2012 ETHZ Summer School on Soft Robotics

Soft actuation in physical human-robot interaction

Roger Gassert

Rehabilitation Engineering Lab, ETH Zurich

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

RELAB
REHABILITATION ENGINEERING LAB

Today's Schedule

- 08h15–10h00 – R. Gassert:
  Soft actuation in physical human-robot interaction
- 10h15–12h00 – O. Lambercy:
  Soft human-robot interaction: The case for rehabilitation robotics
- 13h15–17h00 – RELab (in parallel to 2nd tutorial):
  Haptic Paddle: implementation of a stiff virtual wall, K-B plot and model feedforward

Acknowledgements

- most of material based on RELab pHRI lecture:
  J.-C. Metzger, B. Vigaru, M. Tucker, O. Lambercy,
  R. Gassert
- electrostatic actuator: A. Yamamoto, U Tokyo
- ultrasonic actuator: D. Chapuis, M. Flückiger, EPFL
- B. Nelson, “Introduction to Robotics and Mechatronics”, Lecture Notes, ETHZ, 2005.
- various publications and other sources
  (cited throughout lecture)

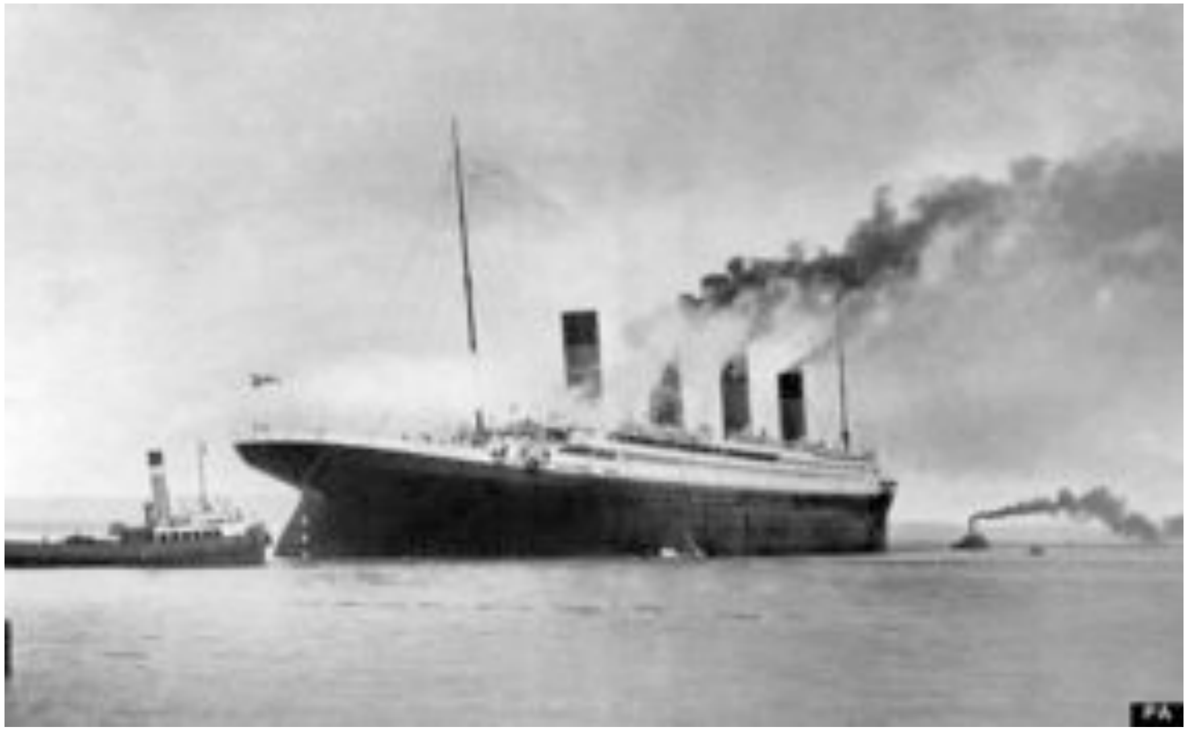
Lecture Goals

- Motivate the need for (variably) soft actuation in pHRI
- Give an overview of actuation methods (commercial and research)
- Discuss ways to make actuators soft, through **mechanical design** and **control**, and how to evaluate their **performance**
- Highlight how biology can inspire innovative robotic designs, and how robots can help shed light on biology

What is Soft Interaction?

It all depends on the context

wallpaper-million.com



Variable Softness

It all depends on the context

Honda Asimo

Honda Walking Assist Device

Variable Softness

in industrial applications

Variable Softness

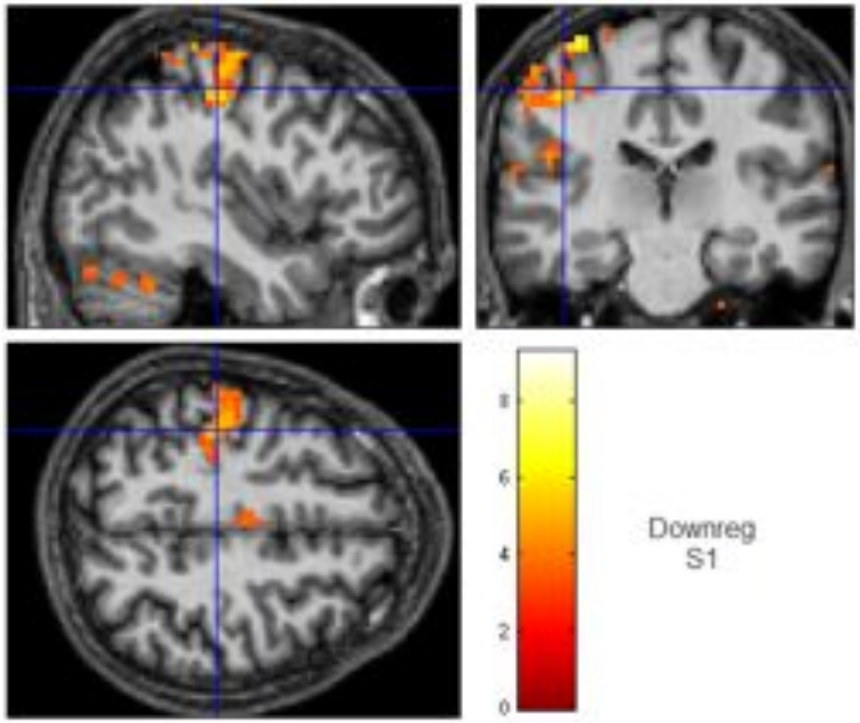
in prosthetics

promise

reality

My personal motivation

Functional Magnetic Resonance Imaging (fMRI)



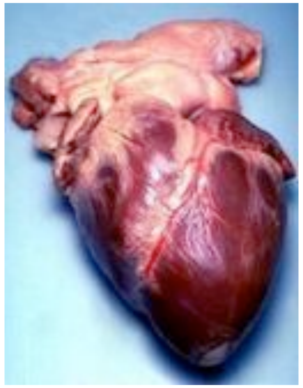
Advantage

Disadvantage

Actuation Principles

Human vs Machine Actuation

human

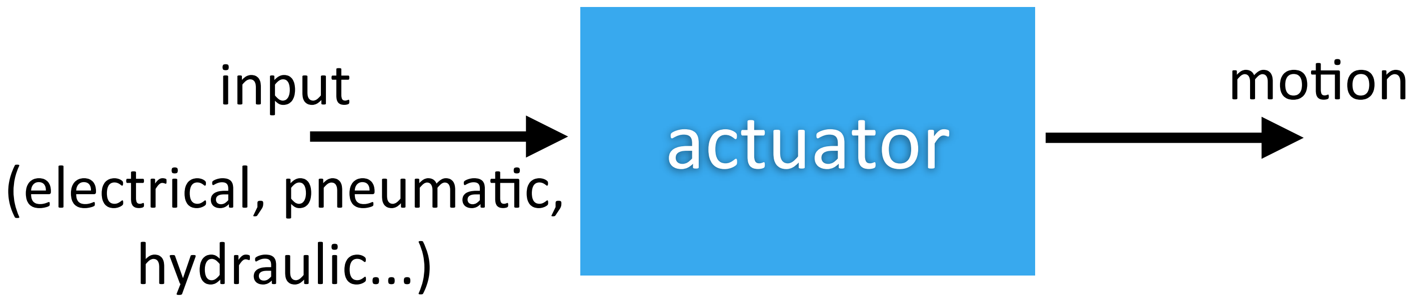


machine

Key definitions

Actuator

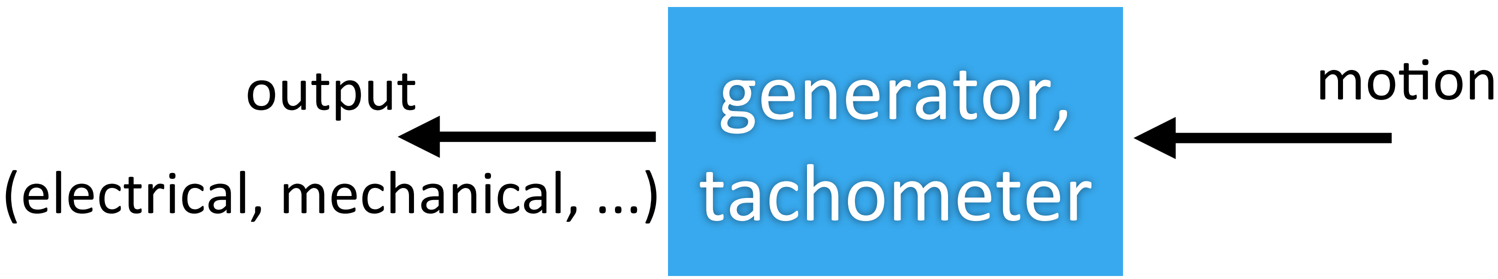
A mechanical device to move or control a mechanism or system, which converts a source of energy into some kind of motion (transducer).



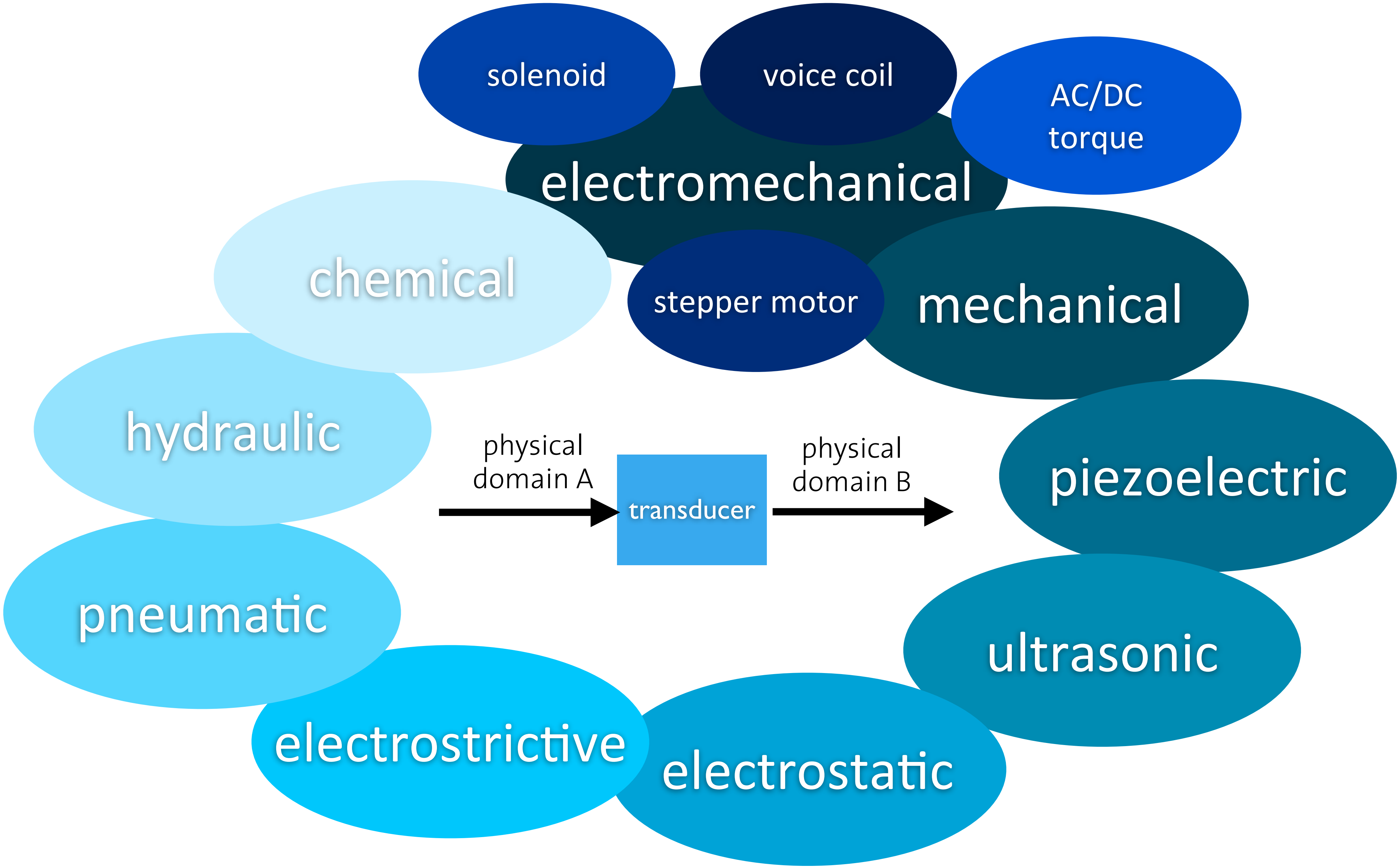
Key definitions

Actuator

A mechanical device to move or control a mechanism or system, which converts a source of energy into some kind of motion (transducer).

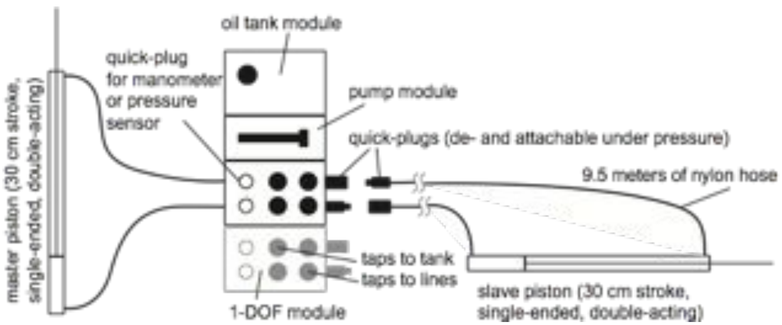


Actuation principles



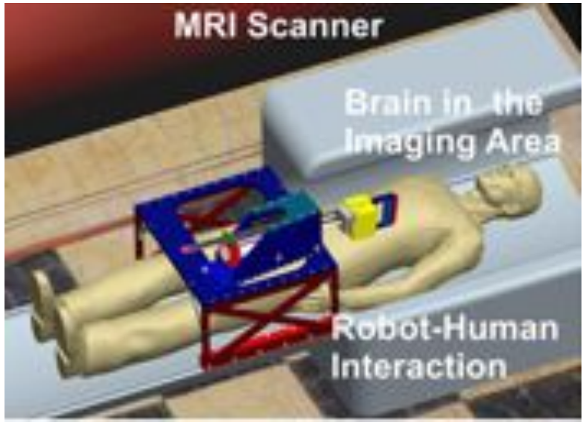
Hydraulic and Pneumatic Actuation

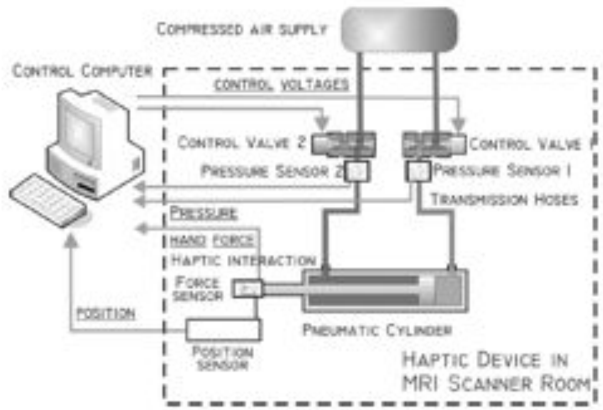
Hydraulic Actuation



Gassert et al., 2006.

