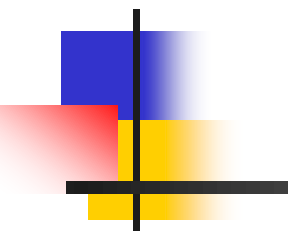# Effects of Adaptive Viscoelasticity Control on Cooperative Work in Remote Robot Systems with Force Feedback

**Ruzhou Ye[1], Yutaka Ishibashi[1], Pingguo Huang[2], Yuichiro Tateiwa[1]**

[1]Nagoya Institute of Technology, Japan
[2]Gifu Shotoku Gakuen University, Japan
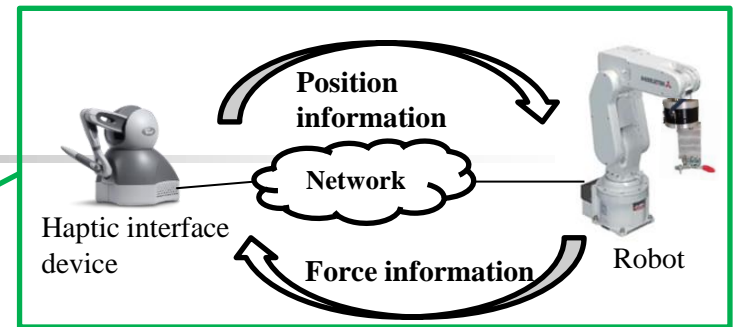
# Outline

- **Background**

- **Previous Work**

- **Purpose**

- **Remote Robot Systems with Force Feedback**

- **Calculation of Position and Force**

- **Adaptive Viscoelasticity Control**

- **Experiment Method**

- **Experimental Results**

- **Conclusion and Future Work**

# Background (1/3)



Haptic interface device — Position information → Network → Robot — Force information

**Remote robot systems with force feedback** have been actively researched.
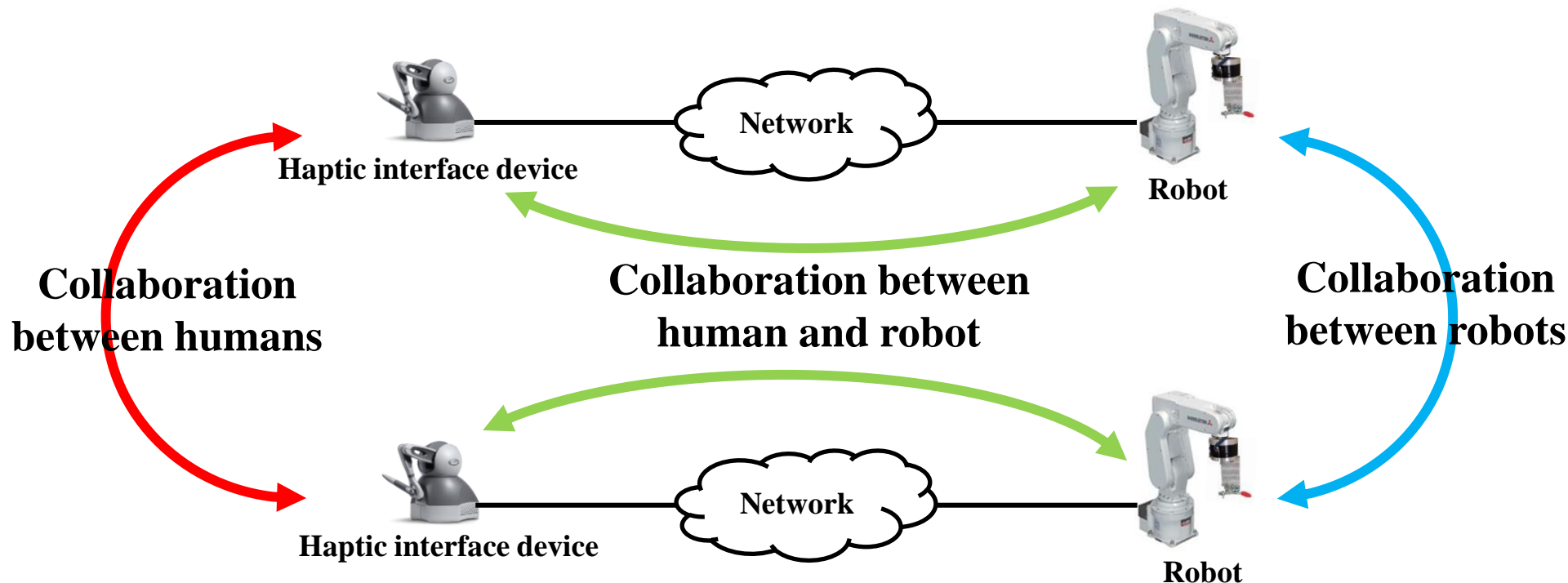We can conduct various types of cooperative work by using remote robot systems.

It is possible for users to perceive shapes, weights, and softness of remote objects hit/touched by robot arms through haptic interface devices (i.e., force feedback).

