Influences of Network Delay on Cooperative Work between Remote Robots with Force Feedback

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Outline

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- Remote Robot System with Force Feedback
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Remote robot system with force feedback has actively been studied.

It is possible for users to feel the shape, softness, surface smoothness, and weight of a remote object by using a haptic interface device (i.e., force feedback).

The efficiency and accuracy of work are expected to be largely improved.
Background (2/3)

When information about force is transmitted over a network such as the Internet, which does not guarantee QoS (Quality of Service), it can lead to:

- Degradation of QoE (Quality of Experience)
- Instability phenomena

Network delay, delay jitter, and packet loss can contribute to these issues. Therefore, QoS control and stabilization control are necessary to mitigate these problems.
We cannot carry out the control efficiently if influences of network delay in work are not clarified enough.

We should investigate the influences of network delay on work.
Previous Study*1

- Cooperative work (carrying an object together) by using two remote robot systems was conducted with a master-slave relation, and the adaptive $\Delta$-causality control is performed.
- The control sends the position information of the robot in the master system to the robot in the slave system and delays its transmission to the master system by the network delay.

The robot movements in the master and slave systems are synchronized with each other.

We can also synchronize the robot movements by sending the position information of one haptic interface device to the two robots.

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*1 K. Kanaishi et al., ICTCE, Nov. 2019.
Purpose

This Study

- We investigate influences of the network delay on cooperative work of carrying an object together.
- The cooperative work is performed by two robots which are remotely operated with one haptic interface device.
- We compare two calculation methods of reaction force outputted though the haptic interface device because there are two force sensors.
  - Calculated from force information sensed by both force sensors
  - Calculated from force information sensed by one force sensor
Remote Robot System with Force Feedback

- Master terminal
  - PC for haptic interface device
  - Switching hub
  - Haptic interface device
  - Display

- Slave terminal
  - Switching hub
  - Network
  - PC for video
  - PC for industrial robot 1
  - PC for industrial robot 2

- Slave terminal
  - PC for video
  - PC for industrial robot 1
  - Force sensor
  - Toggle clamp
  - Hand
  - Force interface unit
  - Robot arm
  - Web camera
  - Master terminal
  - Force sensor
  - Toggle clamp
  - Hand
  - Force interface unit
  - Robot arm
  - Industrial robot 1
  - Industrial robot 2

- Remote Robot System with Force Feedback
  - Haptic interface device
  - Display
Calculation of reaction force (1/2)

We handle two calculation methods of reaction force because the system has two force sensors.

- Uses force information sensed by both force sensors

\[ F^{(m)}_t = K_{\text{scale}} \frac{F^{(s_1)}_{t-1} + F^{(s_2)}_{t-1}}{2} \]  

\( F^{(m)}_t \) : Reaction force outputted at time \( t > 0 \)
\( F^{(s_1)}_t, F^{(s_2)}_t \) : Force received from PC for industrial robot 1 and PC for industrial robot 2 at time \( t > 0 \)

\( K_{\text{scale}} = 0.5^{*1} \)
Calculation of reaction force (2/2)

Reaction force outputted at master terminal

We handle two calculation methods of reaction force because the system has two force sensors.
✓ Uses force information sensed by one force sensors

\[ F_{t}^{(m)} = K_{\text{scale}} F_{t-1}^{(s_2)} \]  

\( F_{t}^{(m)} \): Reaction force outputted at time \( t \ (> 0) \)

\( F_{t}^{(s_2)} \): Force received from PC for industrial robot 2 at time \( t \ (> 0) \)

\( K_{\text{scale}} = 0.5 \)  

*1 K. Kanaishi et al., ICTCE, Nov. 2019.
A user conducted cooperative work of carrying a wooden stick together with the two robot arms.

To move the stick in almost the same way, building blocks and paper blocks were piled up ahead and behind the initial position of the stick, and touched at almost the same velocity.
Experiment Method (2/3)

- We generated a constant delay for each packet transmitted between the master and slave terminals by a network emulator.
  - The constant delay between PC for haptic interface device and PC for industrial robot 1 (called the additional delay 1): 0 ms, 200 ms, 400 ms
  - The constant delay between PC for haptic interface device and PC for industrial robot 2 (called the additional delay 2): 0 ms, 200 ms, 400 ms

- The reaction force is calculated in two cases:
  - Uses both force sensors
  - Uses one force sensor
We carried out the experiment 10 times.

We measured the force applied to the stick during the work and obtained the average absolute force.

We calculated the average of the measure for the 10 times (called the \textit{average of average force}).
Experimental Results (1/2)

**Ⅰ**: 95% confidence interval

- **Average of average force [N]**
  - **Additional delay 1 [ms]**
  - **Additional delay 2**
    - 0 ms
    - 200 ms
    - 400 ms

- **Both force sensors**
- **One force sensor**
Experimental Results (2/2)

Additional delay 1: 0ms
Additional delay 2: 400ms

Reaction force: Both force sensors

Robot arm 2  
Robot arm 1

Additional delay 1: 400ms
Additional delay 2: 400ms

Robot arm 2  
Robot arm 1
Experimental Results (1/2)

Average of average force [N]

Additional delay 1 [ms]

Additional delay 2:
- 0ms
- 400ms

Average of average force [N]

Additional delay 1 [ms]

Additional delay 2:
- 200ms

Both force sensors
One force sensor

I: 95% confidence interval
Conclusion and Future Study

Conclusion

- We conducted cooperative work of carrying a wooden stick together by the two robots, and we investigated influences of network delay on the cooperative work.

The force applied to the object is large when the difference between network delays for each robot is large.

Future Study

- Carry out QoS control such as the adaptive Δ-causality control*1 to alleviate the influence of the network delay
- Exert the stabilization control with filters*2 to avoid unstable phenomena

*1 K. Kanaishi et al., ICTCE, Nov. 2019.
*2 P. Huang et al., IJCNS, July 2019.