Pneumatic Actuation





Yu et al., 2008.

Advantages:

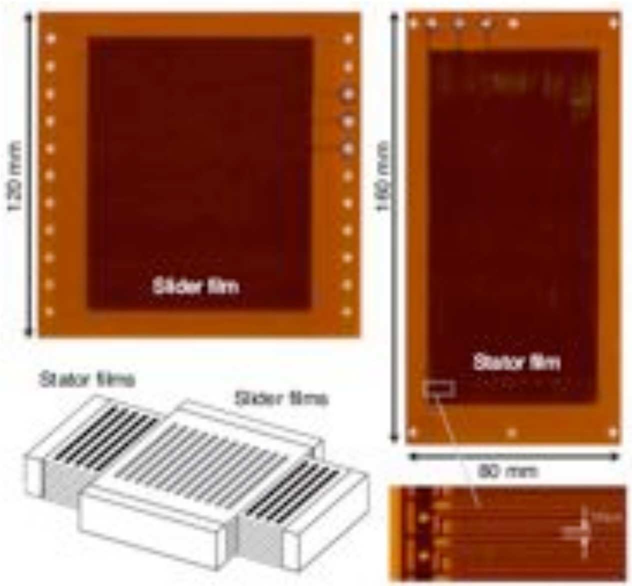
- high power density
- electromagnetic decoupling
- high flexibility of the transmission (hoses)

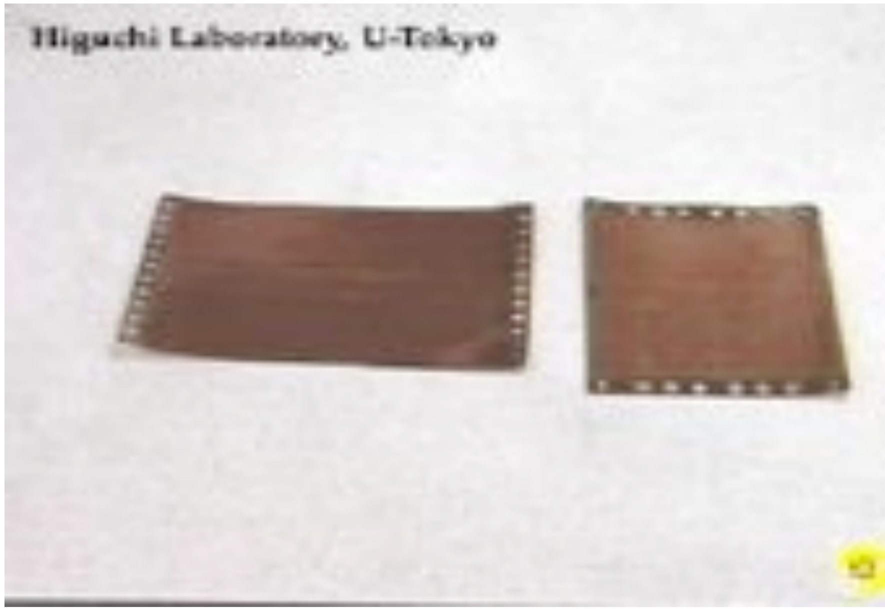
Disadvantages:

- high Inertia (long hoses)
- limited bandwidth (air and oil compressibility)
- friction in the cylinders and transmission system
- oil leakage
- nonlinear, difficult to control

Electrostatic Actuator

- based on the attraction and repulsion of electric charge
- synchronous linear motor driven by a three-phase AC high voltage source (2kV peak-to-peak)
- consists of a pair of films that are equipped with three-phase electrodes (interval of ~200 μm)
- actuation over traveling electrostatic fields
- ~100 Hz bandwidth, ~18 N output force at 2.4 kV (stacked setup on right)
- weak point: high voltage power electronics

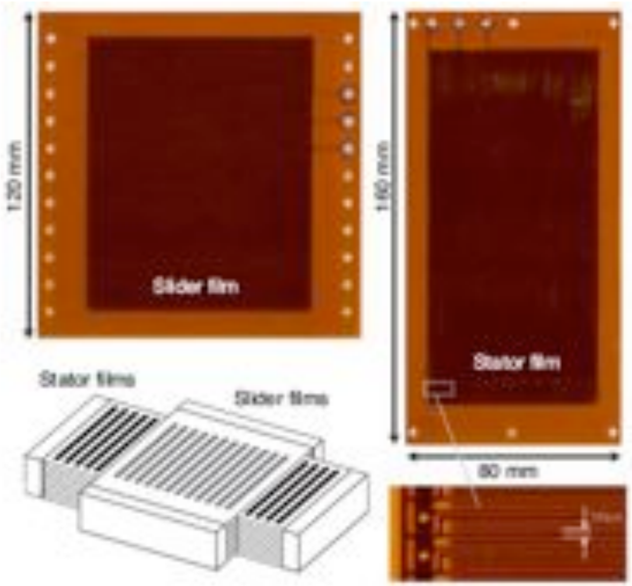




A Yamamoto et al. Evaluation of MR-Compatibility of Electrostatic Linear Motor.
Proc. IEEE International Conference on Robotics and Automation (ICRA), 2005.

Electrostatic Actuator

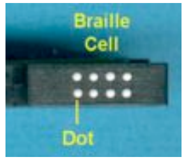
- based on the attraction and repulsion of electric charge
- synchronous linear motor driven by a three-phase AC high voltage source (2kV peak-to-peak)
- consists of a pair of films that are equipped with three-phase electrodes (interval of ~200 µm)
- actuation over traveling electrostatic fields
- ~100 Hz bandwidth, ~18 N output force at 2.4 kV (stacked setup on right)
- weak point: high voltage power electronics

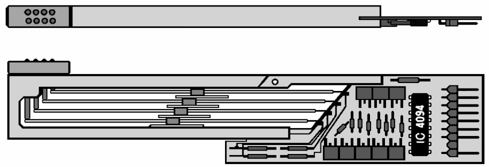


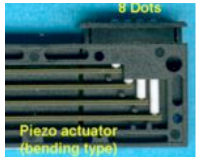
A Yamamoto et al. Evaluation of MR-Compatibility of Electrostatic Linear Motor.
Proc. IEEE International Conference on Robotics and Automation (ICRA), 2005.

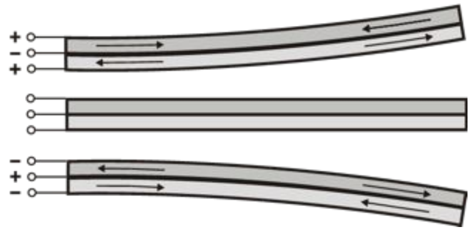
Ultrasonic and Piezoelectric Actuators

- **Piezoelectric actuator**
  - based upon the change in shape of a piezoelectric material when an electric field is applied
  - bimorph; inchworm

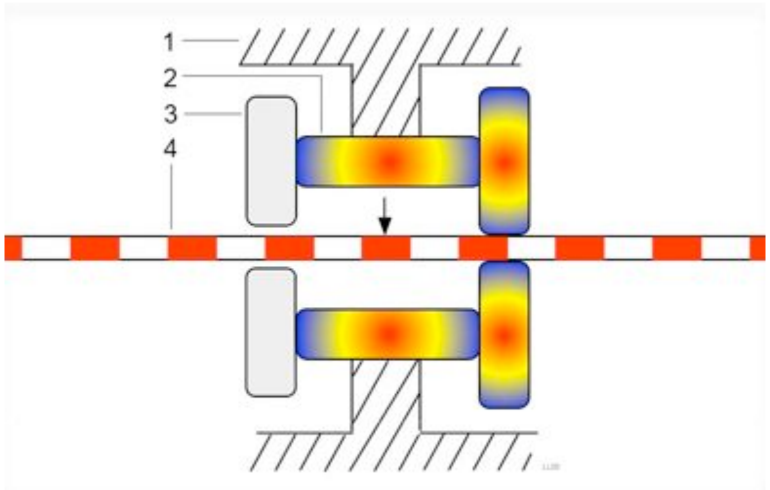


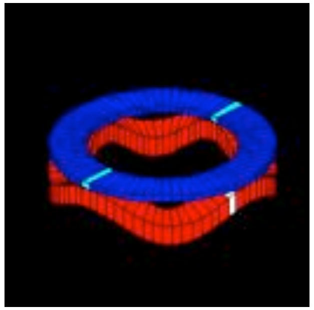


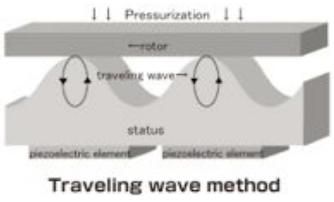




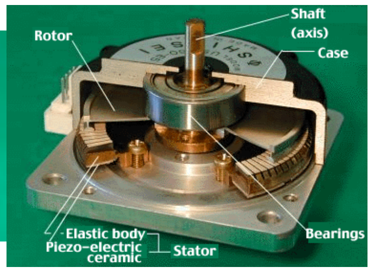
- **Ultrasonic motor**
  - uses resonance to amplify the vibration of the stator in contact with the rotor
  - operate up to 50 MHz → vibrations of only a few nanometers in magnitude







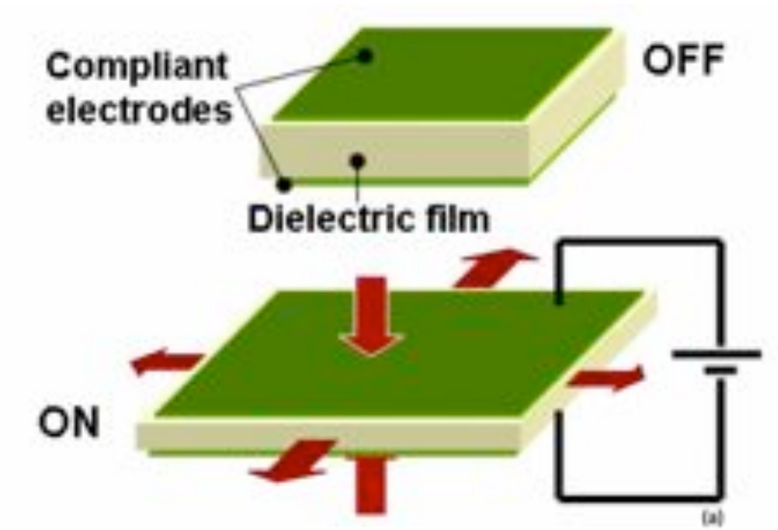
Shinsei Kogyo – S,M,L



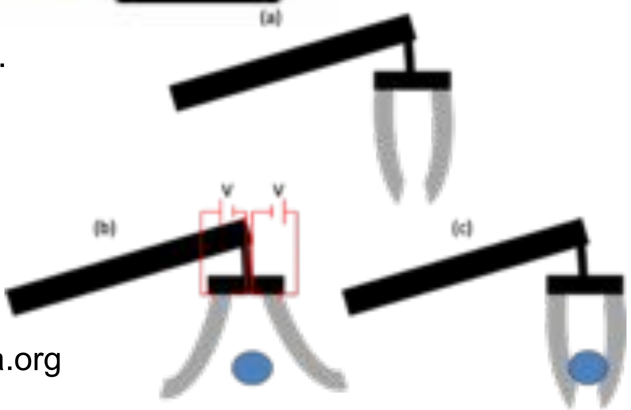
Linear sliders – PMT, Piezo-Tech, Canon Precision

Electroactive Polymers (EAP)

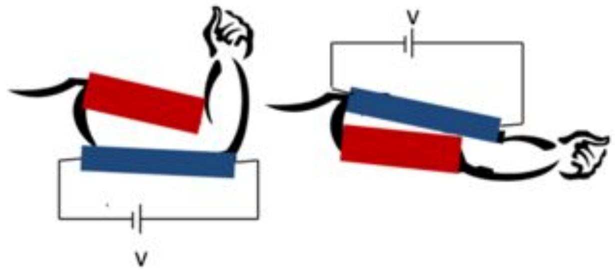
- polymers that exhibit a change in size or shape when stimulated by an electric field
- dielectric elastomer with compliant electrodes on both sides
- shrinks in thickness and expands in area when high DC voltage (typically 1 kV) is applied over electrodes
- undergo a large amount of deformation (up to a 380% strain) while sustaining large forces
- binary actuation
- “digital mechatronics”



Vogan et al. ICRA, 2004.



http://wikipedia.org



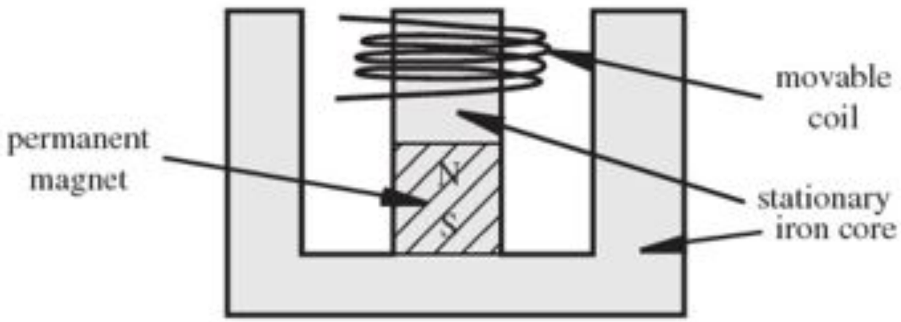
EAP Arm wrestling with human – NASA-JPL

Voice Coils

- consist of a coil that moves in a magnetic field produced by a permanent magnet and intensified by an iron core

$$F \approx I^2$$

- the coil is usually attached to a movable load such as the diaphragm of an audio speaker, the spool of a hydraulic proportional valve, or the read-write head of a computer disk drive



Computer hard-drive track finding
super-slow-motion video

DC Motors

- **General characteristics**
  - used in a most mechatronic designs
  - highly controllable
  - reversible
  - high ratio of torque to rotor inertia
- **Categories**
  - permanent magnet
  - shunt wound
  - series wound
  - compound wound
- **Brushed DC motor**
  - generates torque from DC power using internal commutation, stationary magnets and rotating electrical magnets
  - **advantages**: low initial cost, reliable, simple control of motor speed
  - **disadvantages**: high maintenance, low life span

- **Brushless DC motor**
  - uses a rotating permanent magnet and stationary electrical magnets on the motor housing.
  - has electronic commutation systems, rather than mechanical commutators and brushes
  - **advantages**: long life span, little or no maintenance, high efficiency
  - **disadvantages**: high initial cost, inertia, torque cogging

