PHYSICALLY REALISTIC HAPTIC INTERACTION WITH DYNAMIC VIRTUAL WORLDS

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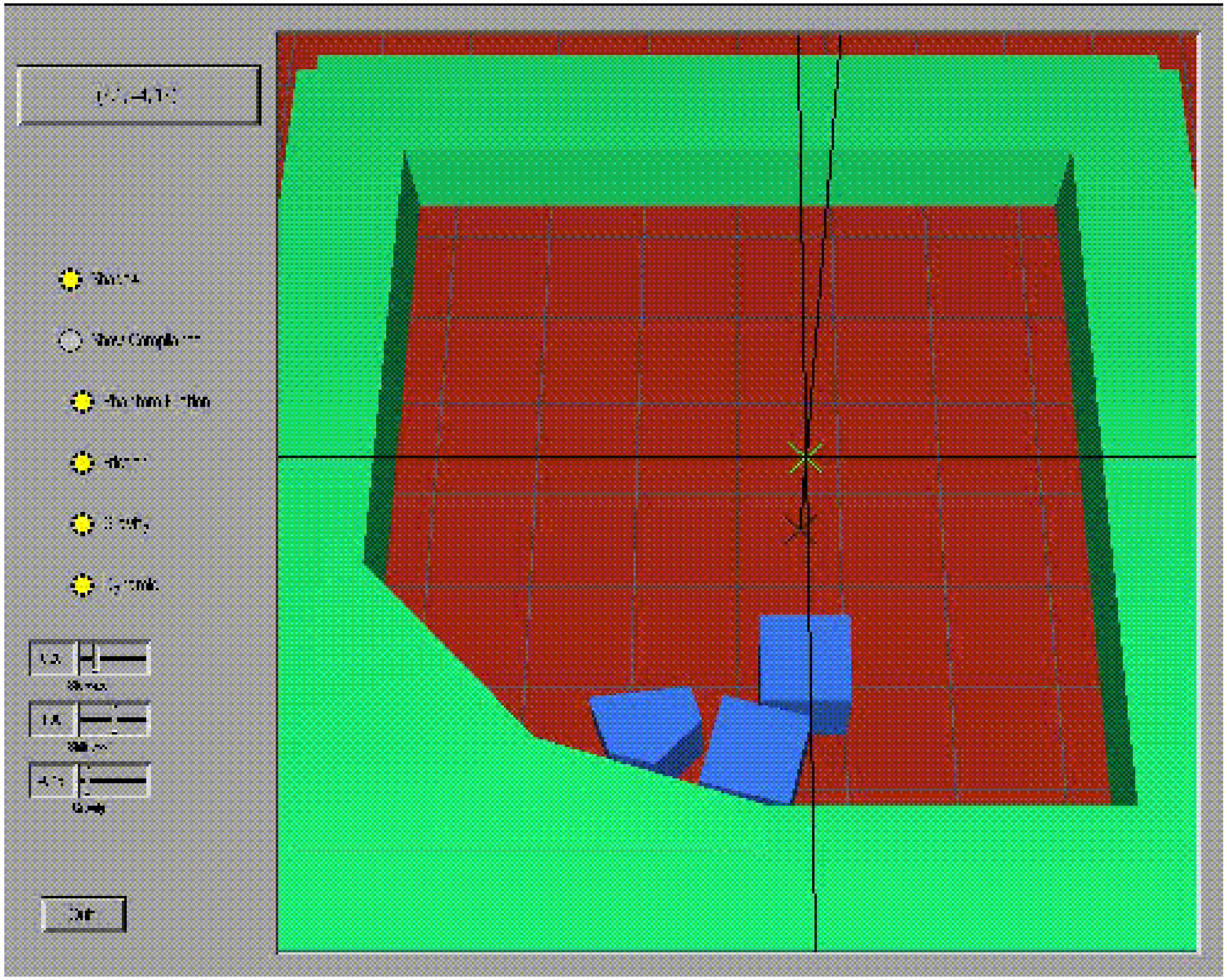
Virtual Environment Example



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Goal

To be able to create an interactive dynamic virtual environment, whose entities have definite physical properties, and have them behave in a physically correct manner under the action of external forces.

Allow a user to manipulate this environment with a probe, and feel the corresponding forces back.