⬇

**The efficiency and accuracy of the cooperative work are expected to be improved largely.**

# Background (2/3)

Since we conduct cooperative work by using remote robot systems, collaboration are necessary as follows:



Collaboration between humans

Collaboration between human and robot

Collaboration between robots

Haptic interface device

Network

Robot

Haptic interface device

Network

Robot

# Background (3/3)

When force information is transmitted over a network such as the Internet, which does not guarantee the quality of service (QoS)

Network delay, delay jitter and packet loss

QoE (Quality of Experience) is degraded

Instability phenomena occur

**QoS control** + Stabilization control

# Previous Work (1/3)

[1] S. Ishikawa *et al*., IJCNS, pp. 1-13, Mar. 2021.
[2] P. Huang *et al*., IJCNS, pp. 99-111, July. 2019.
[3] Y. Hara *et al*., 11th Annual Workshop on NetGames, Nov. 2012
[4] K. Kanaishi *et al*., ICAIT, pp. 94-98, Nov. 2020.

- **Proposed robot position control using force information[1] as QoS control for cooperative work and stabilization control with filters [2] for stable cooperative work.**

> **The combination usage of the two types of control can help the systems to carry the object smoothly without large force.**

- **Dealt with adaptive Δ-causality control [3] for cooperative work [4].**

> **The control can reduce the force exerted on the object by adjusting the output timing of position information dynamically according to the network delay.**

# Previous Work (2/3)

*5 R. Ye *et al.,* ICCC, Dec. 2021.

- **Made a comparison of collaborating methods between two users[5].**

**Clarified how to present two types of force (force from robot and force from user ) by experiment.**

- **Focused on collaboration between humans.**
- **QoS control between two users (i.e., the two haptic interface devices) is not carried out.**

**It is important to improve collaboration between the two users by performing QoS control.**

# Previous Work (3/3)



Remote control

Network

Haptic interface device

Haptic interface device
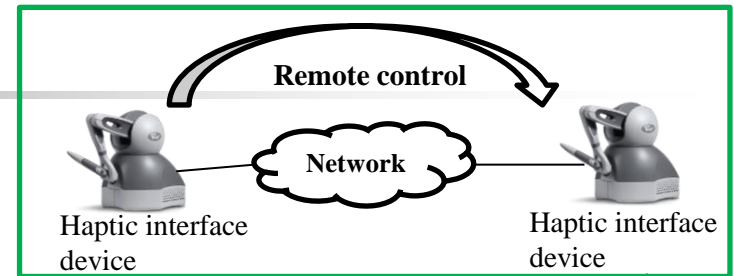
- **Proposed adaptive viscoelasticity control for a remote control system with haptics *6.**

➡️ **Demonstrated the effectiveness of the control by QoE assessment.**

**The control can be applied to collaboration between the two users in the remote robot systems with force feedback**

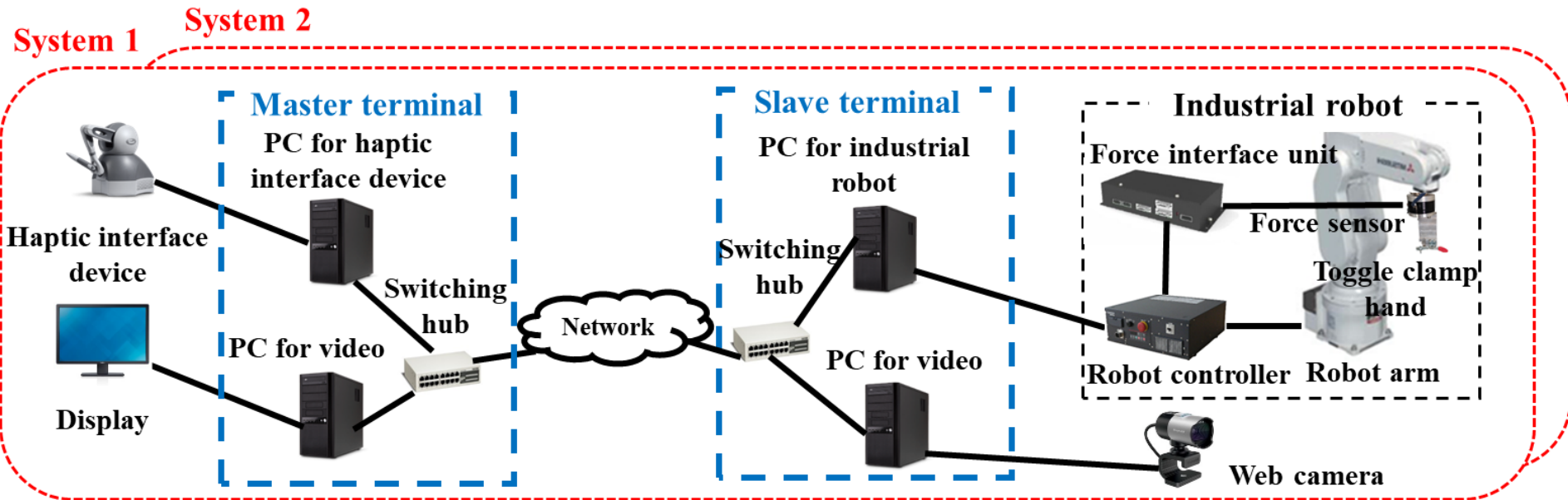**The effects of the control have not been clarified so far**

