Effect of QoS Control for Hand Delivery of Object between Remote Robot Systems with Force Feedback

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Outline

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Remote robot systems with force feedback have been actively studied. Users remotely operate robot arms having force sensors by using haptic interface devices.

Many researchers have paid attention to cooperative work among multiple remote robot systems.

It is possible for users to perceive the shape, smoothness of surface, softness, and weight of a remote object with force feedback.

The efficiency and accuracy of work are expected to be largely improved.
When information about force and/or position is transmitted over the Internet, which does not guarantee the QoS (Quality of Service).

- QoE (Quality of Experience) degradation
- Instability phenomena

- Stabilization control
- QoS control

Network delay, delay jitter and packet loss
Previous Work (1/2)

• To mitigate influences of the network delay in each system on cooperative work (hand delivery of an object) between two moving robot arms, position follow-up control\textsuperscript{1} was proposed.

• The effect of the control was clarified\textsuperscript{1}.

- The average operation time under the control is smaller than that under no control, and smooth hand delivery can be realized.
- The average operation time increases slightly as the network delay becomes larger.

The network delay between the two systems is set to be negligibly small.
Previous Work (2/2)

• Influences of the network delay in each system on cooperative work (*moving an object together*) was investigated*2.
  Work efficiency is damaged due to the network delay.

• Influences of the network delay between two systems on the cooperative work was investigated*3.
  Work efficiency deteriorates and stronger force is applied to the object as the network delay becomes larger.

• Adaptive $\Delta$-causality control*4 was applied to solve the problems, and the effect of the control was clarified by experiment*3.

✓ Influences of the network delay between the two systems can greatly be alleviated under the control.
Purpose

The adaptive $\Delta$-causality control may achieve efficient hand delivery of an object in combination with the position follow-up control.

This work

- We handle the hand delivery of an object between the two moving robot arms with force feedback, in which the position follow-up control is exerted.
- The adaptive $\Delta$-causality control is applied to the systems.$^{*1}$
- We investigate the effect of the adaptive $\Delta$-causality control by experiment.
Robot Arms

Robot arm 2

Robot arm 1

Force sensor

Electric hand

Metal platform

Wooden stick
Position Follow-up Control (1/2)

• One robot arm (robot arm 2) automatically follows up the other robot arm (robot arm 1).

• A position near the location of the hand delivery (called the target position) is determined from the current position information of the robot arm 1.

• The robot arm 2 is automatically moved to the target position.

• The hand delivery of an object is performed in combination with automatic and manual operations after robot arm 2 has reached the target position.
Position Follow-up Control (2/2)

• The movement in the $x$-axis (front-back) direction by the position follow-up control is calculated by the following equation:

$$S_t^{(x)} = \begin{cases} 
S_{t-1}^{(x)} + V_{\text{follow-up}}^{(x)} & (S_{t-1}^{(x)} < S_{\text{target}}^{(x)}) \\
S_{t-1}^{(x)} - V_{\text{follow-up}}^{(x)} & (S_{t-1}^{(x)} > S_{\text{target}}^{(x)}) \\
S_{\text{target}}^{(x)} & (S_{t-1}^{(x)} = S_{\text{target}}^{(x)}) 
\end{cases}$$

$S_t^{(x)}$: Position of robot arm 2 at time $t$

$S_{\text{target}}^{(x)}$: Target position based on position information of robot arm 1

$V_{\text{follow-up}}^{(x)}$: The follow-up speed of robot arm 2 (0.1 mm/ms)

• The equations in the $y$-axis (left-right) and $z$-axis (up-down) directions are the same as that in the $x$-axis direction.
Adaptive $\Delta$-causality Control (1/3)

• When a terminal receives a media unit (MU), which is an information unit for the control, the terminal saves the MU in the terminal’s buffer until the time limit and then outputs it.

• Time limit = the generation time of the MU + $\Delta$ seconds

• Time limit $<$ Receiving time of MU  

• $\Delta$ is dynamically changed according to the network load to reduce the number of discarded MUs.
Adaptive $\Delta$-causality Control (2/3)

Network delay: $\Delta$ ms

Wait for $\Delta$ ms without output

Send position information

Output position information

Robot arm’s motion is delayed

Robot arm’s motion is not delayed
Adaptive $\Delta$-causality Control (1/3)

- Each MU is the position information of robot arm 1.
- $\Delta$ is set to the smoothed network delay $D_t$ obtained by the following equation:

$$
D_0 = d_0 \\
D_t = \alpha D_{t-1} + (1 - \alpha) d_t \quad (t \geq 1)
$$

$d_t$: Network delay measured at time $t$

$\alpha$: Smoothing coefficient ($\alpha = 0.998^{*5}$)

Experiment Method (1/4)

- Two types of cooperative work
  Work A: Robot arm 2 receives a wooden stick of 30 cm from robot arm 1.
  Work B: Robot arm 2 passes the stick to robot arm 1.

- Performance measure: Average operation time
  The average time from the moment the work is started until the instant the stick is hand-delivered.

![Robot arm 2](image1) ![Robot arm 1](image2)

**Work A (receive)**

![Electric hand](image3) ![Wooden stick](image4)

**Work B (pass)**
To make robot arms move in the same way, robot arm 1 moved backward and forward from −6 cm to 6 cm in the $x$-axis (front-back) direction horizontally automatically.

The position follow-up control was applied for robot arm 2 to follow up and approach robot arm 1.

The adaptive $\Delta$-causality control was used to control the output of the position information from robot arm 1 to robot arm 2.
Experiment Method (3/4)

- **Target position**\(^*1\) in position follow-up control:
The electric hand and the wooden stick were set at the same height, at a distance of 0 cm in the \(x\)-axis (front-back) direction and 1 cm in the \(y\)-axis (left-right) direction.

- **Moving speed of robot arm 1:**
  \(0.025 \text{ mm/ms}\)^*1

The constant delay (*additional delay*) was added to each packet transferred between systems 1 and 2 by using a network emulator.

The additional delay was selected from among 0 ms, 100 ms, 200 ms, 300 ms and 400 ms in random order for each experiment.

We carried out the experiment 10 times for each additional delay in work A and work B under the adaptive $\Delta$-causality control and no control.
Demo video (1/2)

Cooperative work: Work B (pass)
Addition delay: 400 ms
Control: No control
Demo video (2/2)

Cooperative work: Work B (pass)
Addition delay: 400 ms
Control: Adaptive Δ-causality control
Average operation time versus additional delay

Work A (receive)
Experimental Results (2/3)

Force of robot arm 2 versus additional delay Work A (receive)

**Average force in front-back direction**

- **No control**
- **Adaptive Δ-causality control**

**Average force in left-right direction**

- **No control**
- **Adaptive Δ-causality control**

**Maximum force in front-back direction**

- **No control**
- **Adaptive Δ-causality control**

**Maximum force in left-right direction**

- **No control**
- **Adaptive Δ-causality control**
Experimental Results (3/3)

Cooperative work: Work A (receive)
Additional delay: 400 ms

Position and force of two robot arms in front-back direction versus elapsed time

No control
Automatic
Automatic + Manual
Adaptive Δ-causality control

Position and force of two robot arms in front-back direction versus elapsed time
Conclusion

- We investigated the effect of the adaptive $\Delta$-causality control for hand delivery of a wooden stick between two moving arms of the remote robot systems with force feedback.

- We examined influences of the network delay between the two systems on the hand delivery under the control.

- Work efficiency is improved.
- Influences of network delay can be alleviated under the control.
Future Work

- Examine influences of network delay in each system and between the systems together
- Apply stabilization control