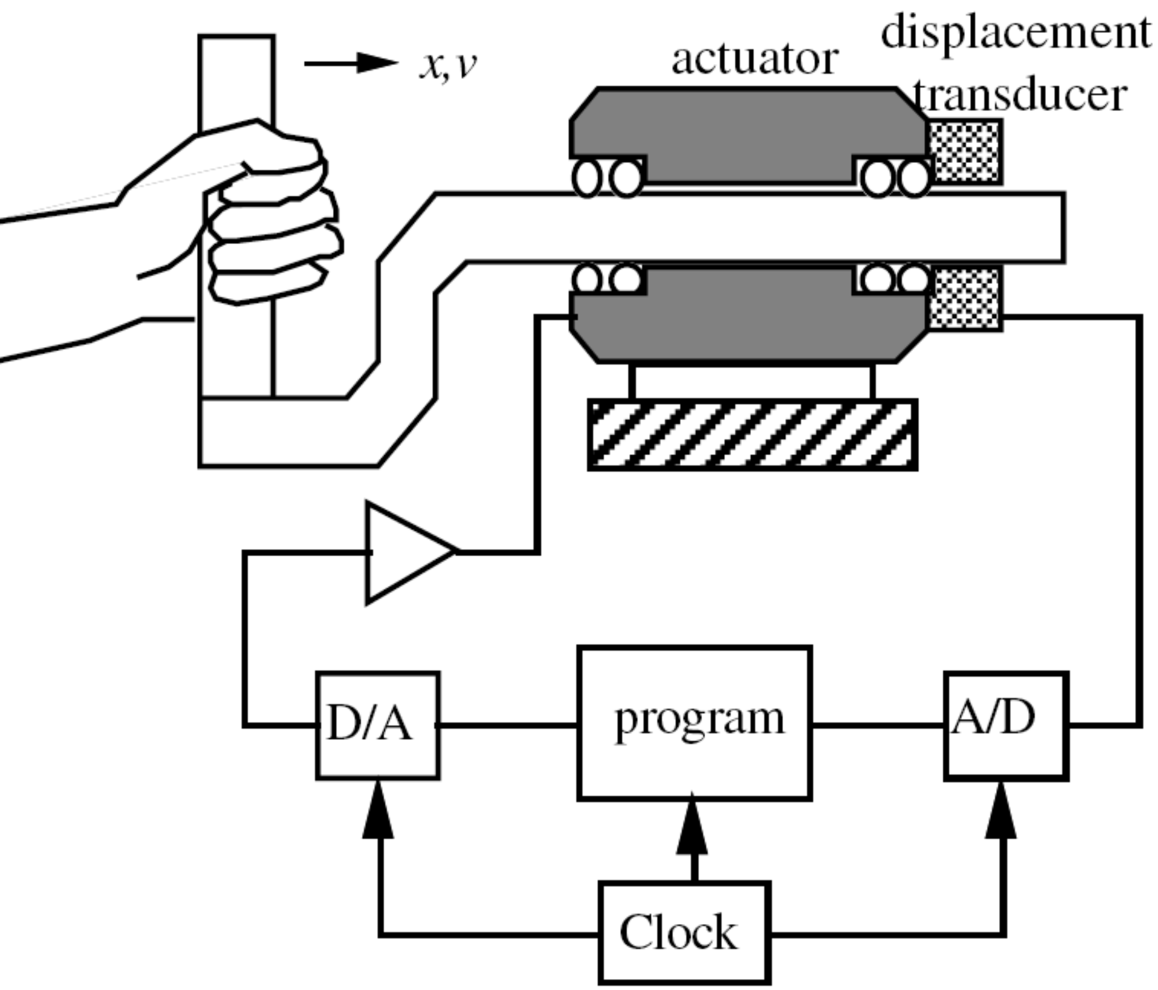
ME 327: Design and Control of Haptic Systems
Spring 2020

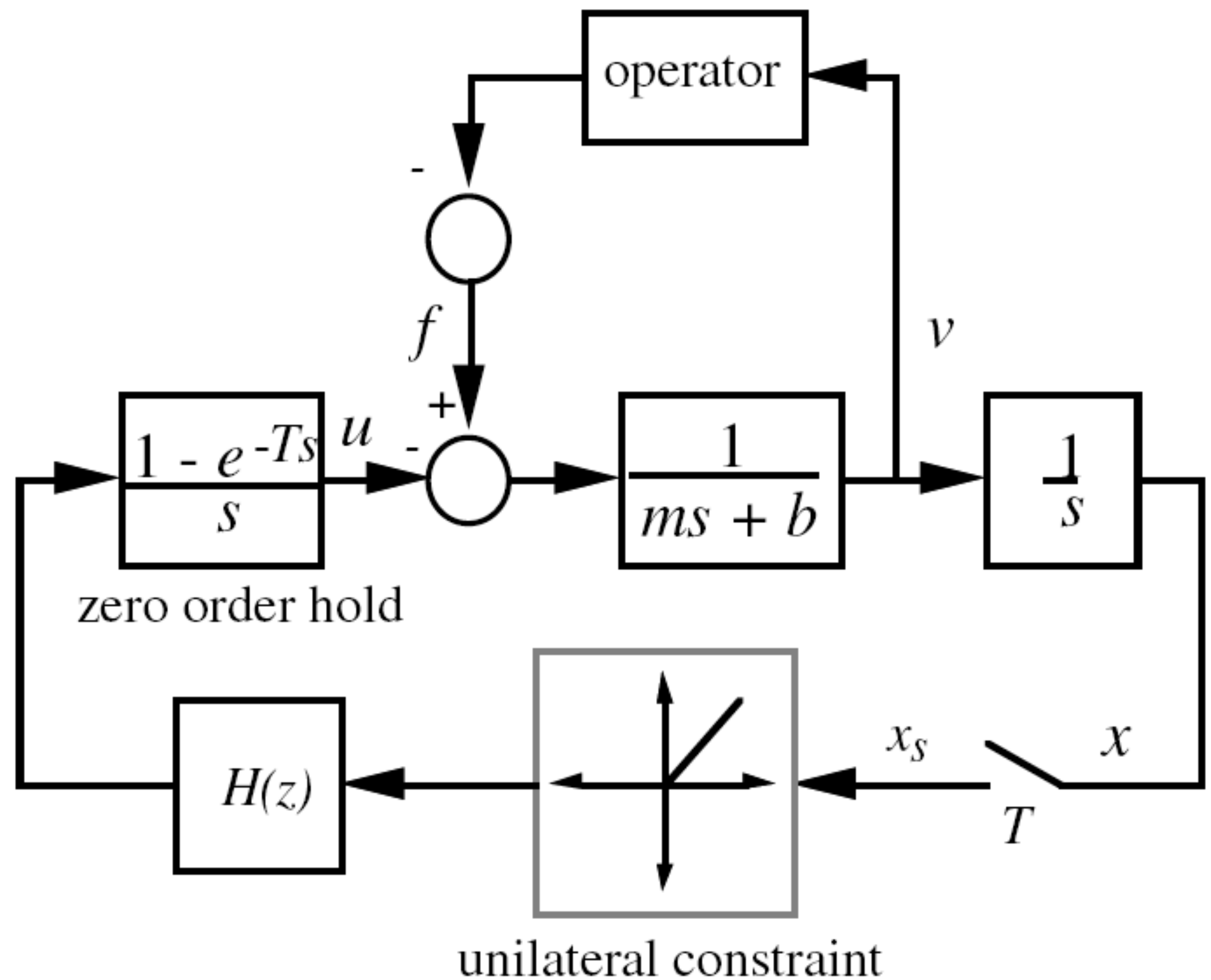
Lecture 10: Kinesthetic haptic devices: stability

