Effects of Adaptive Viscoelasticity Control for Collaboration between Users in Remote Robot Systems with Force Feedback

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The 4th International Conference on Computer Communication and the Internet (ICCCI 2022)
July 3, 2022

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- Remote Robot Systems with Force Feedback
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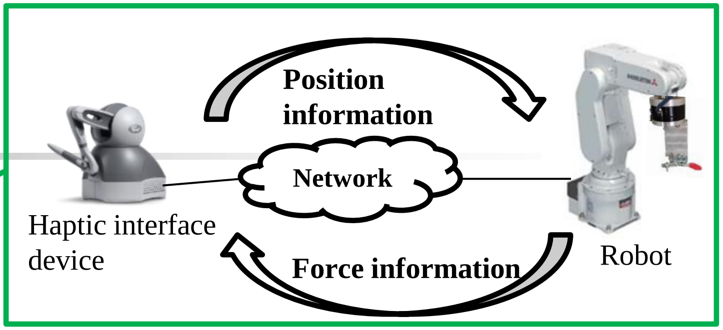
Background (1/3)



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)

When position/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

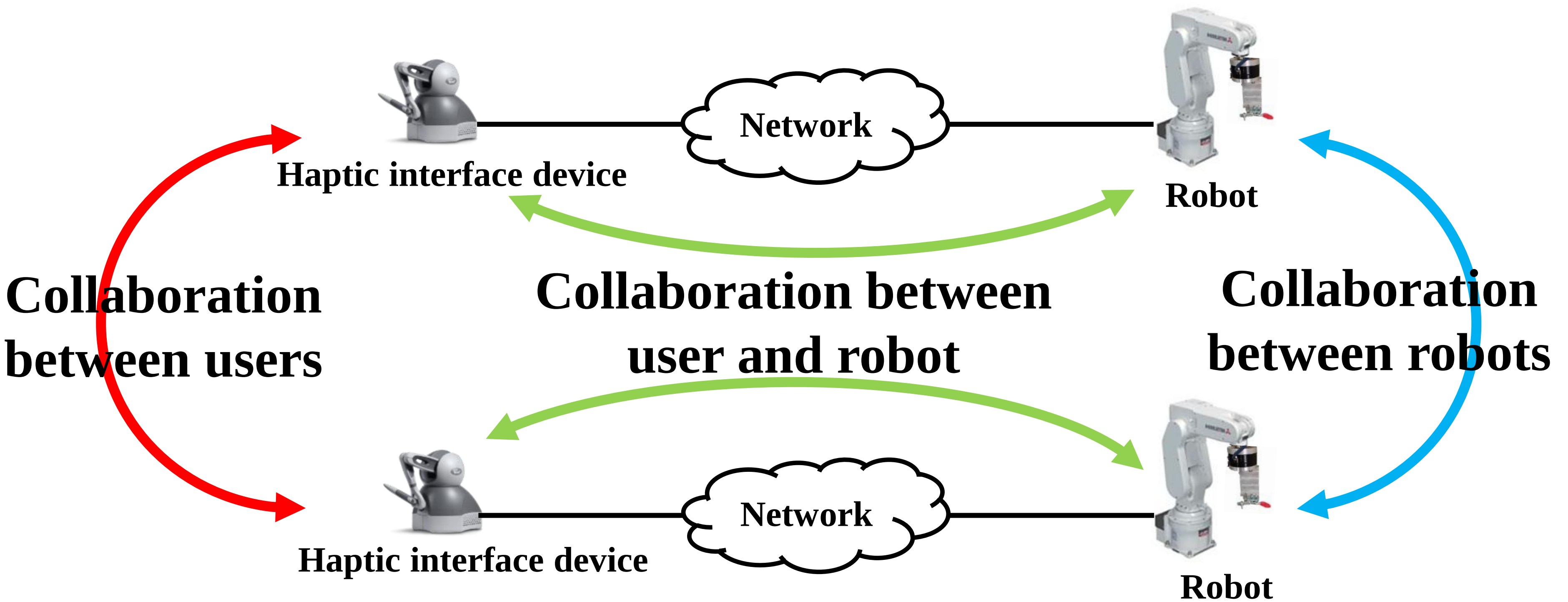
QoE (Quality of Experience) degrade

Instability phenomena occur

QoS control + Stabilization control

Background (3/3)

For efficient cooperative work between the remote robot systems, three types of collaboration are necessary.



