Human-Robot Interaction

Advanced Control – Control Schemes for a Haptic Interface

Part 2- Impedance control and Z-Width

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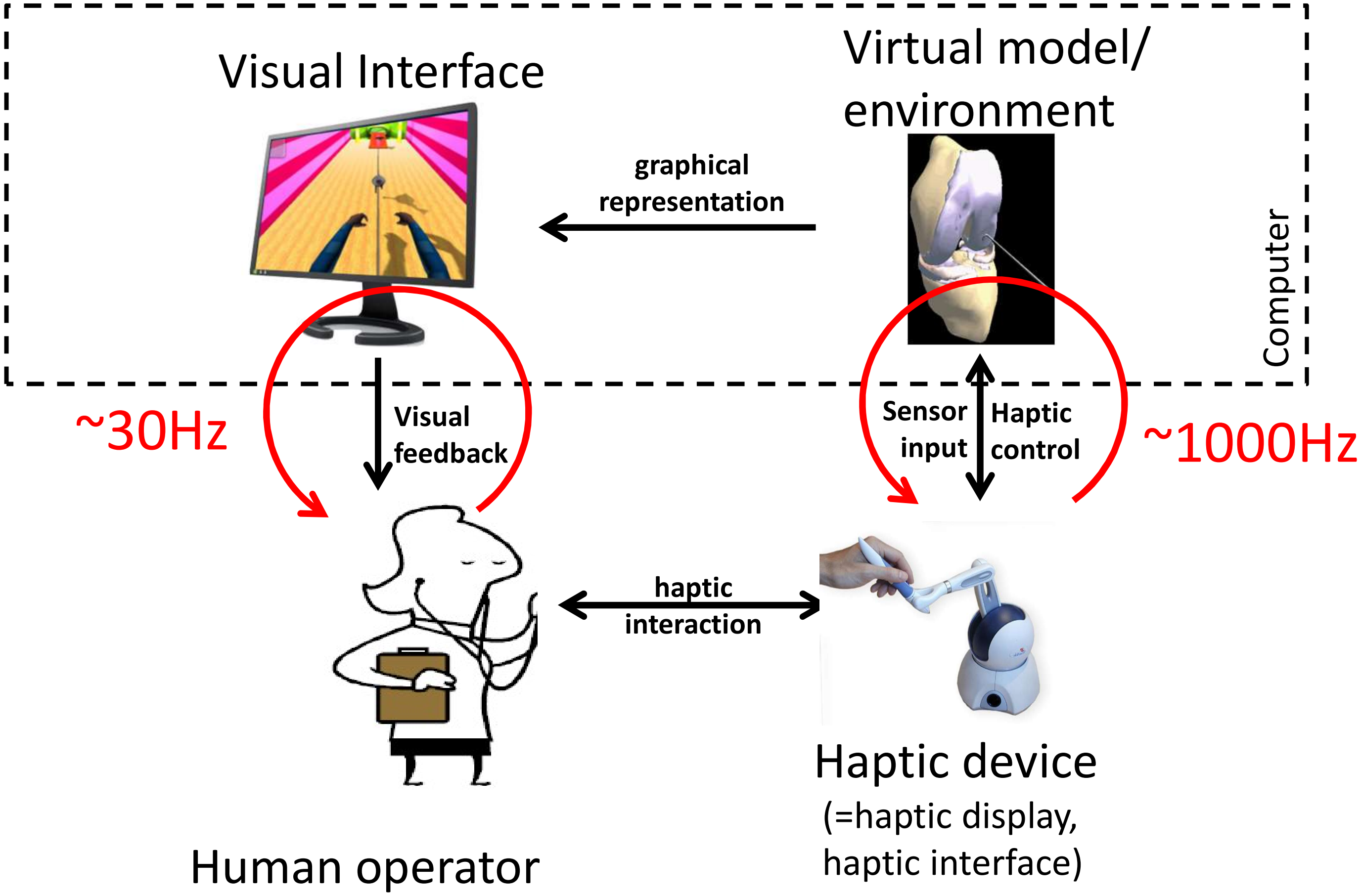
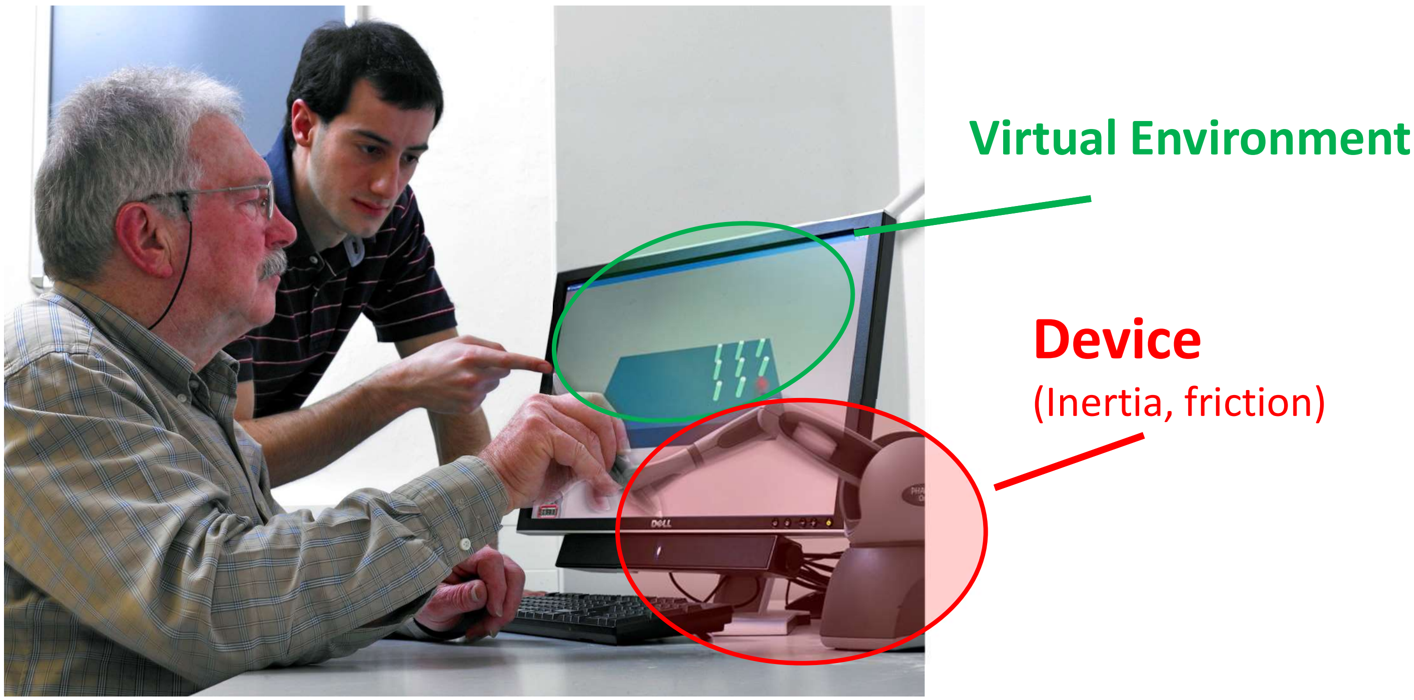
REHAssist, EPFL

Haptic control and a VE



What Would We Like to Feel at a Haptic Device?
What Do We Feel at a Haptic Device?



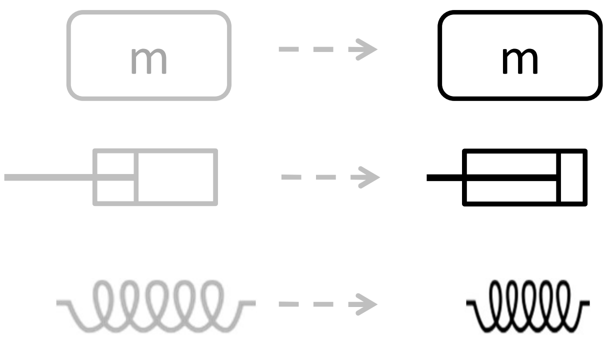
A *haptic interface* let a human operator **touch**, **manipulate** and **feel** a virtual environment

Mechanical Impedance - Z

- *Dynamic* relationship between velocity and force
- Frequency-dependent resistance

$$\mathbf{f}(\omega) = \mathbf{Z}(\omega) \cdot \mathbf{v}(\omega)$$

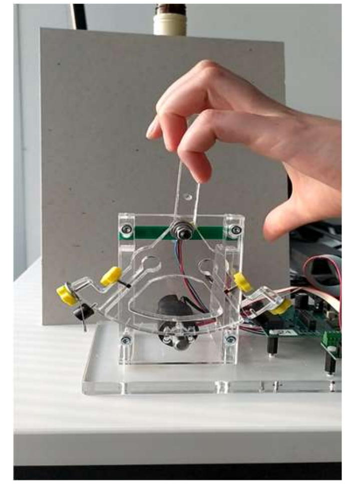
force **velocity**



$$F \sim \ddot{x}$$

$$F \sim \dot{x}$$

$$F \sim \Delta x$$



Mechanical admittance: $Y = Z^{-1}$ → $v(\omega) = Z^{-1} \cdot f(\omega) = Y \cdot f(\omega)$

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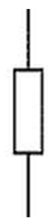
Analogy – Electrical Impedance

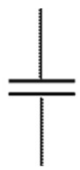
frequency-dependant resistance

Resistor:



$$Z = \frac{V}{I} = R$$

Capacitor:



$$Z = \frac{V}{I} = \frac{1}{j\omega C}$$

$\omega \rightarrow 0$ (DC) → Z large (open circuit)

$\omega \rightarrow \infty$ → Z small (short circuit)

Inductance:

$$Z = \frac{V}{I} = j\omega L$$

$\omega \rightarrow 0$ (DC) → Z small (short circuit)

$\omega \rightarrow \infty$ → Z large (open circuit)

What is the Z-Width?

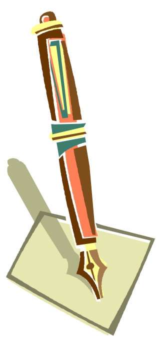
The range of admissible Z-values

Low mass rigid body
(almost no resistance to motion)

Z → 0; **Y** →∞

$$v(\omega) = Z^{-1} \cdot f(\omega) = Y \cdot f(\omega)$$

→ small force f results in a large motion

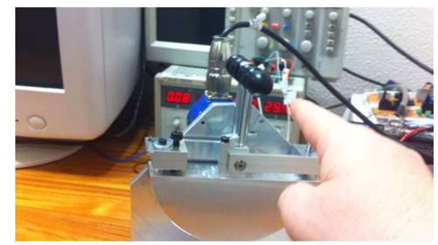


"Stiff viscoelastic body"
(almost complete resistance to motion in direction normal to paper)

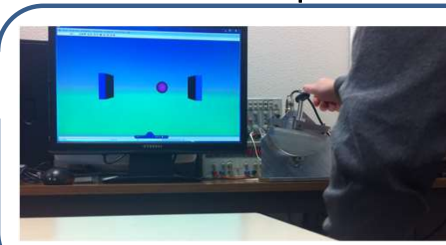
Z → ∞; **Y** →0

$$v(\omega) = Z^{-1} \cdot f(\omega) = Y \cdot f(\omega)$$

→ large force f results in a small motion



Z-Width:
Dynamic range of achievable impedances



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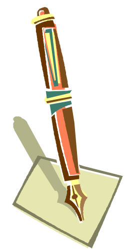
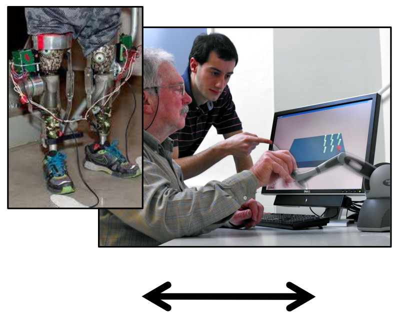
The "Ultimate" Multi Purpose of a Haptic Device