# Purpose

**This work**

- ➤ **Perform and investigate the effects of the <span style="color:red">adaptive viscoelasticity control</span> as QoS control between the two haptic interface devices in the remote robot systems with force feedback.**

- ➤ **Examine the influence of network delay between the haptic interface devices for cooperative work of carrying an object by experiment.**

# Remote Robot Systems with Force Feedback



**System 1**

**System 2**

**Master terminal**
PC for haptic interface device

Haptic interface device

Switching hub

PC for video

Display

**Network**

**Slave terminal**
PC for industrial robot

Switching hub

PC for video

**Industrial robot**
Force interface unit

Force sensor

Toggle clamp hand

Robot controller   Robot arm

Web camera

**Configuration of two remote robot systems with force feedback**

# Calculation of Position

*1 S. Ishikawa *et al*., IJCNS, pp. 1-13, Mar. 2021.

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

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

# Calculation of Force (1/3)

*1 S. Ishikawa *et al*., IJCNS, pp. 1-13, Mar. 2021.

**Force from robot** **in system** $i$ **($i = 1$ or $2$)**

$$F_t^{(\mathrm{mr}i)} = K_{\mathrm{scale}}^{(\mathrm{F})} F_{t-1}^{(\mathrm{sr}i)}$$

- $F_t^{(\mathrm{mr}i)}$ **: Force outputted at master terminal at time $t$ ($t \geq 1$)**
- $F_t^{(\mathrm{sr}i)}$ **: Force received from slave terminal at time $t$**
- $K_{\mathrm{scale}}^{(\mathrm{F})}$ **: Mapping scale about force between industrial**

  **robot and haptic interface device $\left( K_{\mathrm{scale}}^{(\mathrm{F})} = 0.33 \,^{*1} \right)$**

# Calculation of Force (2/3)

**Force from user** in system $i$ ($i = 1$ or $2$)

Elasticity (spring)  Viscosity (damper)

$$F_t^{(u_1)} = K_s \left( P_{t-1}^{(u_2)} - P_{t-1}^{(u_1)} \right) + K_d \left( \dot{P}_{t-1}^{(u_2)} - \dot{P}_{t-1}^{(u_1)} \right) *5$$

**System 1**

**Elasticity is the property that the deformation occurs when force is applied to an object, and the deformation returns to its original state when the force disappears.**

**Viscosity is force or resistance exerted by fluids when we move something through the fluids (e.g., water and oil).**

- $P_t^{(u_i)}$: **Position vector of haptic interface device in system** $i$
- $\dot{P}_t^{(u_i)}$: **Velocity vector of haptic interface device in system** $i$
- $K_s$: **Elasticity coefficient**
- $K_d$ : **Viscosity coefficient**

# Calculation of Force (3/3)

*5 R. Ye *et al.*, ICCC, Dec. 2021.

**Outputted Force** in system $i$ ($i$ = 1 or 2)

**Force from user**

$$\boxed{\boldsymbol{F}_t^{(\mathrm{m}_i)}} = \alpha_i \boxed{\boldsymbol{F}_t^{(\mathrm{u}_i)}} + (1 - \alpha_i) \boxed{\boldsymbol{F}_t^{(\mathrm{mr}_i)}} \textbf{*5}$$

**Outputted Force**

**Force from robot**

- $\alpha_i$: **Parameter of ratio of two kinds of force in system** $i$
  **($0 \le \alpha_i \le 1.0$)**

# Adaptive Viscoelasticity Control (1/3)

*5 R. Ye *et al.*, ICCC, Dec. 2021.

The **adaptive elasticity control** and **adaptive viscosity control** are carried out together at each terminal.

**Elasticity (spring)**　　　　**Viscosity (damper)**

$$\boldsymbol{F}_t^{(\mathrm{u_1})} = K_\mathrm{s}\left(\boldsymbol{P}_{t-1}^{(\mathrm{u_2})} - \boldsymbol{P}_{t-1}^{(\mathrm{u_1})}\right) + K_\mathrm{d}\left(\dot{\boldsymbol{P}}_{t-1}^{(\mathrm{u_2})} - \dot{\boldsymbol{P}}_{t-1}^{(\mathrm{u_1})}\right) *5$$

$K_\mathrm{s}$ and $K_\mathrm{d}$ are dynamically changed by the adaptive viscoelasticity control.

# Adaptive Viscoelasticity Control (2/3)

*6 T. Abe *et al.,* IEICE Trans. Commun. pp. 38-46, Jan. 2020.