Allison M. Okamura
Stanford University

stability of the virtual wall

sampled-data system example





Colgate and Schenkel 1997

sampled-data system example

a necessary and sufficient condition for passivity of a sampled-data system is:

$$b > \frac{T}{2}\frac{1}{1-\cos(\omega T)}\Re\{(1-e^{-j\omega T})H(e^{j\omega T})\} \qquad \text{for} \quad 0 \leq \omega \leq \omega_N$$

where:
b is the physical damping in the mechanism
T is the sampling period
H(z) is a transfer function representing the virtual environment
$\omega_N = \pi/T$ is the Nyquist frequency

Weir and Colgate 2008

for a virtual wall with stiffness and damping:

$$H(z) = K + B\frac{z-1}{Tz}$$

where:
K>0 is the virtual stiffness
B is the virtual damping
T is the sampling period

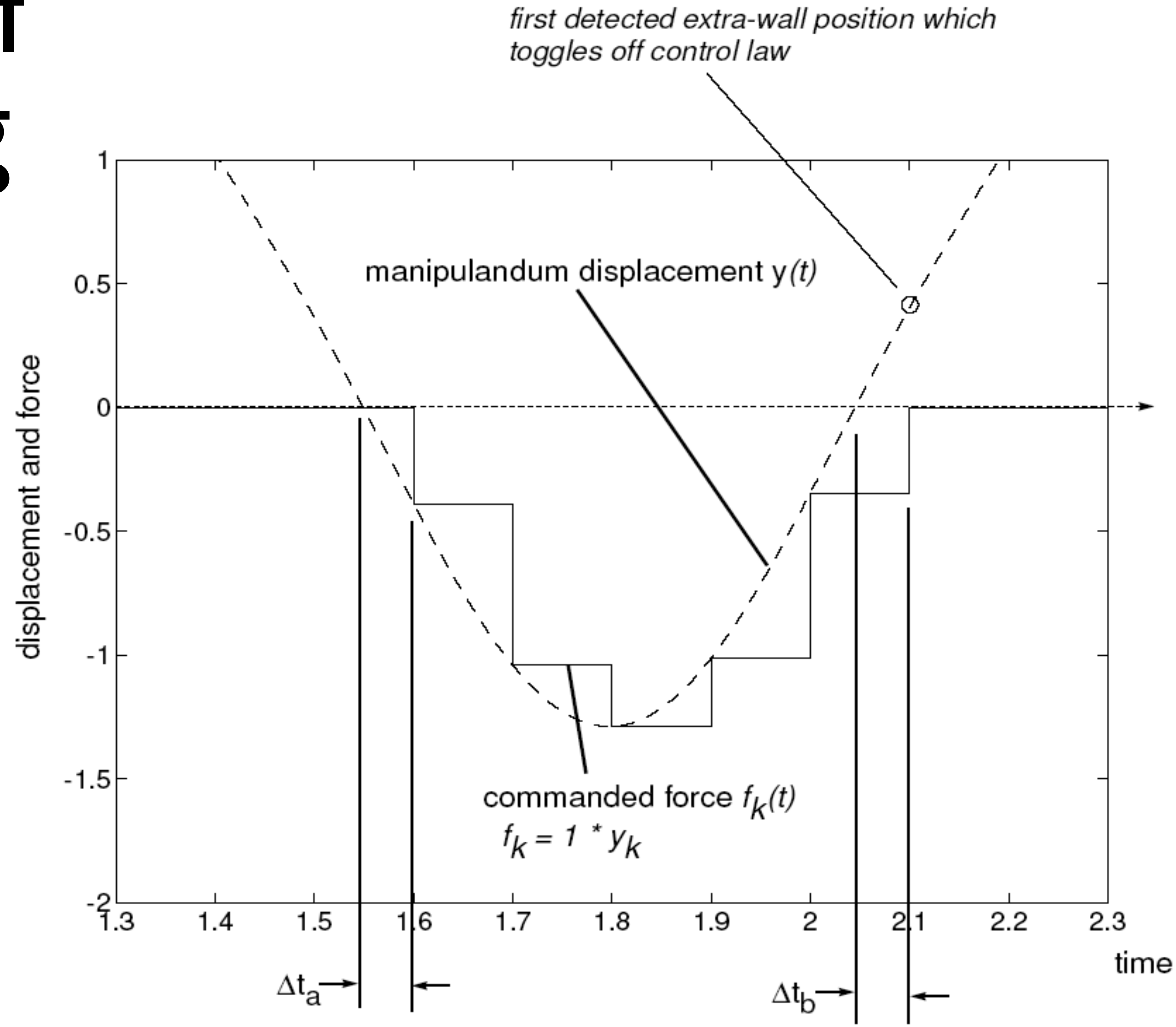
(this assumes a velocity estimate from a backward difference differentiation)

this result can be made into a simple analytical expression:

$$b > \frac{KT}{2} + |B|$$

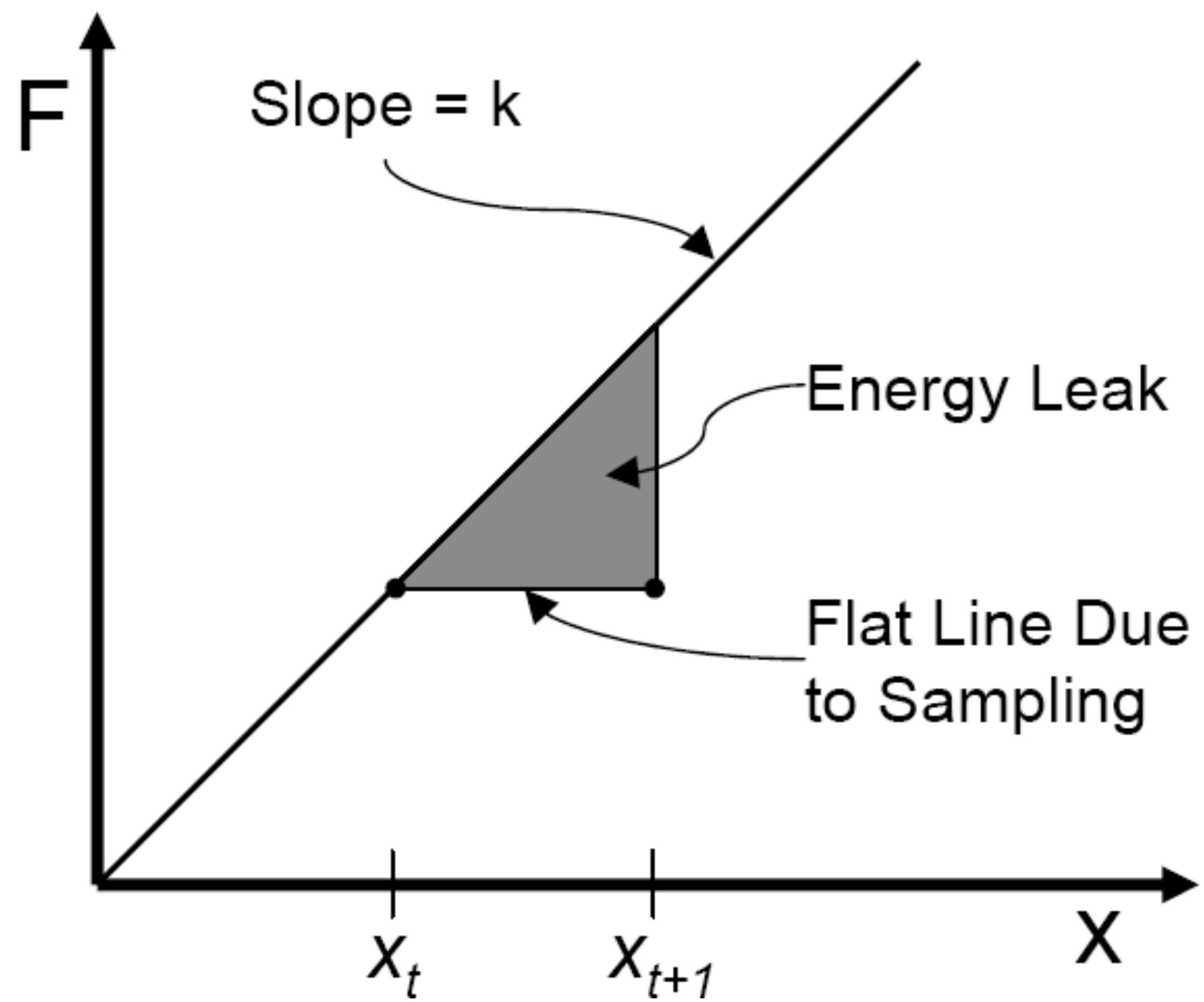
Weir and Colgate 2008

effects of sampling



Gillespie and Cutkosky 1996

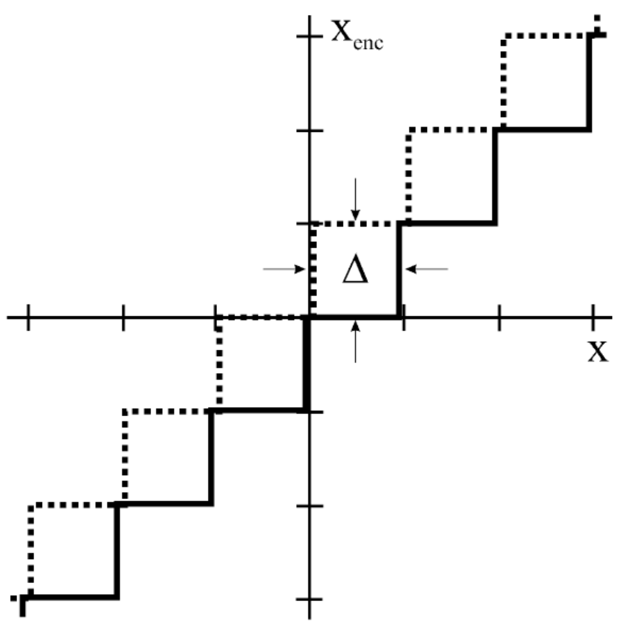
detail of energy leak due to sampling

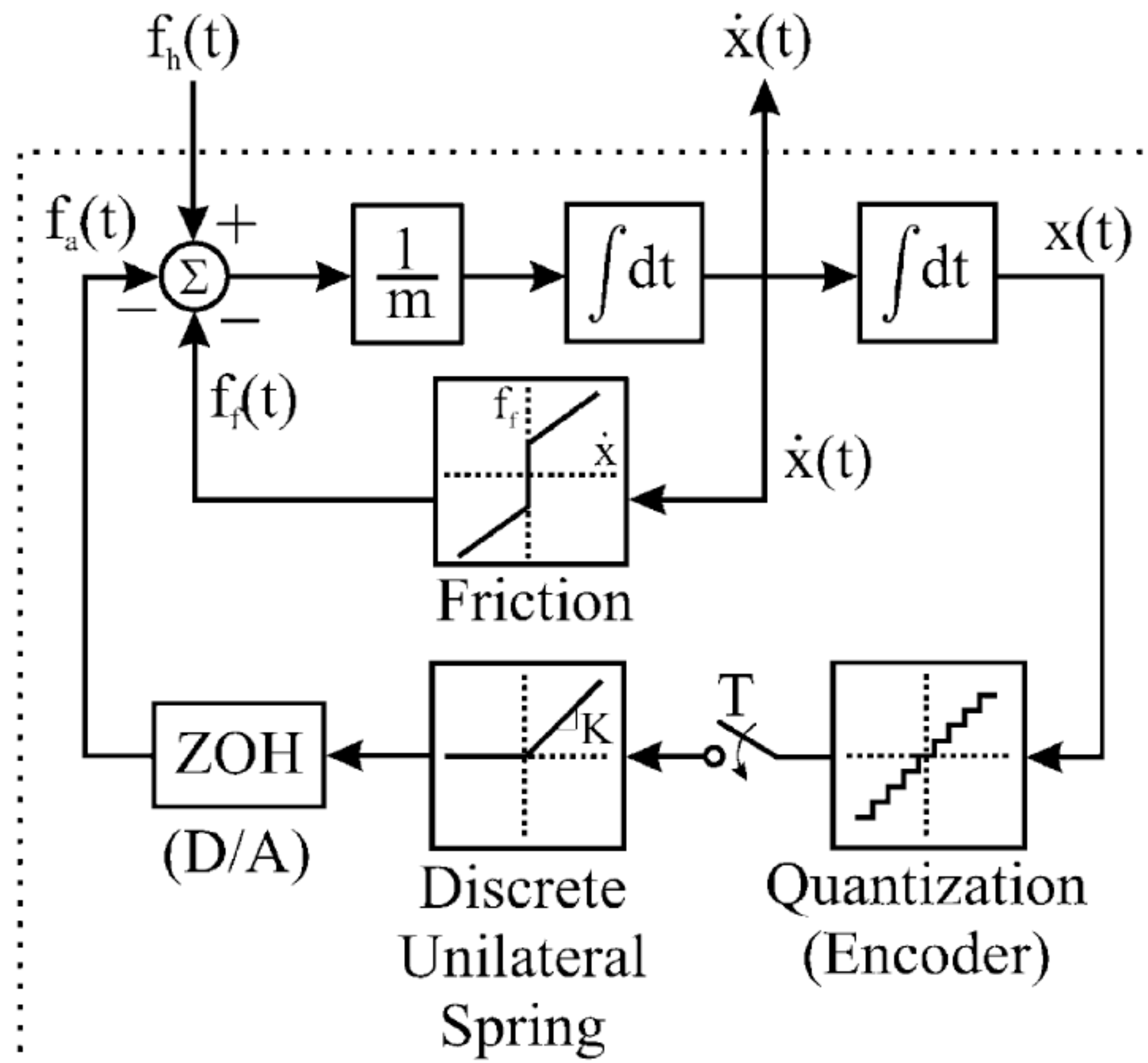


in order to maintain passivity, the energy dissipated must be greater than the energy introduced by the energy leak

Weir and Colgate 2008

position quantization





$$K \leq \min\left(\frac{2b}{T}, \frac{2f_c}{\Delta}\right)$$

Abbott and Okamura 2005

conceptual derivation of passivity limit of virtual stiffness

imaging you are compressing a virtual spring $F = kx$