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.*, 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.

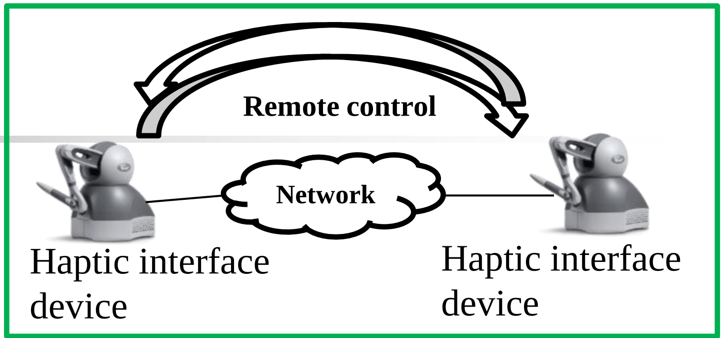
- Made a comparison of **collaborating methods between two users**[*5].

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

- Focused on collaboration between users.
- 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)



- 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.

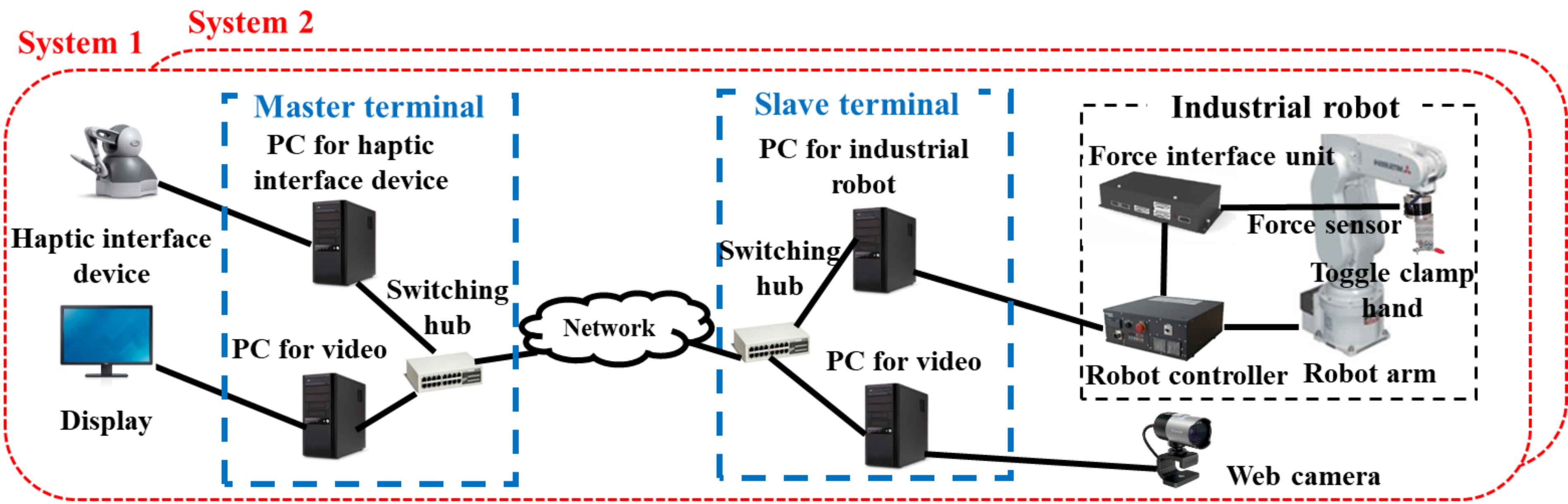
Purpose

This work

- Perform and investigate the effects of the **adaptive viscoelasticity control** as QoS control between the two haptic interface devices in the remote robot systems with force feedback.

