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Some recent results on the problem of

Stable High Performance Haptic Interfaces

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People

- Recent Ph.d. students: Pietro Buttolo, Rick Adams, Steven Venema, Dal-Yun Hwang
- Visiting Student Jee-Hwan Ryu
- Dan Klowden, Manuel Moreyra
- Sponsors: Boeing, Ford, US Air Force, National Science Foundation, LG-Corp.

Haptic Interfaces

- Human - Robot interaction to support physical manipulation of computer simulated objects.
- Example: Extend the desktop metaphor to include mass of objects and magnetic fields.

History

- Nuclear Teleoperators (waldos) 1940’s
- …   etc. etc. etc. (not for this crowd!)

Haptic Interface Technical Issues

- Mechanical design
  - Low mass, high stiffness, high dexterity, kinematics
- Human Factors
  - Psychophysics
  - Ergonomics
- Computation
  - Rendering
  - Collision Detection
- Control Properties
  - Stability, Quality of Force Feedback

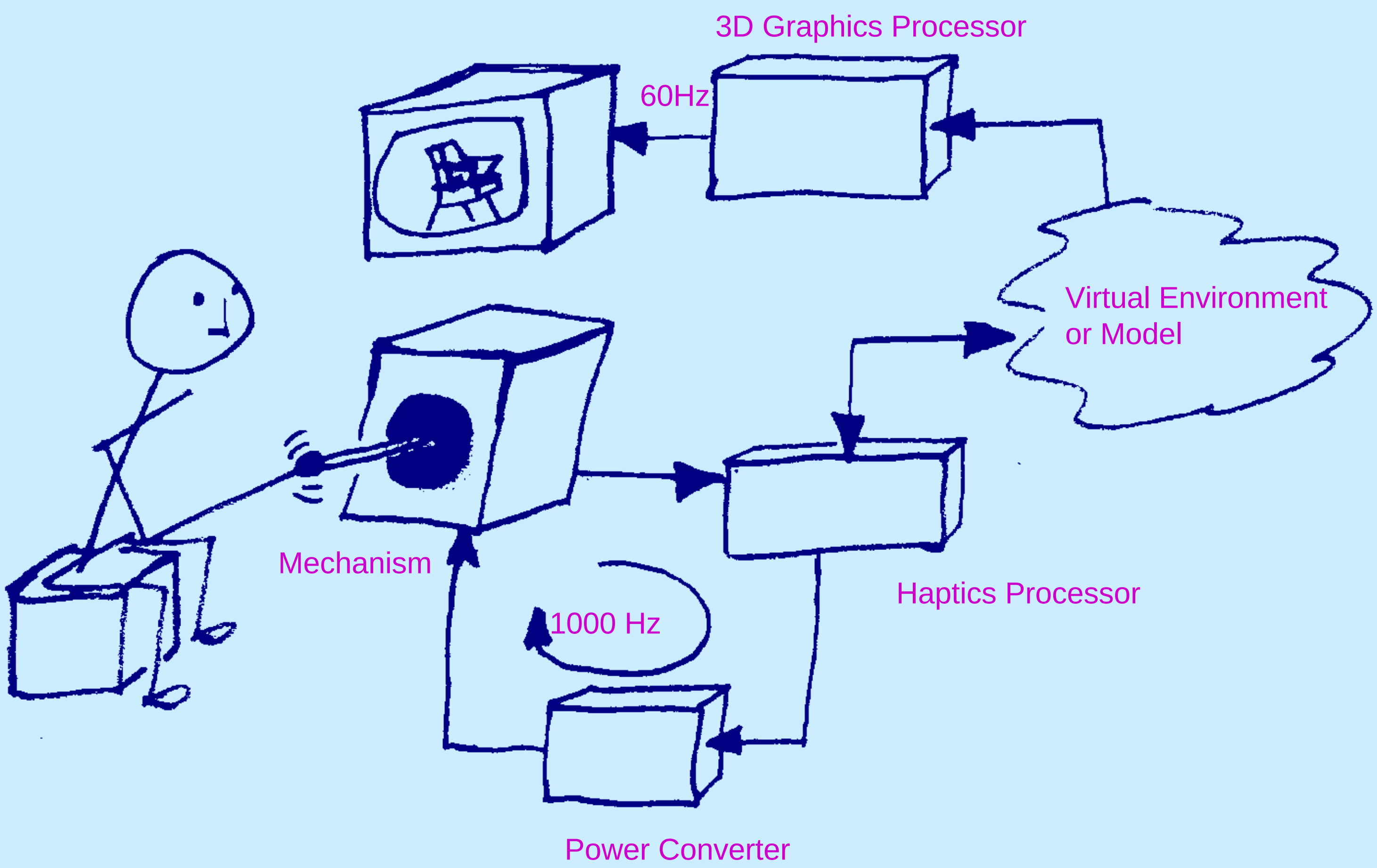
Aspects of Performance

- Does operator feel distinct contact ?
- Does operator feel unimpeded in free motion?
- Is system free of vibration or oscillation?
- What is maximum stiffness that can be rendered?

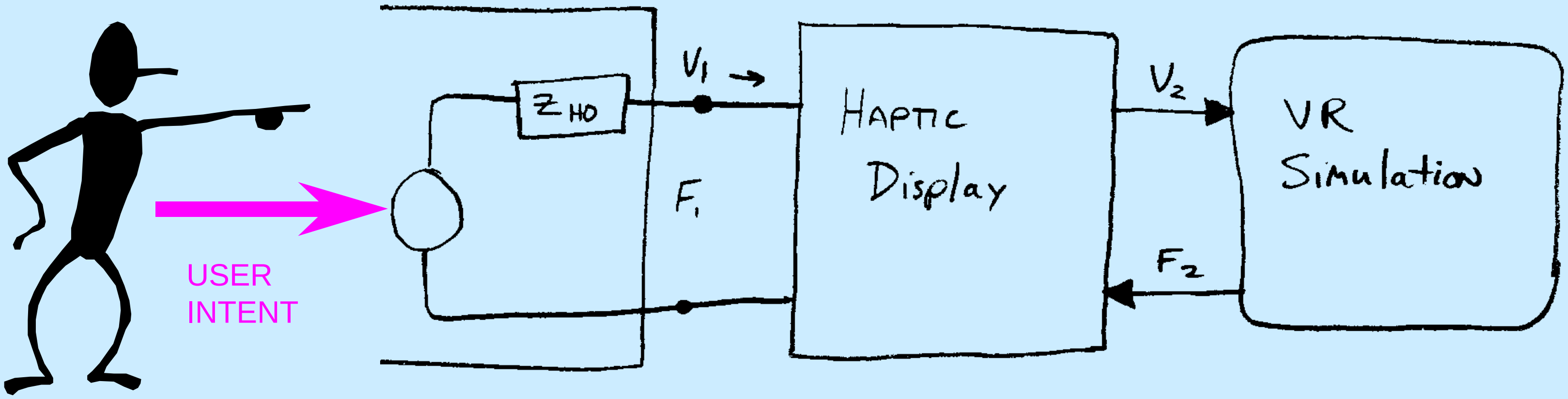
STABILITY

- An emergent property of ENTIRE SYSTEM (including operator and virtual environment)
- Depends on ...
  - Virtual Environment properties
  - Stiffness of operator grasp
  - Sampling rate of control