**Adaptive elasticity control**

$$K_s = 9/(2D + 90)^{*6}$$

$K_s$ **is dynamically changed according to the network delay.**

- $D$**: One-way network delay between two haptic interface devices**

# Adaptive Viscoelasticity Control (3/3)

**Adaptive viscosity control**

$$K_{\mathrm{d}} = \begin{cases} 1.02 \times 10^{-5}D + 4.2 \times 10^{-5}v - 2.03 \times 10^{-4} \\ \qquad\qquad\qquad\qquad\qquad\quad \left(D \leq D_{\mathrm{peak}}\right)^{*6} \\ -6.31 \times 10^{-6}D - 2.12 \times 10^{-4}v + 2.99 \times 10^{-3} \\ \qquad\qquad\qquad\qquad\qquad\quad \left(D > D_{\mathrm{peak}}\right) \end{cases}$$

$$D_{\mathrm{peak}} = -20v + 228 \quad {}^{*6}$$

$K_{\mathrm{d}}$ **is dynamically changed according to the network delay and the moving velocity of a haptic interface device.**

- $D_{\mathrm{peak}}$ **: Network delay when the optimum viscosity coefficient has the peak value**
- $v$**: Moving velocity**

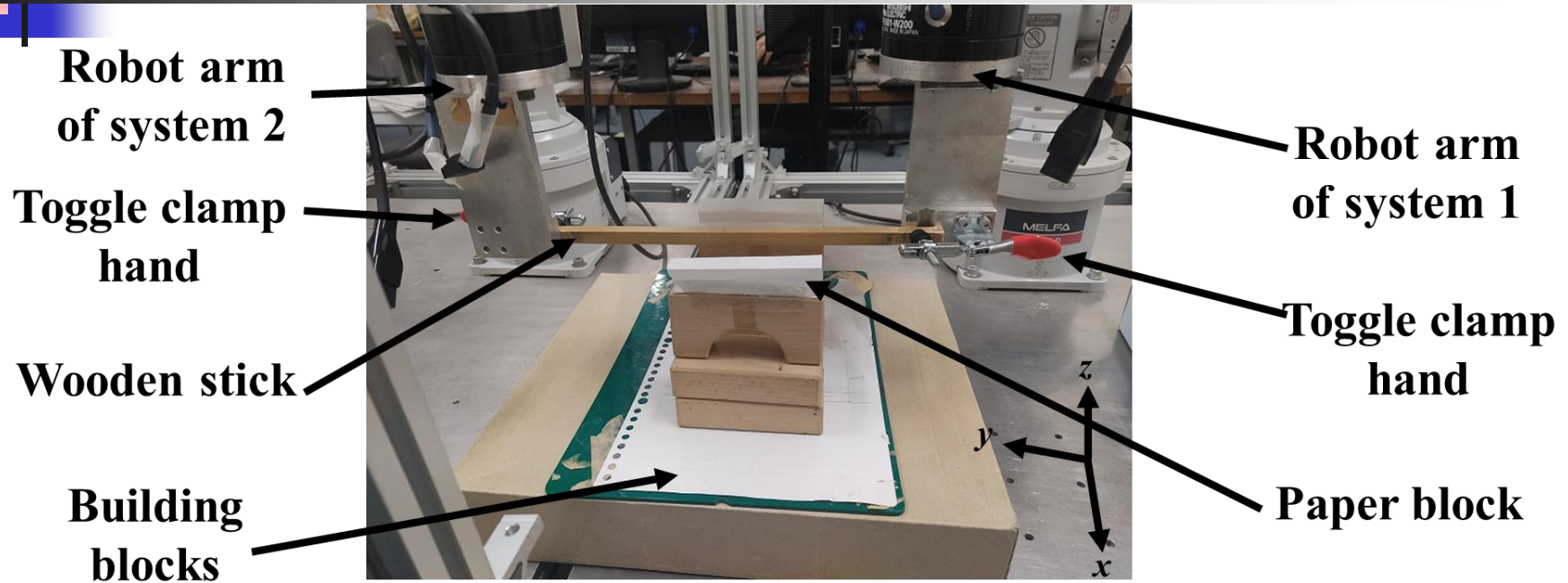# Experiment Method (1/4)



Haptic interface device of system 1

Video

User

Haptic interface device of system 2

**Operation with haptic interface devices**

- **A single user operated two haptic interface devices with his/her both hands while watching video.**

**Robot arm of system 2**

**Toggle clamp hand**

**Wooden stick**

**Building blocks**

**Robot arm of system 1**

**Toggle clamp hand**

**Paper block**

**Work with two robot arms**

- **To move the stick always in almost the same way, building blocks were piled up ahead and behind the initial position of the stick.**