- Examine the influence of network delays between the two haptic interface devices, between the two robots, and between each haptic interface device and its corresponding robot, for cooperative work of carrying an object by experiment.

Remote Robot Systems with Force Feedback



Configuration of two remote robot systems with force feedback

Calculation of Position

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

- $\boldsymbol{S}_t$: 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
- $K_{\mathrm{scale}}^{(\mathrm{P})}$: Mapping scale about position between industrial robot and haptic interface device ($K_{\mathrm{scale}}^{(\mathrm{P})} = 0.5$ [*1])

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

Calculation of Force (1/3)

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

$$\boldsymbol{F}_t^{(\mathrm{mr}_i)} = K_{\mathrm{scale}}^{(\mathrm{F})} \boldsymbol{F}_{t-1}^{(\mathrm{sr}_i)}$$

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

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

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

Calculation of Force (2/3)

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

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

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).

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

Calculation of Force (3/3)

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

Force from user

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

Outputted Force

Force from robot

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

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

Adaptive Viscoelasticity Control (1/3)

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_s and K_d are dynamically changed under the adaptive viscoelasticity control.

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

Adaptive Viscoelasticity Control (2/3)

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

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

Adaptive Viscoelasticity Control (3/3)

Adaptive viscosity control

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

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

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

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

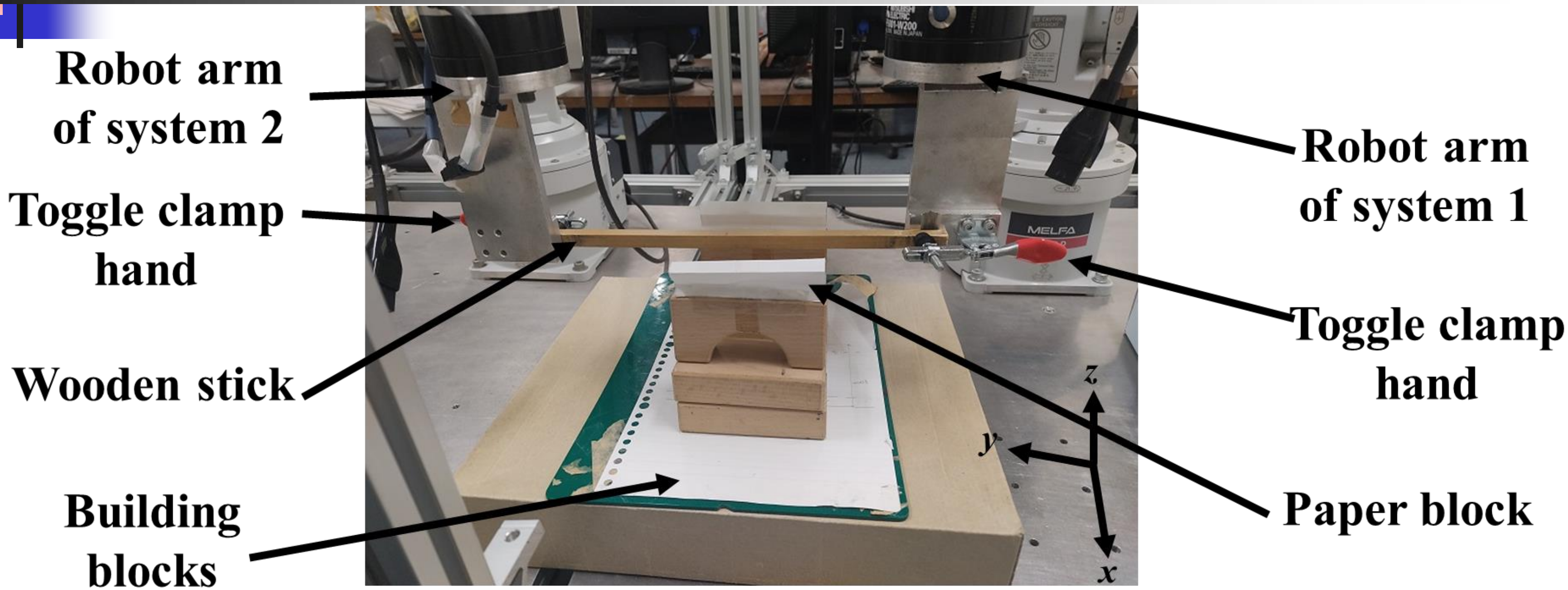
*6 T. Abe *et al.*, IEICE Trans. Commun. pp. 38-46, Jan. 2020.