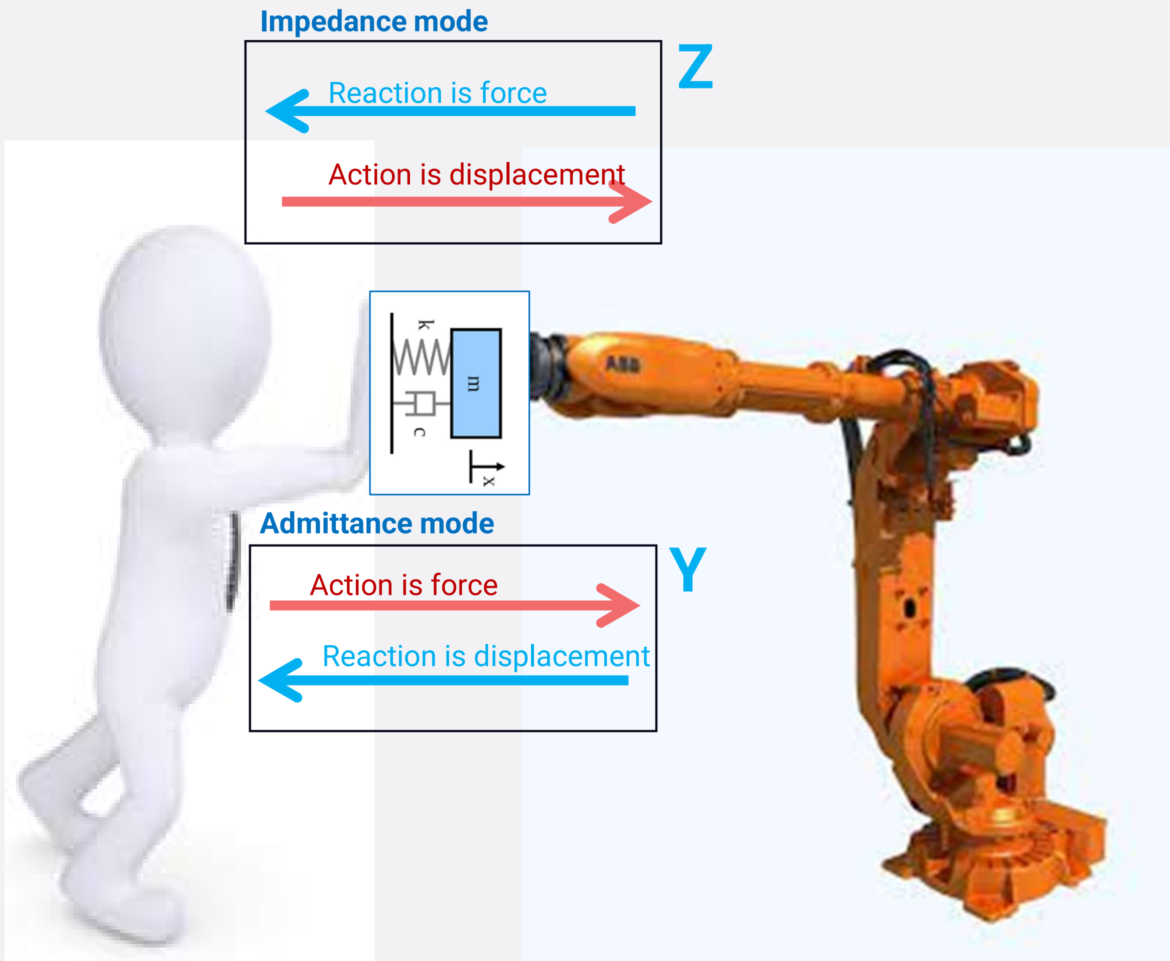
How to build a haptic interface with **a broad Z-Width** and a robust stability property?

Low end: limited by inertia and friction

High end: - limited by system stability

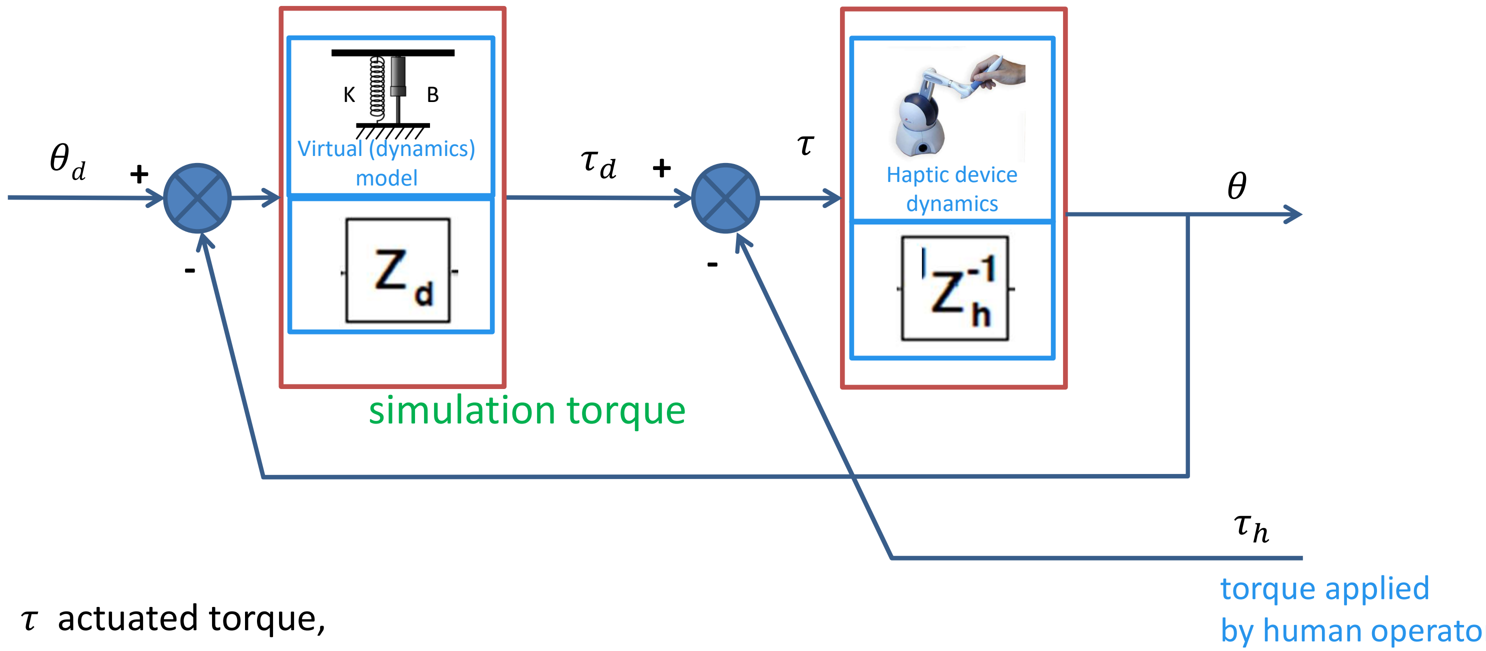
[Increase high-end →More Force needed → larger actuators,
Drive mechanisms, linkages → More inertia, more friction → reduce low-end]
(Clover et al., 1997, Book and Ruis 1981)

Did you say “Impedance” or “Admittance” ?



(Open-loop) Impedance Control

$$F_d = (\theta_d - \theta) * K - \dot{\theta} * B$$

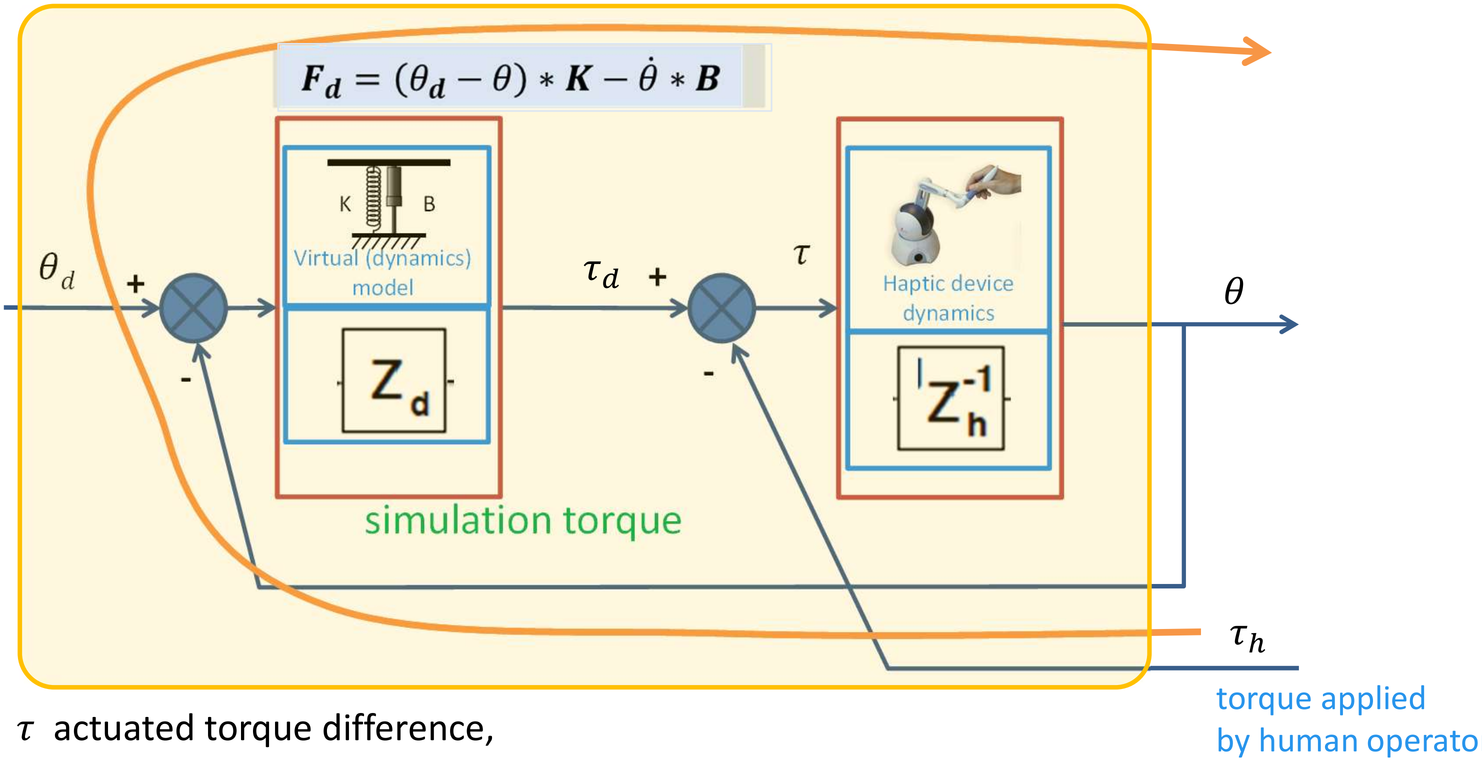


τ actuated torque,
x current position
x_d desired position

What human operator feels = simulation torque + Friction, gravity, inertia

Closed-loop force control for haptic simulation of virtual environments,
Carignan and Cleary, 2000