ETHZ Haptic Paddle

Tutorial Hardware

ETHZ Haptic Paddle

Maxon RE25 brushed DC motor

			302534	339149	339150	339151	339152	339153	339154	33915	339156	339157	339158
Motor Data													
	Values at nominal voltage												
1	Nominal voltage	V	7.2	9	12	18	24	30	36	48	48	48	48
2	No load speed	rpm	10500	9700	9620	10400	10900	9200	10100	9540	8450	6720	4650
3	No load current	mA	133	93.2	68	50.6	40.2	25	23.7	16.4	13.7	9.89	6
4	Nominal speed	rpm	8830	8160	8240	9140	9620	7990	8840	8350	7260	5520	3420
5	Nominal torque (max. continuous torque)	mNm	20.2	22.8	26.2	28.1	28.8	30.8	30.3	31.3	32	32.6	32.5
6	Nominal current (max. continuous current)	A	3.4	2.79	2.33	1.79	1.42	1.03	0.917	0.673	0.608	0.491	0.339
7	Stall torque	mNm	259	238	268	297	304	265	279	270	243	192	127
8	Starting current	A	42.1	28.1	23.2	18.4	14.6	8.61	8.24	5.67	4.51	2.84	1.3
9	Max. efficiency	%	78.6	81.2	84.1	86.4	87.5	87.9	88.2	88.7	88.5	87.8	86.3
	Characteristics												
10	Terminal resistance	Ω	0.171	0.32	0.517	0.98	1.64	3.49	4.37	8.47	10.6	16.9	36.8
11	Terminal inductance	mH	0.0163	0.0308	0.0573	0.112	0.186	0.407	0.493	0.979	1.25	1.97	4.11
12	Torque constant	mNm / A	6.15	8.46	11.5	16.1	20.8	30.8	33.8	47.7	53.8	67.7	97.6
13	Speed constant	rpm / V	1550	1130	828	591	460	311	282	200	177	141	97.8
14	Speed / torque gradient	rpm / mNm	43.2	42.8	37.1	35.9	36.3	35.2	36.5	35.6	35.1	35.2	36.9
15	Mechanical time constant	ms	6.52	6.06	5.62	5.36	5.26	5.17	5.16	5.13	5.12	5.12	5.14
16	Rotor inertia	gcm^2	14.4	13.5	14.5	14.3	13.8	14	13.5	13.8	13.9	13.9	13.3

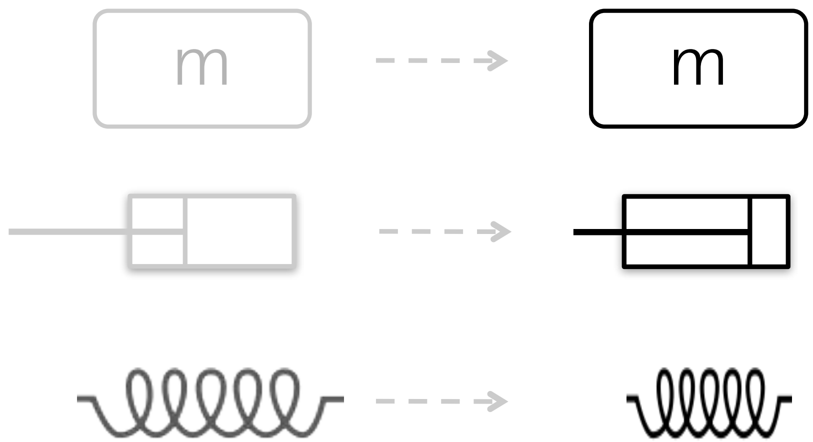
Transparency and Impedance

Mechanical Impedance

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

= high impedance

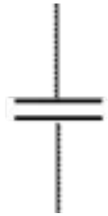
Analogy – Electrical Impedance

frequency-dependent resistance

Resistor:

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

Capacitor:



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

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

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

Inductance:

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

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

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

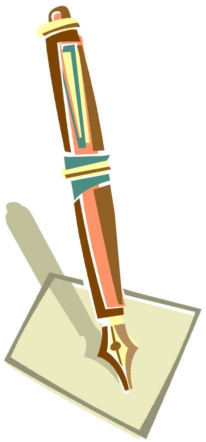
Z-Width

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)

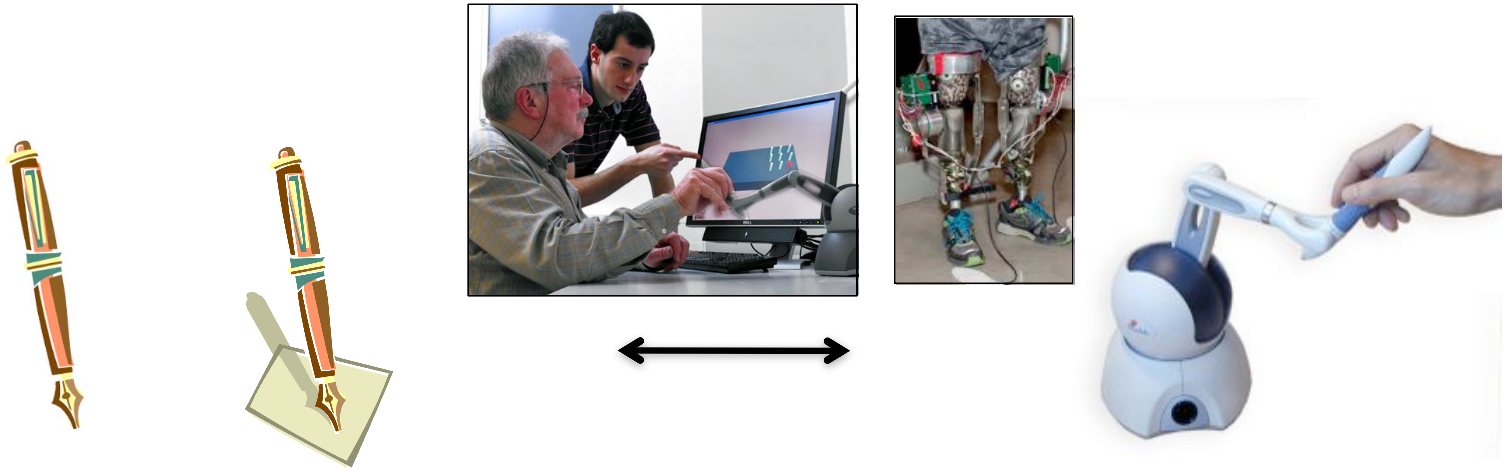
Z → ∞; **Y** →0

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

→ large force f results in a small motion

Z-Width:
Dynamic range of achievable impedances

The "Ultimate" Multi-Purpose 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 saturation and system stability

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

Impedance Rendering

Transparency:
the ability of the device to get out of the way, to mimic free interaction with air

Impedance accuracy:
how close the apparent impedance (felt impedance) matches that of the virtual environment (desired impedance)

Impedance fidelity:
resolution – level of impedance discrimination that can be rendered at the haptic interface (limited by the natural dynamics of the device)

Transmissions/Kinematics

- S.P. Buerger. Stable, High-Force, Low-Impedance Robotic Actuators for Human-Interactive Machines. PhD Thesis, Massachusetts Institute of Technology, 2005.
- H. Vallery, J. Veneman, E. van Asseldonk, R. Ekkelenkamp, M. Buss and H. van der Kooij, Compliant Actuation of Rehabilitation Robots - Benefits and Limitations of Series Elastic Actuators, IEEE Robotics and Automation Magazine, 15(3): 60-69, 2008.
- Tucker, M. and Gassert R. Differential-Clutch Topology for Actuators in Rehabilitation Robotics. Proc. IEEE Engineering in Medicine and Biology Conference (EMBC), 2012.

Robot Kinematics

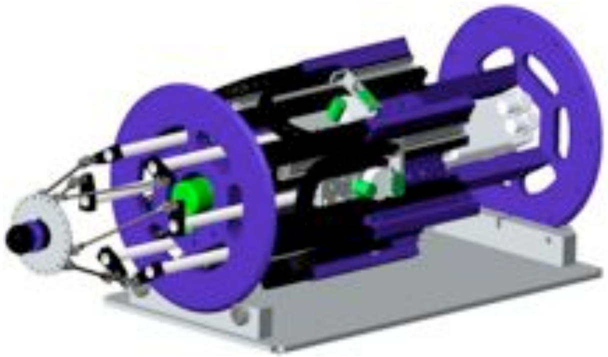
Force Dimension omega.7

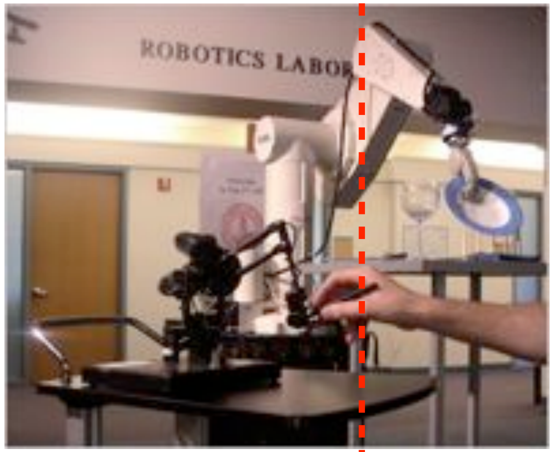
- serial kinematics
- errors add up
- large workspace
- reduction gears (high inertia and friction)

- parallel kinematics
- low inertia
- error averaging
- grounded direct drives

- interaction with human motion
- teleoperation or rendering of virtual environment
- impedance/admittance/force controlled

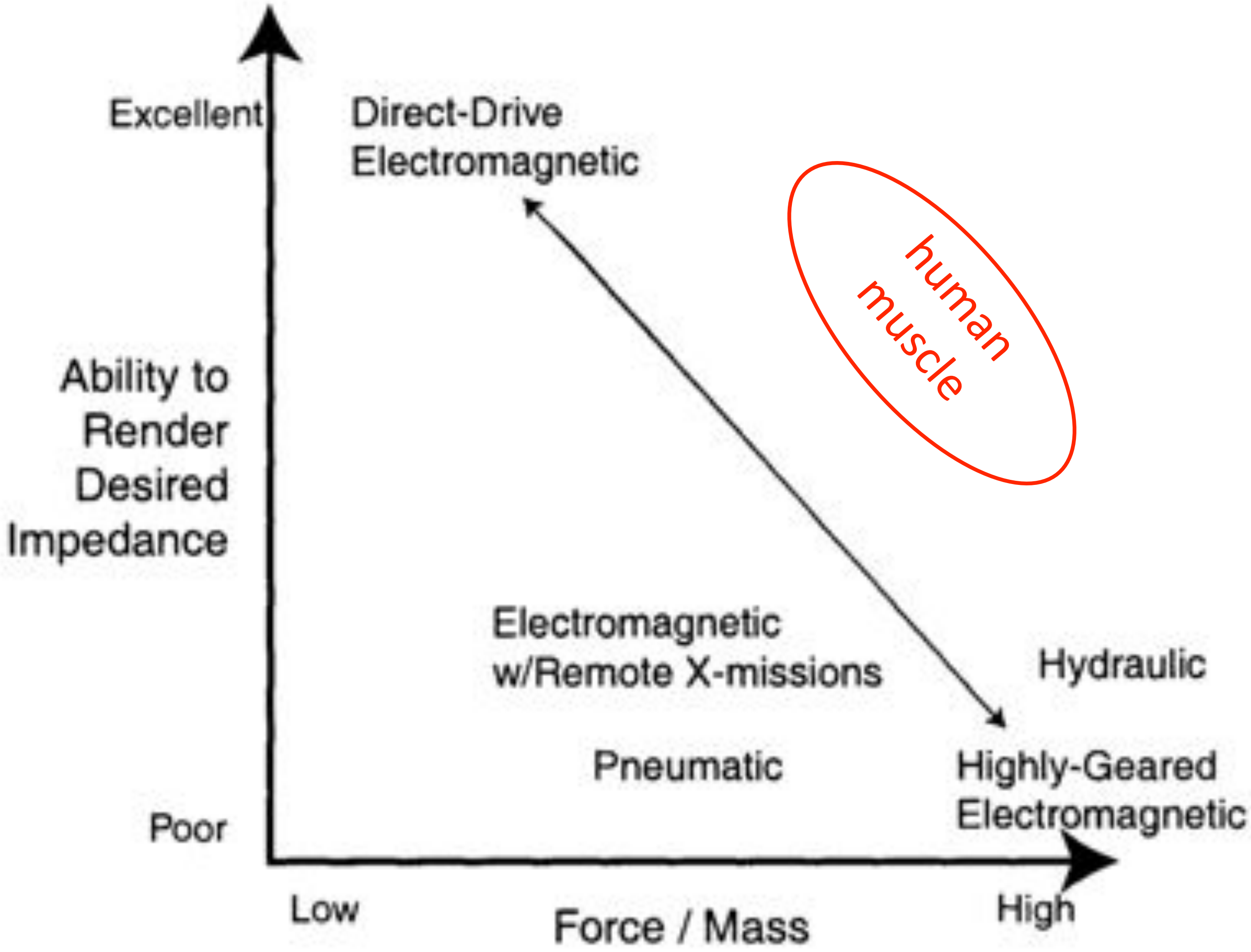
Admittance vs Impedance Type Displays





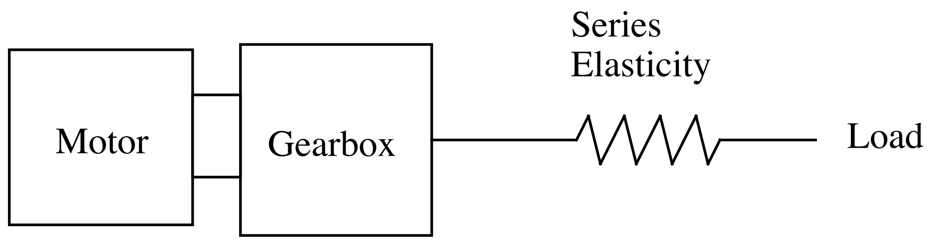
http://haptic.mech.northwestern.edu/intro/gallery/

Force-Controllability



S.P. Buerger. Stable, High-Force, Low-Impedance Robotic Actuators for Human-Interactive Machines. PhD Thesis, Massachusetts Institute of Technology, 2005.