Experiment Method (1/3)

Operation with haptic interface devices

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

Experiment Method (2/3)



Work with two robot arms

- 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 1.5 seconds from the beginning of each work and the second block at about 4.5 seconds.

Experiment Method (3/3)

- Generated a constant delay (called the *additional delay*) for each packet transmitted between system 1, between system 2, between two slave terminals, and between two master terminals.

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

(additional delay 1, additional delay 2, additional delay 3, additional delay 4)

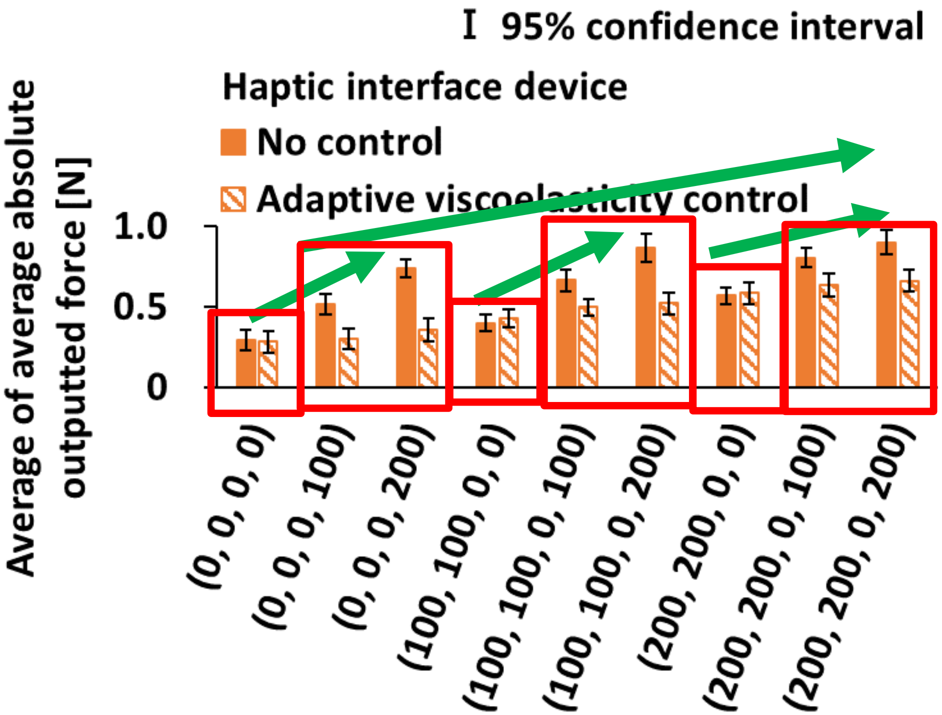
- Conducted 10 times for each combination of the additional delay and whether the adaptive viscoelasticity control is