(Open-loop) Impedance Control

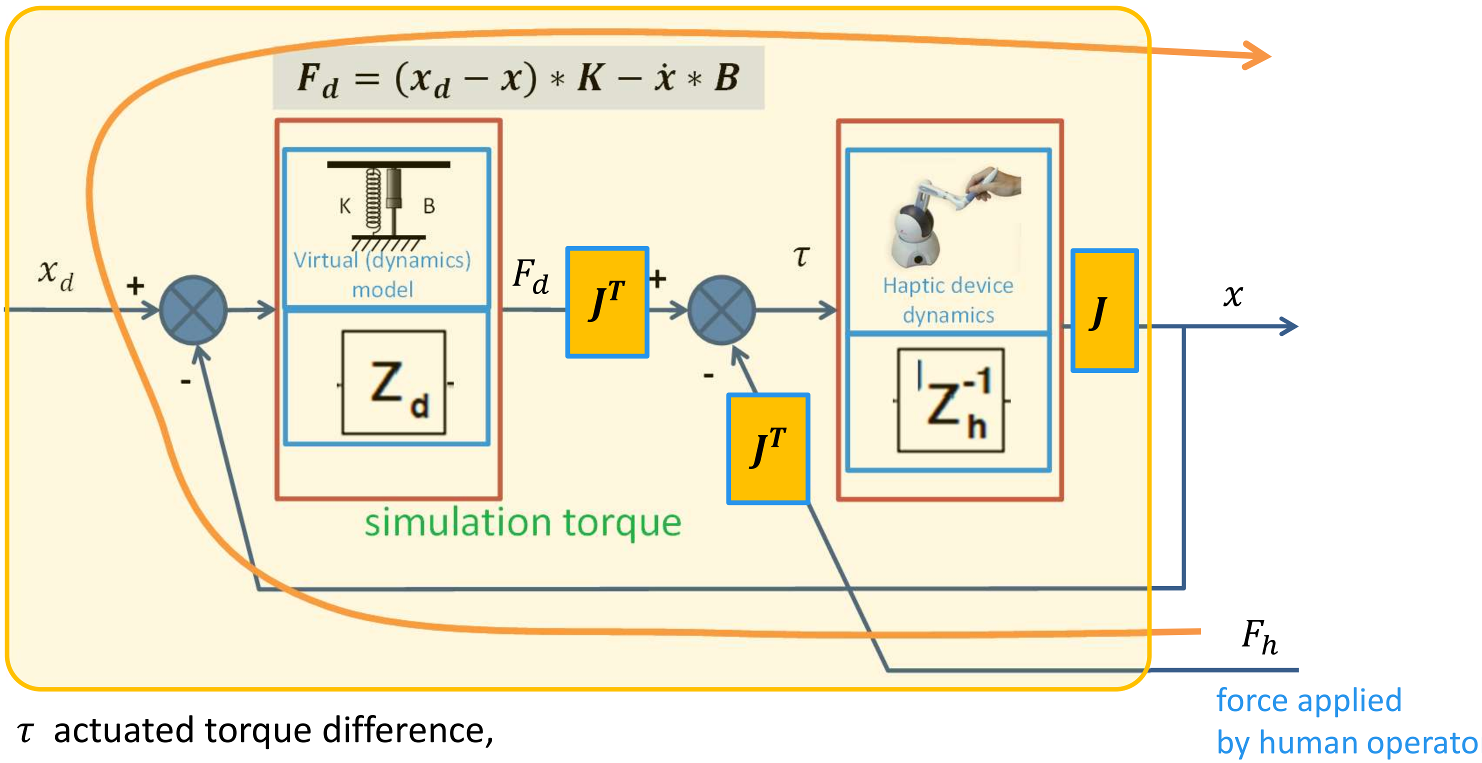


τ actuated torque difference,
x current position
x_d desired position

What human operator feels = simulation torque + Friction, gravity, inertia

Closed-loop force control for haptic simulation of virtual environments, Carignan and Cleary, 2000

(Open-loop) Impedance Control



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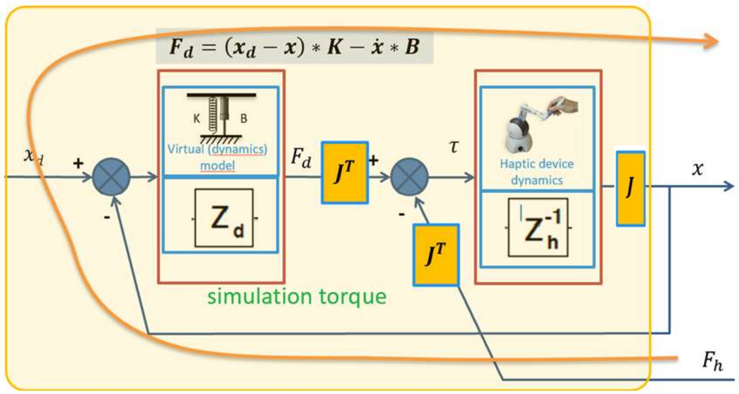


$$F(\omega) = Z(\omega).X(\omega)$$

$$Z(\omega)^{-1}.F(\omega) = X(\omega)$$

[Haptic device]

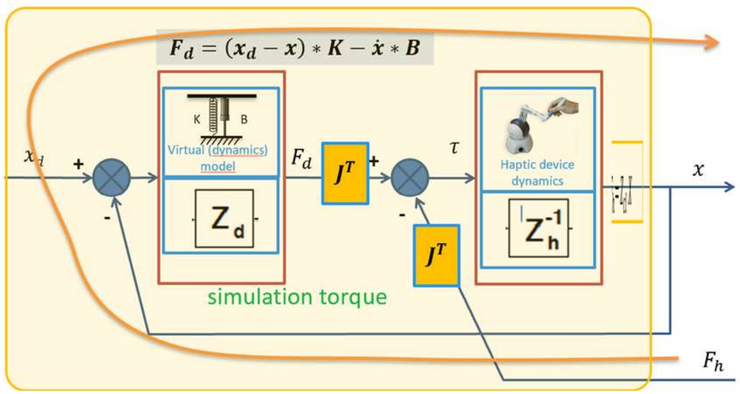
$$Z_h(\omega)^{-1}.F(\omega) = X(\omega)$$

$$Z_h(\omega)^{-1}.\tau(\omega) = \theta(\omega)$$

(if we consider joints)

Closed-loop force control for haptic simulation of virtual environments,
Carignan and Cleary, 2000

(Open-loop) Impedance Control



$$X = Z_h{}^{-1}.(Z_d(X_d - X) - F_h)$$

$$Z_h X = Z_d(X_d - X) - F_h$$

$$F_h = Z_d(X_d - X) - Z_h X$$

Setting X_d = 0, without loss of generality, leads to

$$F_h = -(Z_d + Z_h)X$$

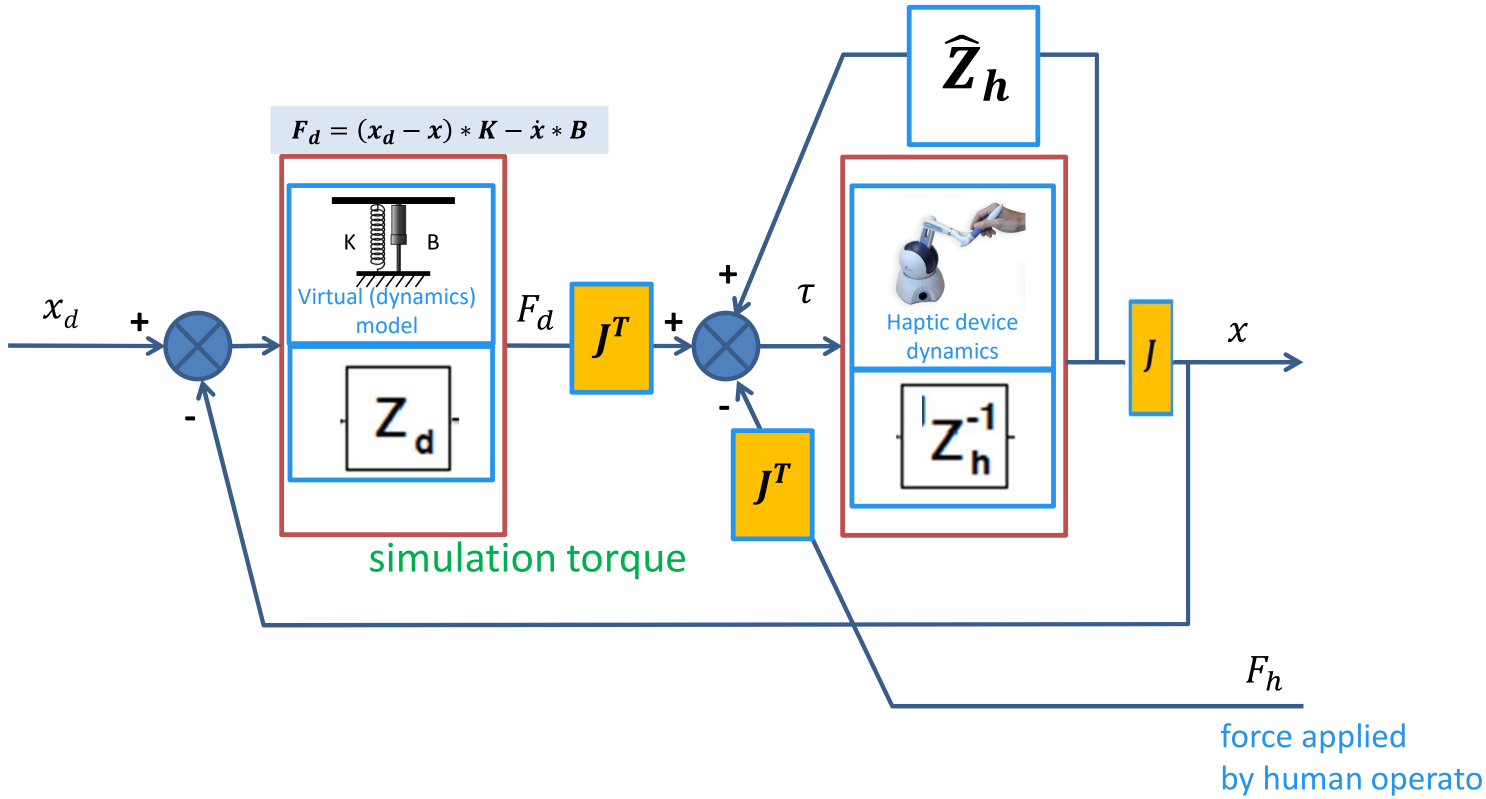
$$F_h = Z_{cl} X$$

$$Z_{h_{CL}} = Z_d + Z_h$$

What human operator feels = simulation torque + Friction, gravity, inertia

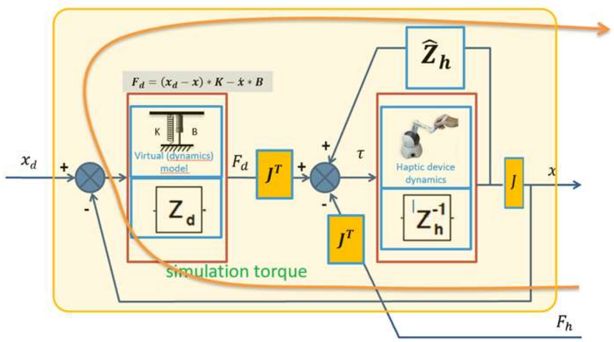
Closed-loop force control for haptic simulation of virtual environments, Carignan and Cleary, 2000

(Open-Loop) Impedance Control with Model Compensation



Closed-loop force control for haptic simulation of virtual environments, Carignan and Cleary, 2000