the energy stored after compressing a distance

$\Delta x = x_{k+1} - x_k = vT$ during one sample period is:

$$E = \frac{1}{2}k(\Delta x)^2$$

due to damping and sampling

$$\begin{aligned} E_{leak} &= \frac{1}{2}K(vT)^2 \\ E_{dissip} &= bv^2T \\ E_{leak} &\leq E_{dissip} \\ \frac{1}{2}Kv^2T^2 &\leq Tbv^2 \\ K &\leq \frac{2b}{T} \end{aligned}$$

due to Coulomb friction and position quantization

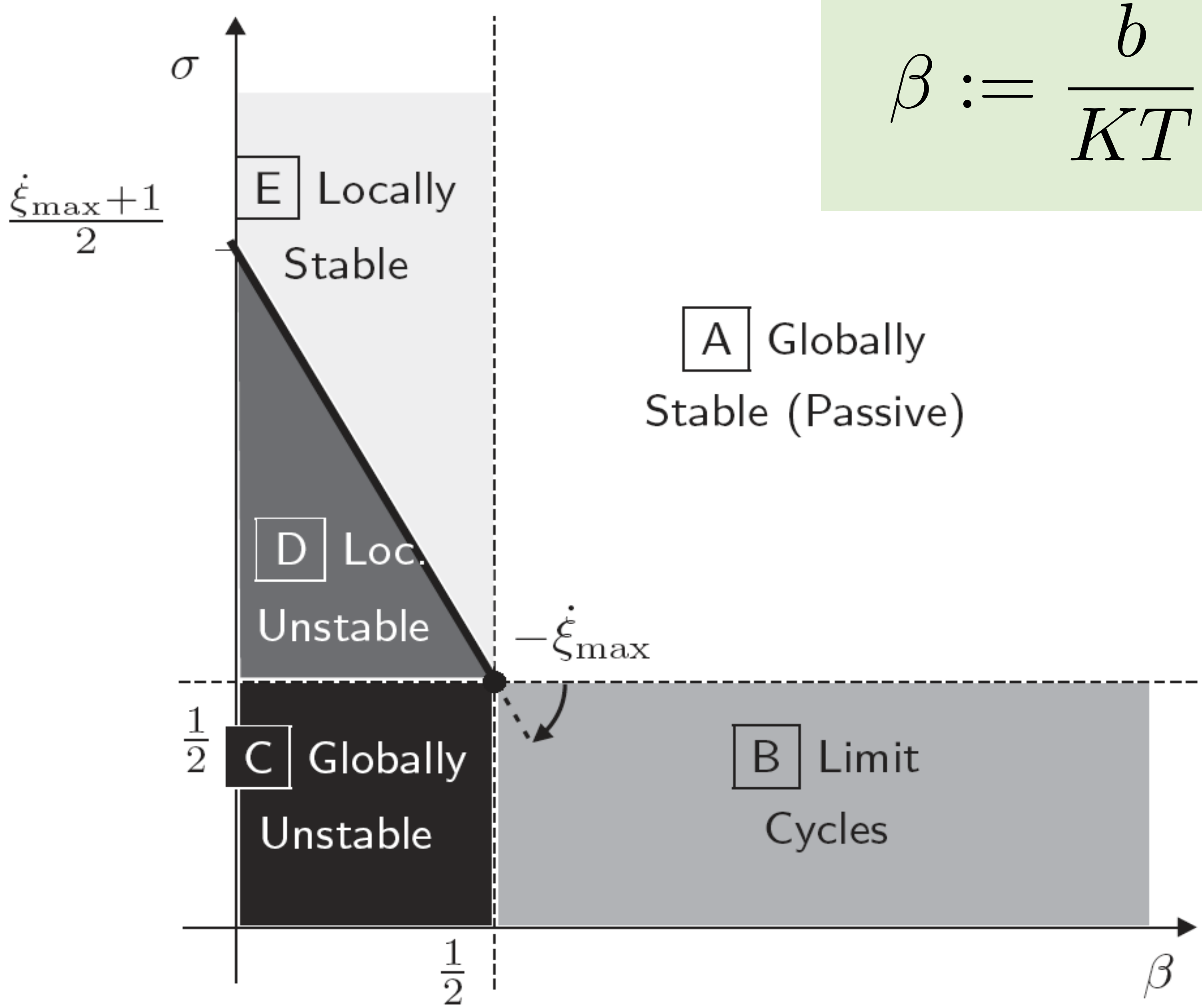
$$\begin{aligned} E_{leak} &= \frac{1}{2}K\Delta^2 \\ E_{dissip} &= f_c\Delta \\ E_{leak} &\leq E_{dissip} \\ \frac{1}{2}K\Delta^2 &\leq f_c(\frac{\Delta}{T})T \\ K &\leq \frac{2f_c}{\Delta} \end{aligned}$$