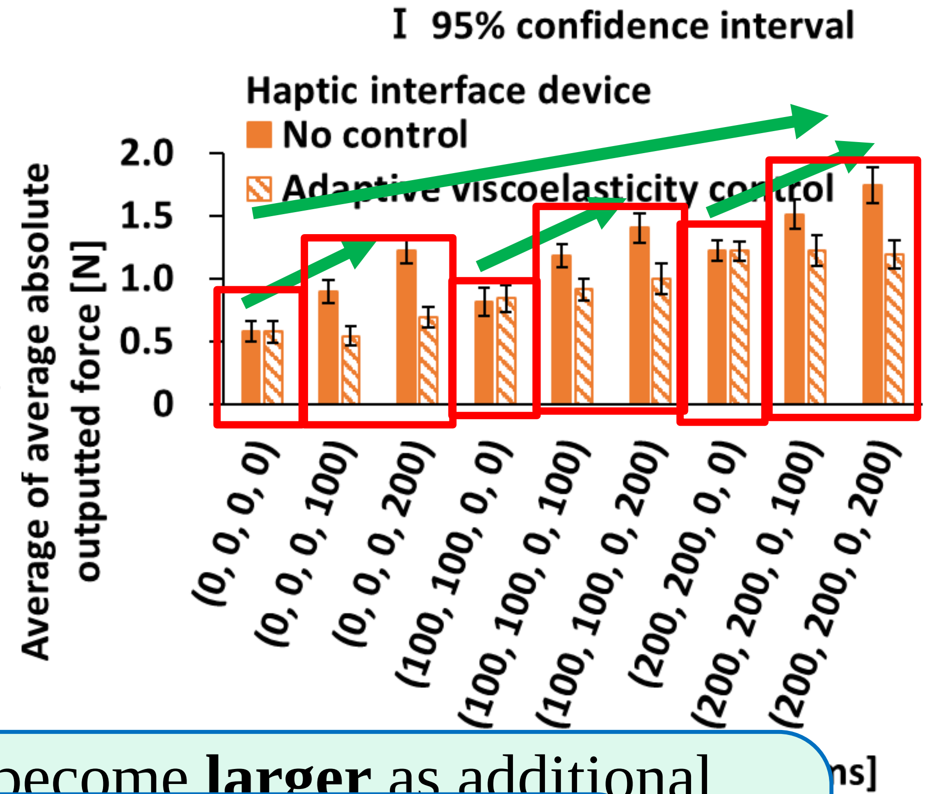
additional delay 1 = additional delay 2: 0 ms, 100 ms, or 200 ms.
additional delay 3: 0 ms or 100 ms.
additional delay 4: 0 ms, 100 ms, or 200 ms.

- and outputted force and calculated the average of the two measures for 10 times.

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

Experimental Results (1/4)





Averages of no control tend to become **larger** as additional

increase.

As addi … oth

types of … larger.