(Open-Loop) Impedance Control with Model Compensation



$$X = Z_h^{-1}.\left(Z_d(X_d - X) + \hat{Z}_h X - F_h\right)$$

$$Z_h X = Z_d(X_d - X) + \hat{Z}_h X - F_h$$

$$F_h = Z_d(X_d - X) + \hat{Z}_h X - Z_h X$$

Setting X_d = 0, without loss of generality,

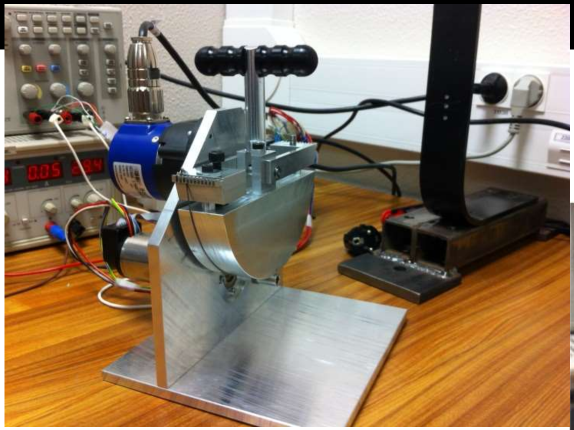
leads to

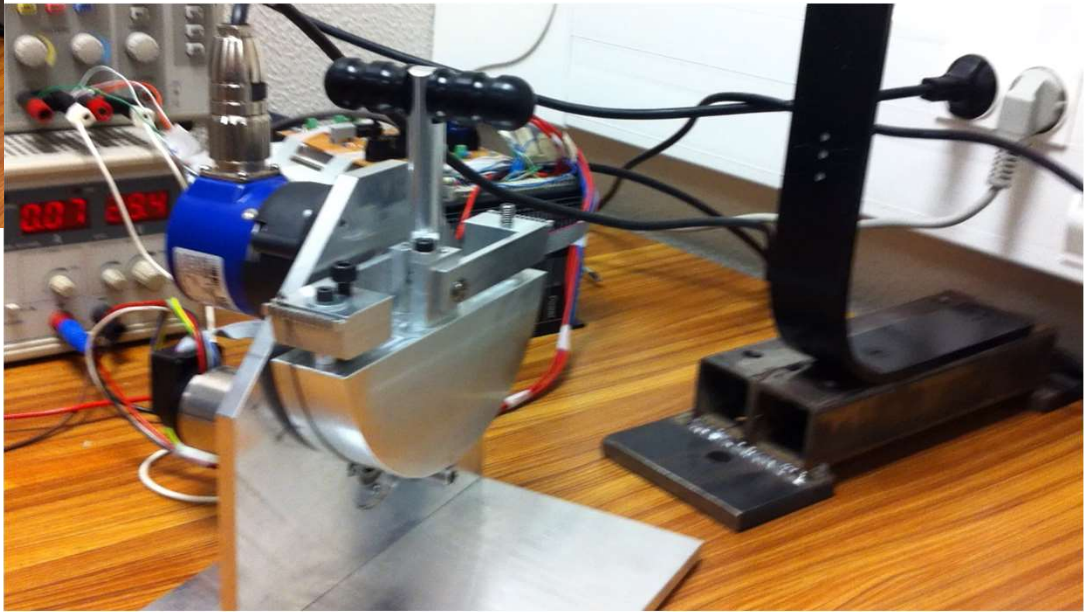
$$F_h = -(Z_d + Z_h - \hat{Z}_h)\, X$$

$$Z_{h_{CL}} = Z_d + \underbrace{Z_h - \hat{Z}_h}_{=0?}$$

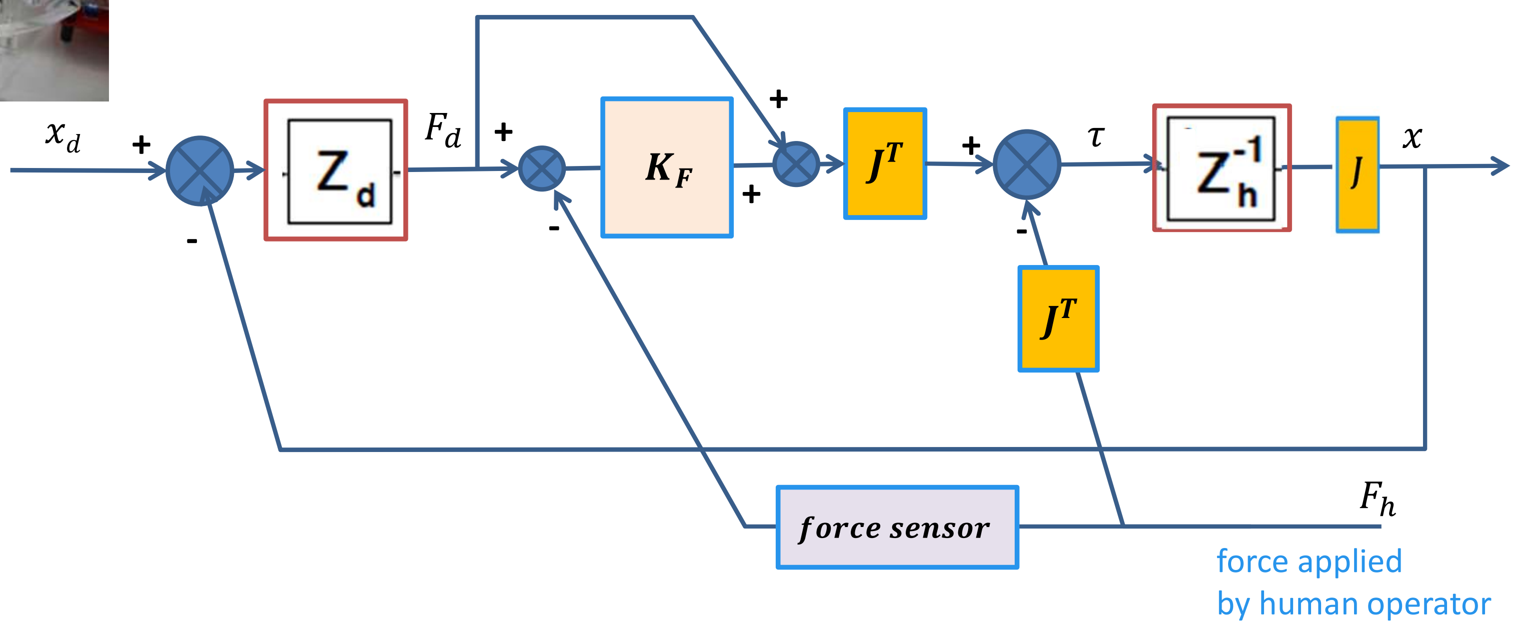
- Modeling errors
- Increased computational load → lower loop rates → compromise maximal stiffness

Example – Gravity and Friction Compensation- transparency

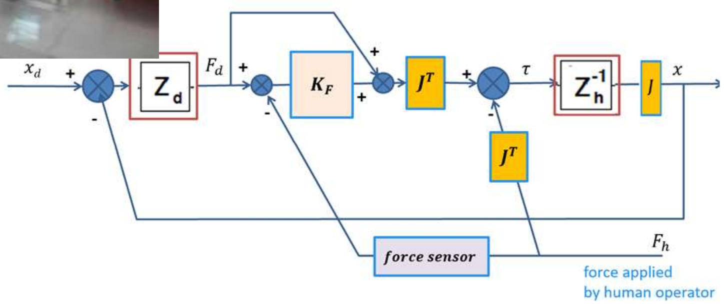




Impedance Control with Force Feedback



Impedance Control with Force Feedback



$$Z_{h_{CL}} = Z_d + (I + K_F)^{-1} Z_h$$

$K_F = 0 \rightarrow Z_h$
(Open loop case)

K_F big $\rightarrow 0$
(stability!)

Lawrence [1988], Newman [1990],
Adams and Hannaford [1999]

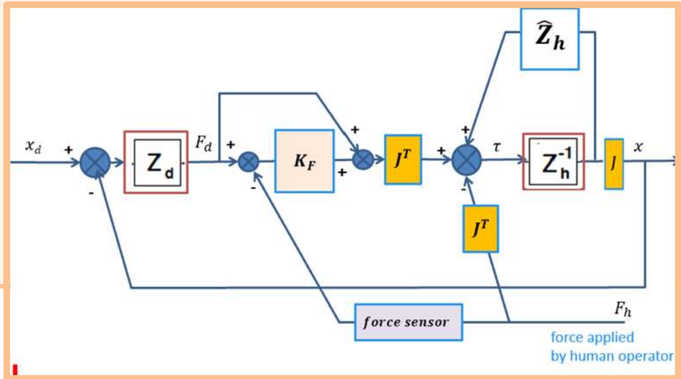
Summary

- Open-loop Impedance control $Z_{h_{CL}} = Z_d + Z_h$
- Open-loop Impedance control with model feedforward $Z_{h_{CL}} = Z_d + Z_h - \hat{Z}_h$
- Impedance control with force feedback $Z_{h_{CL}} = Z_d + (I + K_F)^{-1} Z_h$

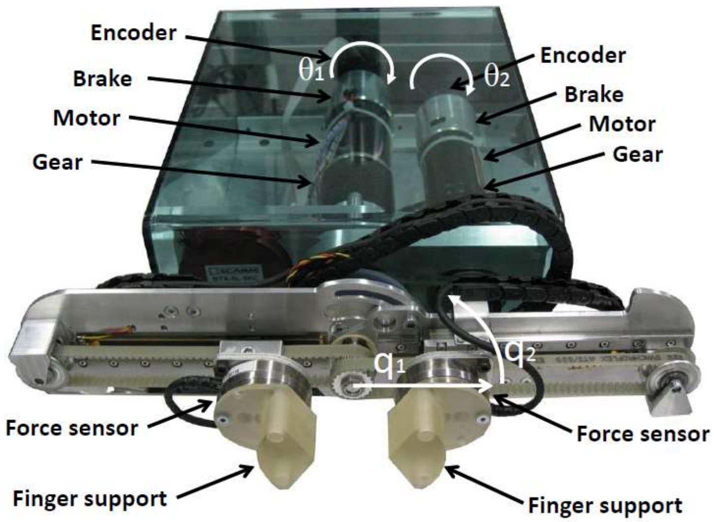
Closed-loop force control for haptic simulation of virtual environments, Carignan and Cleary, 2000

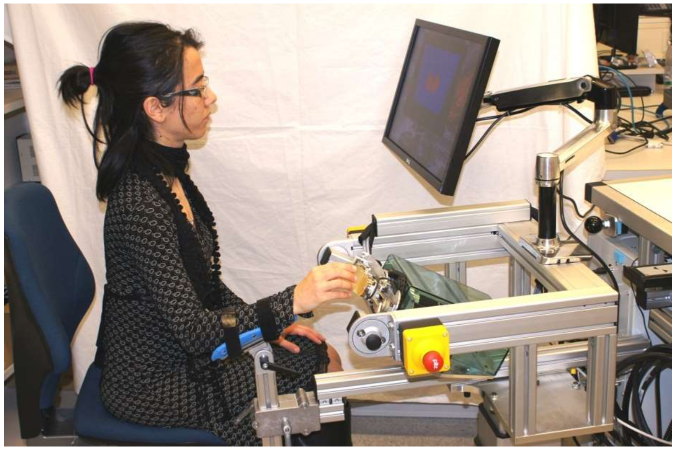
Impedance control with force feedback and model feedforward

→ Smaller feedback error → large force control gain possible



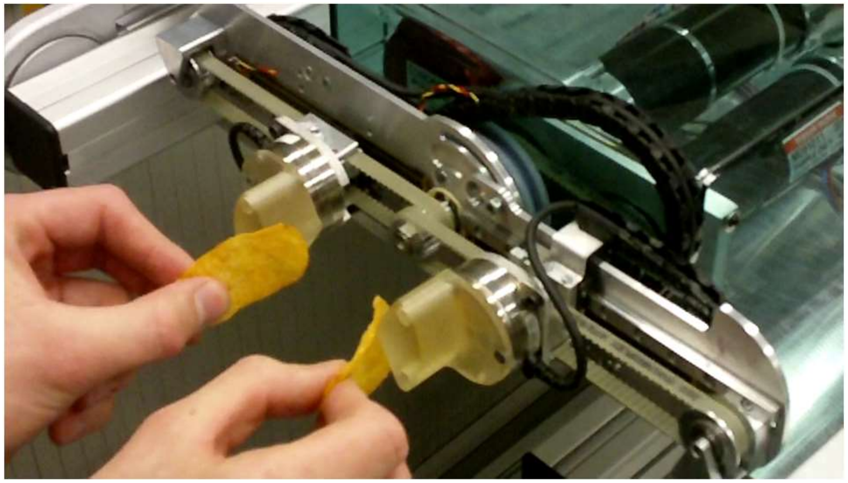
Hand Rehabilitation Robot - ReHapticKnob





ReHapticKnob with healthy subject
RELAB ETH zürich

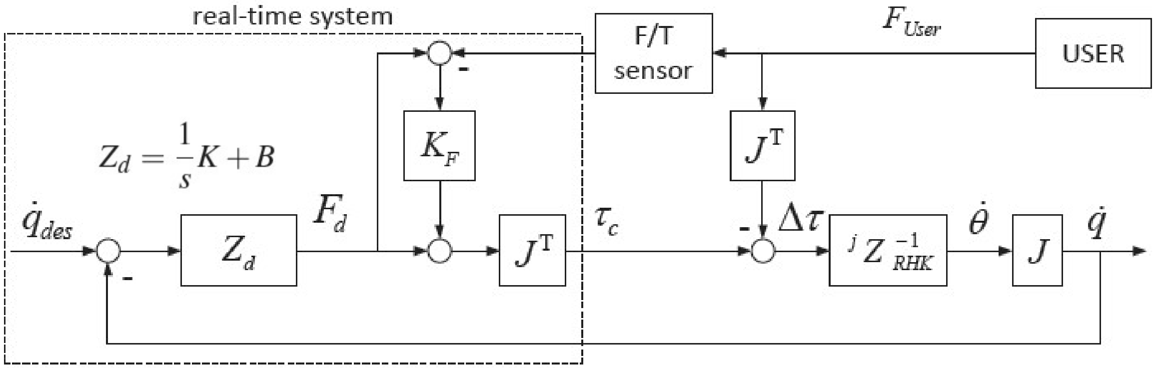
Impedance Control With Force Feedback – Transparent control