Abbott & Okamura 2005
Diolaiti et al. 2006
Weir & Colgate 2008

dimensionless stability plane

$$K \leq \min\left(\frac{2b}{T}, \frac{2f_c}{\Delta}\right)$$ can be nondimensionalized by dividing by K

$$\beta := \frac{b}{KT} \qquad \sigma := \frac{f_c}{K\Delta}$$

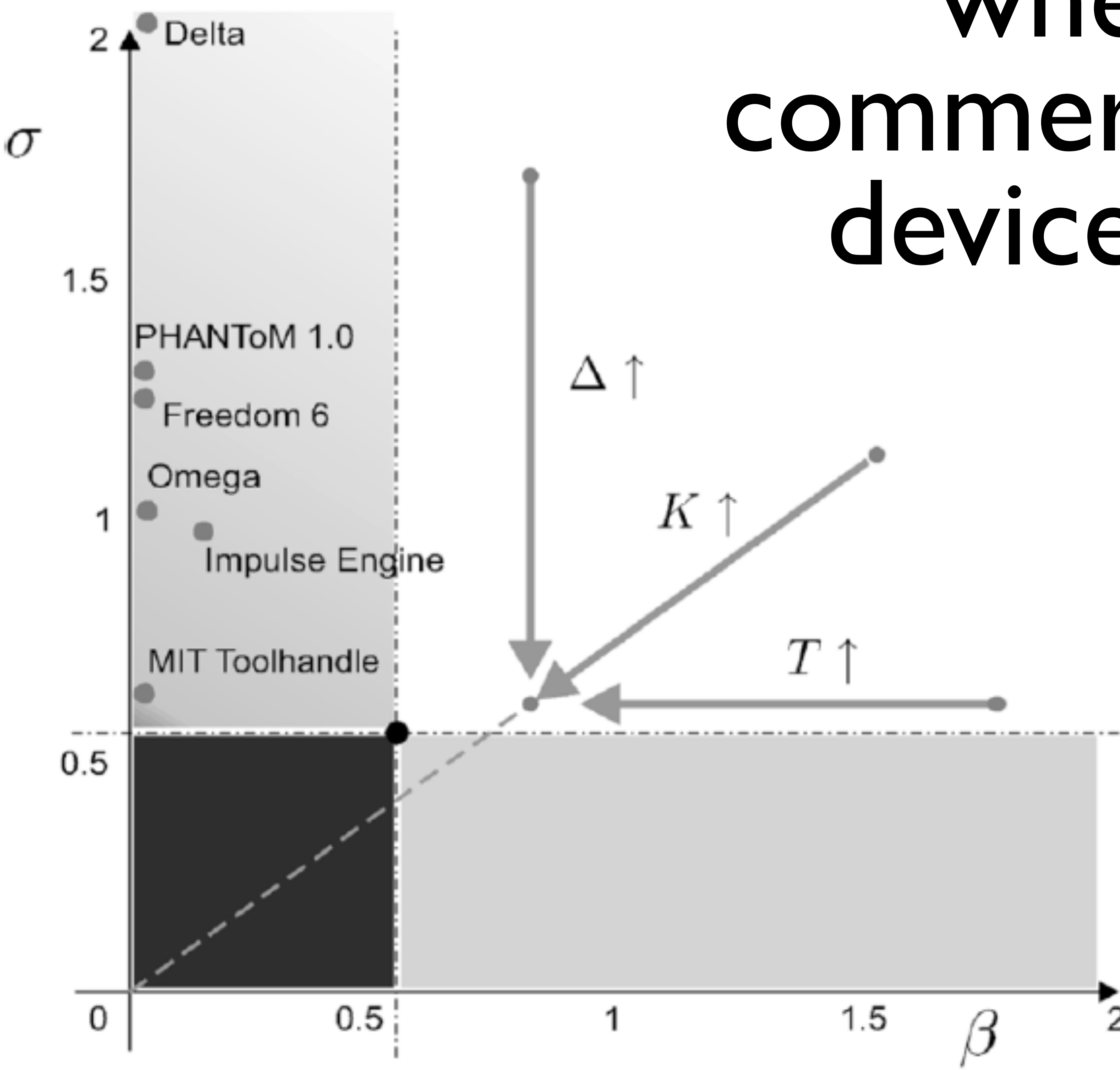


$$\dot{\xi}(\tau) = \frac{\dot{x}T}{\Delta}$$

$\dot{\xi}_{max}$ is the maximum allowable velocity

Diolaiti et al. 2006

where do commercial haptic devices stand?



Diolaiti et al. 2006

how to make your system stable/passive?

approach #1:

lower your expectations (i.e., just respect the existing Z-width)

approach #2:

change your hardware (add damping, increase sampling rate, increase encoder resolution, etc.)

approach #3:

passivity observer/ passivity controller and/or prediction/ compensation

passivity observer/passivity controller

a Passivity Observer (PO) measures energy flow in and out of one or more subsystems in real-time software.

active behavior is indicated by a negative value of the PO at any time

a Passivity Controller (PC) is an adaptive dissipative element which, at each time sample, absorbs exactly the net energy output (if any) measured by the PO.