- **A paper block was placed on each uppermost building block.**

**Demo video**

**Delay: 0 ms**
**Adaptive viscoelasticity**
**control**
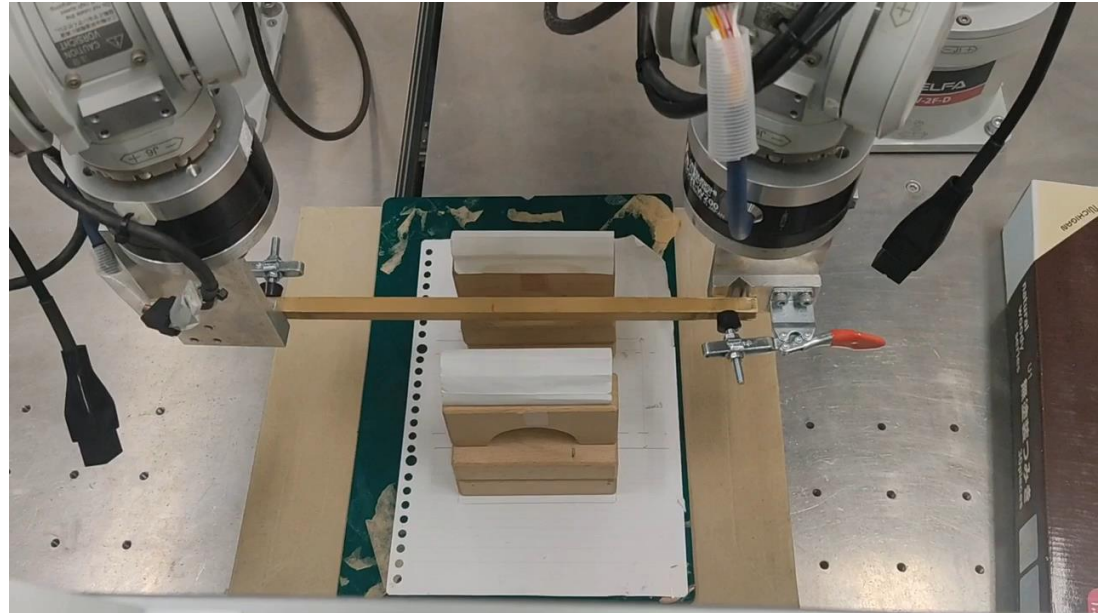


- **The user moved the stick toward the paper blocks to touch the paper blocks while keeping the robot arms parallel to each other.**

- **To move the stick at almost the same speed, he/she touched the first paper block at about 5 seconds from the beginning of each work and the second block at about 15 seconds.**
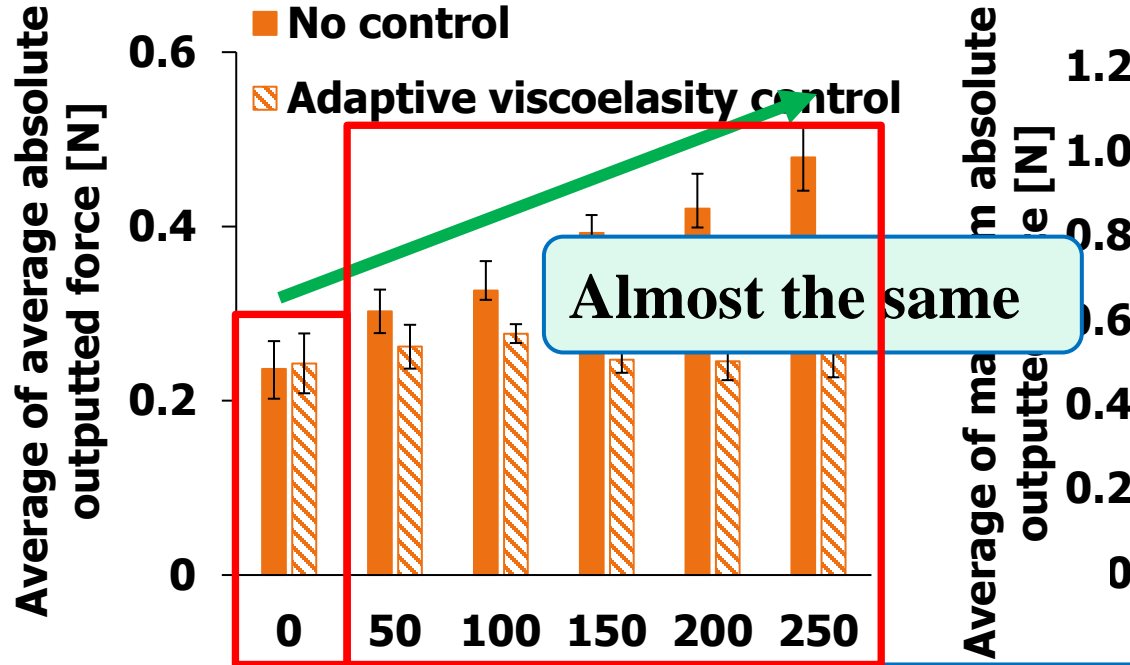
# Experiment Method (4/4)
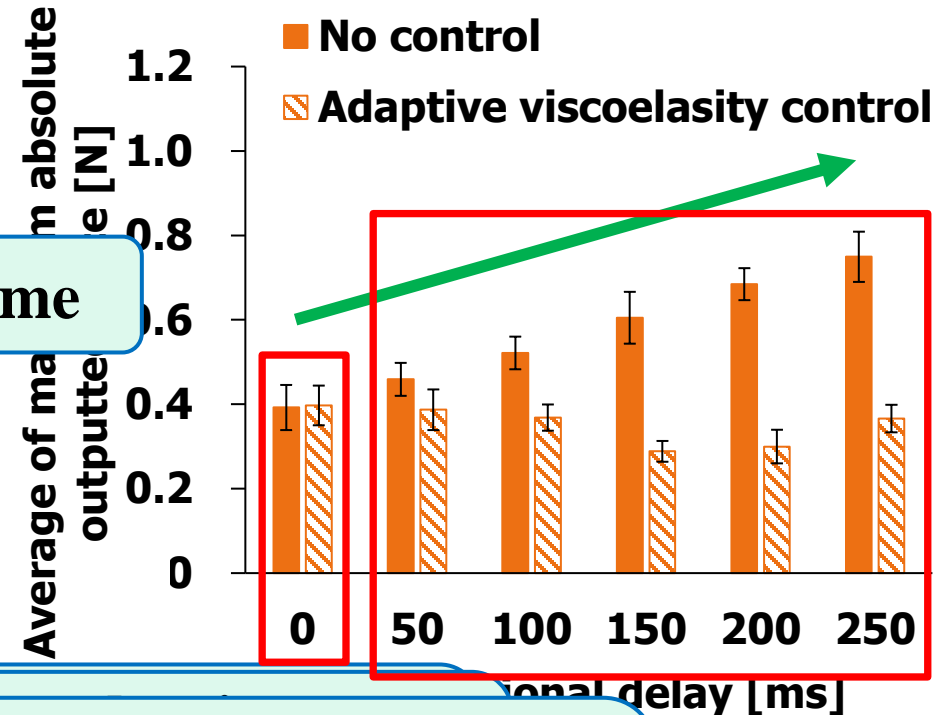
*5 R. Ye *et al.*, ICCC, Dec. 2021.