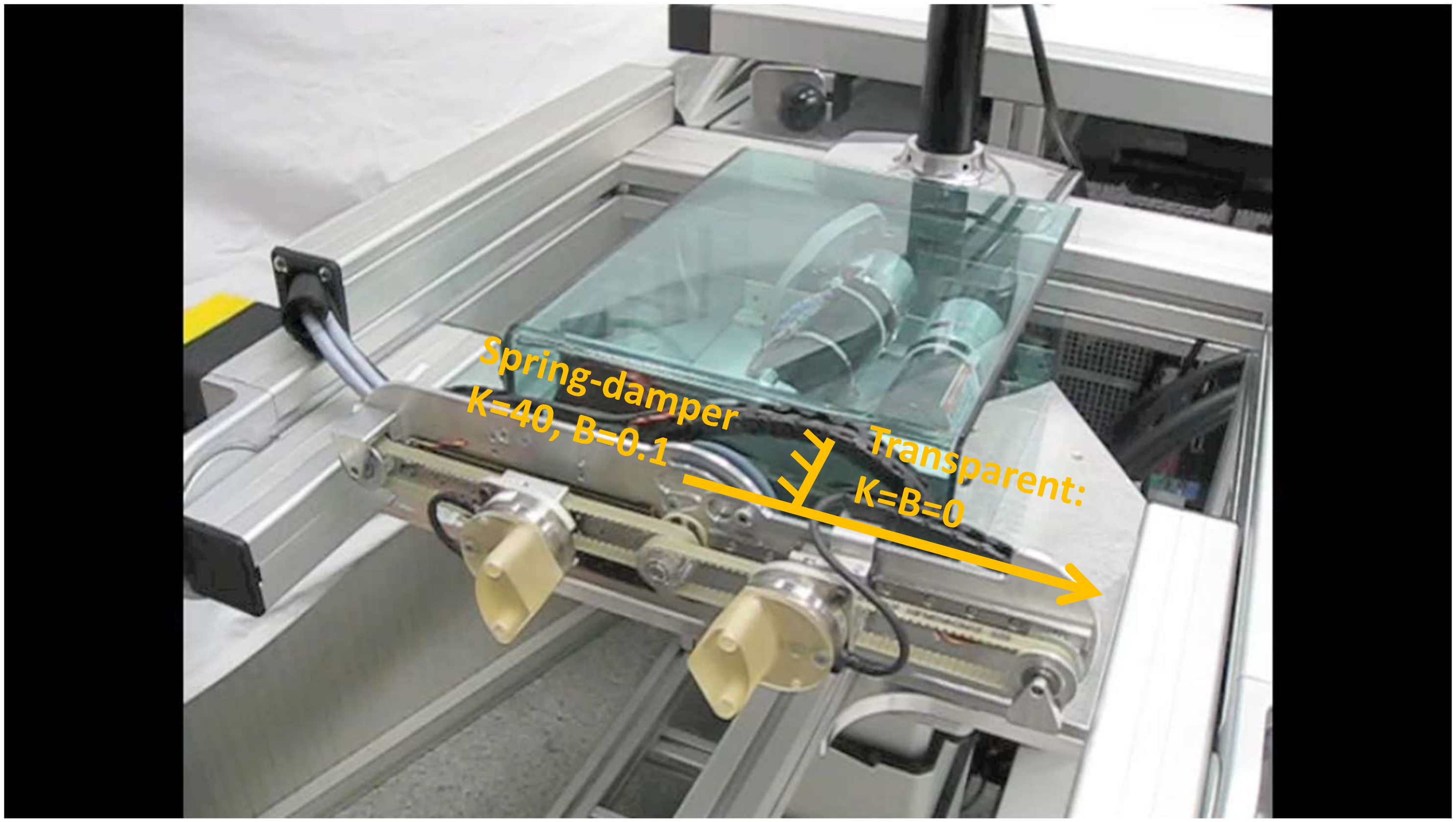
RELAB ETH zürich

K=B=0

K_F large

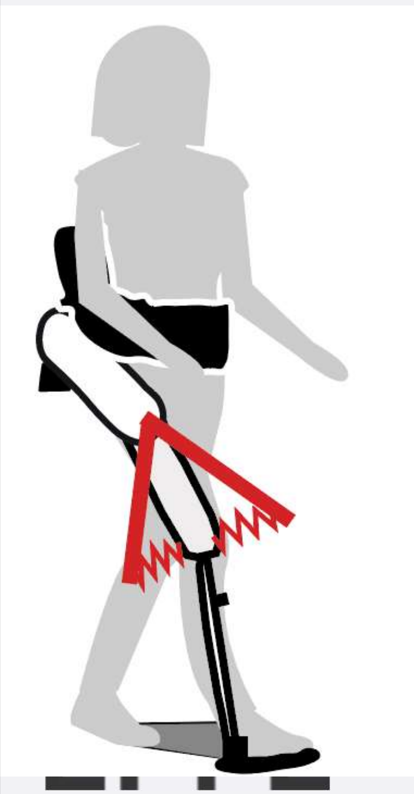


Impedance Control With Force Feedback - Virtual Wall

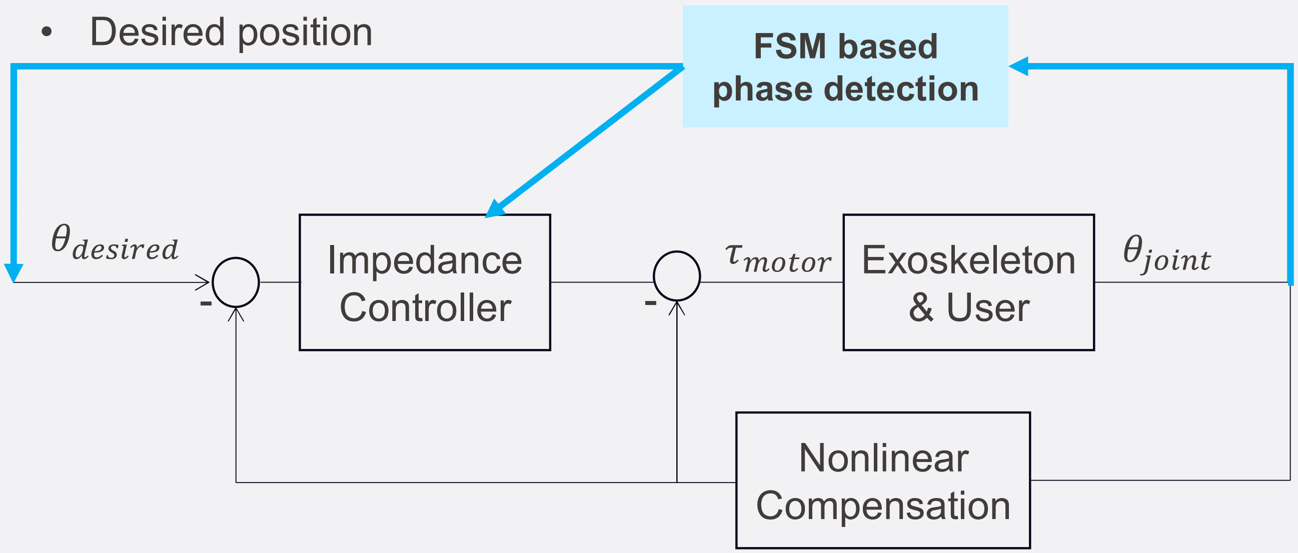


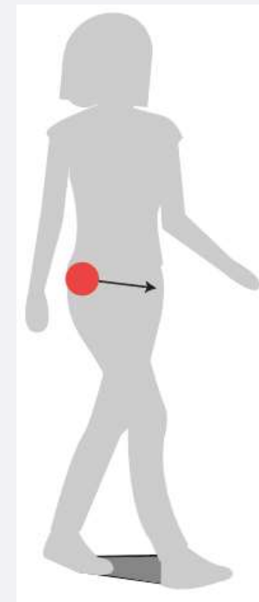
RELAB ETH zürich

Variable impedance gait assistance strategy



- Desired position



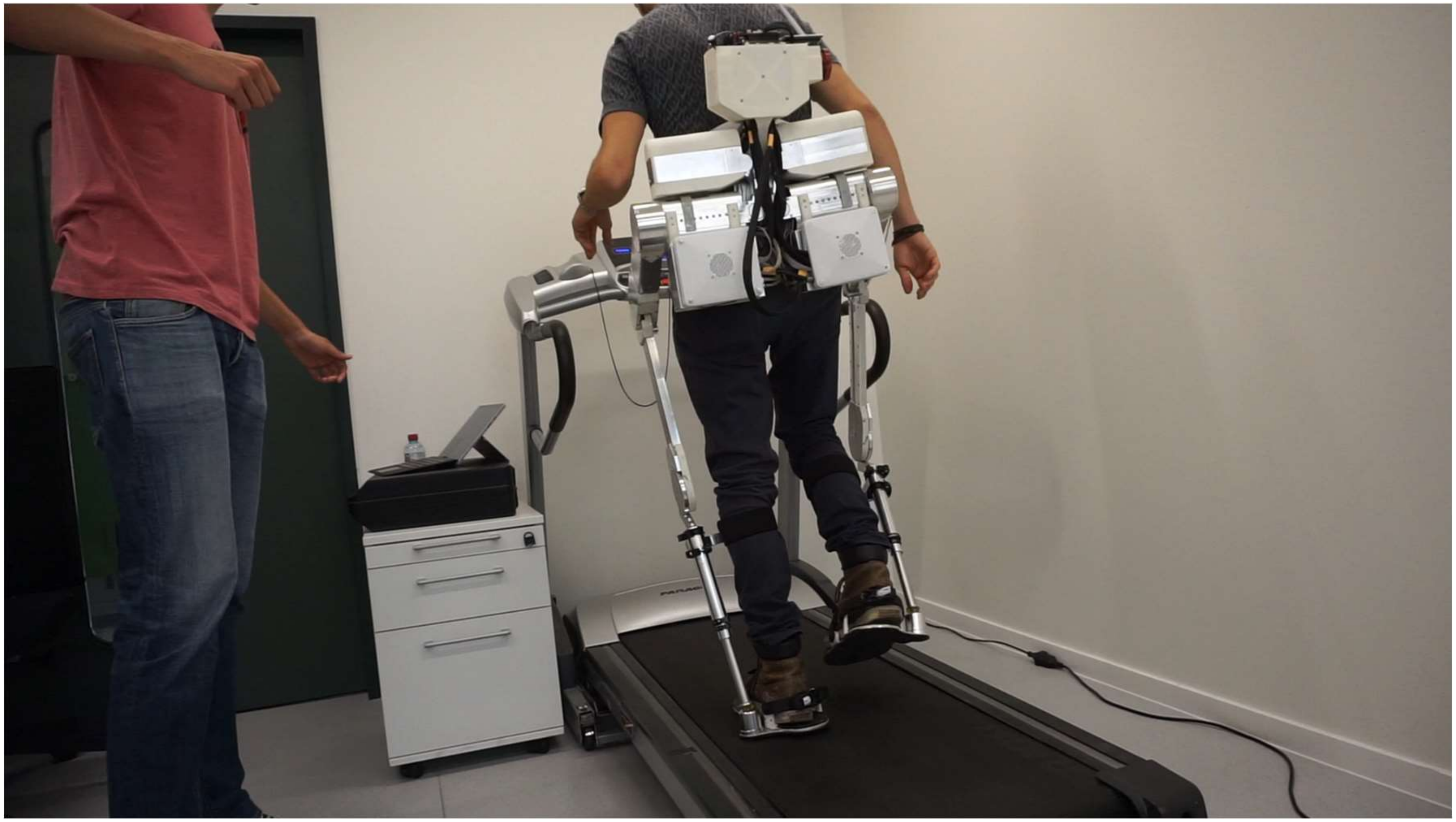


Swing: $V_{hip} > V_{lim+}$

Stance: $V_{opp\_hip} > V_{lim+}$

Double support: $V_{hip} \leq V_{lim+}$, $V_{opp\_hip} \leq V_{lim+}$

Impedance control for assistance



How to qualify a Haptic interface?