Haptic Interaction System Overview



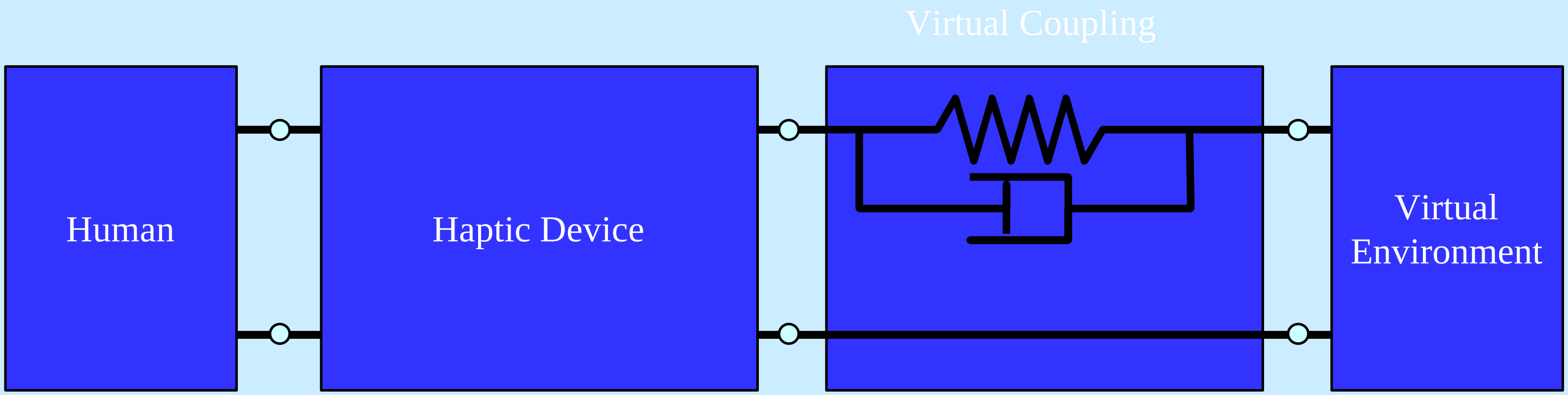
Network Model



Stable Haptic Interaction

- A closed loop human-machine system
- Non-linear
- Time / Space variation
- Virtual World Geometry
- Virtual Coupling Network
  * Colgate (1995), Zilles & Salisbury (1995), Adams & Hannaford (1999)

Virtual Coupling



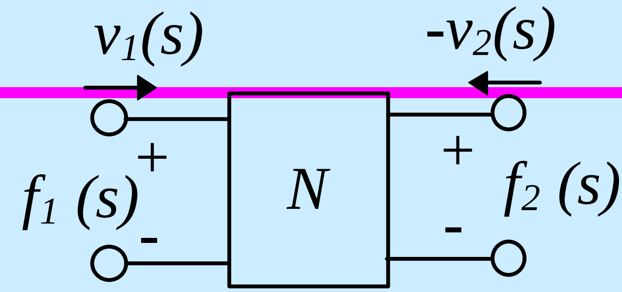
Passivity

- Principle of conservation of energy:
  - "total energy supplied to system must be positive"
- Definitions:

$$\int_0^t f(\tau)v(\tau)d\tau + E(0) \geq 0, \qquad \forall t \geq 0$$

$$E_{obsv}(n) = \sum_{k=1}^{n} f(k)v(k)$$

Absolute Stability



when terminated at either end by an arbitrary passive loading,
N becomes a passive one-port

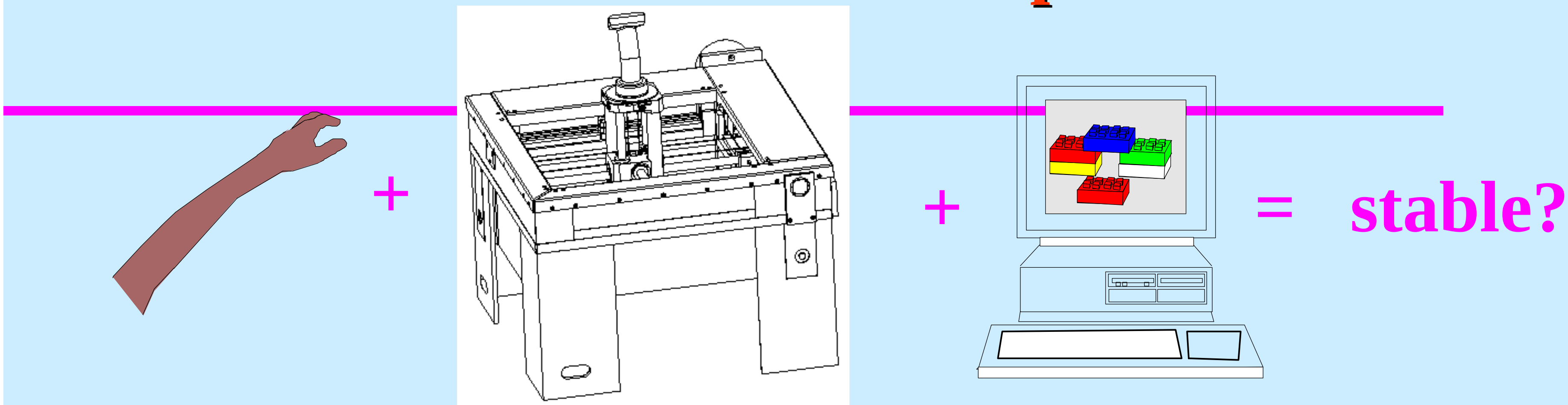
Llewellyn's criteria

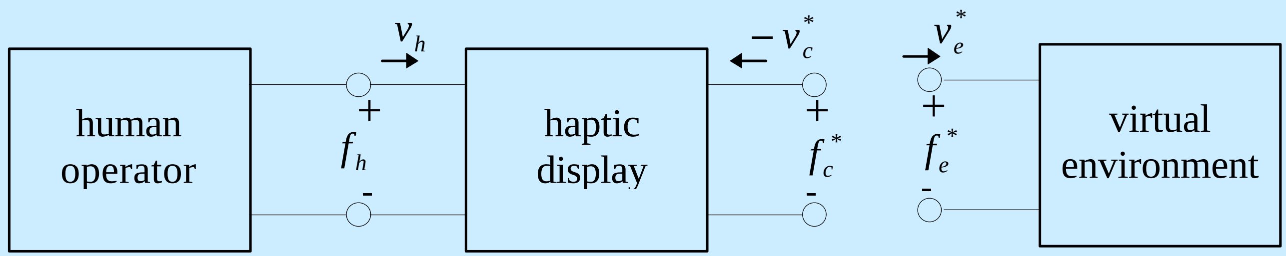
1) p_{11} and p_{22} have no rhp poles.