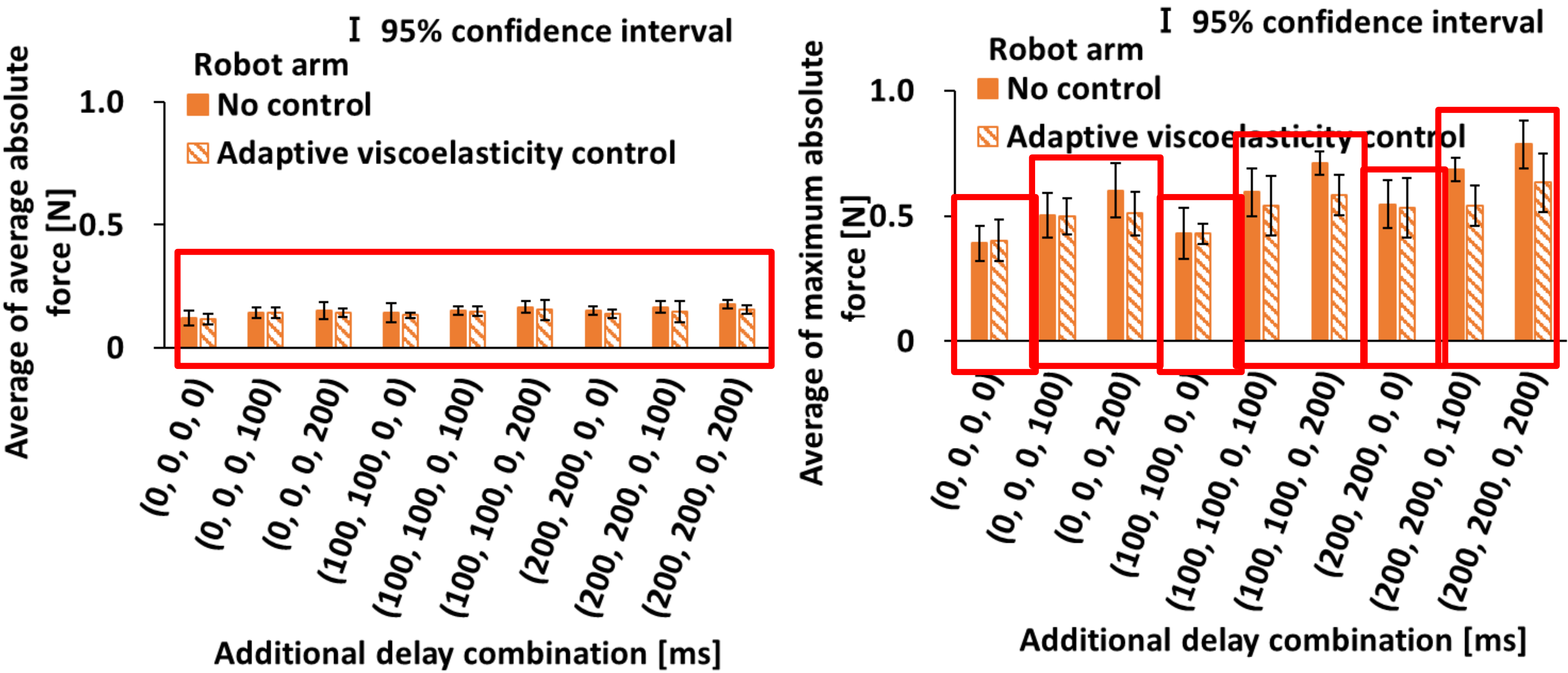
Averages of a … ity control

are **smaller** than those of no control.

Almost the same

Average of average and maximum absolute outputted force (additional delay 3 = 0 ms).

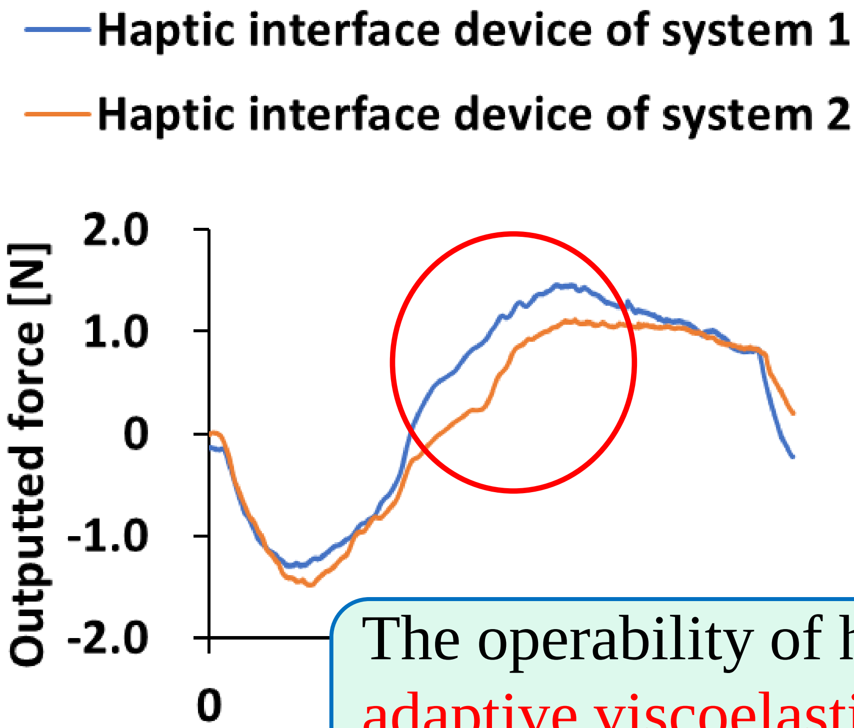
Experimental Results (2/4)

