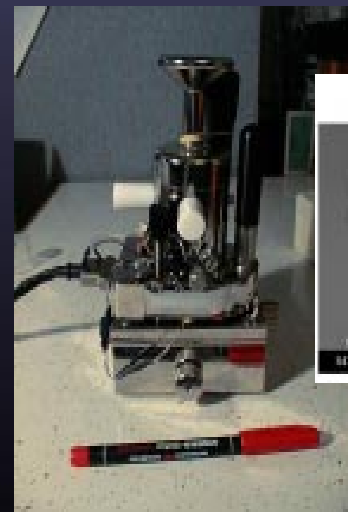
Experiments in Best-Effort Multimedia Networking for a Distributed Virtual Environment

Tom Hudson, Michele Clark Weigle, Kevin Jeffay, Russell M. Taylor II

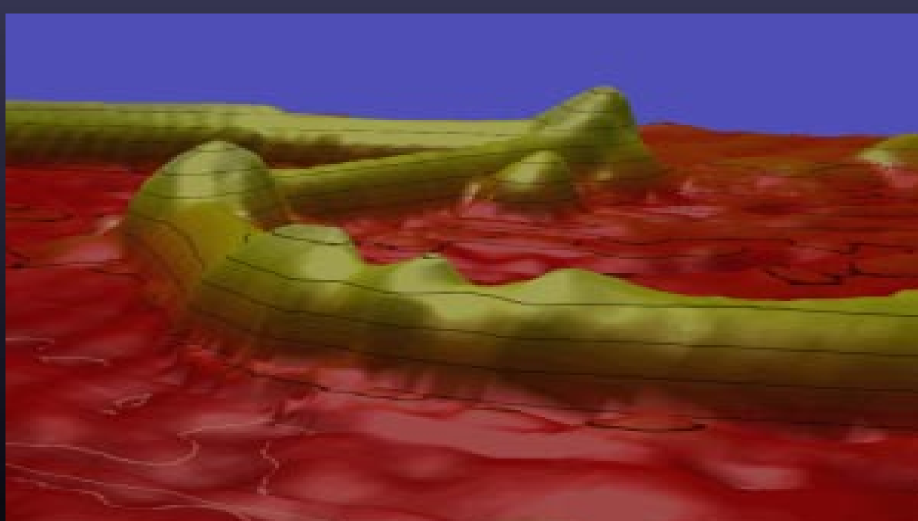
University of North Carolina at Chapel Hill