Series Elastic Actuators

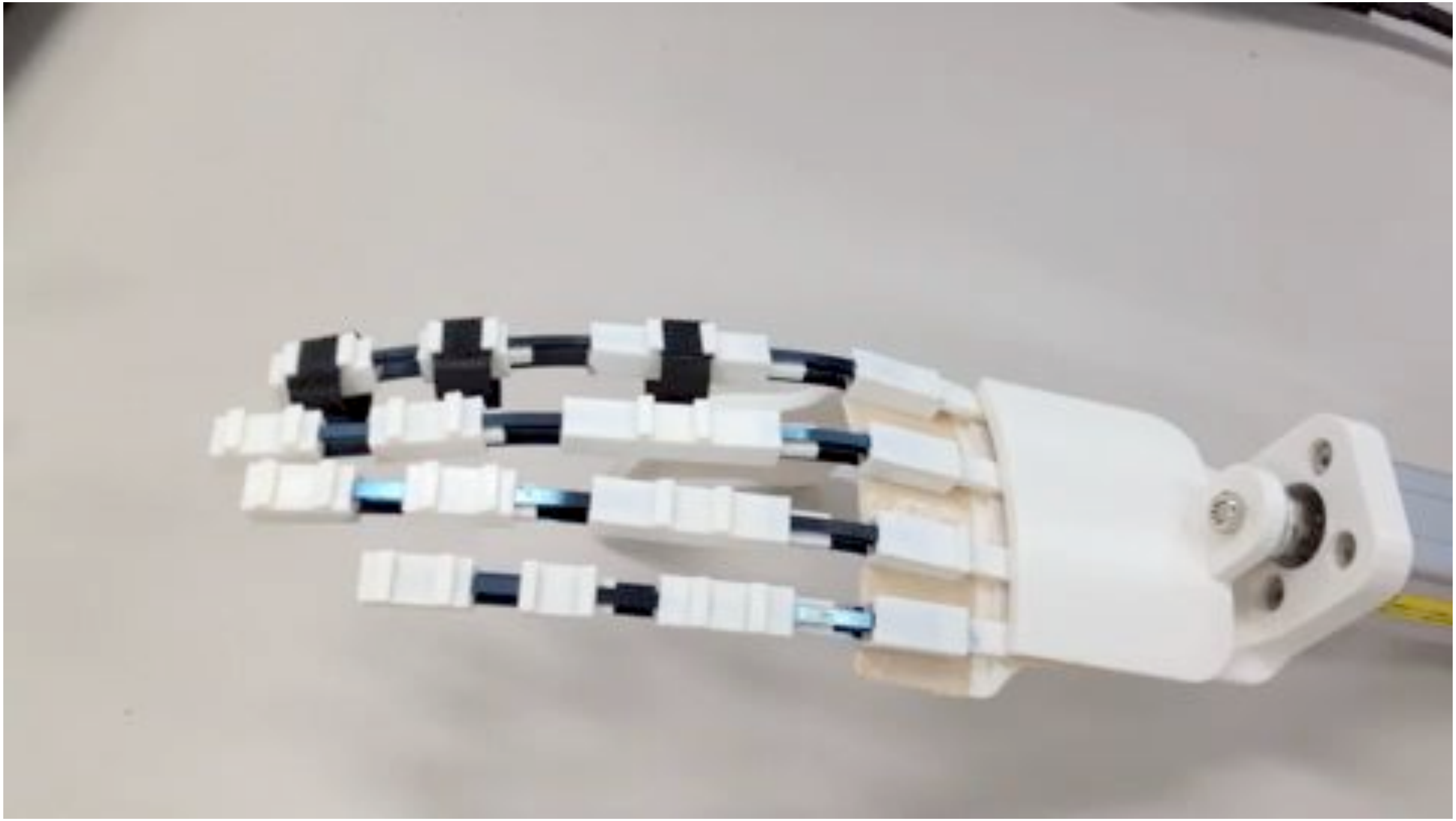


- spring mounted in series to **decouple** high-impedance output of motor-gearbox assembly and improve force controllability

+ protect gears from high impact loads and permit storage of energy in elastic element
+ minimize reflected mass of the actuator
+ improve closed-loop force control performance by trading (possibly unnecessary) high-force bandwidth for improved low-impedance performance

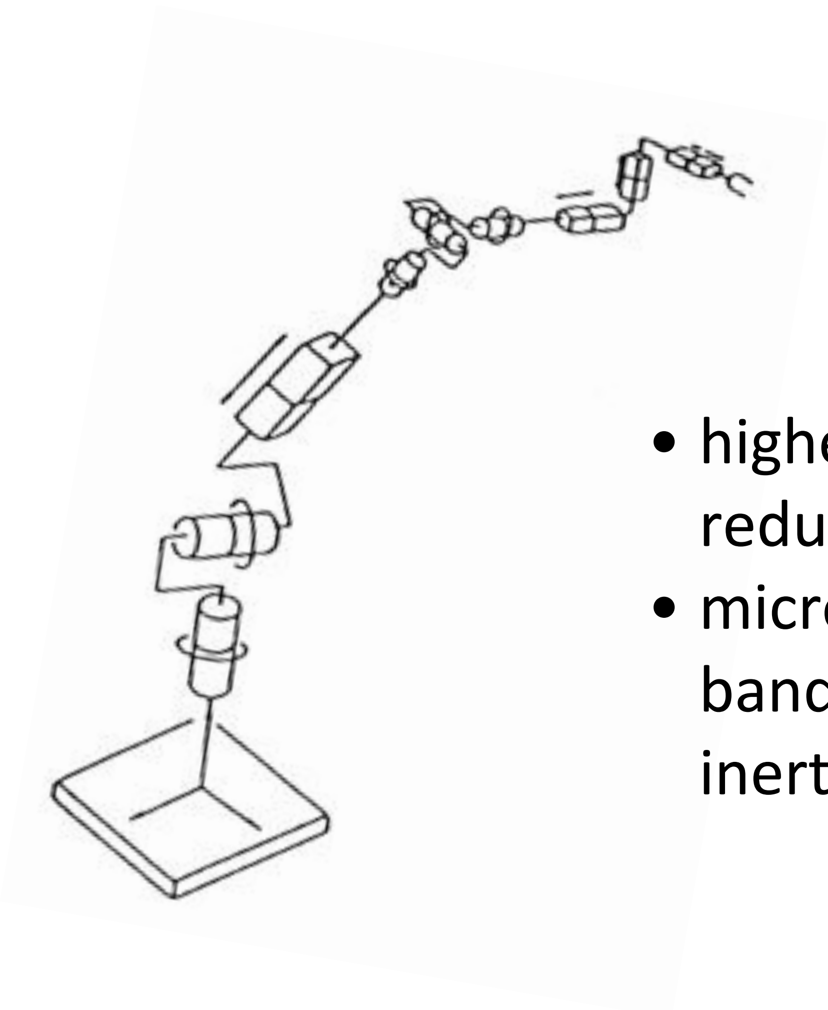
- output stiffness limited by that of elastic element (to preserve passivity)
- reduced bandwidth

Flexible Elements



Collaboration with Prof. Jumpei Arata, Nagoya Institute of Technology, Japan
Arata et al., Robomec 2012

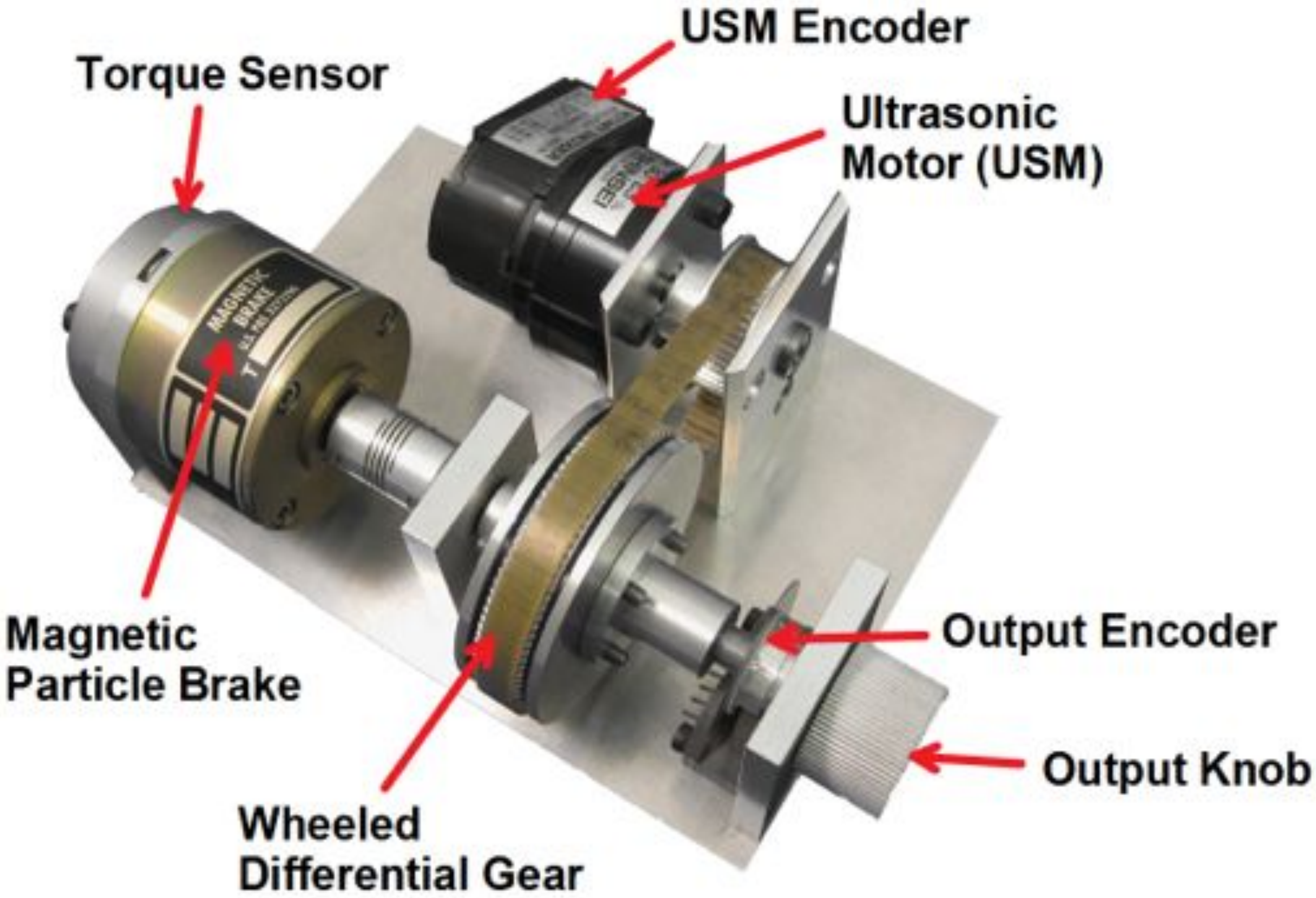
Macro-Micro Approach



- higher dexterity through increased redundancy
- micro-structure increases bandwidth and reduces apparent inertia

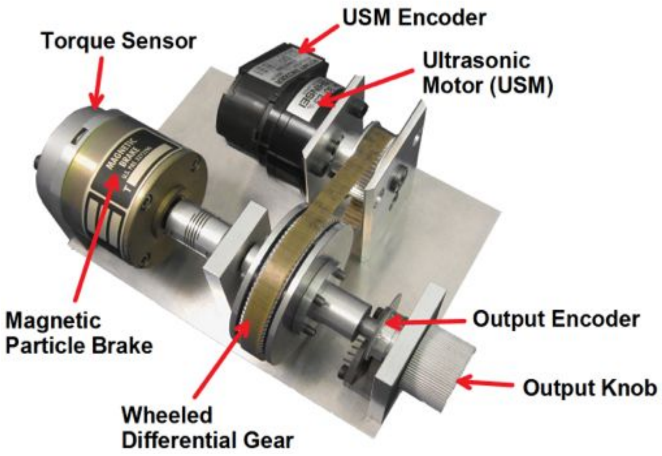
Khatib O., Reduced Effective Inertia in Macro-/Mini-Manipulator Systems, Robotics Research, no. 5, pp. 329-334, 1990

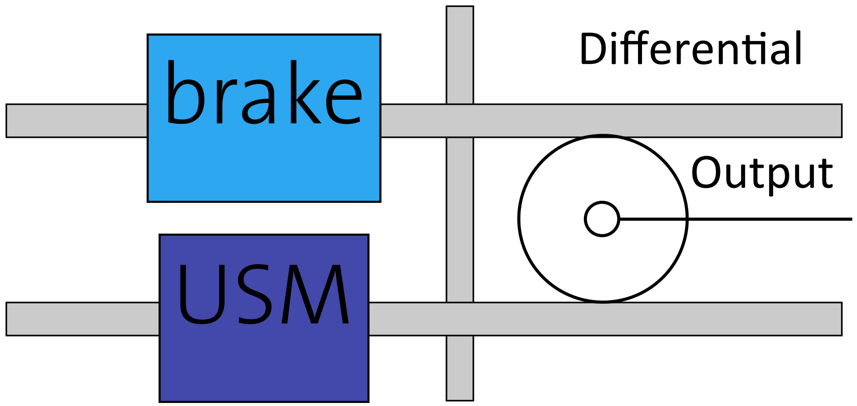
Hybrid ultrasonic motor and clutch actuator – HUCA

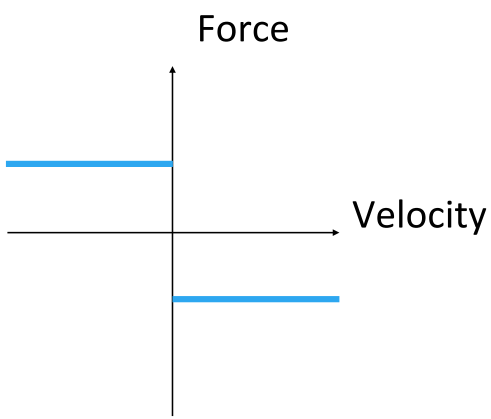


Chapuis et al, World Haptics 2007

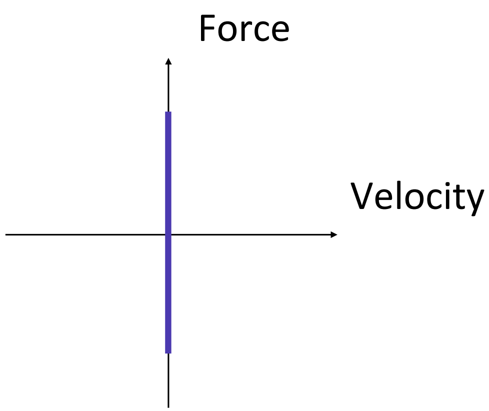
Hybrid ultrasonic motor and clutch actuator – HUCA