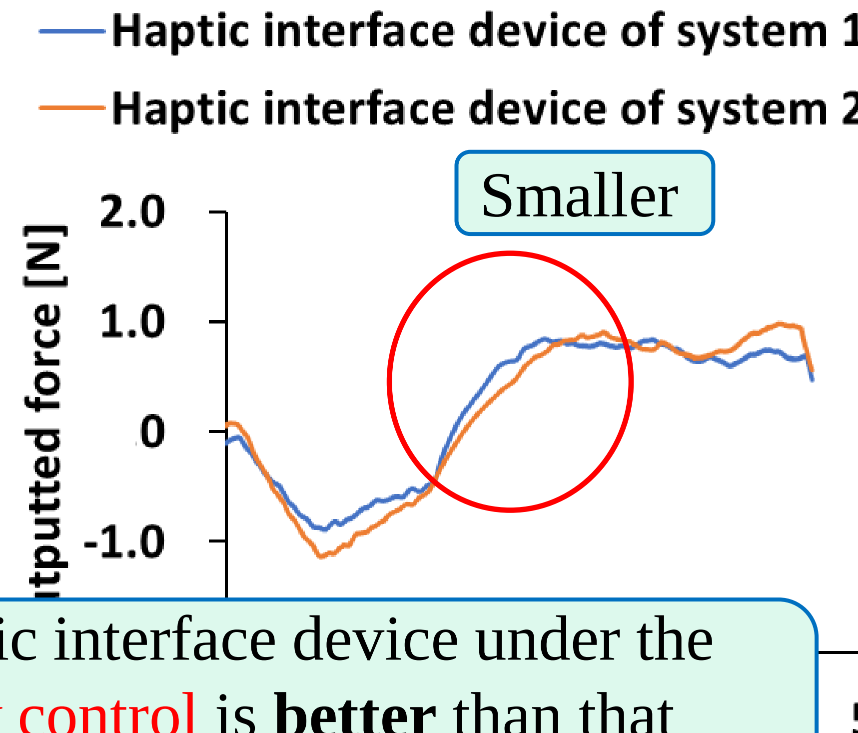


Averages of maximum al Almost the same adaptive viscoelasticity control are **somewhat smaller** than those for no control.

Average of average and maximum absolute force (additional delay 3 = 0 ms).

Experimental Results (3/4)





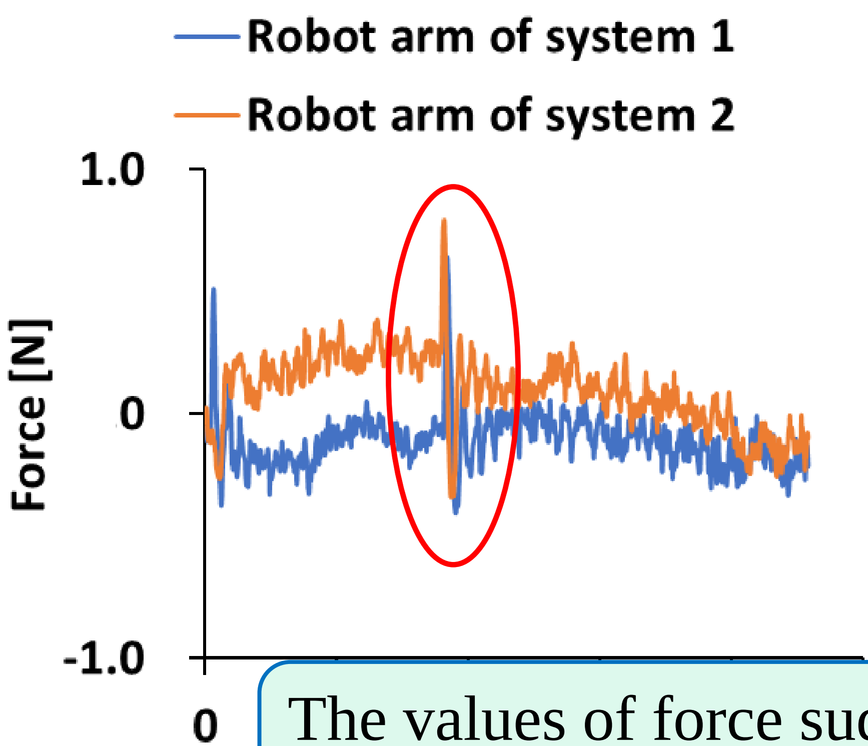
The operability of haptic interface device under the adaptive viscoelasticity control is **better** than that under no control.