- **Generated a constant delay (called the *additional delay* ) and changed the additional delay from 0 ms to 250 ms at intervals of 50 ms.**

- **We set $(\alpha_1, \alpha_2) = (0.5, 0.5)$ [*5].**

- **Conducted 10 times for each combination of the additional delay and whether the adaptive viscoelasticity control is performed or not (called *no control*).**

- **Obtained the average and maximum absolute force of robot arm (force from robot) and outputted force presented to the user and calculated the average of the two measures for 10 times.**

# Experimental Results (1/4)

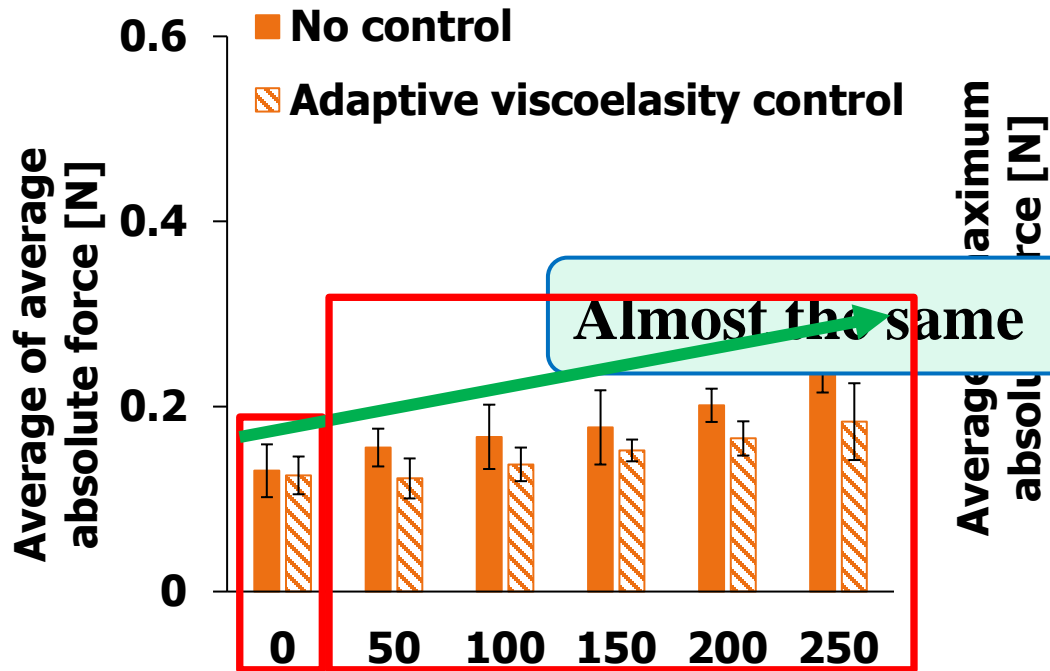I: 95% confidence interval

I: 95% confidence interval

- **No control**
- **Adaptive viscoelasity control**

**Almost the same**

Average of average absolute outputted force [N]

0.6
0.4
0.2
0

0   50   100   150   200   250

Average of maximum absolute outputte... [N]

1.2
1.0
0.8
0.6
0.4
0.2
0

0   50   100   150   200   250

...onal delay [ms]

