

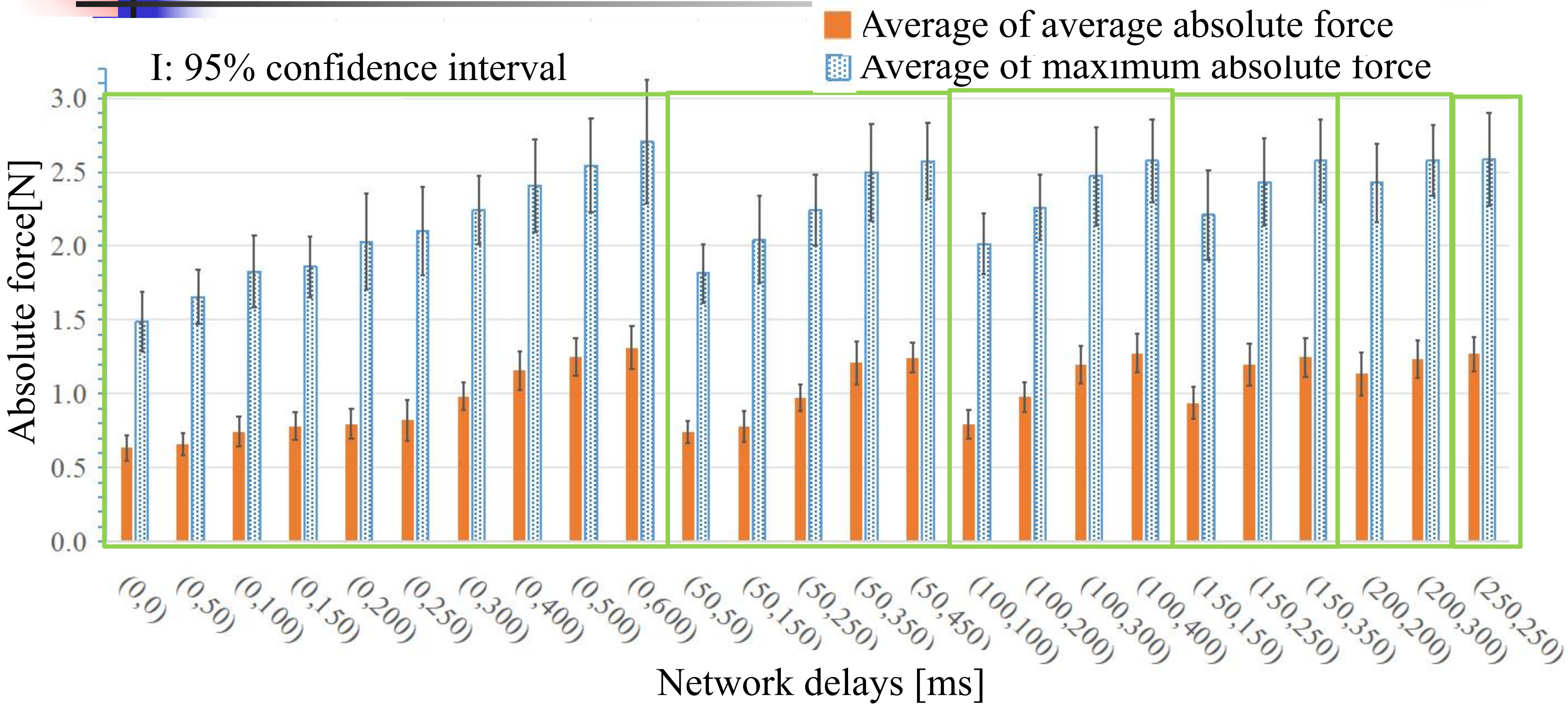
Experiment Method (4/4)

- **The work was performed 20 times for each combination of the network delays.**

- **A constant network delay was generated for each packet transferred between the master and slave terminals by a network emulator. For one user, the constant delay ranged from 0 ms to 250 ms at 50 ms intervals, while for the other user, it varied from 0 ms to 600 ms at 50 ms or 100 ms intervals.**

- **Conducted 20 times for each combination of the additional delay and obtained the average and maximum absolute force of *robot arm 2* and calculated the average of the two measures for 20 times (referred to as the average of average absolute force and average of maximum absolute force, respectively)**

Experimental Results (1/3)



Average of average absolute force and average of maximum absolute force

Experimental Results (2/3)

A part of the results of t-test between combinations of network delays.