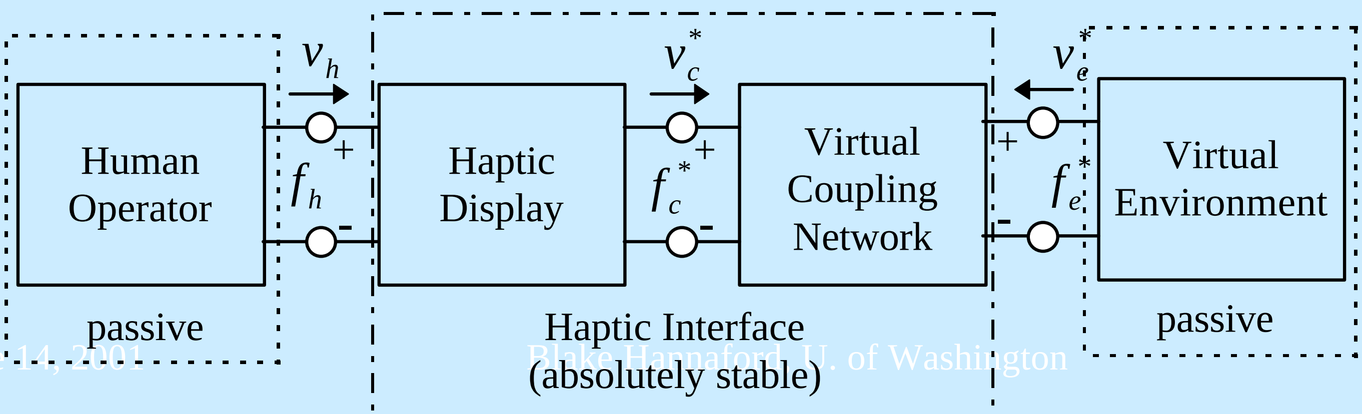
2) any poles of p_{11} and p_{22} on imaginary axis are simple with real and positive residues.

3)
$$\operatorname{Re}\left(p_{11}\right) \geq 0$$
$$2\operatorname{Re}\left(p_{11}\right)\operatorname{Re}\left(p_{22}\right) \geq \left|p_{12}p_{21}\right| + \operatorname{Re}\left(p_{12}p_{21}\right) \quad \forall \omega \geq 0$$

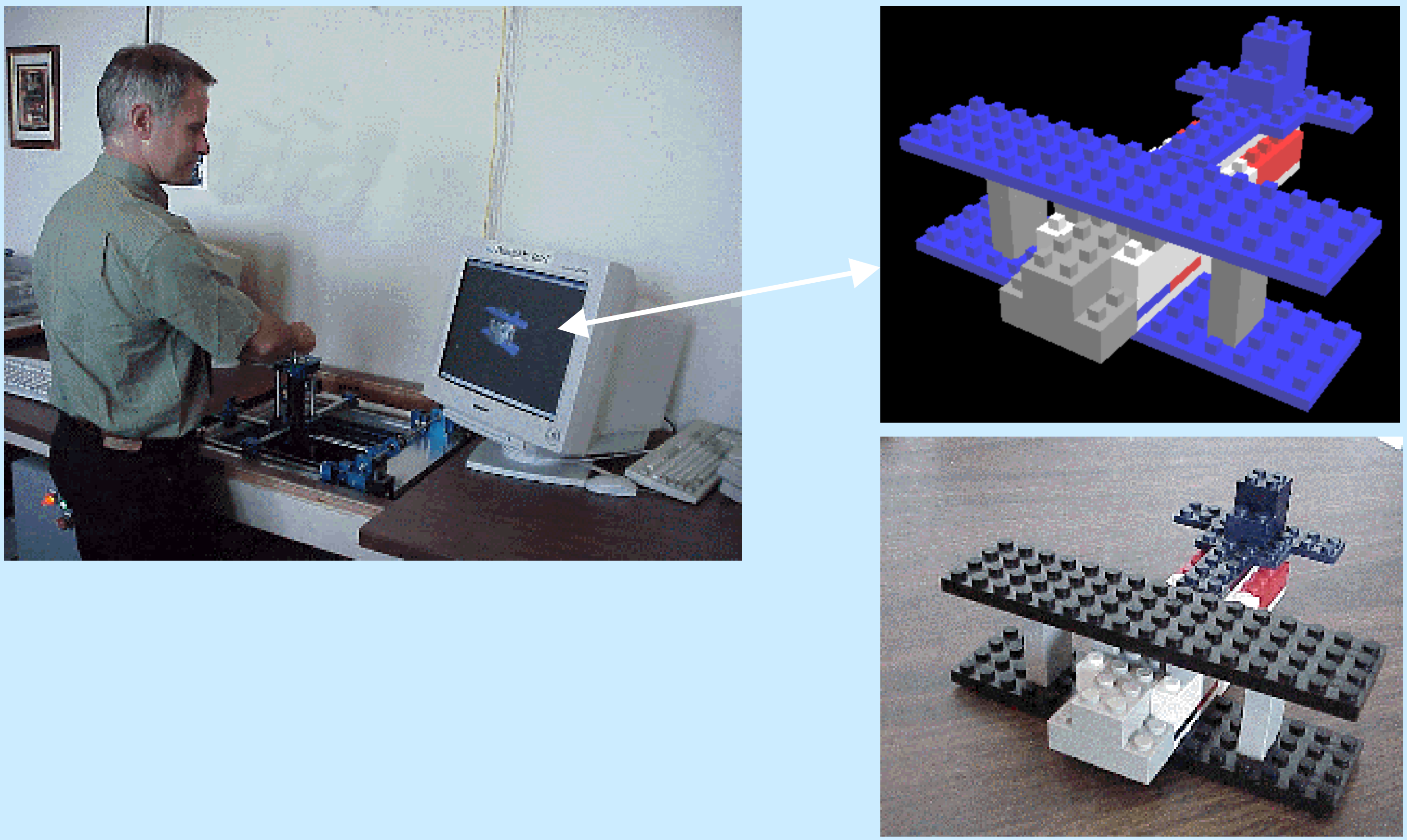
Two-Port Framework for Haptic Interaction