**The averages of the adaptive viscoelasticity control are smaller than those of no control when the additional delay is larger than 0 ms.**
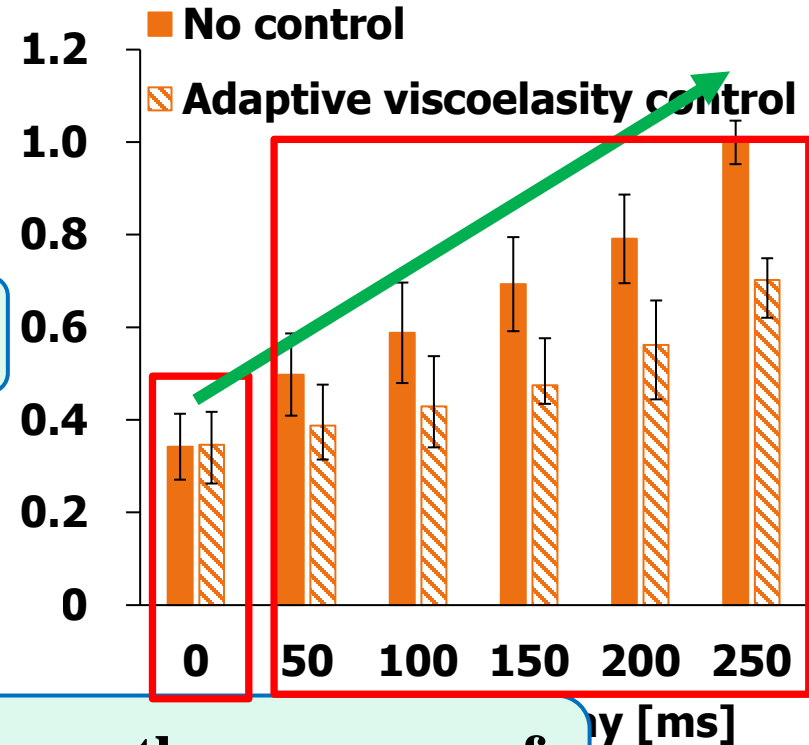
Average ... absolut... ...aximum

# Experimental Results (2/4)



Average of average absolute force [N] — **No control** / **Adaptive viscoelasity control**

I: 95% confidence interval

**Almost the same**

I: 95% confidence interval — **No control** / **Adaptive viscoelasity control**
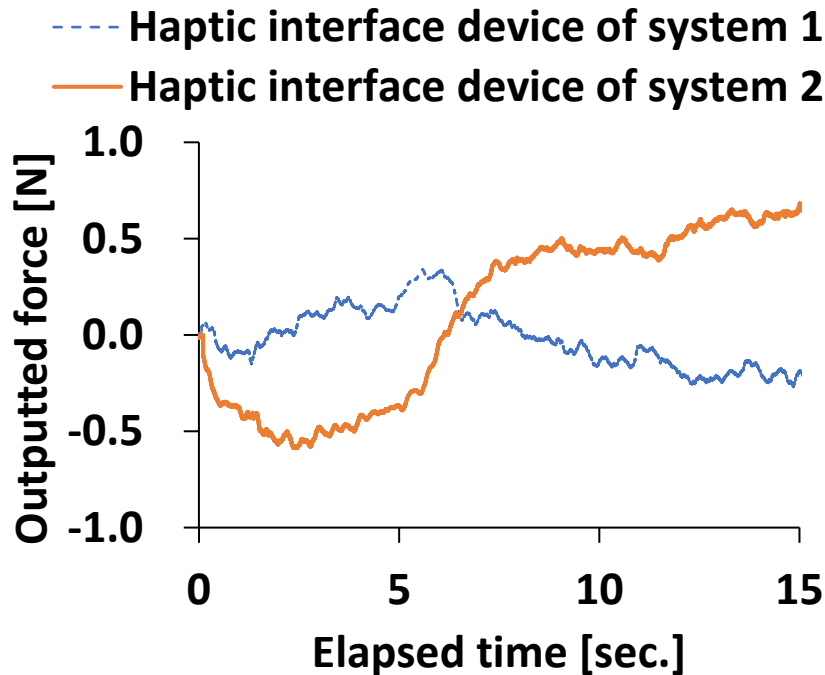
x-axis: 0, 50, 100, 150, 200, 250 [ms]
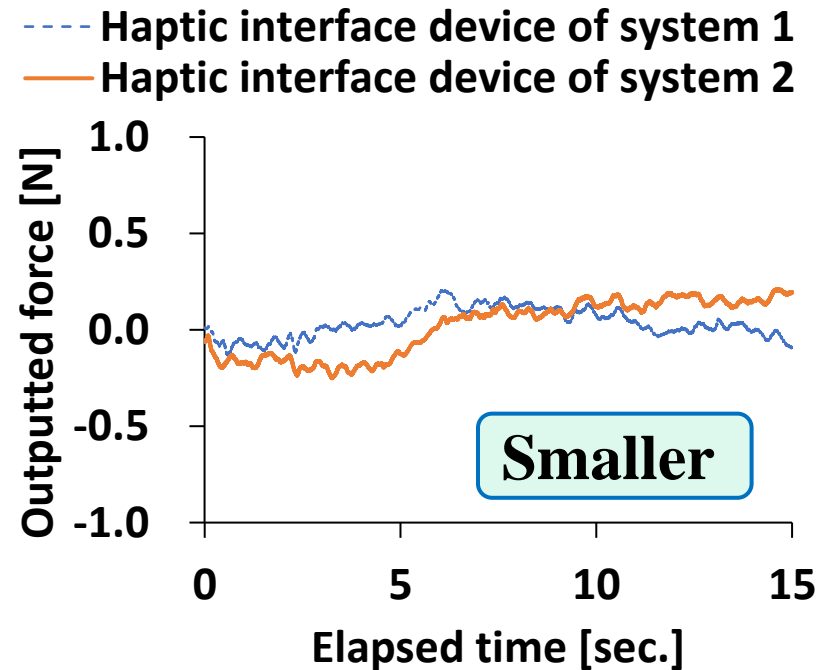
As the additional delay increases, the averages of

The averages of the adaptive viscoelasticity control are somewhat **smaller** than those of no control when the additional delay is larger than 0 ms.