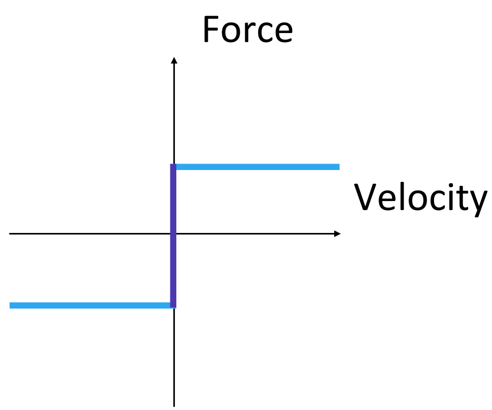




Brake output



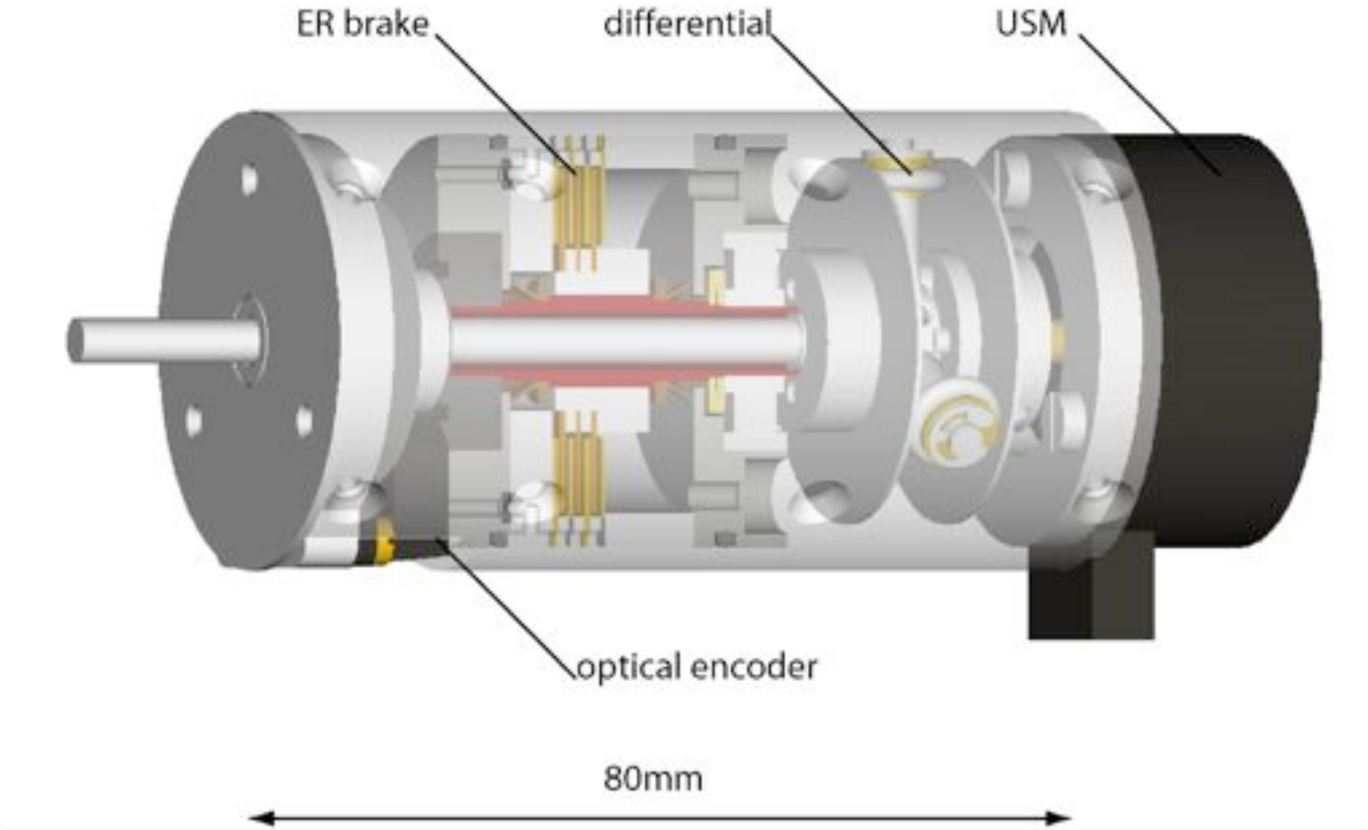
USM output



Combined output

Chapuis et al, World Haptics 2007

Hybrid ultrasonic motor and clutch actuator – HUCA

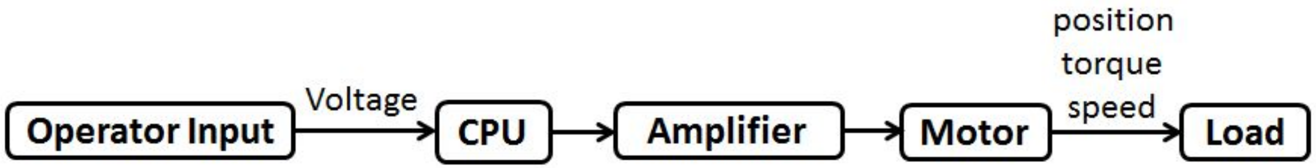


Chapuis et al, EMBC 2008

Control for pHRI

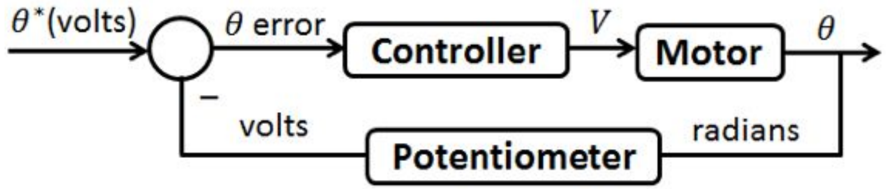
Open Loop vs. Feedback Control

Open loop control (output does not affect input) – imprecise due to load and friction

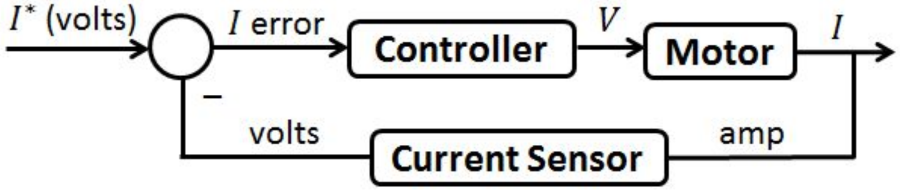


Feedback control (measure output and feed back to input)

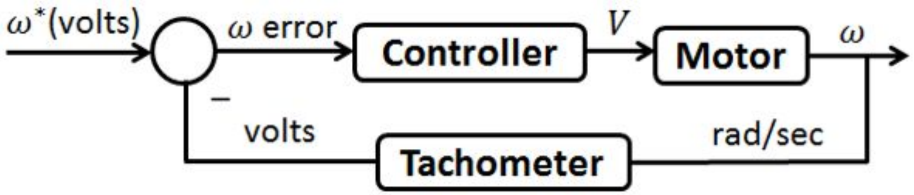
- position control (potentiometer, optical encoder, hall effect sensor)



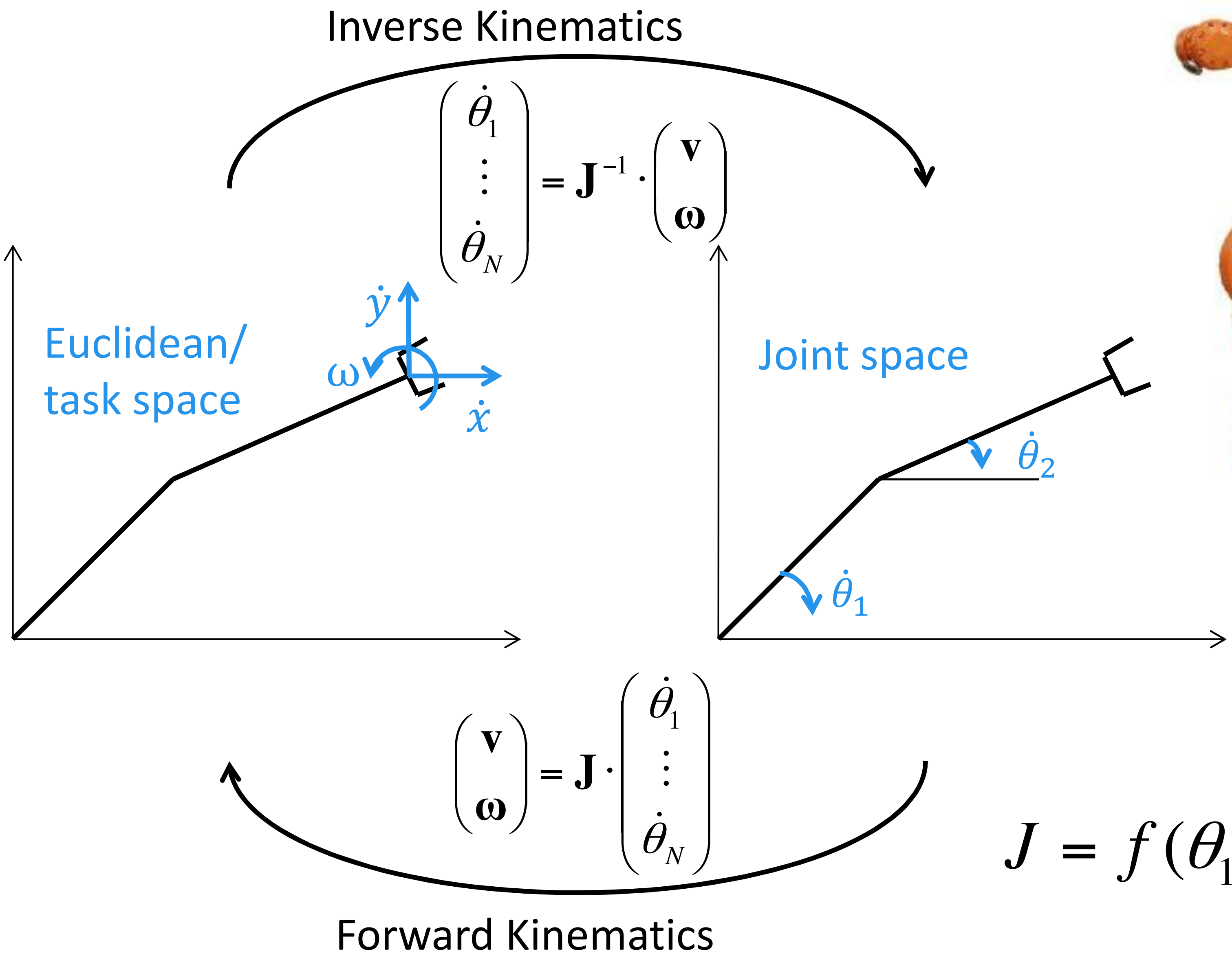
- torque control (current sensor)



- velocity control (optical encoder or tachometer)



Jacobian



$$\begin{pmatrix} \dot{\theta}_1 \\ \vdots \\ \dot{\theta}_N \end{pmatrix} = \mathbf{J}^{-1} \cdot \begin{pmatrix} \mathbf{v} \\ \boldsymbol{\omega} \end{pmatrix}$$

$$\begin{pmatrix} \mathbf{v} \\ \boldsymbol{\omega} \end{pmatrix} = \mathbf{J} \cdot \begin{pmatrix} \dot{\theta}_1 \\ \vdots \\ \dot{\theta}_N \end{pmatrix}$$

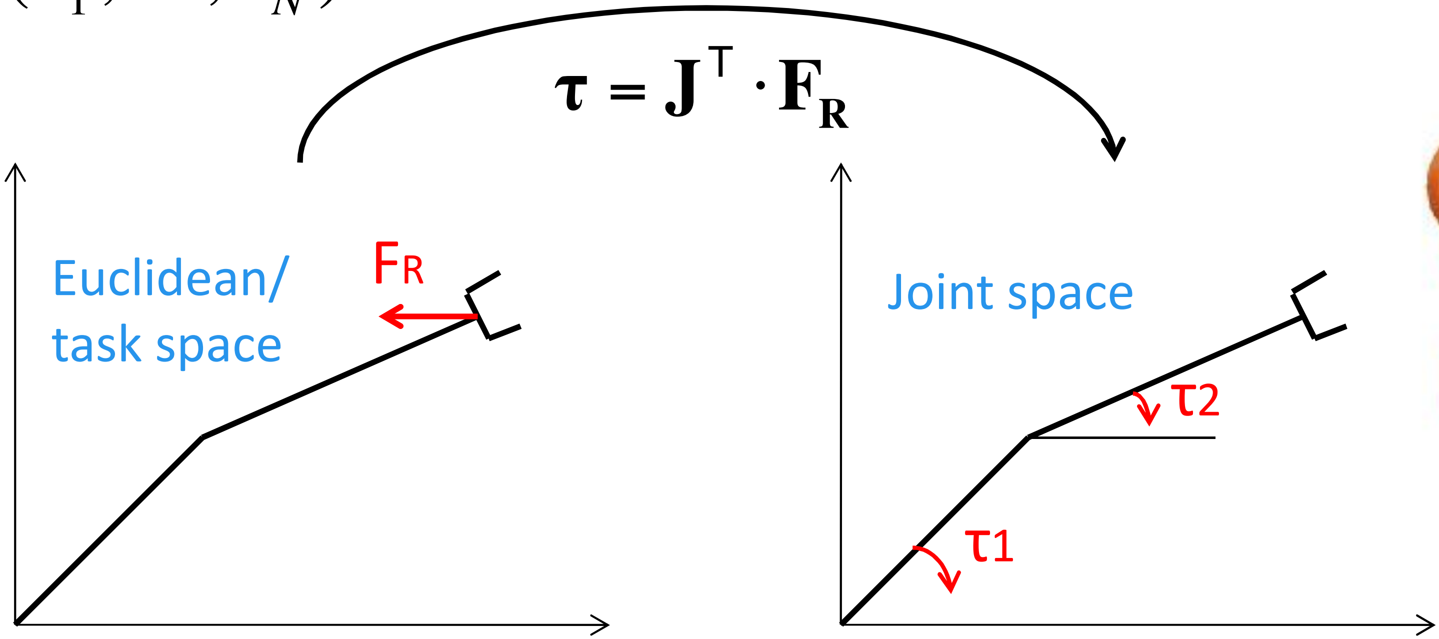
$$J = f(\theta_1, \ldots, \theta_N)$$

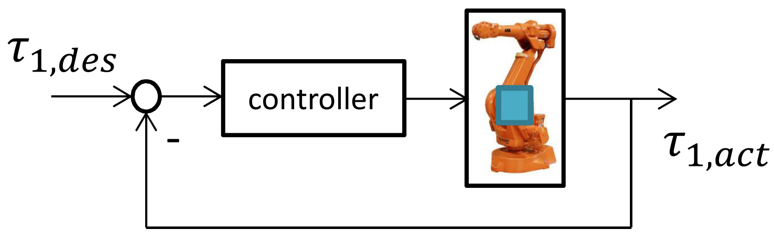
Static Force Torque Relationship

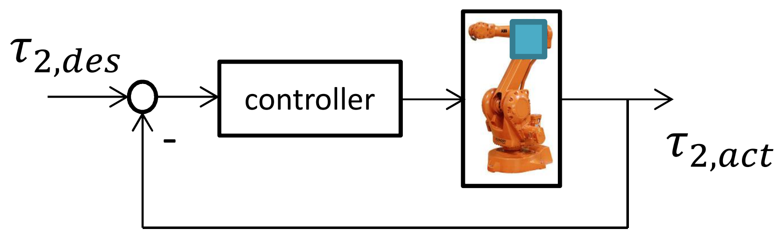
$$J = f(\theta_1, \ldots, \theta_N)$$

Inverse Kinematics

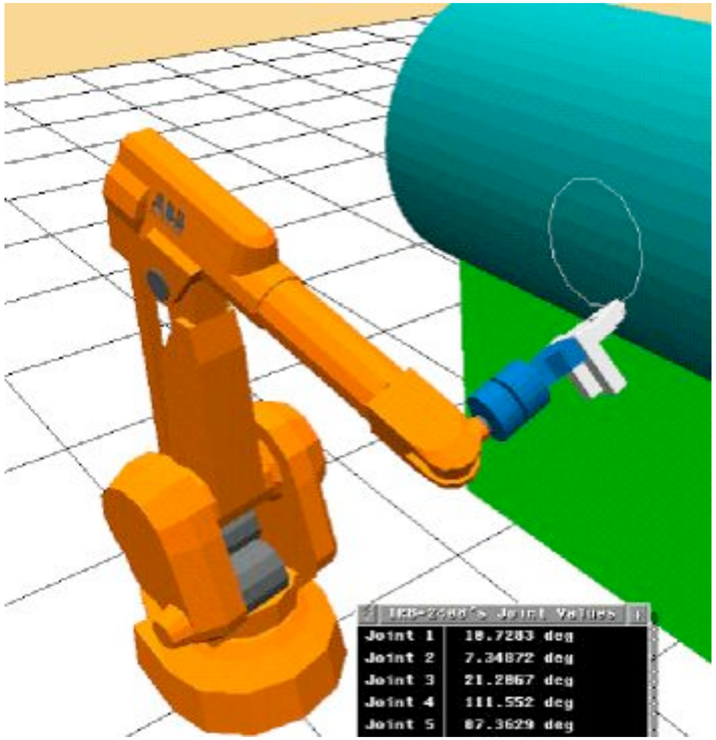
$$\boldsymbol{\tau} = \mathbf{J}^{\mathsf{T}} \cdot \mathbf{F_R}$$