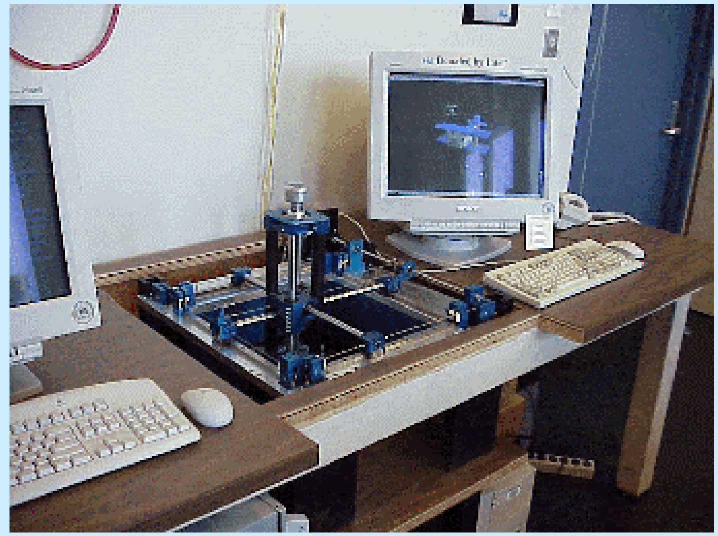


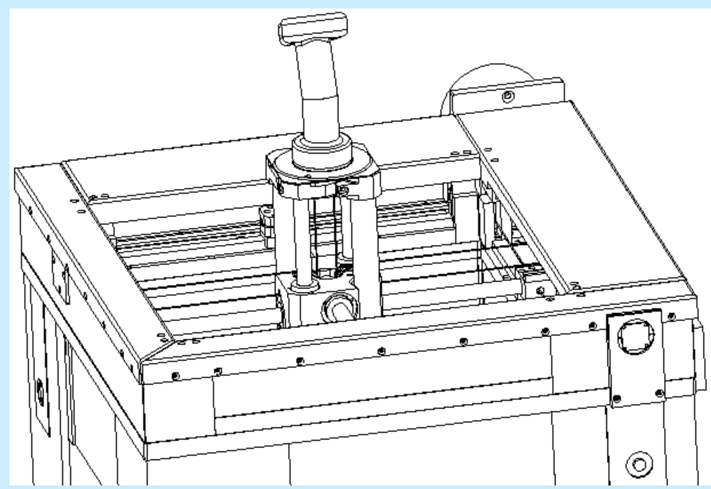
“Excalibur” Haptic Device



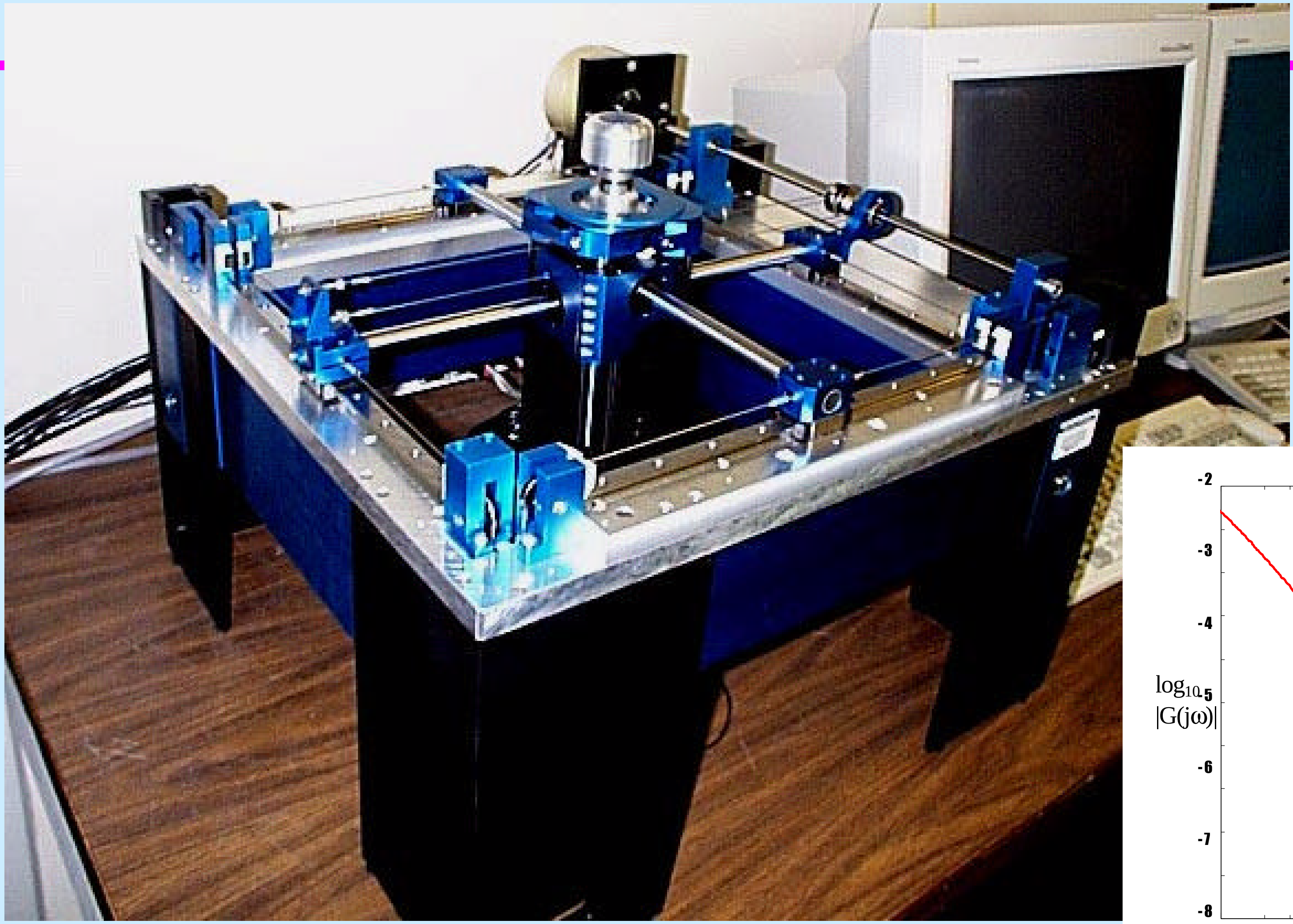
Specifications

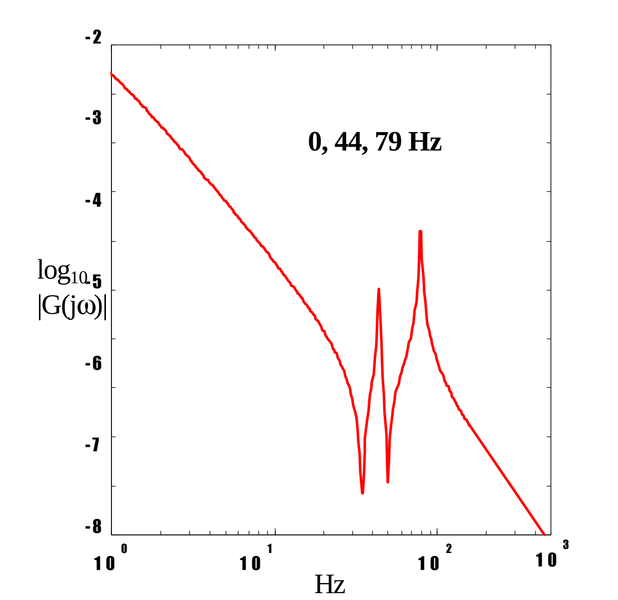
- Peak Force: 200N
- Cont. Force: 100N
- Workspace: 200x200x300mm
- Brushless disk-wound motors
- 1000Hz control