# Experimental Results (3/4)

--- **Haptic interface device of system 1**
— **Haptic interface device of system 2**

--- **Haptic interface device of system 1**
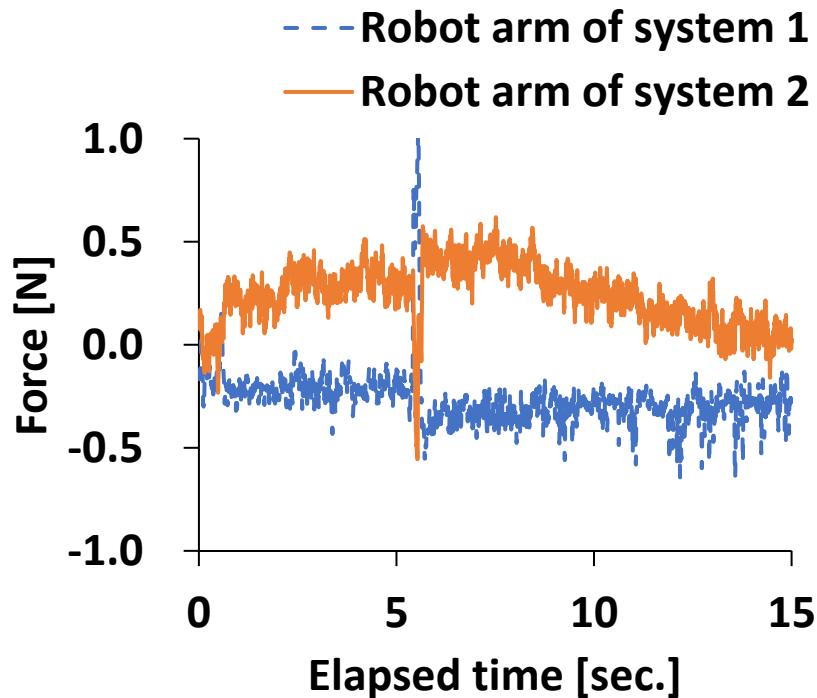— **Haptic interface device of system 2**
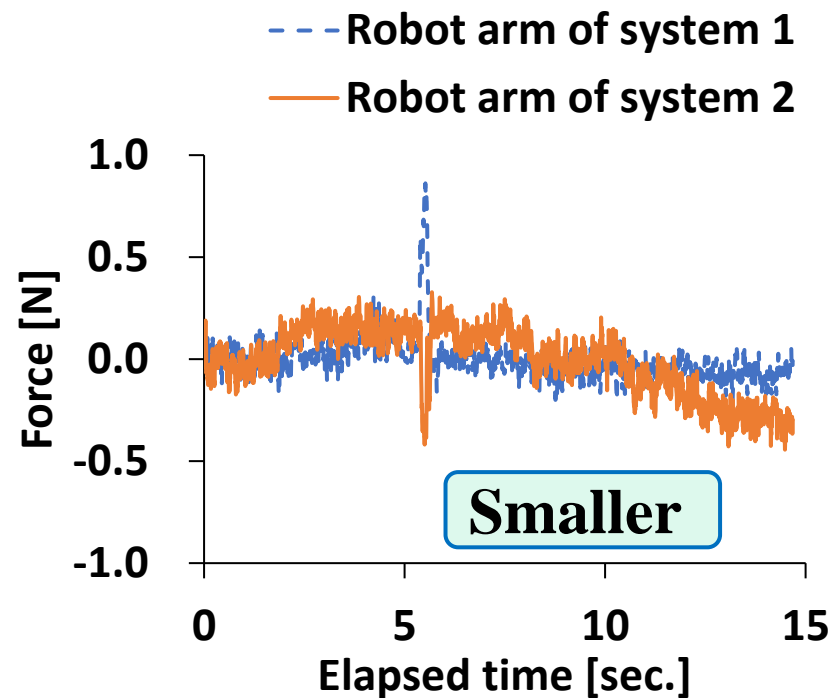


(e) No control



**Smaller**

(f) Adaptive viscoelasticity control

**Outputted force at haptic interface devices
versus elapsed time (additional delay: 150 ms).**

# Experimental Results (4/4)



(g) No control

(h) Adaptive viscoelasticity control

**Force at robot arms versus elapsed time
(additional delay: 150 ms).**

# Conclusion

- We investigated the effects of the adaptive viscoelasticity control.
- We examined the influence of network delay between the two haptic interface devices.

⬇

- ➢ We found that the force applied to the object tends to become larger as the network delay increases.
- ➢ The adaptive viscoelasticity control is more effective than a case where the control is not performed (no control).

# Future Work

- **Perform the work with two different users.**

- **Examine the influences of network delays between the two robots and between each haptic interface device and its corresponding robot.**

- **Carry out the experiment with various movement velocities of the haptic interface device.**