Influences of Network Delay Variation on Haptic Perception under Adaptive Reaction Force Control

Shota Suzuki†, Kazuki Matsunaga†, Hitoshi Ohnishi††, Yutaka Ishibashi†

†Graduate School of Engineering, Nagoya Institute of Technology
††Faculty of Liberal Arts, The Open University of Japan

Oct. 10, 2014 Makuhari Messe, Tokyo, Japan IEEE GCCE2014
Outline

- Background
- Purpose
- Contents of Work
- Methods
- Results
- Conclusions and Future Work
A number of systems using haptic interface devices over a network in virtual and real spaces

When the devices are used over a network like the Internet

- Network delay
- Delay jitter
- Packet loss

The quality of experience (QoE) seriously deteriorate

To improve QoE, a QoS (quality of service) control is required
The adaptive reaction force control
dynamically changes the elastic coefficient according to the network delay
to keep QoE high in a virtual and real spaces*1, 2.

improved QoE

can keep haptic perception constant against network delay variation?

Previous Work (2/3)


The perceived stiffness depended on the elastic coefficient before the change.

The influence of network delay variation on haptic perception of reaction force?
Previous Work (3/3)


A model of the perceived stiffness *3

\[
\text{Perceived Stiffness} = k_1 \frac{\int_0^T \lambda_1^{T-\tau} f(\tau) d\tau}{\int_0^T \lambda_1^{T-\tau} d\tau} + k_2 \frac{\int_0^T \lambda_2^{T-\tau} \frac{df}{dx} d\tau}{\int_0^T \lambda_2^{T-\tau} d\tau} + k_3 \frac{\int_0^T \lambda_3^{T-\tau} \frac{df}{d\tau} d\tau}{\int_0^T \lambda_3^{T-\tau} d\tau}
\]

\(f(\tau): \text{reaction force at time } \tau, \ 0 \leq \lambda_1, \lambda_2, \lambda_3 \leq 1\)

The model fitted the perceived stiffness

When the network delay varies, the model fits the experimental results?
We investigate the influences of network delay variation on haptic perception of reaction force for work in a virtual space and in a real space.

We compare the perceived force under the adaptive reaction force control and the perceived force under the naive control (w/o adaptive).

We examine whether the estimation model for the perception of the reaction force is applicable to investigation results under the control and no control.
Contents of Work in Virtual Space

Initial position of target

End position of target

Distance | 100 [mm]
---|---
Time | 1000 [ms]
Mass of object | 0.6 [kg]
Acceleration of gravity | 2.0 [m/s²]
Damper coefficient | 0.2 [N·ms/mm]

Object

Target sphere

Cursor

Haptic interface device (PHANToM Omni)
Calculation of Reaction Force in Virtual Space

\[ F = -(K_s x + K_d v) + mg \]

- **F**: Reaction force
- **K_s**: Elastic coefficient
- **K_d**: Damper coefficient
- **x**: Cursor penetration into object
- **v**: Relative velocity of cursor to object
- **m**: Mass of object
- **g**: Acceleration of gravity
Adaptive Reaction Force Control in Virtual Space

\[ K_s = \begin{cases} 
\frac{b}{\Delta T_n} & (\Delta T_n > T_{hd}) \\
\frac{b}{T_{hd}} & (\Delta T_n \leq T_{hd}) 
\end{cases} \]

\(b\): Positive constant

\(T_{hd}\) (ms): Threshold value

\[
\Delta T_n = \begin{cases} 
\Delta t_n & (n = 1) \\
\alpha \Delta T_{n-1} + (1 - \alpha) \Delta t_n & (n \geq 2) 
\end{cases}
\]

\(\alpha\): Smoothing coefficient

\(\Delta t_n\) (ms): Round-trip network delay at \(n\)-th period

\(b = 4, T_{hd} = 4\) ms, and \(\alpha = 0.985\)

Case 1: the network delay changes in the process of lifting the object
Case 2: the network delay does not change

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Delay before change</strong></td>
<td><strong>Elastic coefficient</strong></td>
</tr>
<tr>
<td>4 ms</td>
<td>Naive control</td>
</tr>
<tr>
<td>14 ms</td>
<td>0.17 N/mm</td>
</tr>
<tr>
<td>24 ms</td>
<td>Adaptive control</td>
</tr>
<tr>
<td>34 ms</td>
<td>Calculated dynamically</td>
</tr>
<tr>
<td>44 ms</td>
<td>Calculated dynamically</td>
</tr>
</tbody>
</table>

We change the network delay after 500 ms from the start time.
The Method of Constant Stimuli

- The subject judged the object in the succeeding task was “heavier” or “lighter” than the object in the preceding task
- the weight at the end position of the lifting task
- The subject compared each pair 40 times (1400 times in total)
- The order of pairs was randomized
- The order within a pair was counterbalanced
Method in Virtual Space (3)

- PSE (Point of Subjective Equality)
  - The perceived weight was measured as PSE
  - PSE is defined as the weight (represented as elastic coefficient) in case 2 where the subject judges the object in case 2 is heavier than the object in case 1 in 50% of trials
Perceived weight [N/mm]

Results in Virtual Space

Subject 1 (adaptive reaction force control)

Subject 1 (naïve control)

95% confidence interval

Delay before change [ms]
Model of the Perceived Force

\[ \text{Perceived Force (Weight)} = k_1 \frac{\int_0^T \lambda_1^{T-\tau} f(\tau) d\tau}{\int_0^T \lambda_1^{T-\tau} d\tau} + k_2 \frac{\int_0^T \lambda_2^{T-\tau} \frac{df}{dx} d\tau}{\int_0^T \lambda_2^{T-\tau} d\tau} + k_3 \frac{\int_0^T \lambda_3^{T-\tau} \frac{df}{d\tau} d\tau}{\int_0^T \lambda_3^{T-\tau} d\tau} \]

\( f(\tau) \) reaction force at time \( \tau \)

\( T \) duration of the lifting

\( 0 \leq \lambda_1, \lambda_2, \lambda_3 \leq 1 \) forgetting parameters

\( k_1, k_2, k_3 \) weights
Estimation Results (Adaptive Reaction Force Control)

Perceived elastic coefficient [N/mm]

Measured PSE (subject 1)
Estimated PSE

95\% confidence interval

Delay before change [ms]
Estimation Result (naive control)

Perceived elastic coefficient [N/mm]

Delay before change [ms]

Measured PSE (subject 5) - Estimated PSE
Conclusions

- The adaptive reaction force control method keeps the perceived force constant under network delay variation
  - in a virtual space
  - in a real space
- The adaptive reaction force control method is expected to improve work efficiency of haptic communication systems
Future Works

- Apply the adaptive reaction force control method to variety kind of works
- Improve the fitness of the model