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Physically Based Modeling

- Model objects as polyhedral, rigid bodies
- State = position and velocity for all degrees of freedom
- Given:

    Object geometries, initial state, External Forces

  Solve for:

    New state

  Subject to:

    kinematic constraints

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Physically Based Modeling(cont.)

- In short, solve

$$\frac{d}{dt}\begin{pmatrix} x(t) \\ \theta(t) \\ mv(t) \\ I\omega(t) \end{pmatrix} = \begin{pmatrix} v(t) \\ \omega(t) \\ F(t) \\ \tau(t) \end{pmatrix} \quad \textbf{(1)}$$

- Constraints can be equalities or inequalities
- Permanent and Transient Constraints enforced by additional constraint forces (not penalty)
- Coulomb friction model used
- Step through time, backtrack on collisions
- Display updated world model
- Key requirement: Display at real-time, i.e. 30Hz
- Plenty of published work

Distributed Processing

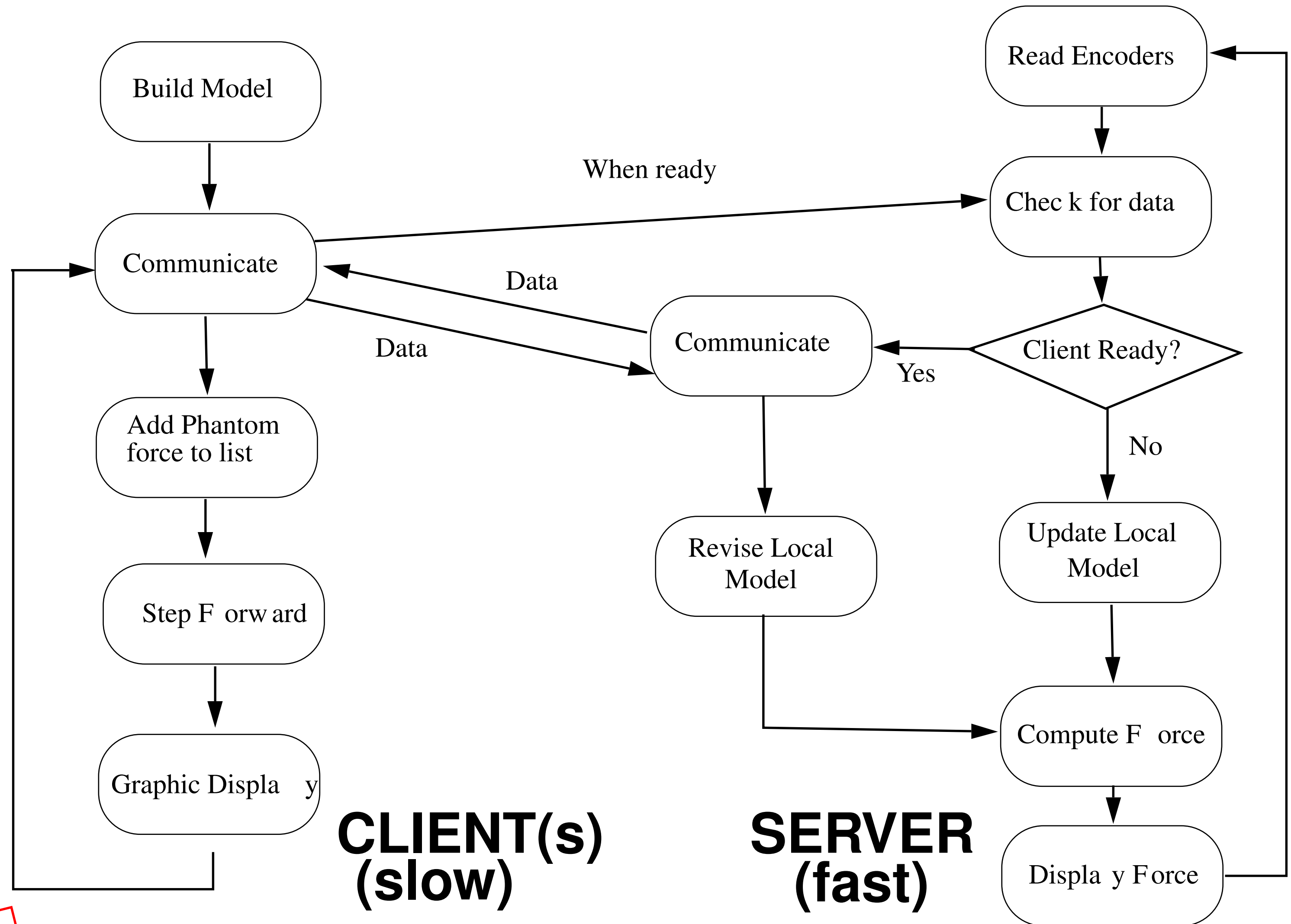
Why?