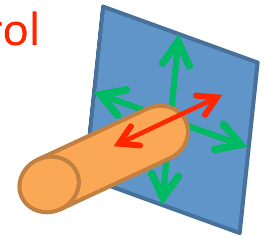


Position Control vs. Force Control



Hybrid position and force control

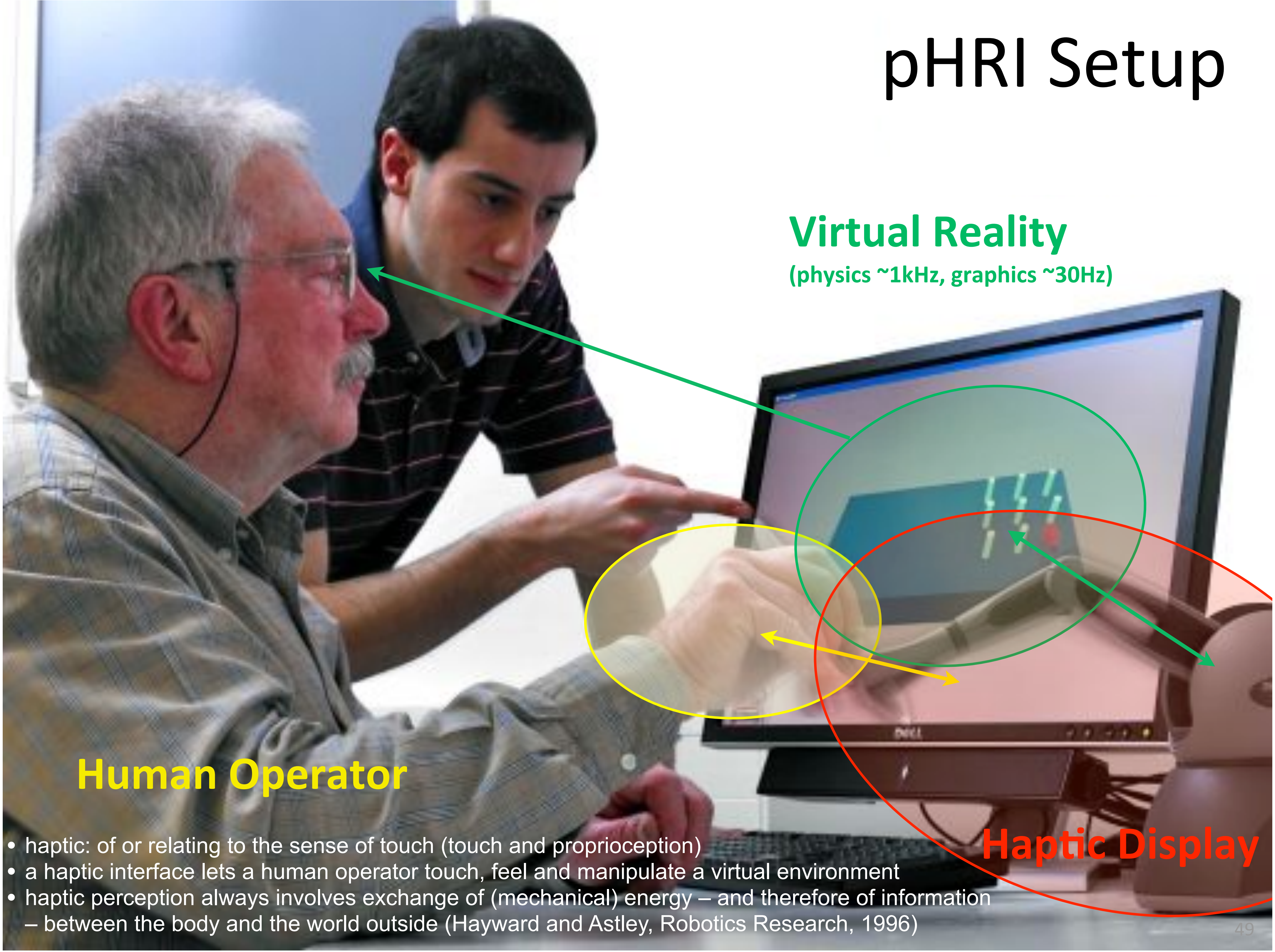
Force control (normal)



Position control (tangential)

Force/Impedance control for robotic manipulators, Nagarkatti and Dawson, 2005

pHRI Setup



- haptic: of or relating to the sense of touch (touch and proprioception)
- a haptic interface lets a human operator touch, feel and manipulate a virtual environment
- haptic perception always involves exchange of (mechanical) energy – and therefore of information – between the body and the world outside (Hayward and Astley, Robotics Research, 1996)

pHRI Setup WYDINWYF

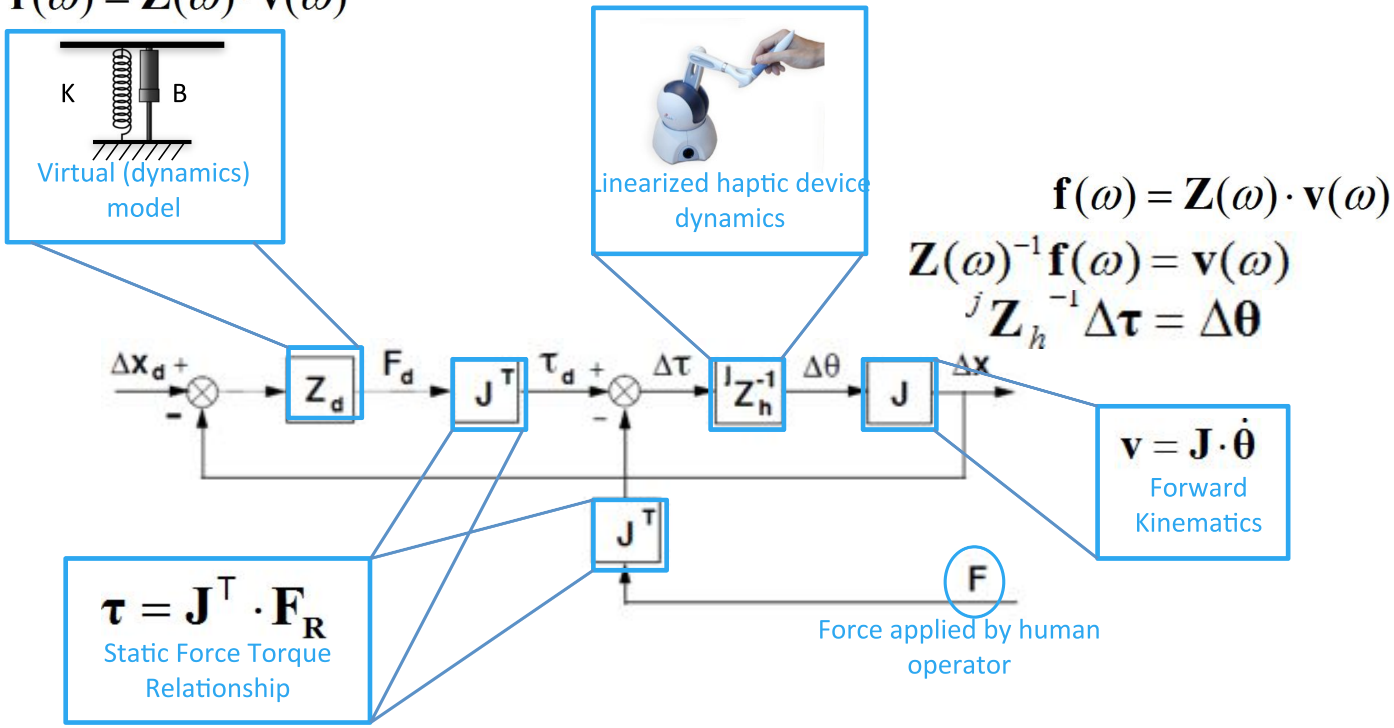
Virtual Reality + **Device dynamics**
(inertia, friction)

- WYDINWYF: what you display is not what you feel

(Open-loop) Impedance Control

$F_d = (x - x_d) * K + \dot{x} * B$

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



$\Delta\tau$ torque difference, $\Delta\theta = \theta_k - \theta_{k-1}$ “speed”, $\Delta x = x_k - x_{k-1}$ “speed”

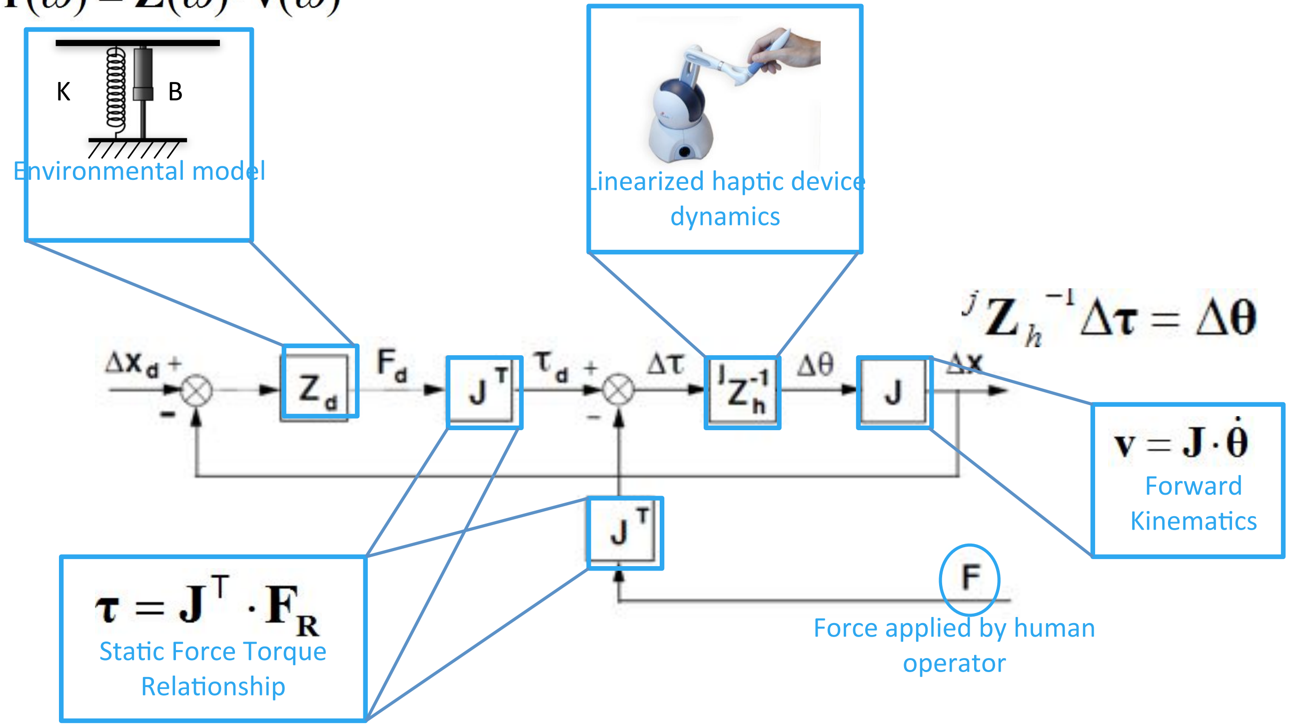
apparent dynamics = virtual dynamics + device dynamics

(what the human operator feels) (friction, gravity, inertia)

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

(Open-loop) Impedance Control

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



$$\Delta x_d = 0$$

$$\Delta x = Z_h^{-1}[Z_d(\Delta x_d - \Delta x) - F]$$

$$[Z_h + Z_d]\Delta x = -F$$

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

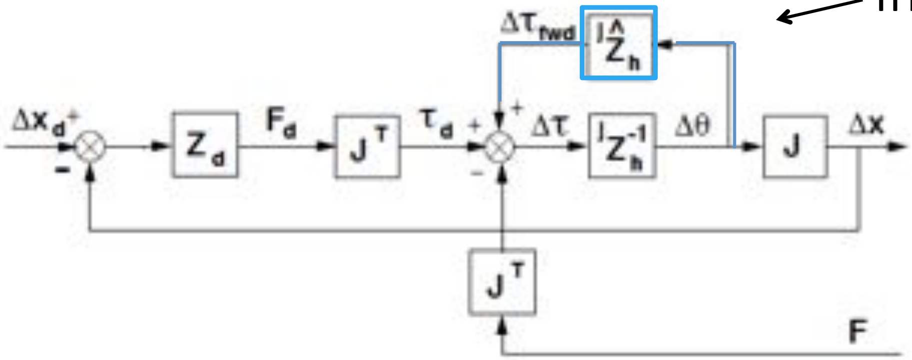
$\Delta\tau$ torque difference, $\Delta\theta = \theta_k - \theta_{k-1}$ "speed", $\Delta x = x_k - x_{k-1}$ "speed"

Impedance control: detect *motion* command by the operator and control the *force* applied by the haptic device

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

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

(Open-Loop) Impedance Control with Model Feedforward



friction and gravity compensation

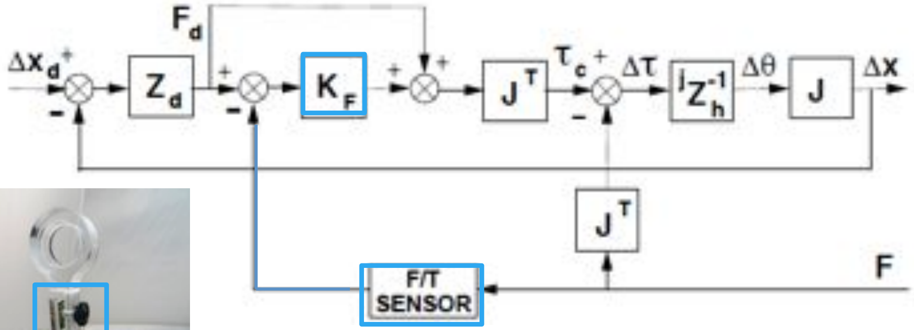
$$[Z_d + Z_h - \hat{Z}_h]\Delta x = -F$$

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

- modeling errors
- increased computational load → lower loop rates → compromise maximal stiffness

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

Impedance Control with Force Feedback



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

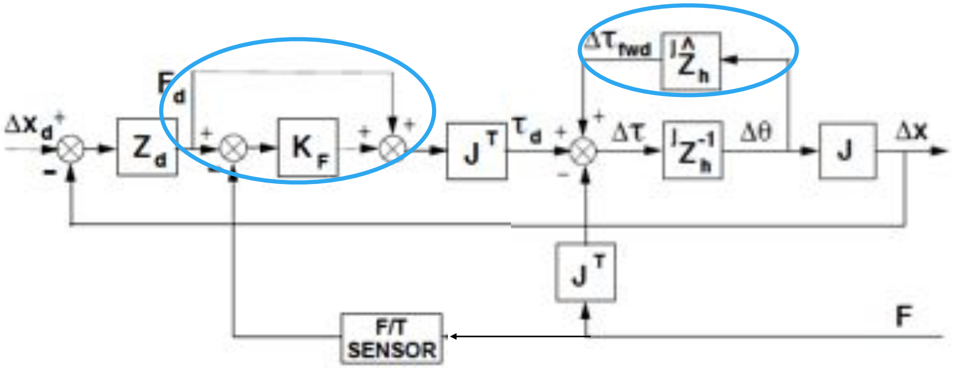
$K_F=0$ → Z_h
(Open loop case)

K_F big → 0
(stability!)