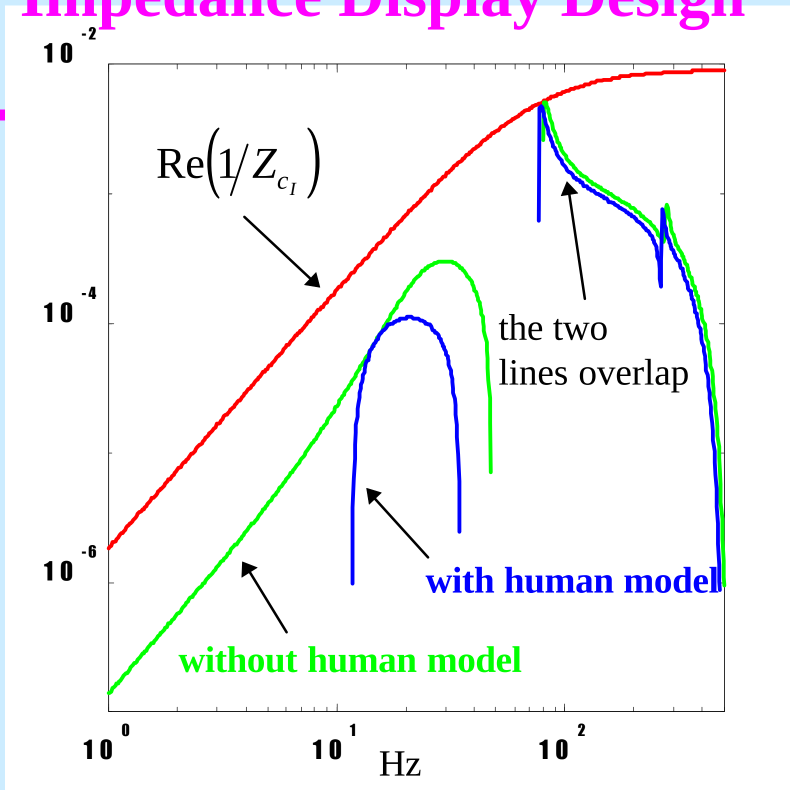
Excalibur Design Example

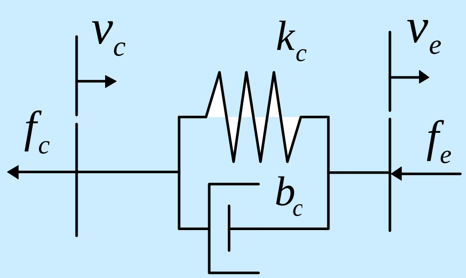




Excalibur Numerical Design

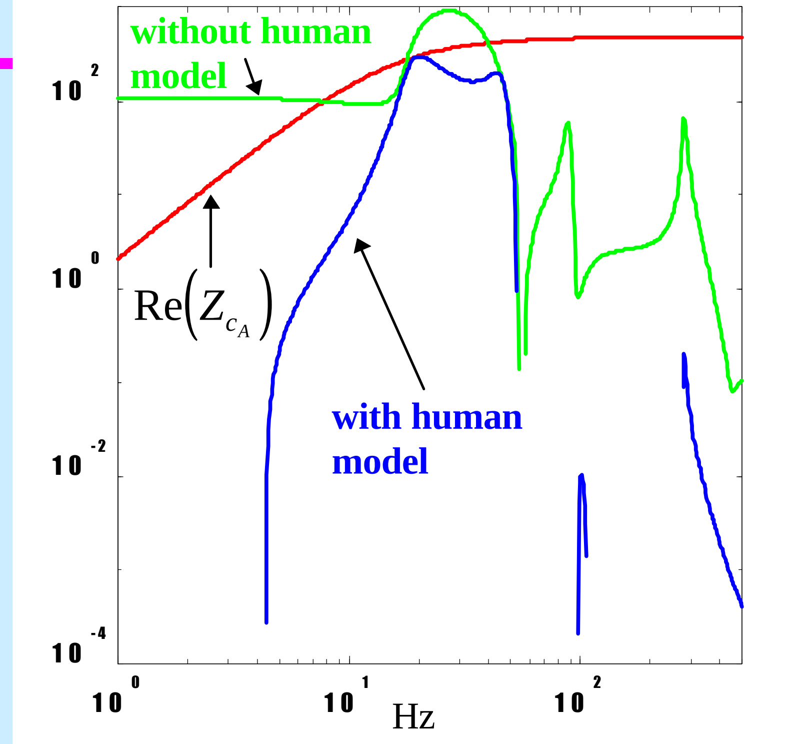
Impedance Display Design

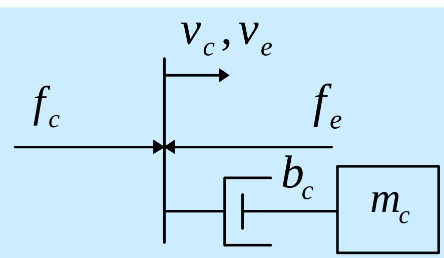




$k_c = 51\ {}^{kN}\!/_{m}$ $\quad b_c = 90\ {}^{N}\!/_{{}^{m}\!/_{s}}$

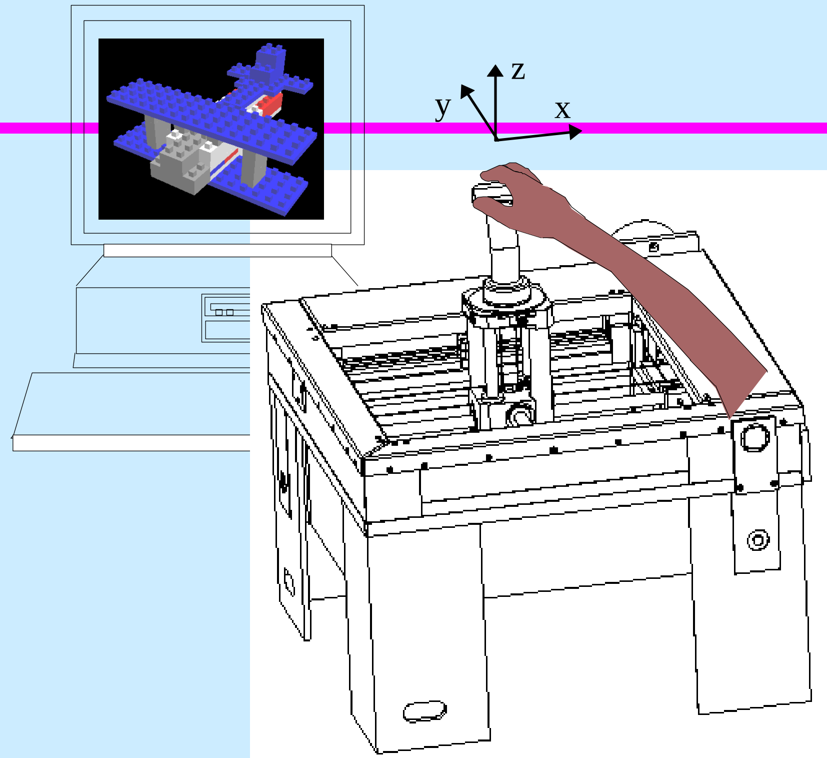
Admittance Display Design





$m_c = 5.0\ kg$ $\quad b_c = 500\ {}^{N}\!/_{{}^{m}\!/_{s}}$

Excalibur Experimental Results



	Impedance		Admittance	
	k_{c_I}	b_{c_I}	m_{c_A}	b_{c_A}
Theoretical	51,000	90	5.0	500
Experimental	75,000	90	4.3	500

+50% -20%

Time Domain Passivity Control

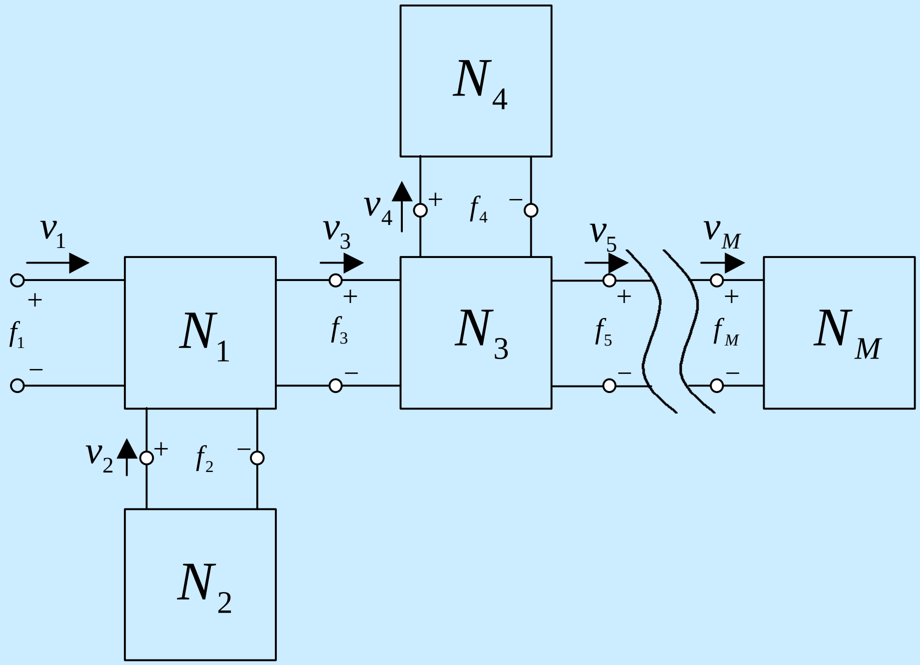
- Consider defintion of passivity (p17)
- Can implement in software if signals are available
- For an *M*-port network without energy storage:

$$E_{obsv}(n) = \sum_{k=1}^{n} \left[f_1(k) v_1(k) + \cdots + f_M(k) v_M(k) \right]$$