Quality of a haptic interface:

accuracy – fidelity – Z width

Impedance „**accuracy**“:

how close matches the apparent impedance (felt impedance) that of the virtual environment

Impedance „**fidelity**“:

resolution – level of impedance discrimination that can be rendered at the haptic interface

(→ Fidelity is limited by the natural dynamics of the device)

„Z width “:

Defines the range of accessible stable Z, from (fully transparent capabilities, **Z = 0**) to (very stiff, **Z=∞**)

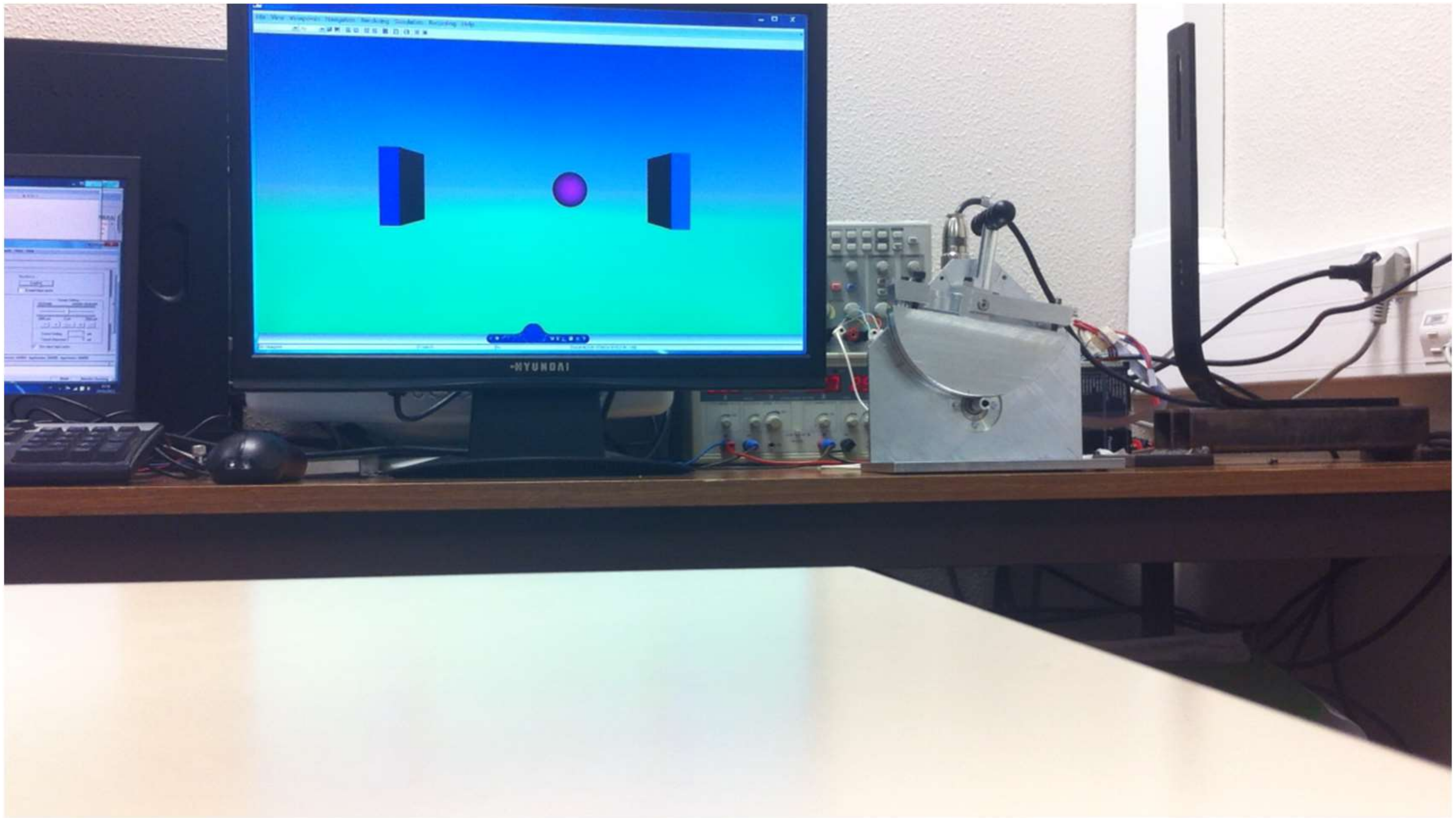
How to achieve a good-performance Haptic Device?

Take care about:

- The current loop Bandwidth. **Why?**
- Current resolution. **Why?**
- Position resolution. **Why?**
- Velocity resolution. **Why?**
- Sampling rates of both VR loop and force loop. **Why?**
- Reduce the dry friction in the mechanical transmissions. **Why?**

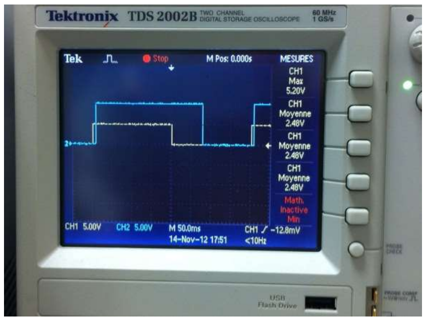
Performances – Effects of the Feedback Delay

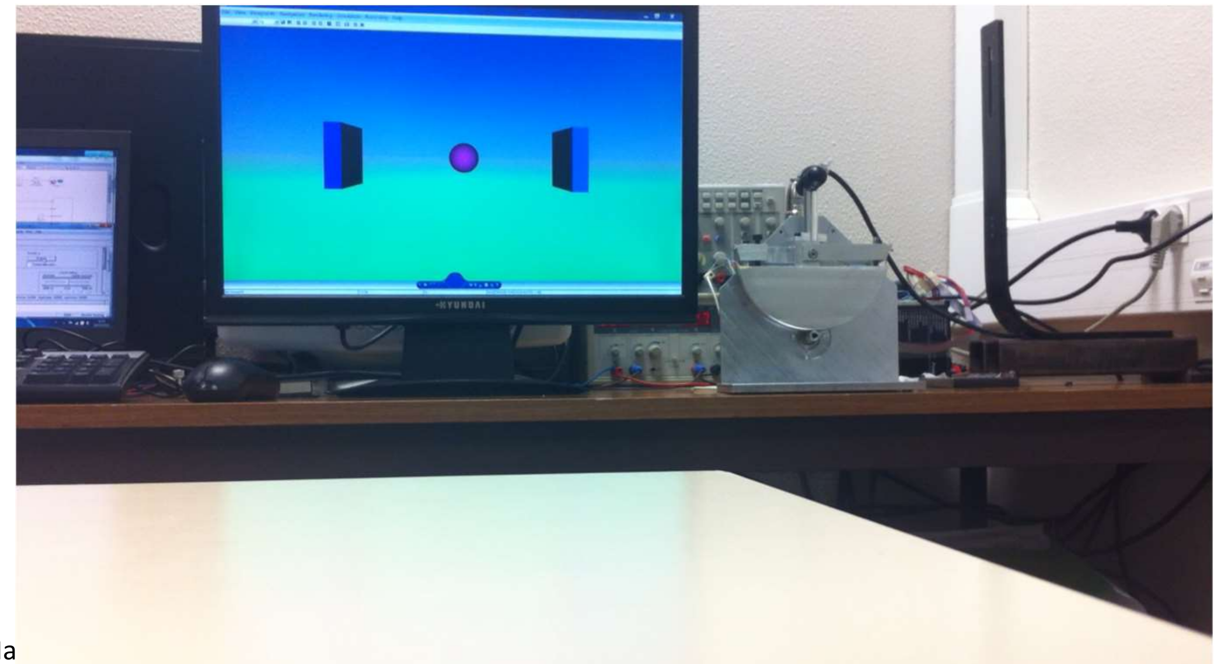
Wall effect stability – **No delay**



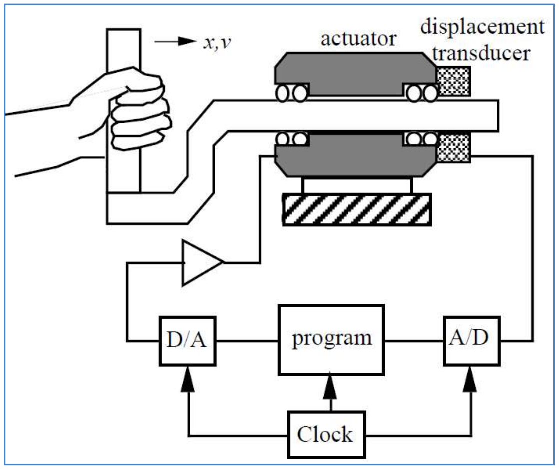
Performances – Effects of the Feedback Delay

Under Delay

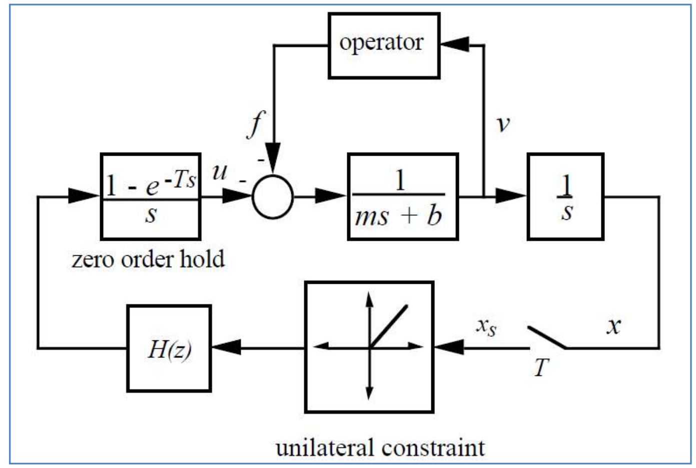




Colgate's experiment : 1 DoF Haptic Interface

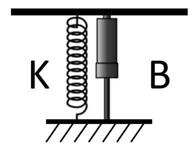


Illustration



Block diagram

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

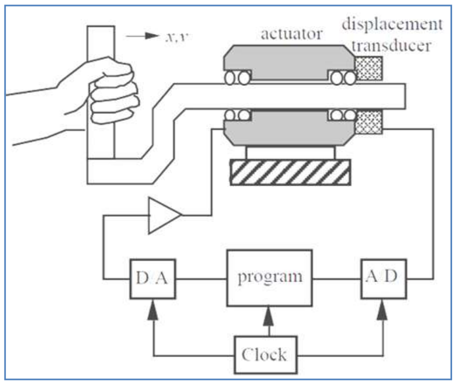


Factors Affecting the Z-Width of a Haptic Display, J. Edward Colgate, J. Michael Brown, 1994

Z-transform: converts a discrete time-domain signal, which is a sequence of real or complex numbers, into a complex frequency-domain representation. One of its properties is the *time shifting*:

$x_k = z \cdot x_{k-1}$ and therefore: $v_k = \frac{x_k - x_{k-1}}{T} = \frac{x_k - \frac{1}{z}x_k}{T} = \frac{z-1}{Tz}x_k$

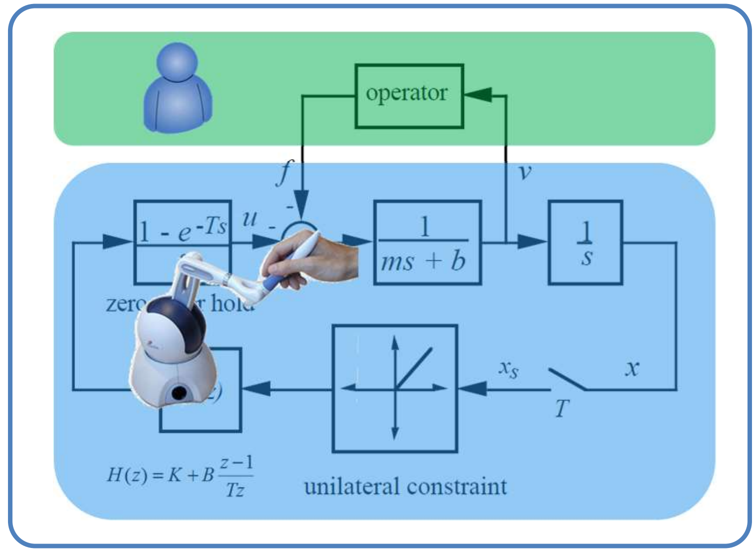
Colgate's experiment : 1 DoF Haptic Interface



If the haptic display behaves passively, then the operator can never extract energy from it. Here, we will use the slightly more stringent statement that the energy input to the haptic display from the operator must be positive for all admissible force histories *f(t)* (see discussion in Section 3.2) and all times greater than zero:

$$\int_0^t f(\tau)v(\tau)d\tau > 0, \ \forall\ t > 0, \text{ admissible } f(t) \qquad (2.1)$$

A system which does not satisfy 2.1 is said to be "active."