The Atomic Force Microscope



AFM tip scanning buckytubes

Graphics

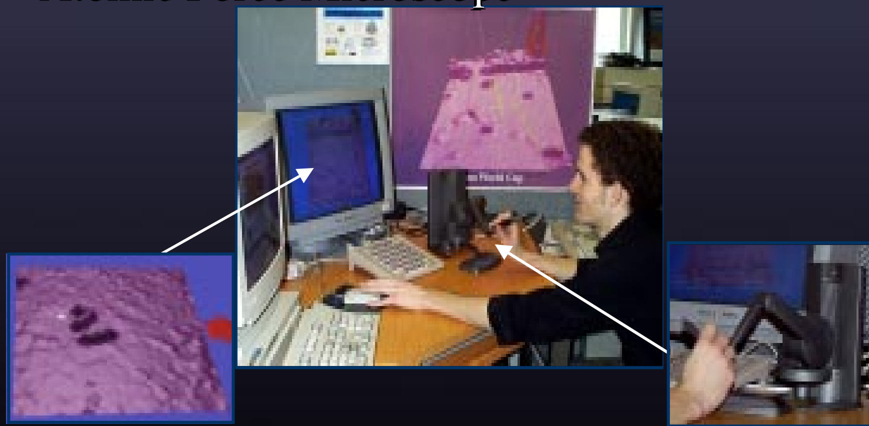


Haptics

PHANTOM force-feedback device

The nanoManipulator

A virtual environment interface to an Atomic Force Microscope

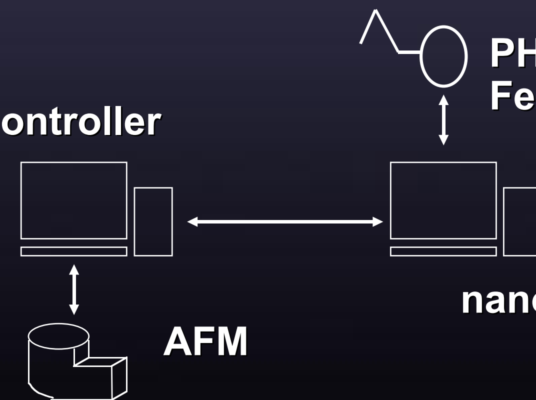


http://www.cs.unc.edu/Research/nano/

How do you transmit "feeling"?

Position-Force Control

- measure position, output force at 1000 Hz



How do you transmit "feeling"?

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

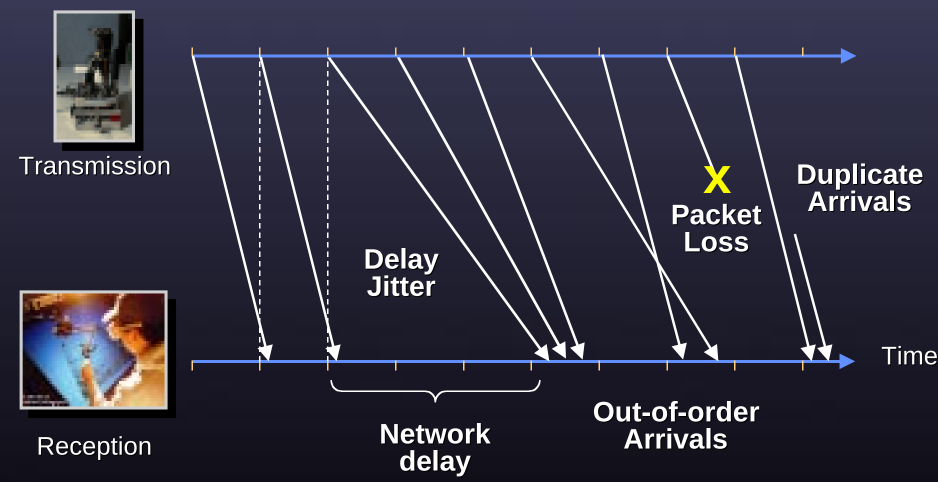
How do you transmit "feeling"?

Series of approximating planes

Classes of Service

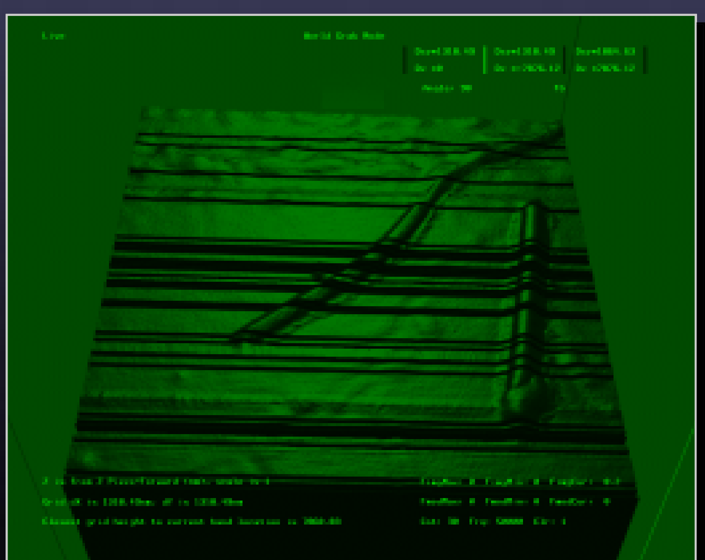
- Best-Effort
  - Contend randomly with all other flows for resources
- Quality of Service
  - Guarantee performance