Passivity Observer

- If $E_{obsv}(n) \geq 0$ for every *n*, the system dissipates energy; else the system generates energy (is active).

Arbitrary System



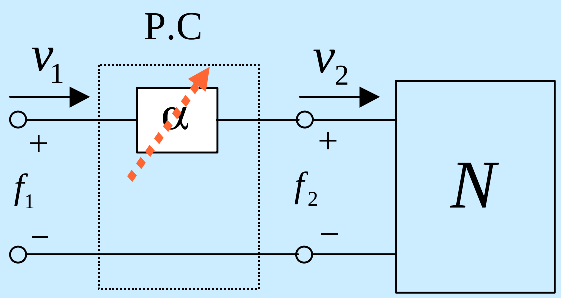
$$E_{obsv}(n) = E_{N_1}(n) + E_{N_2}(n) + E_{N_3}(n) + E_{N_4}(n) + \cdots + E_{N_M}(n)$$

$$E_{obsv}(n) = \sum_{k=1}^{n} f_1(k) v_1(k)$$

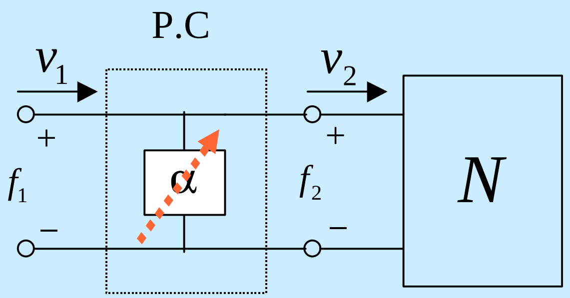
Passivity Controller

- adjustable dissipation element
- makes system passive
- implemented in software using Passivity Observer

- Series



- Parallel



Series Passivity Controller Algorithm

1) $v_1(k) = v_2(k)$ is an input

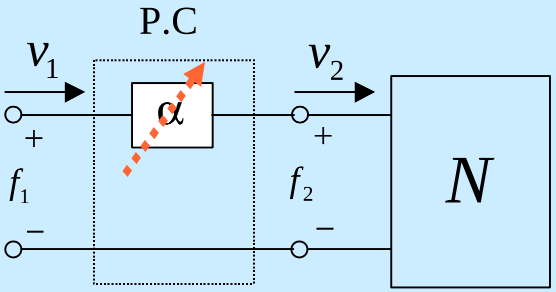
2) $f_2(k) = F_{VE}(v_2(k))$

where $F_{VE}(\;)$ is the output of the virtual environment.

3) $W(n) = W(n-1) + f_2(n)v_2(n) + \alpha(n-1)v_2(n-1)^2$

4) $$\alpha(n) = \begin{cases} -W(n)/v_2(n)^2 & \text{if } W(n) < 0 \\ 0 & W(n) \geq 0 \end{cases}$$

5) $f_1(n) = f_2(n) + \alpha(n)\,v_2(n) \Rightarrow \text{output}$



Passivity Controller (cont.)

- Extendable to:
  - parallel case (admittance)
  - dissipative loads: (negative RHS)
  - large networks
- Problems
  - large control amplitude
  - storage

Result

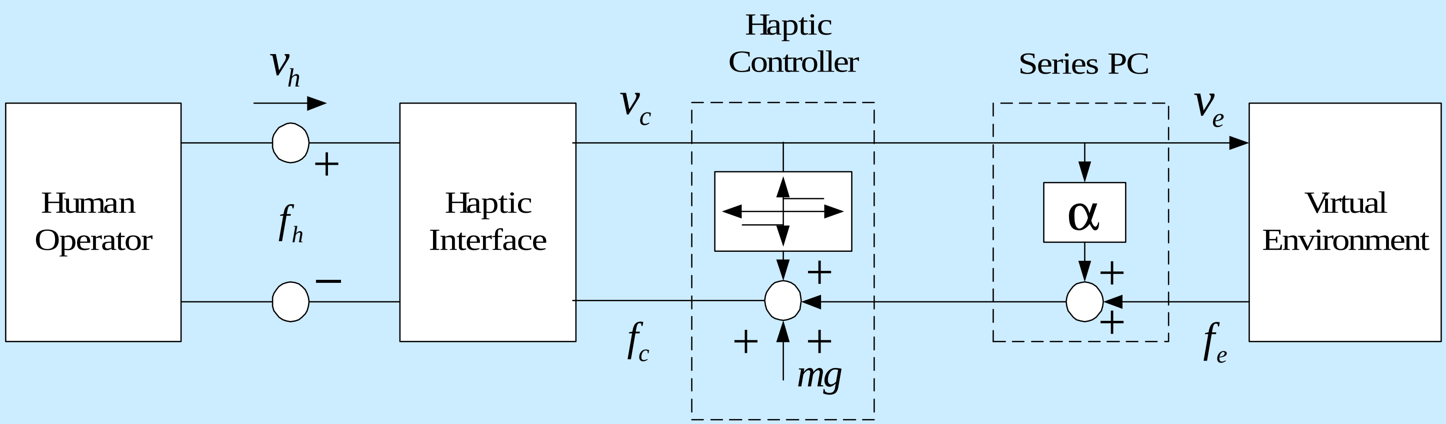
- The resulting system is passive for all *n* in the sense that

$$\sum_{k=1}^{n} f_1(k) v_1(k) \geq 0 \quad \forall n$$

- (proof is easy, see paper)

