Experiments in Best-Effort Multimedia Networking for a Distributed Virtual Environment

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The Atomic Force Microscope

What is the nanoManipulator?

AFM tip scanning buckytubes

Graphics

Haptics

PHANTOM force-feedback device
The nanoManipulator

A virtual environment interface to an Atomic Force Microscope

http://www.cs.unc.edu/Research/nano/

How do you transmit "feeling"?

Position-Force Control
- measure position, output force at 1000 Hz

What is the nanoManipulator?

Plane Approximation
- At the microscope, find an approximating plane
  - "Taylor Series" of a surface
  - Update at 20 Hz to feel smooth
- At the user interface, display with a local loop
  - Update at 1000 Hz to feel stiff

How do you transmit "feeling"?

Microscope tip
- PHANTOM stylus
- approximating plane
- Series of approximating planes
**Classes of Service**

- **Best-Effort**
  - Contend randomly with all other flows for resources
- **Quality of Service**
  - Guarantee performance

**Internet Pathologies**

Worries: loss and delay, jitter a distant third

**Loss**

**Delay**

- Audio: delay introduces heard gaps
- Haptics: delay introduces felt gaps and incorrect surface shape; jitter makes it worse
### Delay
- Audio: delay introduces heard gaps
- Haptics: delay introduces felt gaps and incorrect surface shape; jitter makes it worse

### Dealing with Loss

**ARQ (Automatic Repeat Request):** react to an error after it occurs
- TCP: retransmit when an error is detected
- Can’t detect error until one round-trip-time after segment was first sent

**FEC (Forward Error Correction):** anticipate an error before it occurs
- Transmit every piece of data multiple times
- Increases bandwidth requirements, but statistically reduces loss
- If zero loss is necessary, can combine with ARQ

### FEC Example

- **Send:** d, e, f, g, h, i, j, k, l, m, n
- **Receive:** X, X, X
- **Display Queue:**
  - Display:
    - e, d, c
  - Queue:
    - e, f, g, h, i, j, k, l, m, n
Receiver Buffering

Gaps can be caused by loss or by jitter

Best-Effort Adaptations

Queue Monitoring (QM)

• Continuum between I-policy and E-policy
• As the queue gets longer, QM drops frames more aggressively
• Two parameters: threshold and decay

(Stone & Jeffay 1994)

Static Buffering

• I-policy
  • discard late frames
  • constant latency; allow gaps
• E-policy
  • keep late frames
  • increasing latency; no gaps

(Naylor & Kleinrock 1982)

Queue Monitoring Parameters

Threshold = number of playout periods queue can exceed a given length before a frame is dropped

Decay = ratio between successive thresholds
Distributed nM: What Changes?

- The nanoManipulator was designed for LAN:
  - requires very low network delay
  - occasionally consumes high bandwidth
- Collaboration requires deploying over WAN:
  - high network delay
  - frequent bandwidth bottlenecks

Experimental Setup

Using FEC in the nanoManipulator

- Surface data is sent to the client for two purposes:
  - Display — requires low latency
  - Logging — requires zero loss

(Christiansen, Jeffay, Ott, Smith 9?)
### Using FEC in the nanoManipulator

- Logging at the server lets us tolerate loss
- TCP is only used because it guarantees 0 loss
- Use UDP instead
  - Cuts mean network delay, jitter
  - Add FEC when loss is high
    » Base bandwidth is low, so we can afford the bandwidth penalty

### Forward Error Correction Results

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Bandwidth</th>
<th>Loss</th>
<th>Latency</th>
<th>Jitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCP</td>
<td>23 kbps</td>
<td>0</td>
<td>145 ms</td>
<td>124 ms</td>
</tr>
<tr>
<td>UDP</td>
<td>20 kbps</td>
<td>1.8%</td>
<td>97 ms</td>
<td>33 ms</td>
</tr>
<tr>
<td>UDP x2</td>
<td>40 kbps</td>
<td>0.2%</td>
<td>94 ms</td>
<td>33 ms</td>
</tr>
<tr>
<td>UDP x4</td>
<td>72 kbps</td>
<td>0.02%</td>
<td>95 ms</td>
<td>33 ms</td>
</tr>
</tbody>
</table>

For the haptics data stream from the nanoManipulator, Forward Error Correction reduces network delay 50 ms, jitter 90 ms

### Delay-Tolerant Haptics

- **Plane Approximation**
  - Highly sensitive to delay
  - Highly sensitive to delay jitter
- We can’t remove delay in the network

- **Warped Plane Approximation**
  - Very little sensitivity to delay
  - Highly sensitive to delay jitter
- We can do something about jitter
Using QM in the nanoManipulator

- To improve the quality of the warped plane approximation, reduce delay jitter
- How do we measure jitter?
  - Gap rate: standard metric from audio/video
  - Gaps can be caused by loss or by jitter

Queue Monitoring results

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Loss</th>
<th>Drop rate</th>
<th>Gap rate</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDP</td>
<td>10%</td>
<td>12%</td>
<td>22%</td>
<td>89 ms</td>
</tr>
<tr>
<td>QM (30, 2)</td>
<td>10%</td>
<td>1%</td>
<td>11%</td>
<td>94 ms</td>
</tr>
<tr>
<td>QM (150, 2)</td>
<td>10%</td>
<td>0.02%</td>
<td>10%</td>
<td>96 ms</td>
</tr>
<tr>
<td>QM (3600, 2)</td>
<td>10%</td>
<td>0.001%</td>
<td>10%</td>
<td>91 ms</td>
</tr>
</tbody>
</table>

For the haptics data stream from the nanoManipulator, high-threshold Queue Monitoring drove the gap rate to equal the loss rate.

Conclusions

- Audio and video adaptations can also be applied to haptics
- The teleoperation literature has regarded 100 ms as “impossible” latency, but we can function in that regime
- VR can operate over best-effort networks

Current Research Directions

- Combining FEC with QM: 0 gap rate
- Find quantitative metrics more appropriate to this class of applications
- Find other representations more amenable to wide-area distribution

New Work
Combining FEC and QM

- FEC drives the application-level loss rate to 0
- QM drives the gap rate to equal the loss rate

So, by combining the two we should be able to drive the gap rate to 0

Quantitative Measures

- Gap rate is a derived metric from standard multimedia; how do we measure performance of this application?
- Discrepancy between surface displayed to user and surface measured at the microscope
  - RMS error
  - peak error
  - histogram

Other Representations

- Change intermediate representation
  - The standard approach requires 16 kbps and 20 Hz; we can’t maintain this over a long-haul network.
  - We’re exploring alternate representations
    - 30 kbps base bandwidth
    - 5 Hz
    - much more latency-tolerant.