Hannaford and Ryu 2002

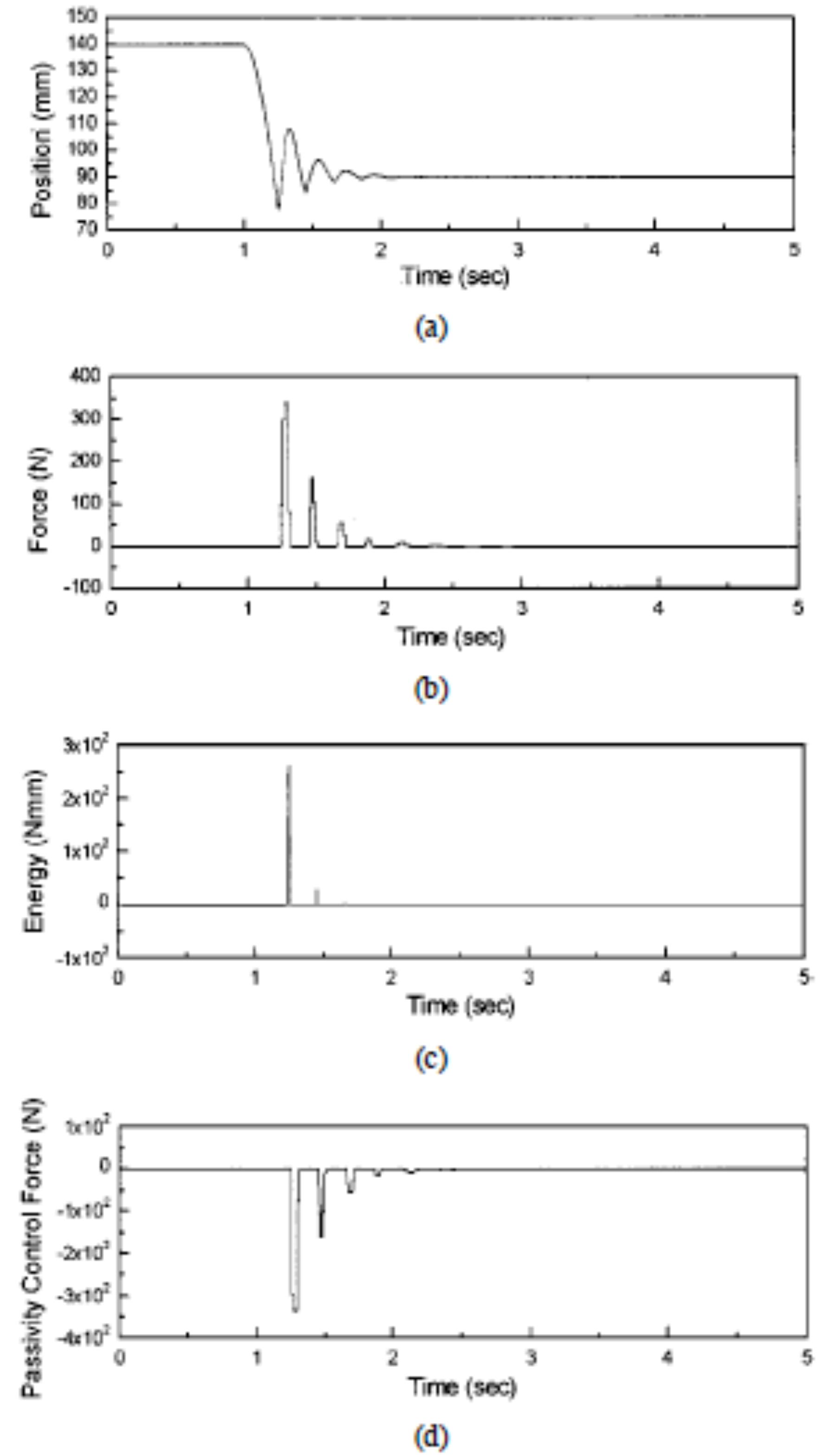
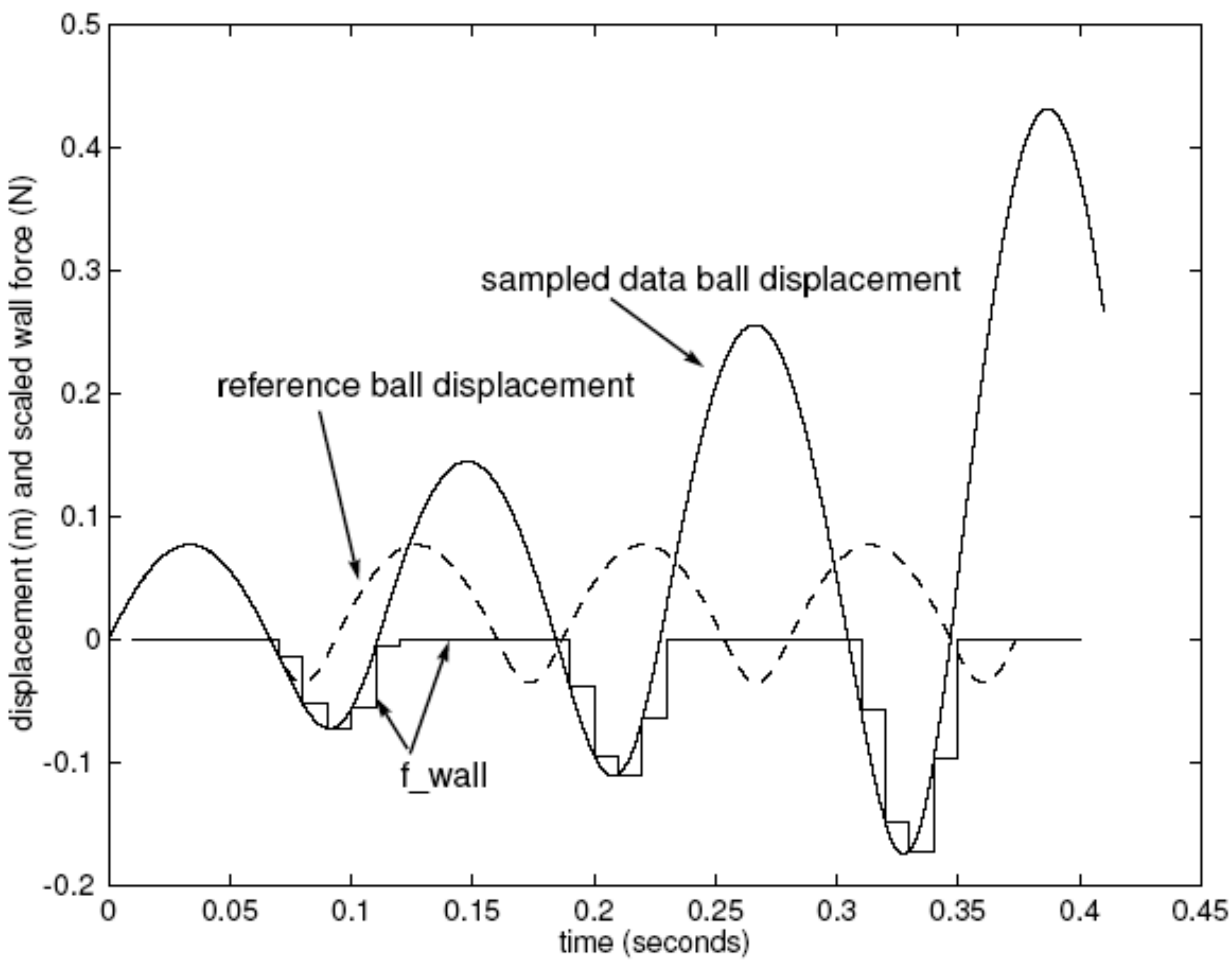


Fig. 10. Simulation of haptic interface system (Fig. 8) with passivity controller enabled. Passivity controller operates briefly (bottom trace) to damp out oscillations and constrain energy dissipation to be positive. (a) Position. (b) Force. (c) Energy. (d) Passivity control force.