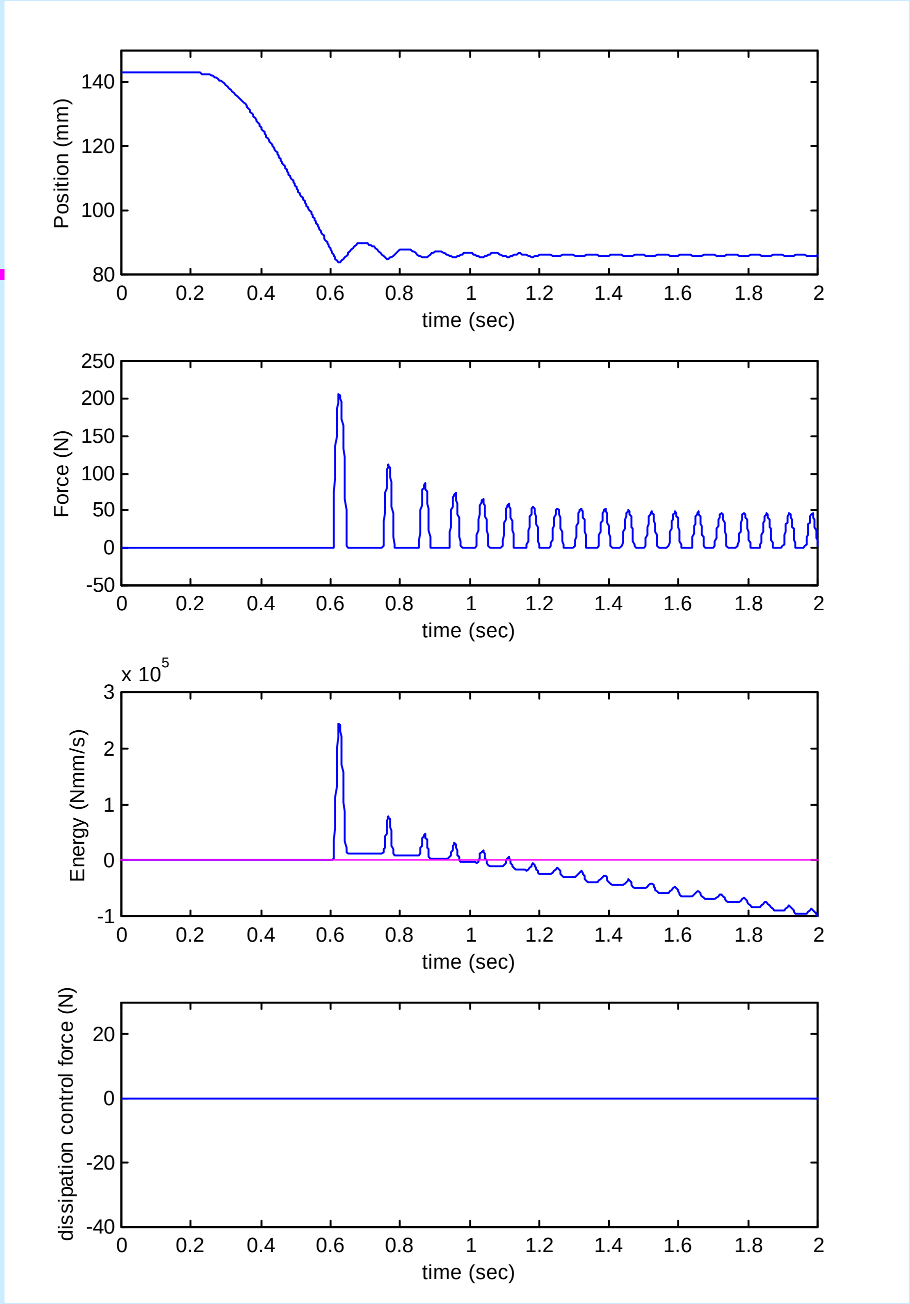
Experiment

- Implemented PO/PC on Excalibur
- Tests:
  - High Stiffness (> 70 kN/M)
  - Delayed Environment