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

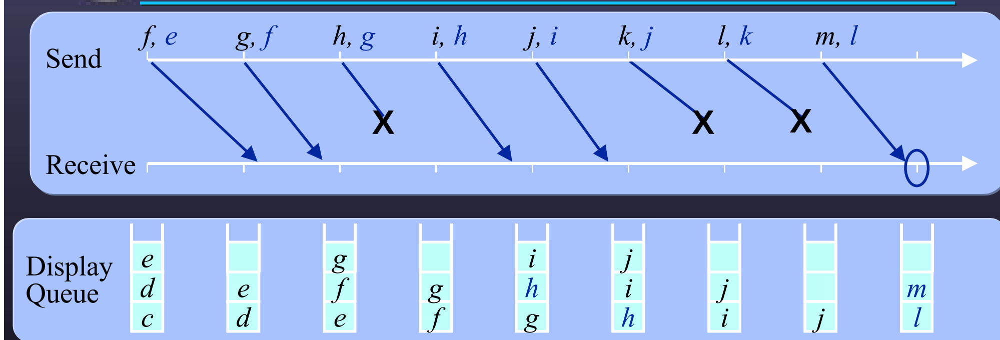
- TCP: retransmit when an error is detected
- Can't detect error until one round-trip-time after segment was first sent

Dealing with Loss

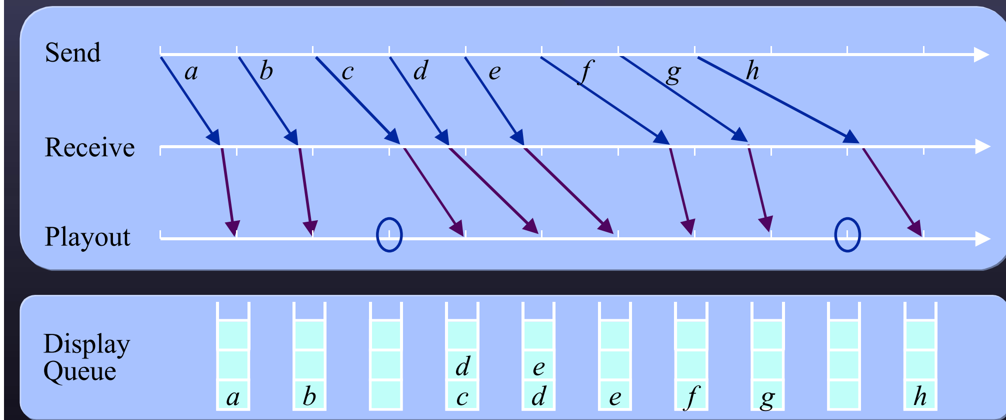
FEC (Forward Error Correction): anticipate an error before it occurs

- 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



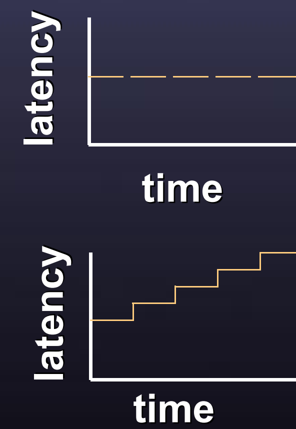
Receiver Buffering



Gaps can be caused by loss or by jitter

Static Buffering

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



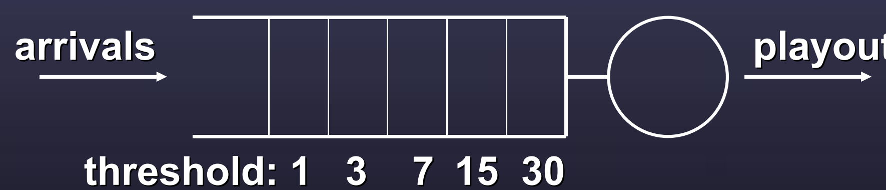
(Naylor & Kleinrock 1982)

Queue Monitoring (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)