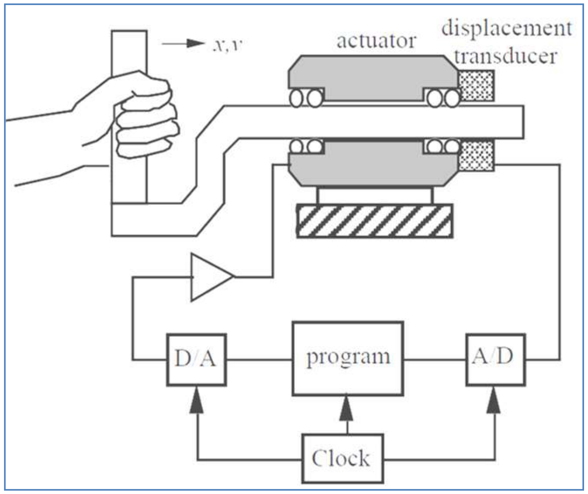


Block diagram

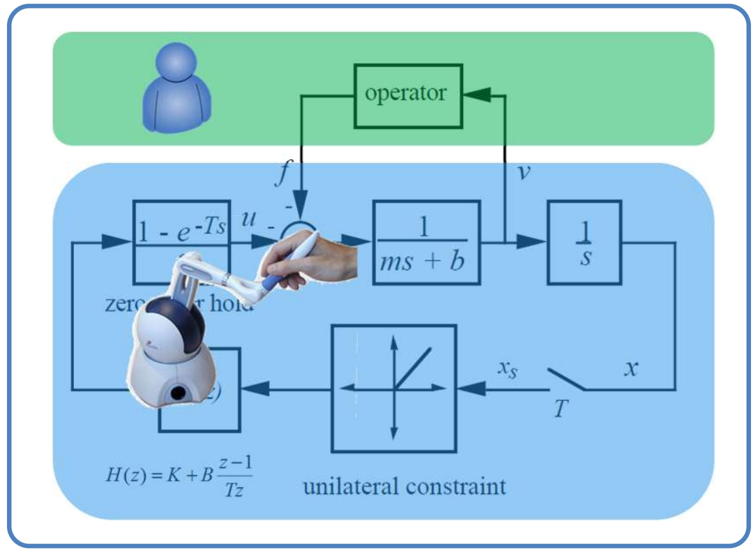
One of the well-known consequences of passivity is the following: a strictly passive system, connected to any passive environment, is necessarily stable. Thus, stability when connected to a linear time-invariant, passive, but otherwise arbitrary environment may be considered a necessary condition for passivity. This idea is the basis of the necessity proof.

Passivity of a Class of Sampled-Data Systems: Application to Haptic Interfaces,
J. Edward Colgate, Gerd G. Schenkel, 1995

Colgate's experiment : 1 DoF Haptic Interface



Illustration



Block diagram

Condition for passivity:

$$b > \frac{T}{2}\frac{1}{1-\cos\omega T}\mathrm{Re}\left\{\left(1-e^{-j\omega T}\right)H\left(e^{j\omega T}\right)\right\}$$

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

Passivity of a Class of Sampled-Data Systems: Application to Haptic Interfaces, J. Edward Colgate, Gerd G. Schenkel, 1995

Conclusion from Passivity Analysis

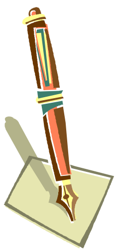
Inherent damping → b; Virtual stiffness → K; Sampling time → T; Virtual damping → B

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

- Passivity only with some physical dissipation b

- With b and B fixed:
achievable stiffness ~ sampling rate

→ Minimize T (fast sampling)
→ Maximize b (maximize physical damping)



High stiffness K due to high physical damping b

High physical damping!?

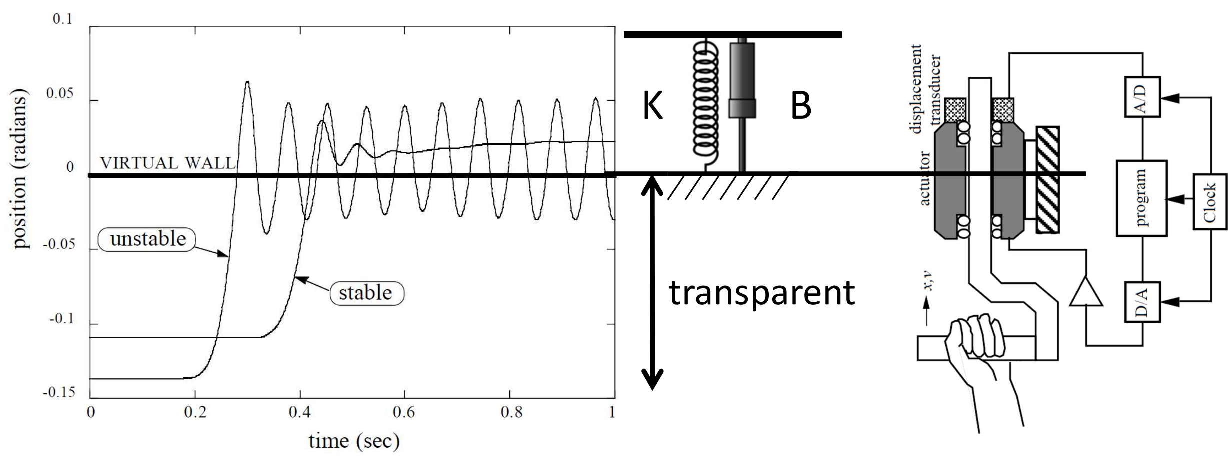
$$B = -b$$

Factors Affecting the Z-Width of a Haptic Display, J. Edward Colgate, J. Michael Brown, 1994

Colgate's experiment : 1 DoF Haptic Interface

16 possible configurations:

Damper	engaged	disengaged
Sampling rate	high (1 KHz)	low (100 Hz)
Encoder resolution	high (900K cpr)	low (8K cpr)
Velocity filter	first order, 30 Hz cutoff	none



Factors Affecting the Z-Width of a Haptic Display, J. Edward Colgate, J. Michael Brown, 1994

Sensor Quantization & Velocity Filtering

Minimize T (fast sampling) $v = \frac{x_k - x_{k-1}}{T}$

→ Velocity resolution of sensor increases $\frac{\Delta encoder}{T}$

→ BUT: Velocity used for virtual damping!

$$F = (x - x_d) \cdot K + \dot{x} \cdot B$$

Example:

Position encoder: 2000 counts/turn (4x500)

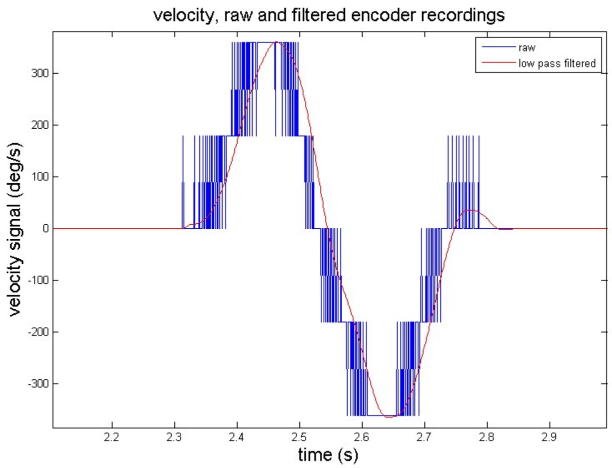
Position resolution: 360°/2000 = **0.18°/count**

Sampling time: 0.01s (100 Hz)

Velocity resolution: 0.18°/0.01s = **18°/s**

Sampling time: 0.001s (1 kHz)

Velocity resolution: 0.18°/0.001s = **180°/s**

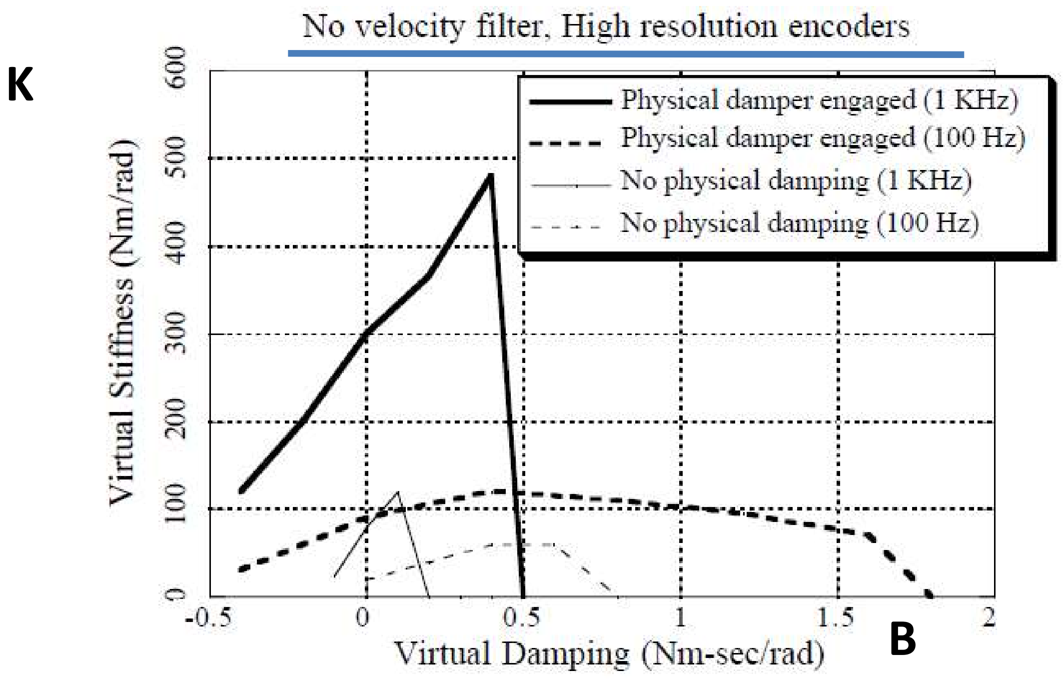


1. Slower sampling (bigger T) → stiffness!
2. Use encoder with higher resolution
3. Digital velocity filter
4. Analog sensor

K-B-Plot

Z-Width

Experimental Results. Plots indicate Z-Width (area beneath the curves)



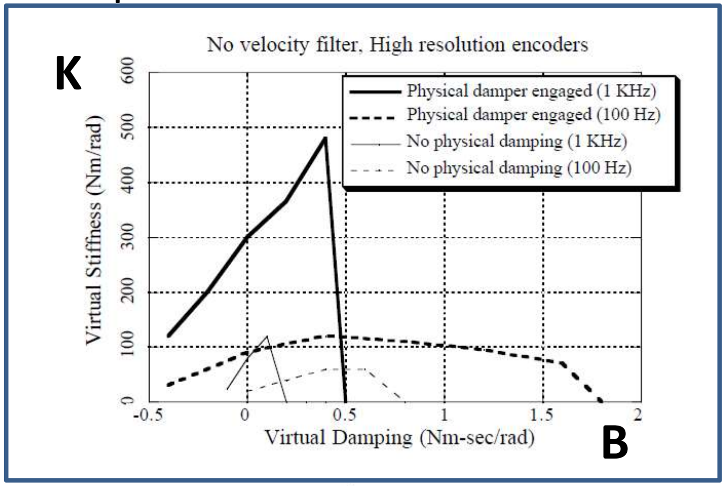
4a.