- Generalized physical simulation, with display can only go at around 30Hz
- Better modularity
- Force server doesn't need to know about model away from the probe location
- Servo rate independent of model complexity (easier real-time control)

How?

- Use one processor for dynamic simulation and graphics, and one for low-level force control of each haptic interface
- Have simulator communicate with each force server separately

Multi-processor model



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Simulation algorithm

- **Simulation processor acts as haptic *client***
- **Query each force server for position and force information (what object, where, and how hard the user pushed on during the last cycle)**
- **From position, determine appropriate local model for each probe, and communicate to server**

  force(object->probe) = - force(probe->user)
  = - force(probe->object)
- **Add haptic forces to list of external forces for simulation**
- **Step forward in simulation and display new state**
- **Display <u>constrained</u> probe position**

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Force Server Algorithm

- Check to see if simulator has new local model
- If yes,
  - send current probe position, amount and location of force applied during previous cycle
  - Receive new local model (position, velocity, and orientation of relevant plane, if any)
- If not,
  - Update local model appropriately (more later)

- Compute normal force from penetration using a simple penalty method
- Compute frictional force using Coulomb model
- Display force to user

Local Model Schemes

1. Closest Plane
   - Use closest plane for force computation
   - Position Discontinuities at client update rate (nasty clicking at 30 Hz)

2. Plane with velocities of end-points
   - Approximate velocity of contact point by linear interpolation between edges
   - In 2-D, edge length changes
   - In 3-D, nasty things happen to plane dimensions
   - Works for objects with high moments of inertia, i.e., ones that don't rotate easily

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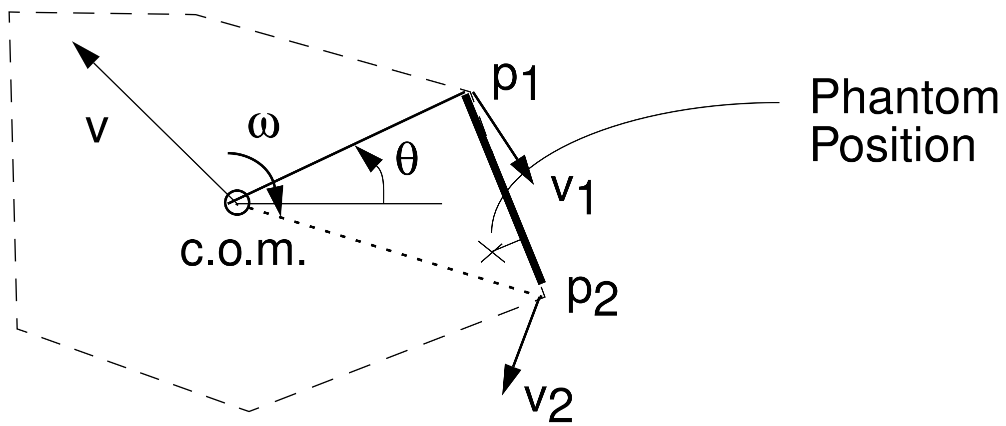
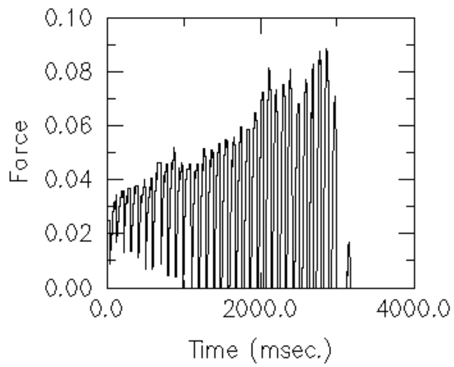
Local Model Schemes (cont.)