t-test	(50,50)	(50,150)	(50,250)	(100,100)	(100,200)	(150,150)	……
(0,100)	0.93 0.97	0.00 0.62	0.03 0.01	0.12 0.39	0.03 0.01	0.07 0.01	
(0,200)	0.28 0.38	0.82 0.39	0.33 0.03	0.93 0.96	0.27 0.05	0.51 0.16	
(0,300)	0.01 0.00	0.00 0.01	0.84 0.45	0.11 0.00	0.97 0.94	0.39 0.51	
⋮							

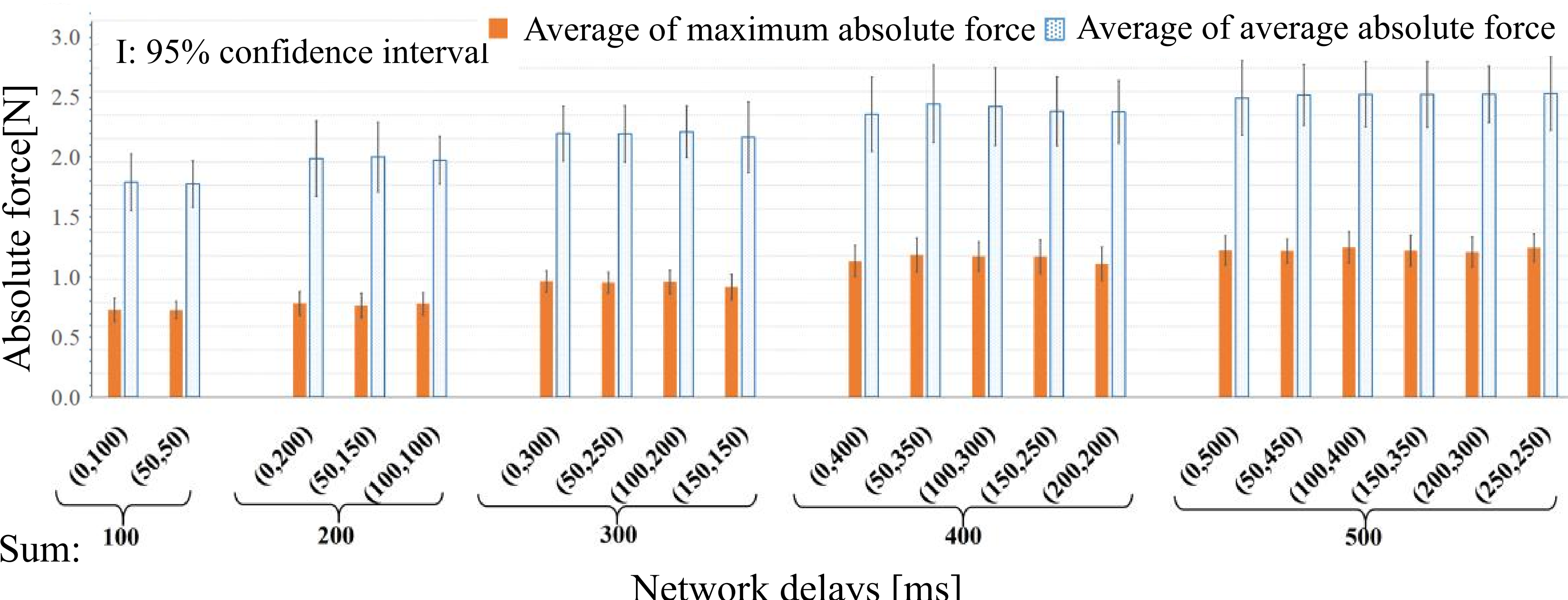
x y

x: p-value for average of average absolute force
y: p-value for average of maximum absolute force

- **We carried out t-test to confirm whether there exist significant differences among different network delays .**
- **The t-test result indicated that there is no statistically significant difference between pairs of network delays.**

Experimental Results (3/3)

- **As a result, it was found that there is no significant difference in force when the sum of network delay 1 and network delay 2 is the same. To confirm this, we illustrated the results, and indeed, this confirmation can be observed from the figure.**



Average of average absolute force and average of maximum absolute force when sum of network delay 1 and network delay 2 is same

Conclusion and Future Work

We investigated influences of network delays on dual-user operation by experiment.

- **As the network delays increase, the force applied to the object tends to become larger.**
- **When the total network delay is the same, the force is almost the same.**

Future Work

- **Analyze the force and position information at both master terminals 1 and 2 to gain a deeper understanding of how the user with the smaller delay assists the other user.**