Factors Affecting the Z-Width of a Haptic Display,
J. Edward Colgate, J. Michael Brown, 1994

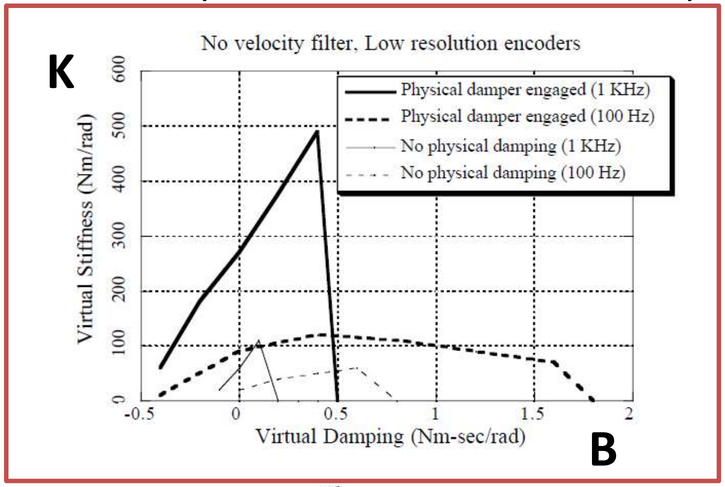
K-B-Plot

Z-Width

Experimental Results. Plots indicate Z-Width (area beneath the curves)



4a.

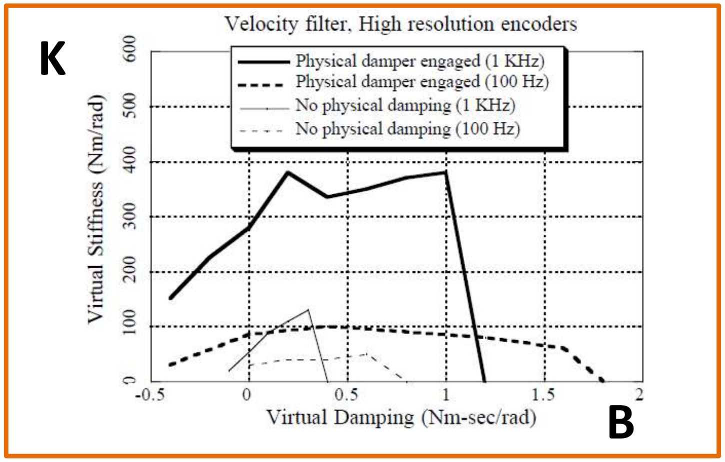


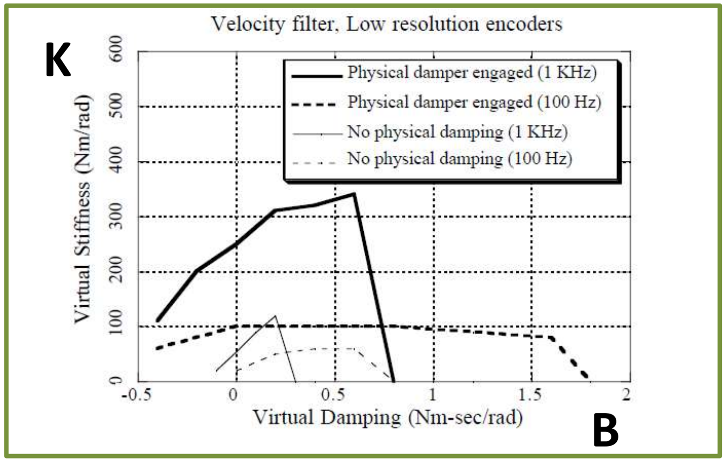
4b.

K-B-Plot

Z-Width

Experimental Results. Plots indicate Z-Width (area beneath the curves)



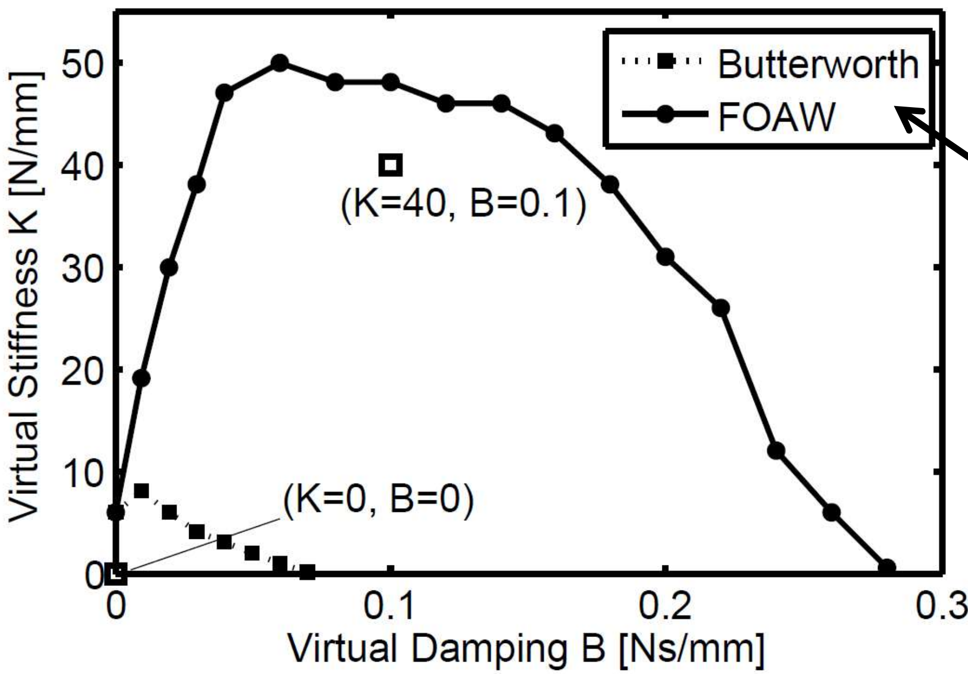


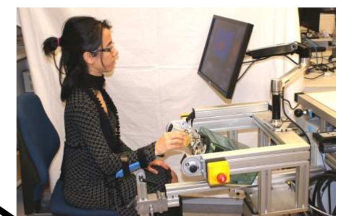
Factors Affecting the Z-Width of a Haptic Display, J. Edward Colgate, J. Michael Brown, 1994

K-B-Plot of the ReHapticKnob

Z-Width comparison between two velocity estimators:

- Backward euler differentiation + 2nd order butterworth
- First order adaptive windowing (FOAW) estimator





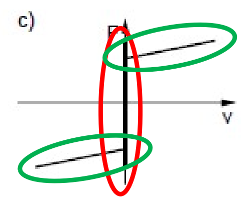
$$F = (x - x_d) \cdot K + \dot{x} \cdot B$$

Some comments about your Lab3

Some Comments on Stability

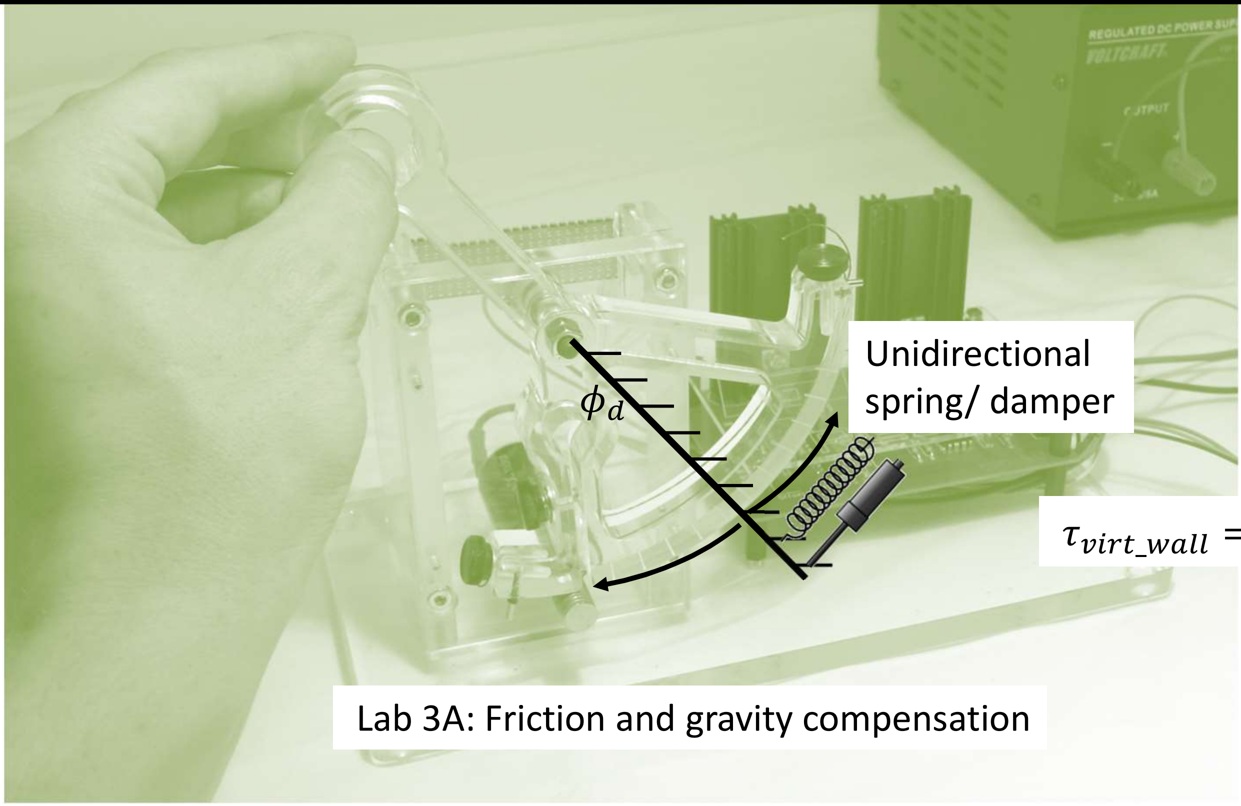
- *Factors Affecting the Z-Width of a Haptic Display*, J. Edward Colgate, J. Michael Brown, 1994
- *Passivity of a Class of Sampled-Data Systems: Application to Haptic Interfaces*, J. Edward Colgate, Gerd G. Schenkel, 1995
- *Stable Haptic Interaction with Virtual Environments*, R.Adams and B. Hannaford, 1999
- *Control architectures, design and implementation for 1-DoF haptic interfaces*, Suleman Khan

The main possible sources for stability problems of haptic devices:



- stiction and Coulomb friction
- actuator saturation and bandwidth
- sensor noise
- sampling rate of time discrete implementation
- stiffness of robot joints and links
- sensor dynamics
- virtual environment dynamics
- human arm dynamics
- operator's dynamic force/motion input

Lab 3 – K-B-Plot

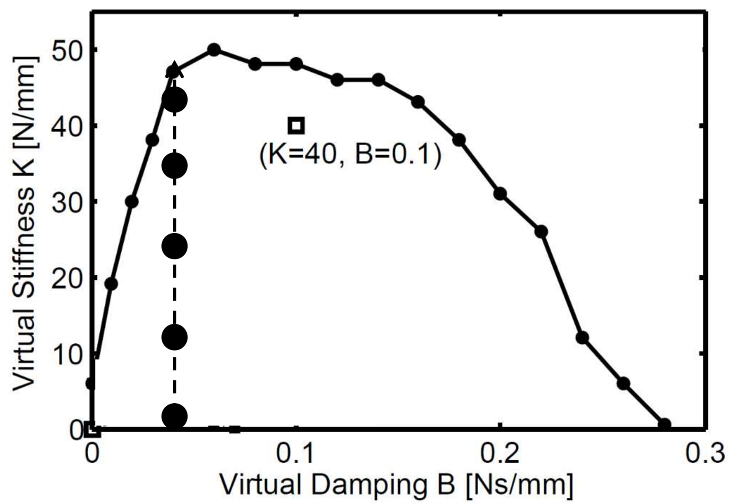


Measured filtered

$$\tau_{virt\_wall} = (\hat{\phi} - \phi_d)K + \widehat{\omega}B$$

Using friction and gravity compensation $i_m = \frac{1}{\bar{K}}\left(\hat{\tau}_{friction} + m_p g l sin(\hat{\phi}_p) - \tau_{virt\_wall}\right)$

Lab 3 – K-B-Plot



1. Select a damping value B (e.g. 0.05)
2. Increase K until virtual wall *feels* unstable (trembling)

Questions?

Important comments about your lab 3,

- Unit of Kp and Kd (or B)
  In Nm_output / rd and Nm_output/rd/sec
- Always present torque in unit Nm_output
- Keep the same scaling when comparing graphs (in X and in Y coordinates of the associated figure)
- I suggest that you remind in the report
  - Sampling period,
  - Resolution of position (encoder and Hall sensor)
  - Resolution of velocity
  - Resolution of output torque, assuming that the resolution of current is 4Amps / 256 (8 bits)
- More general : Never forget units
- Take care that even in simulation, the ranges of values are not infinite (there is always physical limits)