prediction and compensation

bouncing ball simulation

original

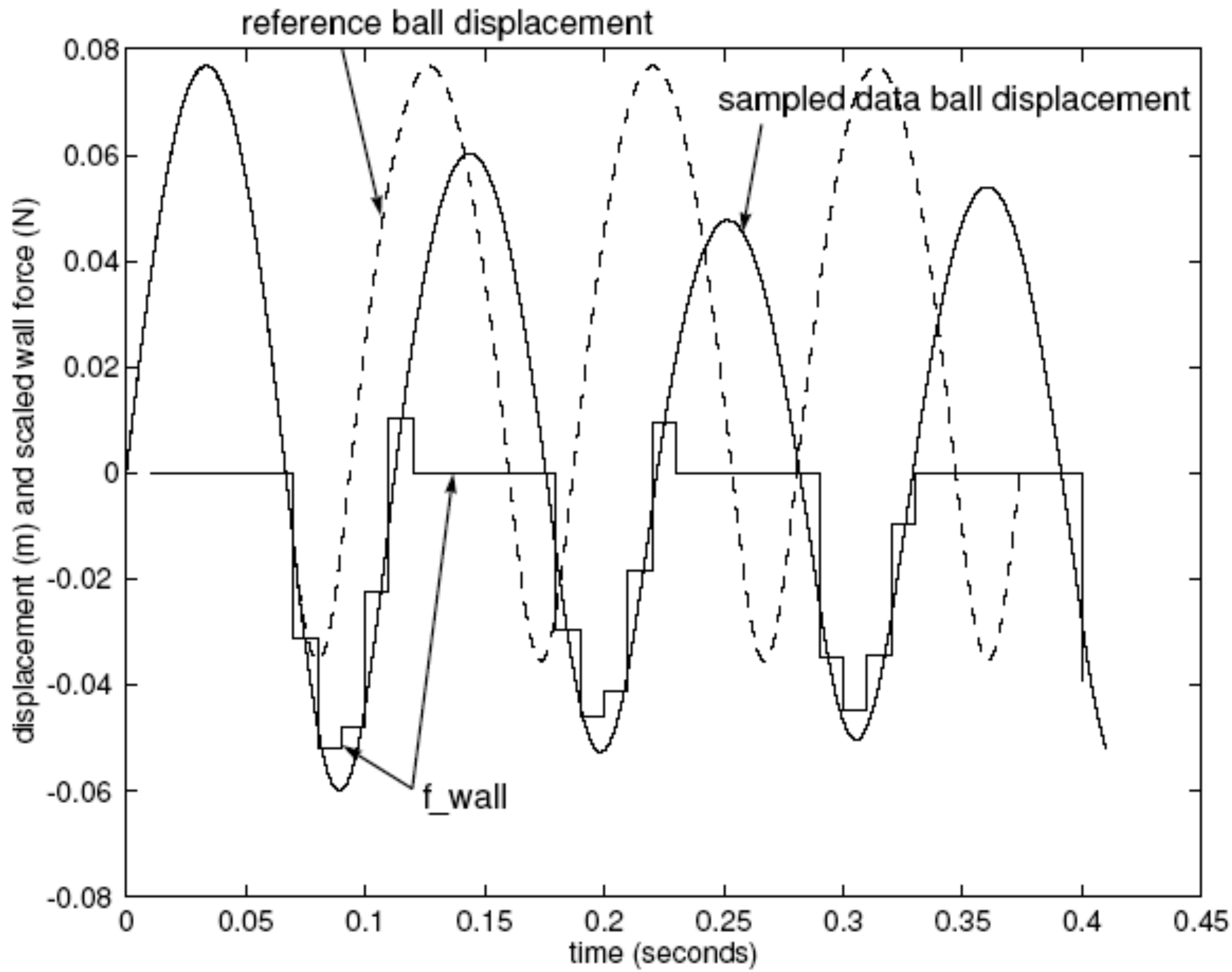


Gillespie and Cutkosky 1996

prediction and compensation

bouncing ball simulation

prediction

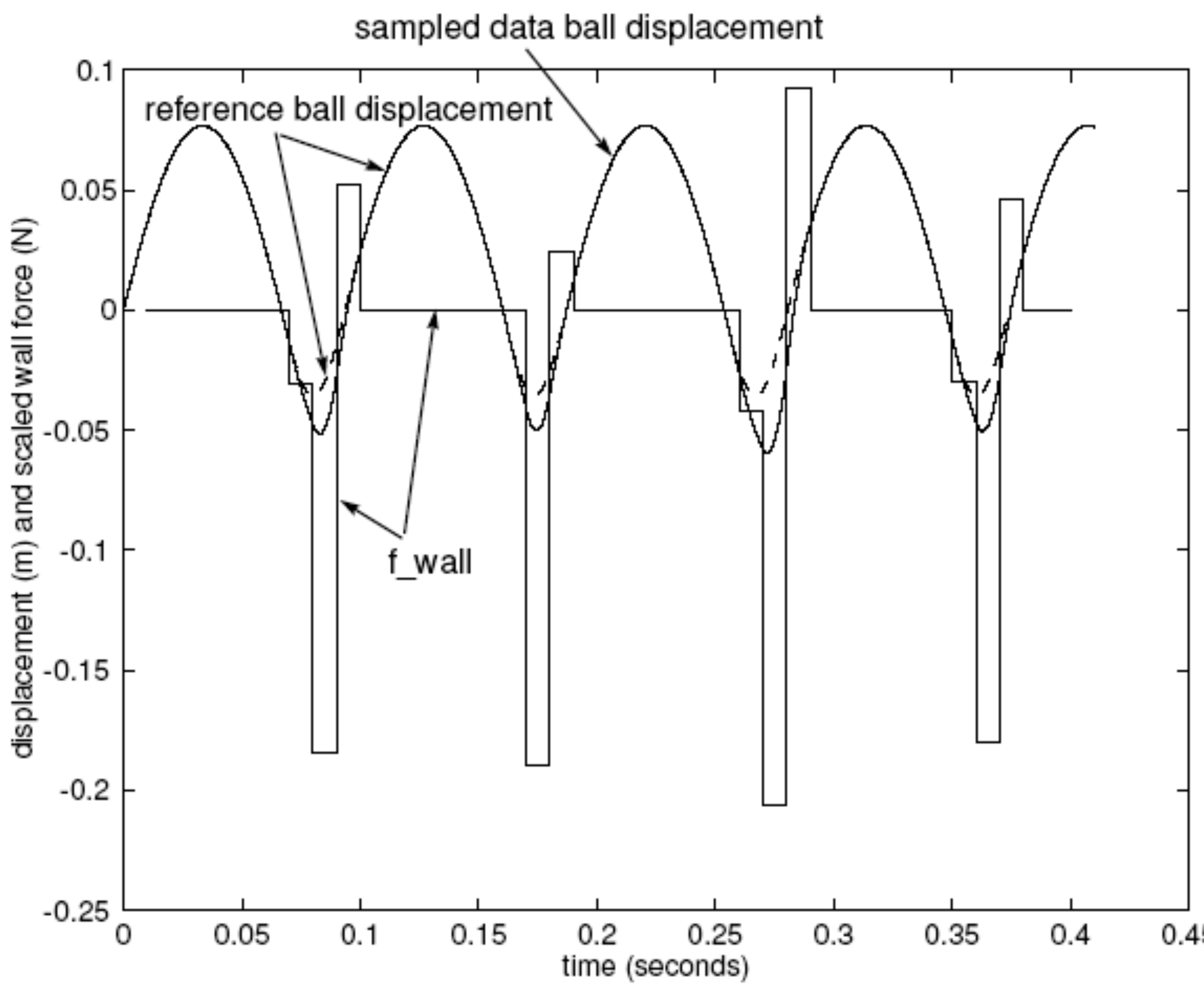


Gillespie and Cutkosky 1996

prediction and compensation

bouncing ball simulation

correction

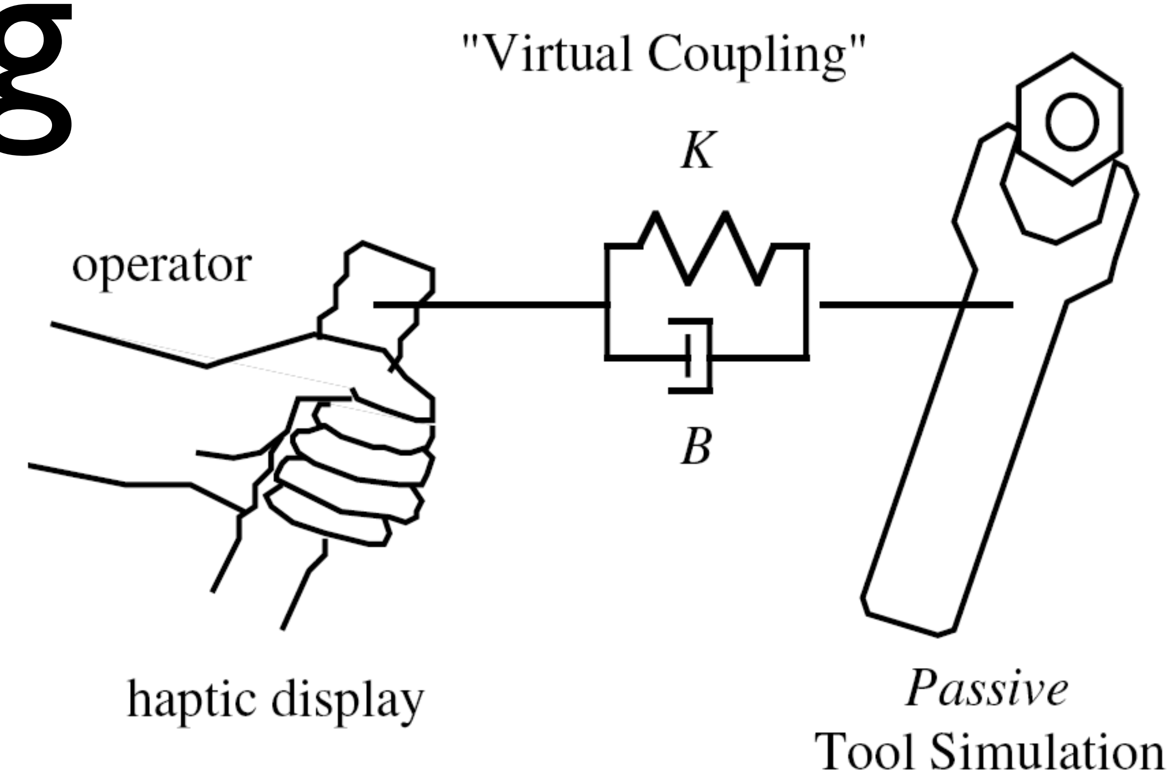


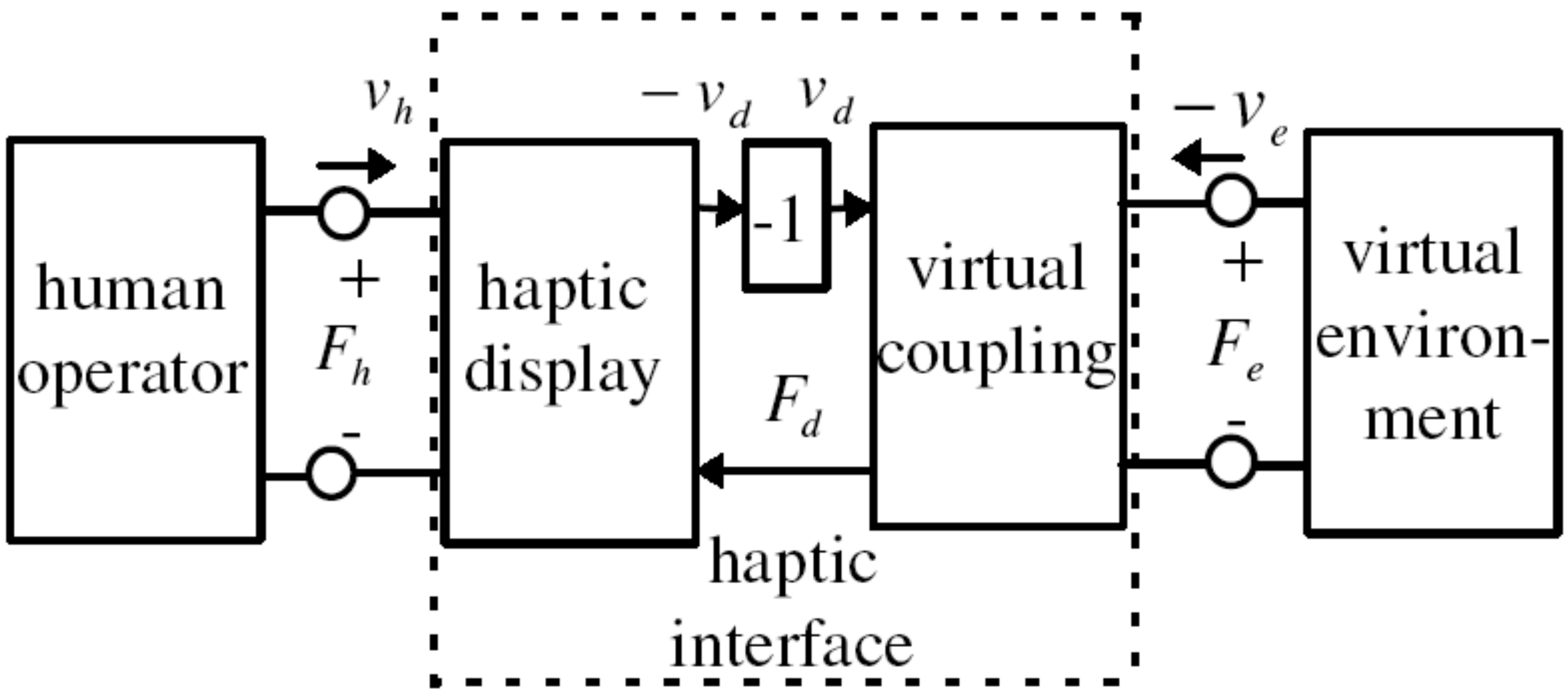
Gillespie and Cutkosky 1996

approach #4:

virtual coupling

virtual coupling





Adams and Hannaford 1998

summary: design for passivity

- haptic instability arises from a lack of passivity when rendering virtual environments
- in order to maintain passivity, virtual environment impedance can be reduced to acceptable levels for passivity
- given a perfect model of a haptic device, we can compute the requirements for passivity

summary: control for passivity

- passivity observers and controllers can effectively damp out any oscillations occurring due to non-passivity
- virtual couplings can be used to modulate the impedance transmitted between the haptic display and the virtual environment to ensure passivity
- perceptual methods of improving performance take advantage of the limits of human perception to create the illusion of higher performance rendering on existing haptic display hardware

key point

in order to make the system passive (guaranteed stable), you are likely to lose some accuracy/fidelity of your virtual environment in the process