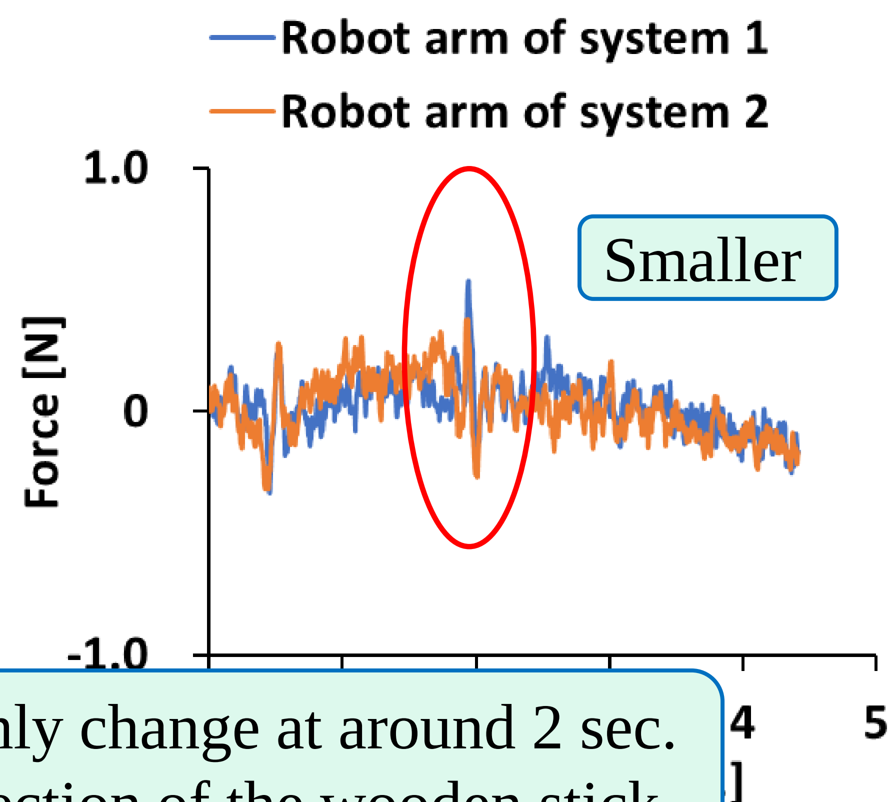
No control

Adaptive viscoelasticity control

Outputted force at haptic interface devices versus elapsed time for delay combination of (200, 200, 0, 100).

Experimental Results (4/4)





The values of force suddenly change at around 2 sec. because of the moving direction of the wooden stick.

No control

Adaptive viscoelasticity control

Force at robot arms versus elapsed time for delay combination of (200, 200, 0, 100).

Conclusion

- We investigated the effects of the adaptive viscoelasticity control.
- We examined the influences of network delay between two haptic interface devices, between two robots, and between each haptic interface device, and its corresponding robot.

⬇

- ➢ The force applied to the object tends to become larger as the network delays increase.
- ➢ 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.
- Carry out the experiment with various movement velocities of the haptic interface device.