3. Full Kinematic Interpolation

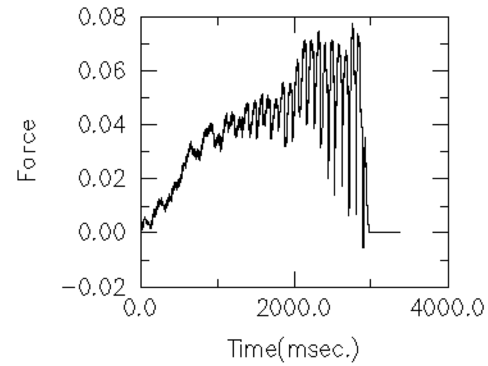


- **Position, Velocity, Orientation, and Angular Velocity of c.o.m.**
- **Local co-ordinates of plane boundaries**

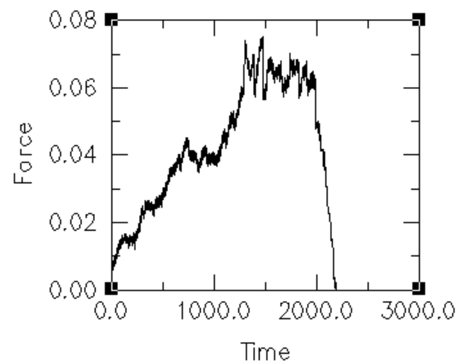
Comparison of Local Models



Plane Interpolation



Velocity Interpolation



Kinematic motion model

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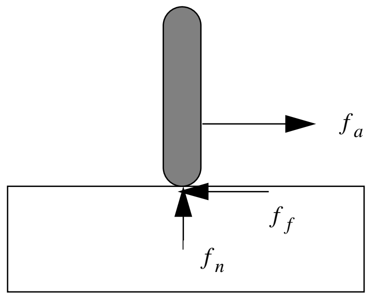
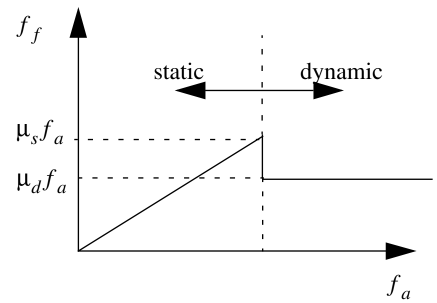
Coulomb friction model





- Static friction is a function of x, $x_{stopped}$, and k
- Dynamic friction is a function of v, v_l, and v_h
- Switching between friction modes avoided by a hysteresis technique
- Switching from dynamic to static friction should not involve force discontinuity, so $x_{stopped}$ and k are set appropriately

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Why is Coulomb friction hard?

- Firstly, we have no force sensors to measure force, to determine impending direction of motion
- Secondly, no tachometers to measure velocity, to decide between static and dynamic friction
- Workarounds:

    Exponential differentiating filter on position to approximate velocity

    Threshold velocity to determine if one has *stopped*
- Reasonable results with right threshold and spring constant for static friction
- Strongly dependent on good velocity estimate near zero

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Results

- Dynamic simulation - 40Hz on 250MHz R4400 SGI Indigo Extreme
- Phantom™ haptic interface controlled at 10kHz on 200MHz Pentium Pro
- 3-D haptic display with 2-D dynamic simulation, i.e. objects can be pushed in the plane, but their top and bottom surfaces can be felt but not pushed
- Preliminary manipulation experiments with two probes demands experience, and finite sized fingers
- Can assign physical properties to probe and make it a part of the simulation - stability issues become significant

Conclusions

- Framework for effective haptic interaction using multiple force feedback devices with single physically based simulation system
- Ability to work around measurement of force and velocity
- Local model update strategy for good dynamic performance at low communication rates
- Coulomb friction model for surface properties
- Support for multiple, distributed users manipulating one virtual environment

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Research Issues

- How much knowledge on the force server?
- Choices for concave surfaces
- Better control strategies
- Is second-order dynamics really good with a point tool? (especially in 3-D)
- Ways of constraining motion
- Interfaces in 3-D for better interaction
- Manipulation and HCI issues - what can you really do with a point?
- Ergonomic considerations