Queue Monitoring Parameters



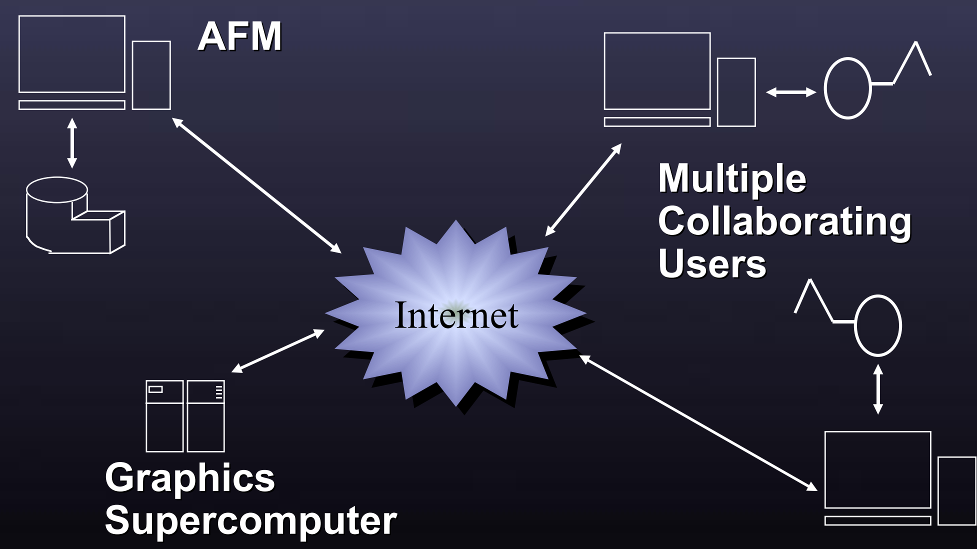
Threshold = number of playout periods queue can exceed a given length before a frame is dropped

Decay = ratio between successive thresholds

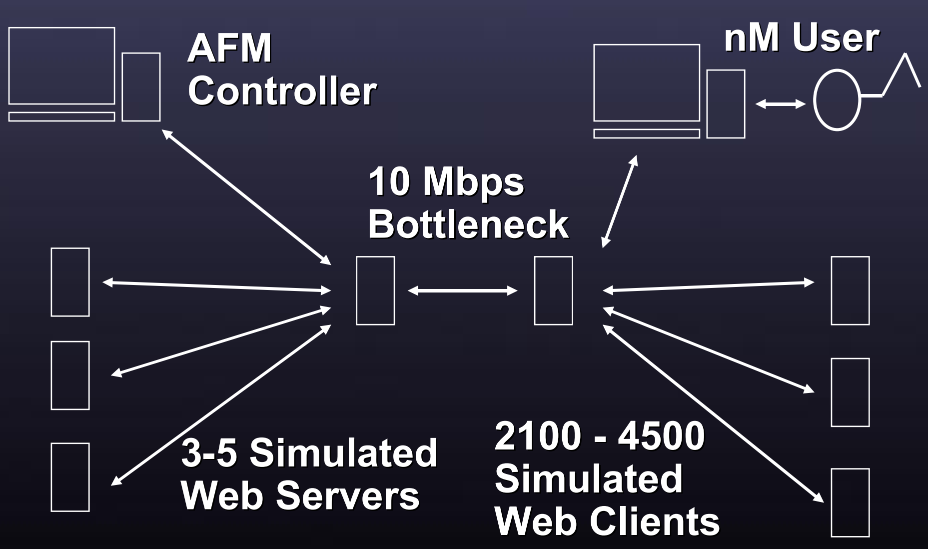
Distributed nM: What Changes?

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

System Diagram



Experimental Setup



(Christiansen, Jeffay, Ott, Smith 9?)

Using FEC in the nanoManipulator

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

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

Protocol	Bandwidth	Loss	Latency	Jitter
TCP	23 kbps	0	145 ms	124 ms
UDP	20 kbps	1.8%	97 ms	33 ms
UDP x2	40 kbps	0.2%	94 ms	33 ms
UDP x4	72 kbps	0.02%	95 ms	33 ms

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

Delay-Tolerant Haptics

- 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

Protocol	Loss	Drop rate	Gap rate	Latency
UDP	10%	12%	22%	89 ms
QM (30, 2)	10%	1%	11%	94 ms
QM (150, 2)	10%	0.02%	10%	96 ms
QM (3600, 2)	10%	0.001%	10%	91 ms

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

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.