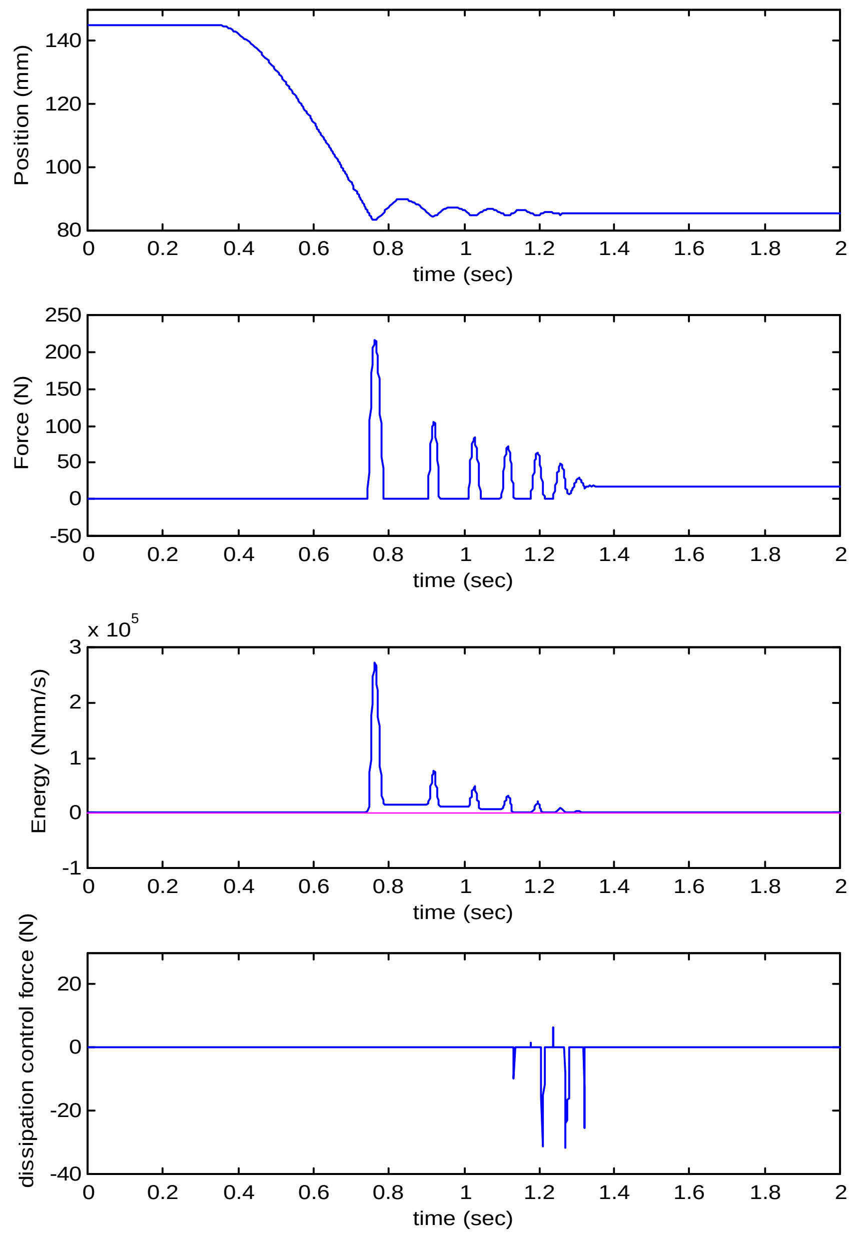
Results

- Stiff wall (90kN/M)
- No Passivity Ctl
- Unstable Contact
- PO < 0



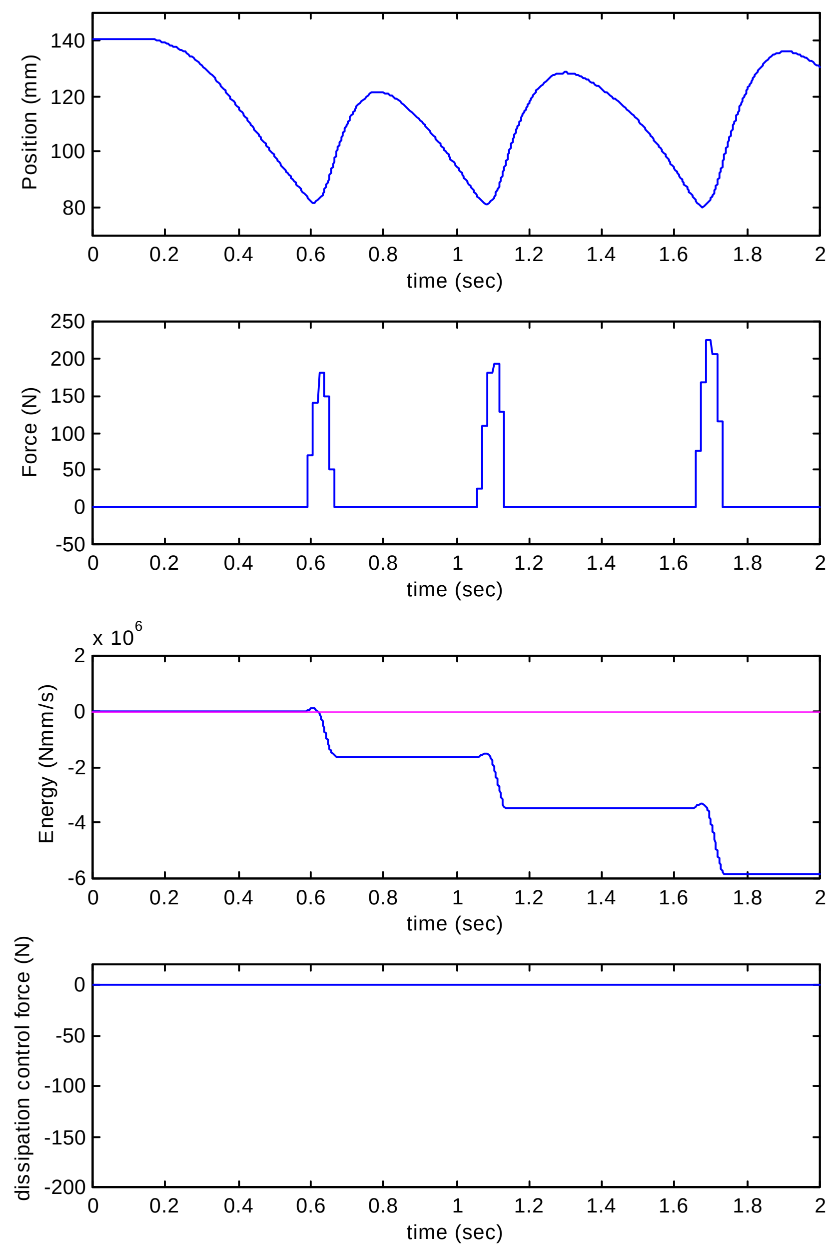
Results

- Stiff wall (90kN/M)
- *With* Passivity Ctl
- *Stable* Contact
- PO >= 0



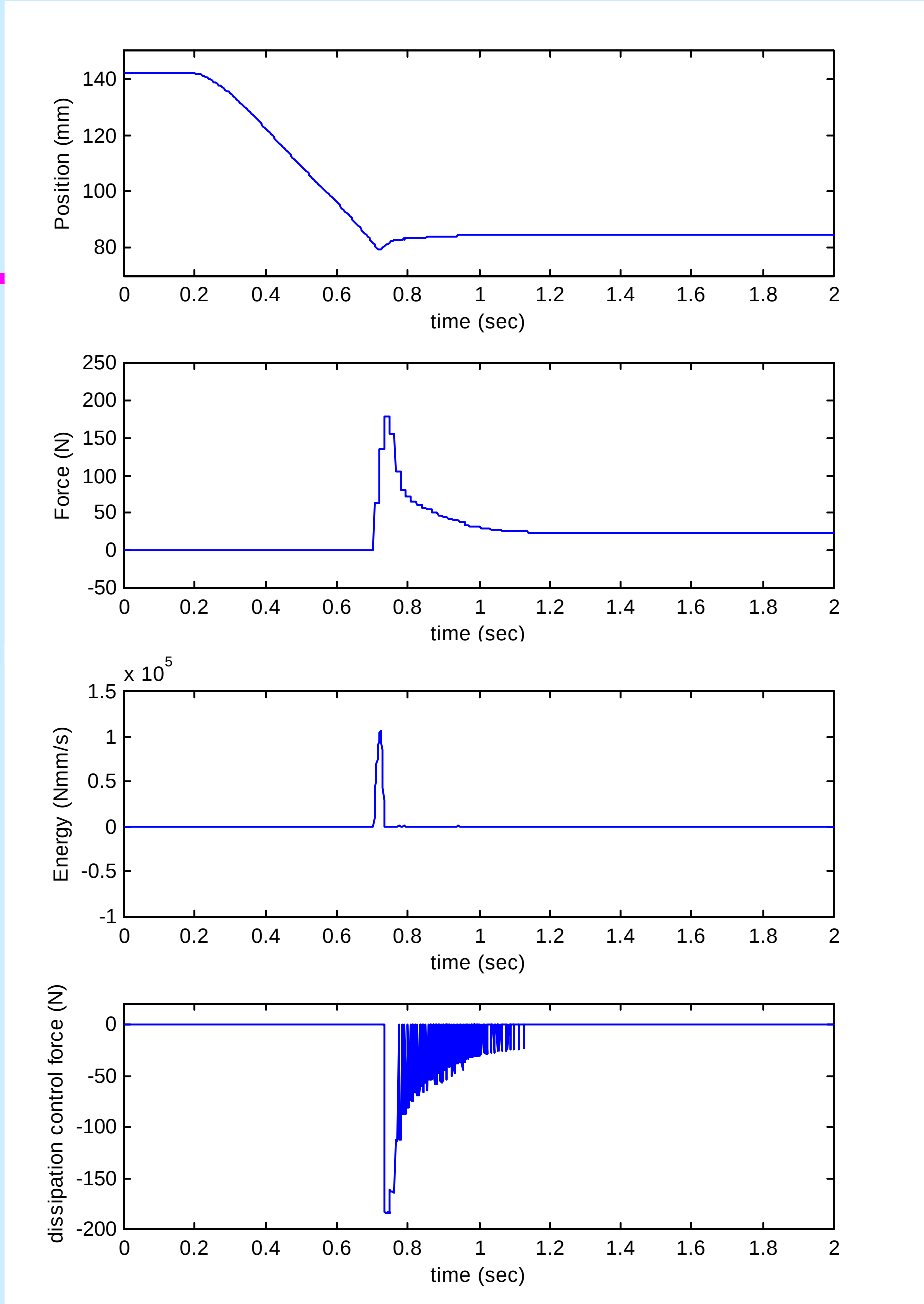
Results

- Slow wall (30kN/M, d=15ms)
- No Passivity Ctl
- Unstable contact
- PO < 0



Results

- Slow wall (30kN/M, d=15ms)
- *With* Passivity Ctl
- *Stable* contact
- PO >= 0



Conclusions

- A new control method for haptic interfaces with the following attributes
  - PO and PC are very simple to implement in software
  - Provable stability yet not fixed parameter, worst-case design
  - PC only degrades performance when needed
  - Need not model energy storage (states) only dissipation
  - Experimentally tested

Remaining Issues

- “Noise” when velocity (force) is low.
- Dissipation can accumulate in a “passive” section of VE (x = x1) causing problem in another section (x = x2).
- Actuator saturation

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