Considerations for Robust Haptic Interaction with Virtual Dynamic Systems

Ed Colgate
Department of Mechanical Engineering
Northwestern University

IMA Haptics Workshop, June 14, 2001
A grand challenge...

- Complex, physics-based simulations
- Simple percepts
- CAD, Medical
- Arcade joysticks
- Few sophisticated users
- Many unsophisticated users

Our target
Imagine a piece of software – a “haptic environment editor and simulator.” To use it one must:

- Tune to the selected display device
- Create parts
  - Geometry
  - Bulk dynamic properties (mass, elasticity, damping)
  - Surface properties (texture, coefficients of friction and restitution)
- Interact!
Challenges
which stem from this vision

- Device independence
- Performance
  - Dynamic range of impedances (“Z-width”)
- Stability
- “Physics-based” simulation
  - With a “hard” real-time constraint
Framework for addressing challenges

- **Passivity**
  - Impedance presented to human should be passive

- **Why?**
  - NOT because we expect haptic displays to be passive
  - NOT because we believe that humans are passive
  - RATHER, because focus on passivity:
    - Reflects primacy of physical *law* over physical *behavior*
    - Provides access to powerful theoretical tools (e.g. Circle Criterion)
    - Provides a means of breaking down system into manageable pieces
An early passivity result

\[ \begin{align*}
&b > T \frac{1}{2(1 - \cos \omega T)} \Re \left\{ 1 - e^{-j\omega T} \right\} H(e^{j\omega T}) \\
&\quad \text{for } 0 \leq \omega \leq \omega_N
\end{align*} \]
Passivity of a virtual wall

- Let \( H(z) = K + B \frac{z^{-1}}{Tz} \)
  - \( T \): sample rate
  - \( K \): virtual stiffness
  - \( B \): virtual damping

- For passivity: \( b > \frac{KT}{2} + B \)
**Experimental results**

J. Michael Brown, MS Thesis

- Area **under** each curve corresponds to virtual walls that operators could not destabilize.

- Stability does **not** correspond to passivity, yet:

- Physical damping has a pronounced benefit
**Implications for haptic display design**

- At a given frequency $\omega$, the mechanical impedance of a haptic display may be written as:

$$Z(j\omega) = B(\omega) + j\left[\omega M(\omega) - \frac{K(\omega)}{\omega}\right]$$

Most of us would agree on the imaginary part:

0 (structurally stiff)

ε (low moving mass)

But what about the real part?
High frequency damping: the key to dynamic range

Normalized Damping $B(\omega)$

Bandwidth of voluntary motion

Bandwidth of tactile sensing

Frequency (Hz)

Laboratory for Intelligent Mechanical Systems
Aside: why cobots?
Key advantage of cobots: dynamic range
From virtual walls to complex simulations: the virtual coupling concept

operator

haptic display

from virtual walls to complex simulations: the virtual coupling concept

operator

haptic display

operator

haptic display

Passive Tool Simulation

"Virtual Coupling"

operator

1 - e^{-Ts} s

u

1

ms + b

s

v

H(z)

unilateral constraint

1

s

x_s

T

x

F_1 k

H(z)

x_{1k}

T

x

F_2 k

E(z)

v_{2k}
Virtual coupling: passivity

- Recall conditions for passivity of the virtual wall:
  \[ b > \frac{T}{2} \frac{1}{1 - \cos \omega T} \Re \left\{ 1 - e^{-j \omega T} H(e^{j \omega T}) \right\} \quad 0 \leq \omega \leq \omega_N \]

- Passivity of an environment \( E(z) \) seen through virtual coupling \( H(z) \) requires:
  - The same condition as above, plus:
  - \( E(z) \) must be discrete-time passive
Virtual coupling: significance

- Establishing passivity is easier:
  - Easier to establish discrete-time passivity of simulation alone than continuous-time passivity of system as a whole

- Simulation \( (E(z)) \) may be developed without regard for details of operator, display device, or virtual coupling:
  - This is the key to device independence
    - Virtual coupling \( (H(z)) \) is initially tuned to display device
    - Simulation \( (E(z)) \) is designed subject only to discrete-time passivity constraint
But it doesn’t work in practice!