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

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

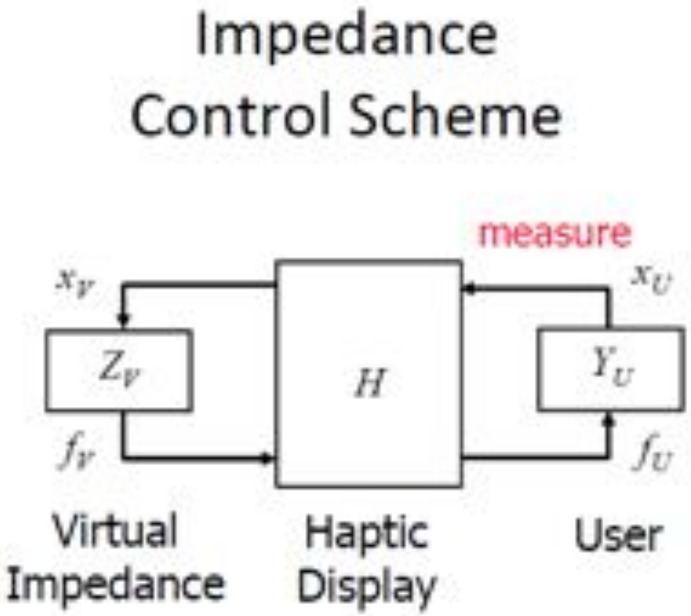
Closed-loop force control for haptic simulation of virtual environments, Carignan and Cleary, 2000

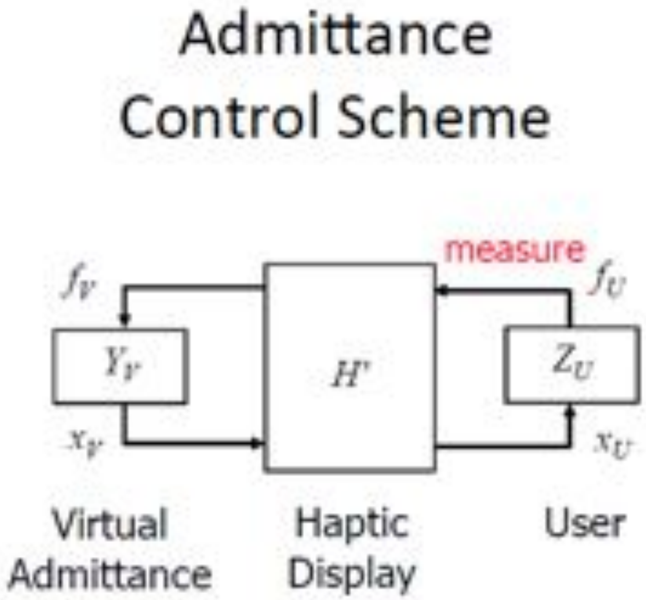


Impedance control with force feedback and model feedforward

→ Smaller feedback error → larger force control gain possible

Haptic Control Schemes Compared





motion command by user
→ *force* applied by haptic device

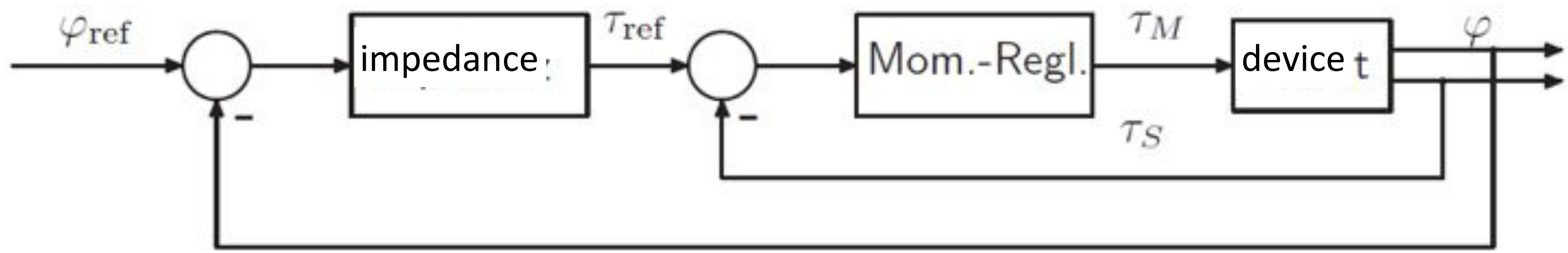
force command by user
→ control *motion of* haptic device

$$m\ddot{x} = F_{User} \rightarrow \ddot{x} = \frac{F_{User}}{m}$$

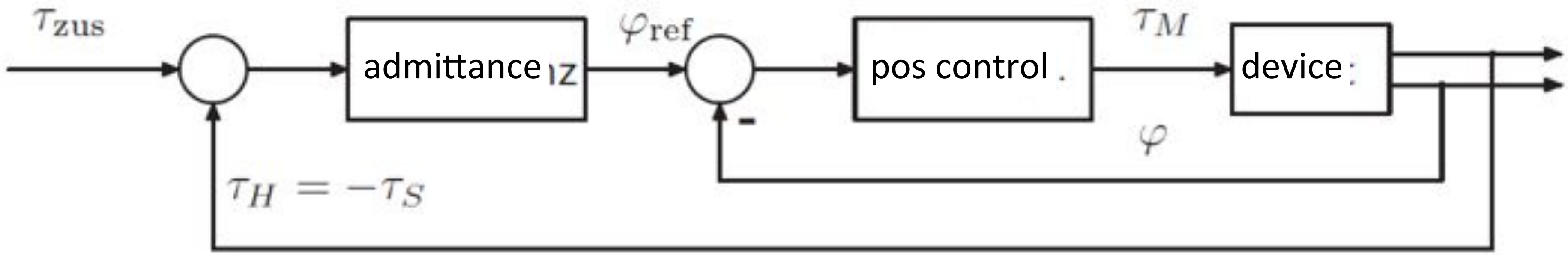
$$\rightarrow \dot{x} = \frac{1}{s}\ddot{x} \rightarrow \text{control } \dot{x}$$

Inner and Outer Loop Structure

Impedance control: *motion* command by operator → *force* applied by haptic device



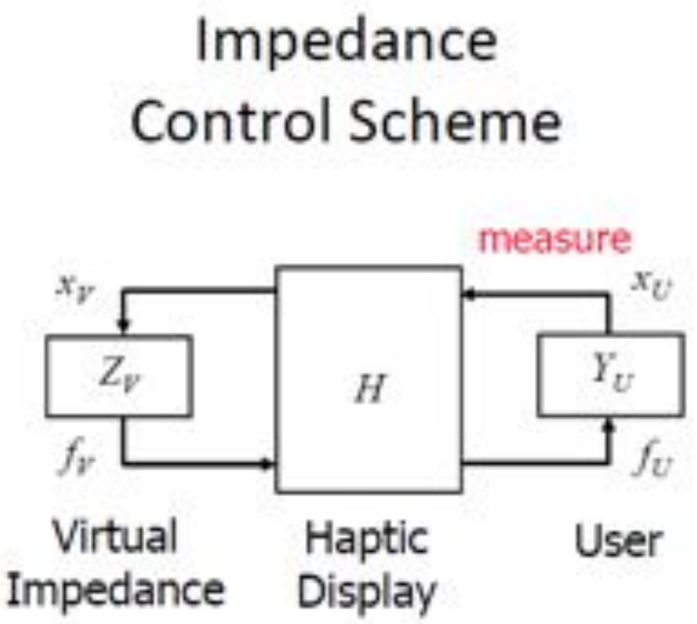
Admittance control: *force* command by operator → control *motion of* haptic device

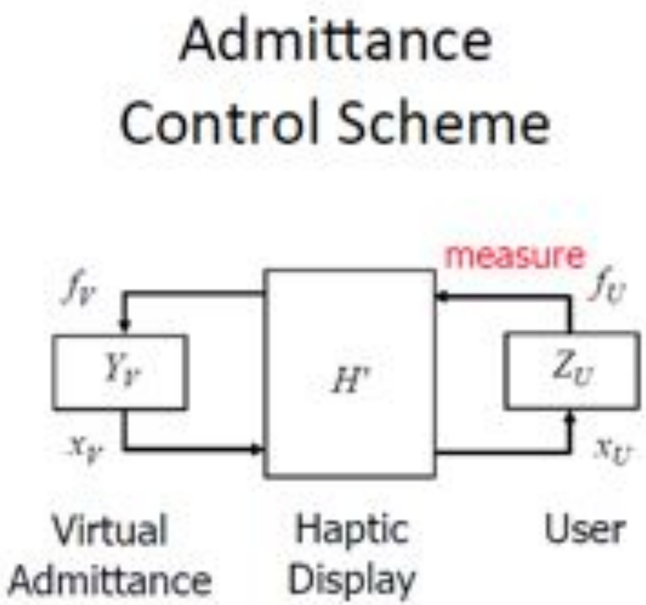


"forced dynamics" → force the virtual dynamic behavior with the position control over the (real) dynamic behavior of the device (inner loop of the admittance control)

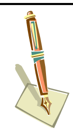
adapted from H. Vallery

Impedance vs Admittance Control





Low impedance device

stability	**effect**	**interaction behavior**	**effect**	**stability**
stable	small control gain	simulate "free air" 	large control gain	unstable
stable	Y_{obj} → 0 large contact force → small Δx	End-effector touchs physical object (Z → ∞; Y →0) 	Z_{obj} → ∞ small Δx → large force	unstable
unstable	large control gain	touch stiff virtual object 	small control gain	stable

High impedance device

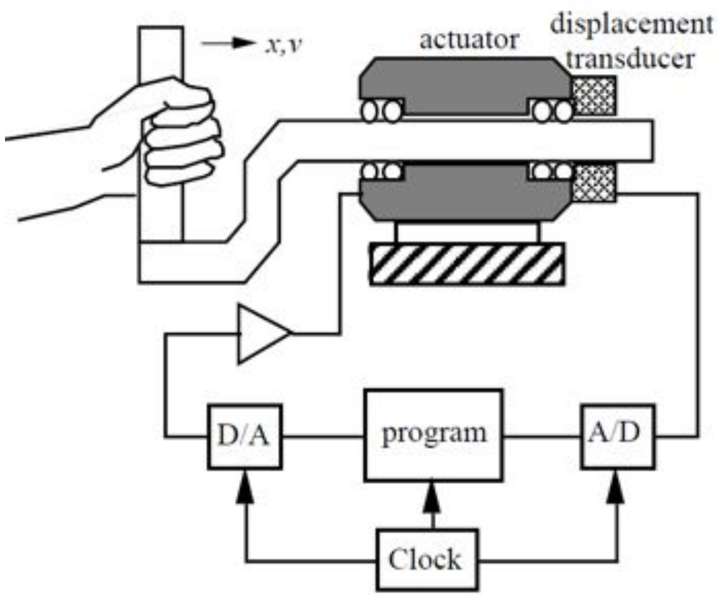
Some Comments on Stability

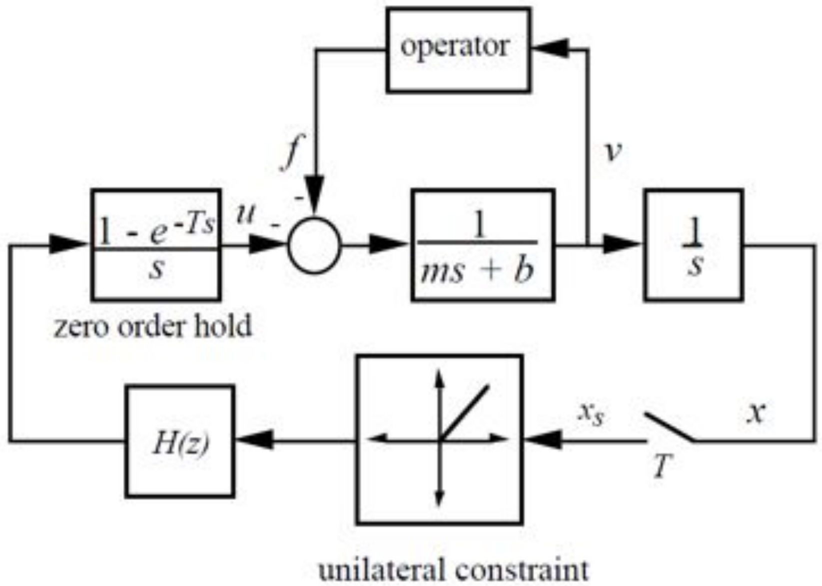
The main possible sources for stability problems of haptic devices:

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

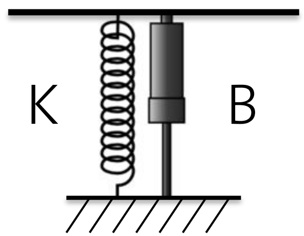
- *Factors Affecting the Z-Width of a Haptic Display*, J. Edward Colgate, J. Michael Brown, 1994
- *Passivity of a Class of Sampled-Data Systems: Application to Haptic Interfaces*, J. Edward Colgate, Gerd G. Schenkel, 1995
- *Stable Haptic Interaction with Virtual Environments*, R.Adams and B. Hannaford,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

1-DOF Haptic Interface





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



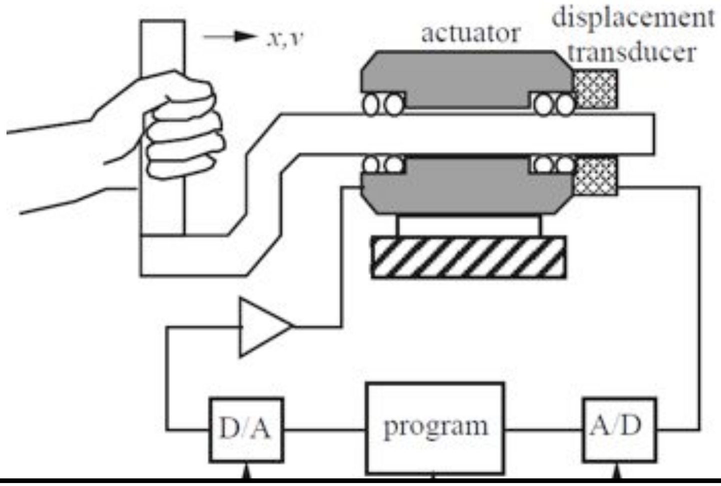
J. Colgate and M. Brown. Factors Affecting the Z-Width of a Haptic Display, 1994

m: inherent mass of the display
b: inherent damping
v: velocity
x: position
x_S: sampled position
T: sampling rate,
u: control effort
f: force applied by the operator

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

1 DoF Haptic Interface

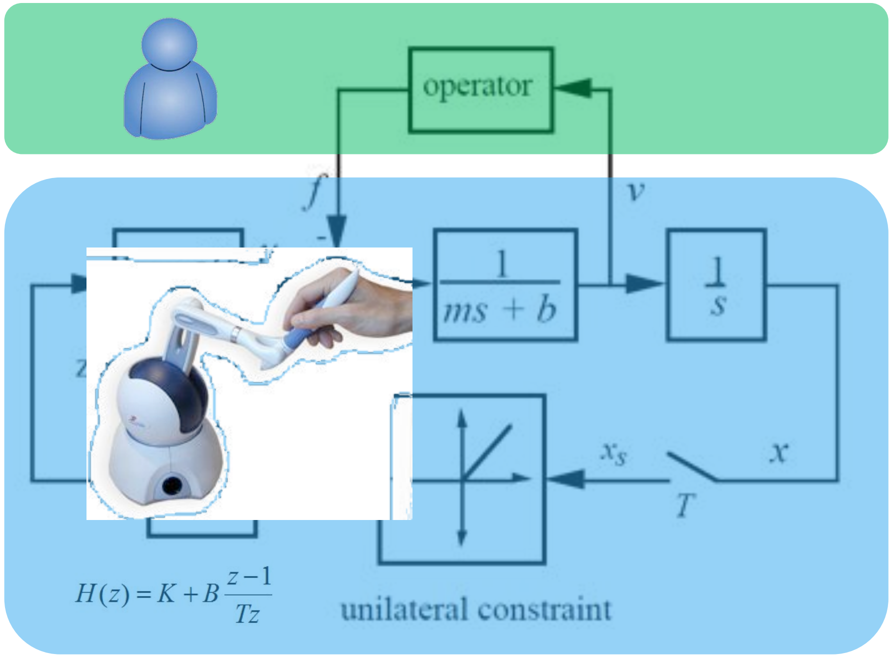


If the haptic display behaves passively, then the operator can never extract energy from it. Here, we will use the slightly more stringent statement that the energy input to the haptic display from the operator must be positive for all admissible force histories $f(t)$ (see discussion in Section 3.2)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