- Passive simulations must be implicit
  - Implicit integration techniques are slow!
- In practice, virtual environment simulations are:
  - Explicit
  - Time-delayed
  - Nonlinear
- Virtual environment simulations are never discrete time passive!
An improved framework: energy management
Brian Miller’s work

- Key idea much the same as with earlier passivity work:
  - Bound energy growth (negative damping) due to simulation
  - Ensure that haptic display damping outpaces energy growth

- No longer possible to establish continuous-time passivity, but:
  - Possible to establish stability under the assumption of passive human dynamics
  - Possible to establish “cyclo-passivity”

- Suitable bounds on energy growth can be found for a variety of linear and nonlinear virtual environments
Energy management framework
Transformed haptic system

- $\hat{G}$: transformation of $G$ constructed to have same level of damping – $\delta$ – as $D$ (haptic display device)

- $\hat{V}$: transformation of $V$ forced by transformations of $G$ and $E$. $\hat{V}$ has positive damping of level $\gamma$.

- $\hat{E}$: transformation of $E$ having the property that $\hat{E} + \alpha$ is discrete time passive
Energy management in the transformed system

- Relations exist between $\delta$, $\gamma$ and $\alpha$ that guarantee system stability. Specifically:

  $$\alpha < \frac{\delta \gamma}{\delta + \gamma}$$

- Device independence is recovered

- Reasonable bounds on $\alpha$ can be found for many virtual environments, including those that:
  - Are delayed
  - Exhibit piecewise continuous nonlinearities
For more detail...


A case study: impulse-based simulation of rigid body systems

Beeling Chang and Brian Miller

- “Impulse-based simulation” introduced by Mirtich and Canny
  - All contact modeled using impulses (i.e., no forces between bodies)
  - Collision detection via Lin-Canny closest features algorithm
  - Scheduler ensures that only one collision at a time is handled

- Some nice features for use with haptics:
  - Very fast
  - Employs realistic models of friction and restitution (thus, prospects are good that energy growth can be bounded)
The “real-time” constraint

- What “real-time” means for graphics/animation:
  - Average integration time step exceeds average computational time
  - Furthermore, integration time step may well be variable

- What “real-time” means for haptics:
  - Every integration time step must exceed its associated computational time
  - Furthermore, the integration time step is typically fixed
  - We call this “hard real-time”

- Can impulse-based simulation be adapted for hard real-time?
The key problems with hard real-time impulse-based simulation

- Impact state determination
- Multiple simultaneous contacts
A strategy that seems to work...

- If the impulse at one point of contact is large enough to change the bodies’ velocities, and advance the simulation to a valid (non-overlapping) state, let it do so.
- Else, if a constraint force at this point of contact is sufficient to advance the simulation to a valid (non-overlapping) state, let it do so.
- Else, model contacts with springs and dampers (or solve the LCP).
A closer look at contact state determination

- A typical collision:
  - “previous state”
    - no overlap
    - no extra computation
  - “next state”
    - overlap
  - “exact state”
    - no overlap
    - extra computation
A closer look at contact state determination (2)

- A problematic collision (bodies are receding at beginning of time step):

  - “previous state”
    - no impulse!
    - “stuck” simulation

  - “next state”
    - overlap

  - “exact state”
    - no overlap
    - impulse
    - extra computation
Contact state determination is important!

- Key to advancing simulation
  - Use of previous state often results in “stuck” simulation
  - Use of next state results in overlap
  - “Inter-sample” state is needed

- Also important in energy growth
  - “Inter-sample” state increases energy growth (experimentally confirmed)
  - Bounds have been found for some simple cases (e.g., direct impact with no tangential impulse)
  - Effect is comparable in magnitude to that introduced by a time step delay
Conclusions

- The physical world presents us with a vast range of dynamic behaviors
- The haptic display of such wide-ranging behaviors leads to some interesting challenges:
  - Dynamic range
  - Guaranteed stability
  - Device independence (or, at least, “atomic” design)
  - “Hard” real-time simulation
- Energy management is a powerful framework for the design and analysis of haptic systems, but…
  - Parameter limitations are unavoidable
  - Melding of psychophysical data and system design parameters is needed