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

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

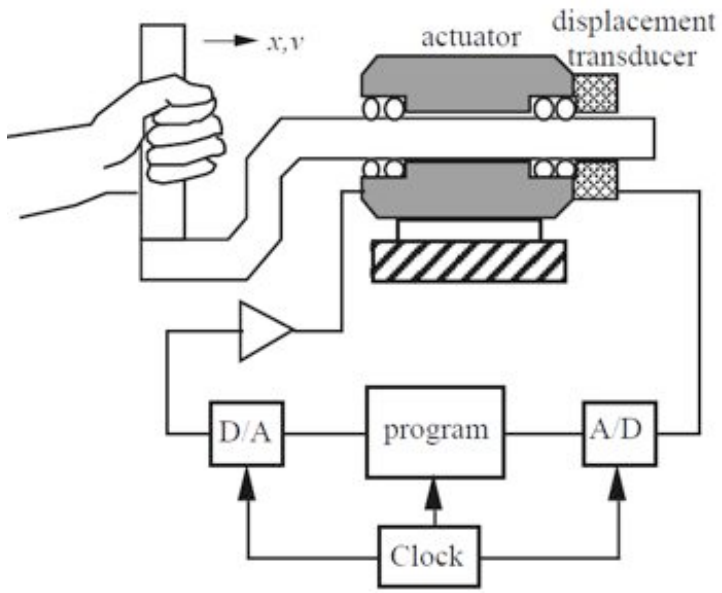
Passivity of a Class of Sampled-Data Systems: Application to Haptic Interfaces, J. Edward Colgate, Gerd G. Schenkel, 1995



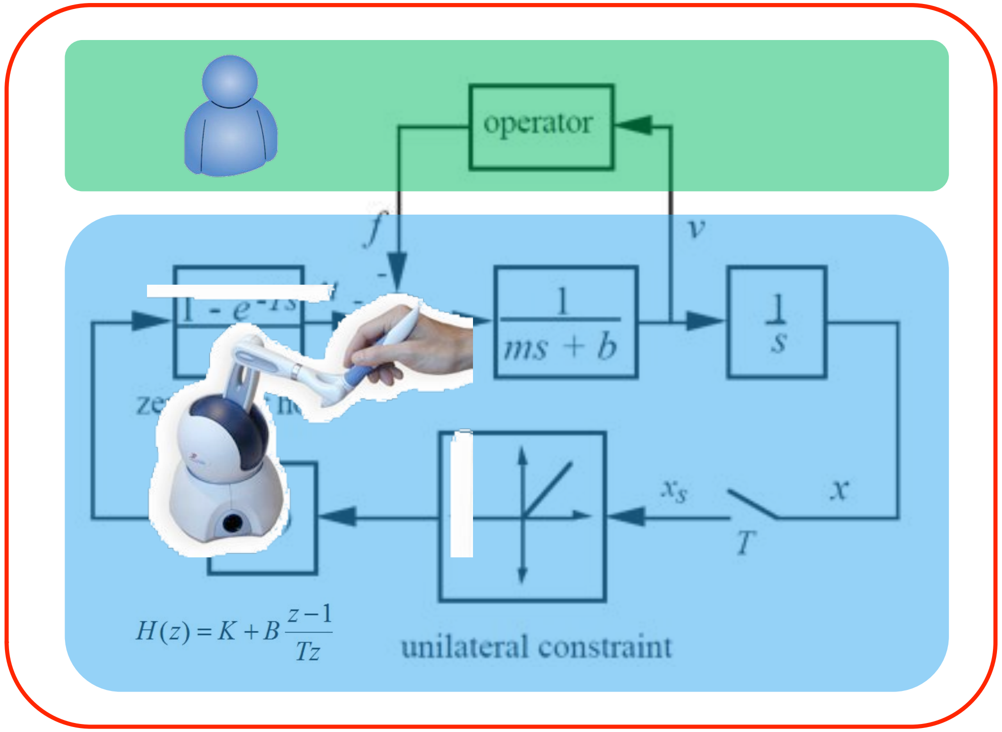
Block diagram

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.

1 DoF Haptic Interface



Schematic



Block diagram

Condition for passivity: $$b > \frac{T}{2}\frac{1}{1-\cos\omega T}\operatorname{Re}\left\{\left(1-e^{-j\omega T}\right)H\left(e^{j\omega T}\right)\right\}$$

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

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

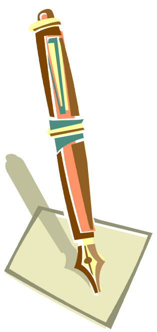
Conclusion from Passivity Analysis

Inherent damping | Virtual stiffness | Sampling time | Virtual damping

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

- 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*

Sensor Quantization & Velocity Filtering

Minimize T (fast sampling)

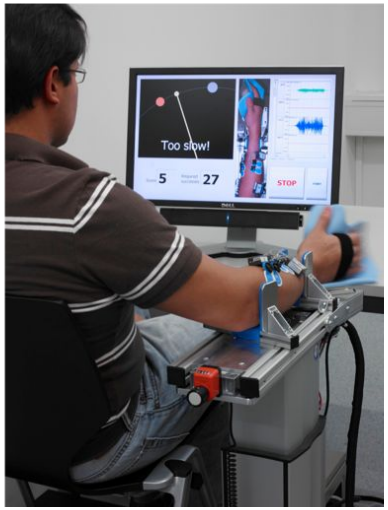
$$v = \frac{x_k - x_{k-1}}{T}$$

→ <u>Velocity resolution</u> of sensor increases

→ BUT: Velocity used for virtual damping!

$$\frac{\Delta encoder}{T}$$

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



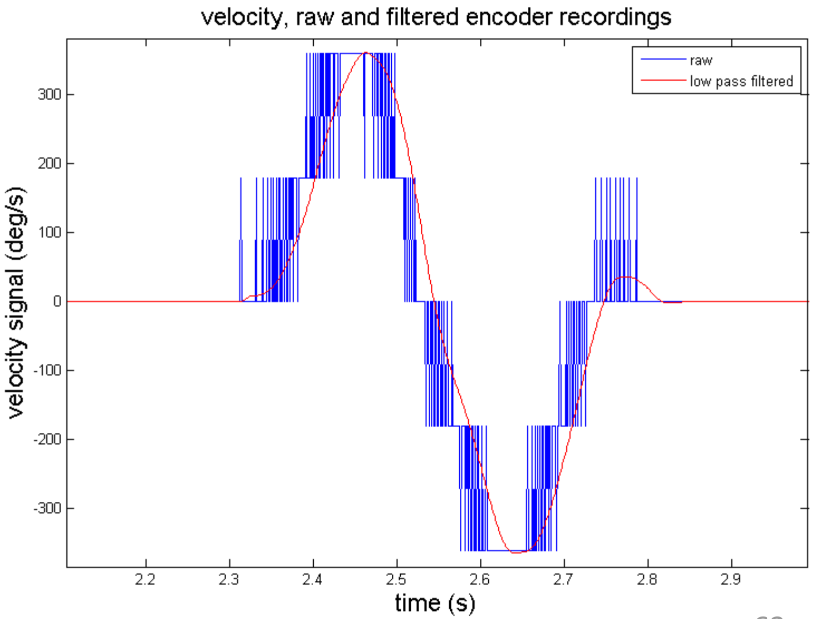
Example:

Position encoder: 2000 counts/turn (4x500)
Position resolution: 360°/2000 = **0.18°/count**

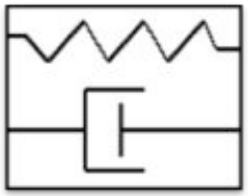
Sampling time: 0.01s (100 Hz)
Velocity resolution: 0.18°/0.01s = **18°/s**

Sampling time: 0.001s (1 kHz)
Velocity resolution: 0.18°/0.001s = **180°/s**

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



Maximize Impedance Through Velocity Estimator



K
B

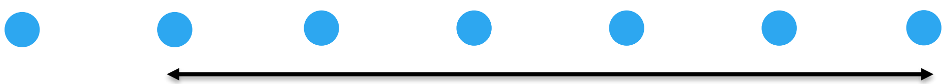
$$F_{desired} = (x - x_d) \cdot K + \dot{x} \cdot B$$

Velocity estimation:

Euler backward approximation +
1st and 2nd order Butterworth (BW)

$$\dot{x} = (x_k - x_{k-1})/T$$

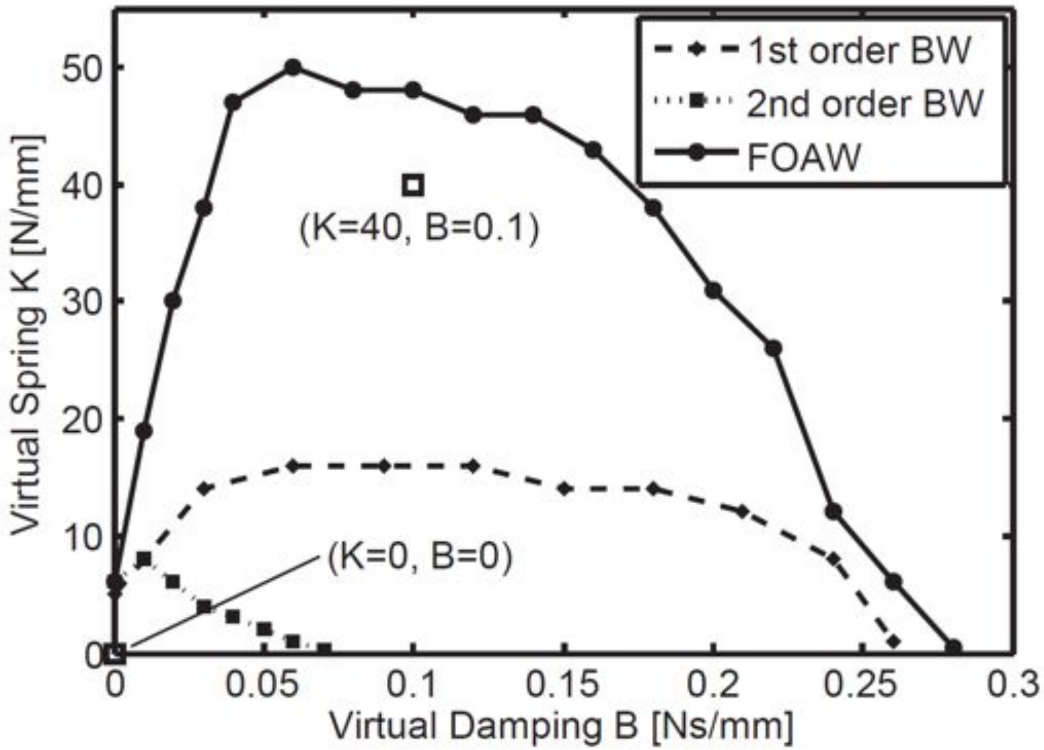
First Order Adaptive Window (FOAW)



Adaptive window length $n=f(|x|)$

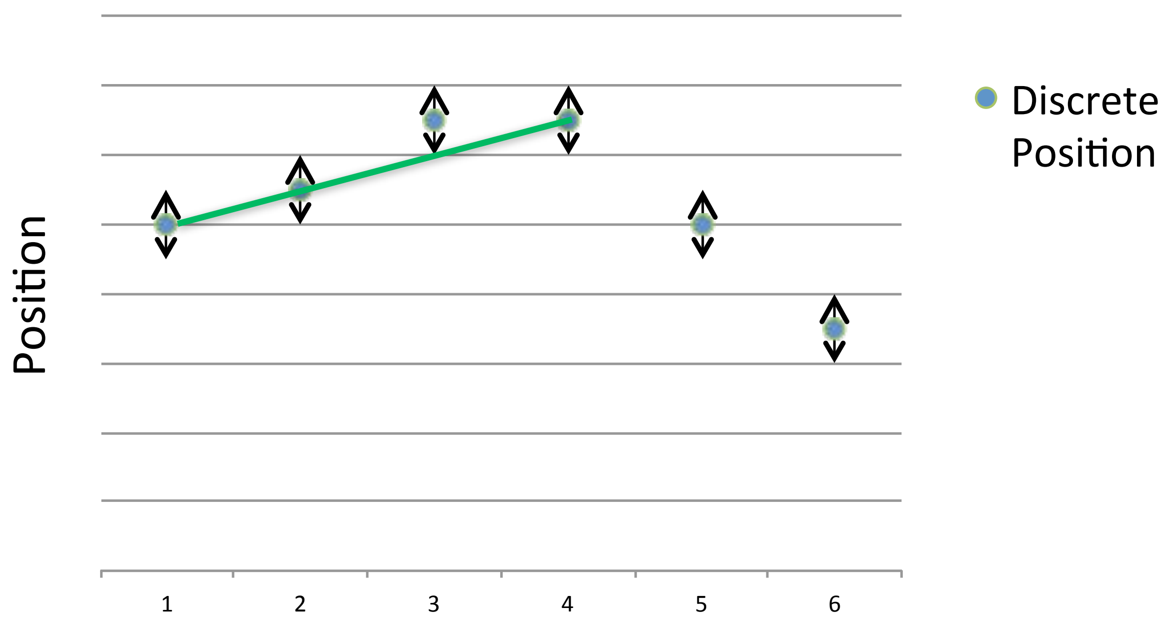
$$\dot{x} = g(x_k, x_{k-1}, \dots, x_{k-n})$$

(Janabi-Sharifi 2000)



(KB plot, Colgate and Brown 1994)

First Order Adaptive Window (FOAW)

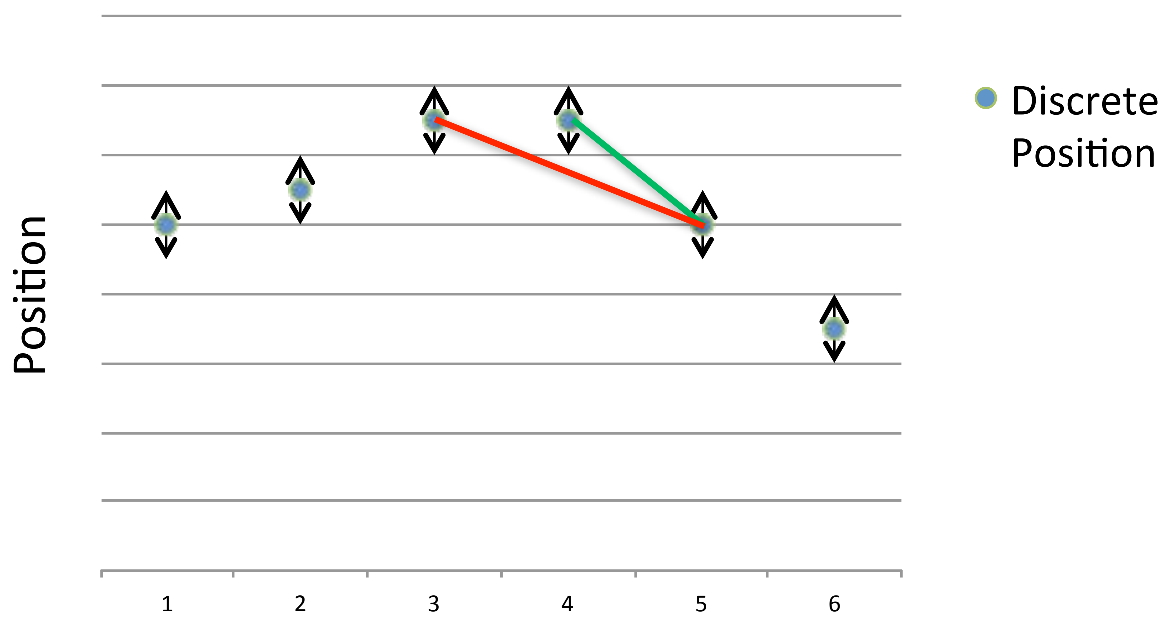


Short window when velocity is high more reliable estimates and faster calculation

Large window when velocity is low produce more precise estimates.

(Janabi-Sharifi, 2000)

First Order Adaptive Window (FOAW)



Short window when velocity is high more reliable estimates and faster calculation

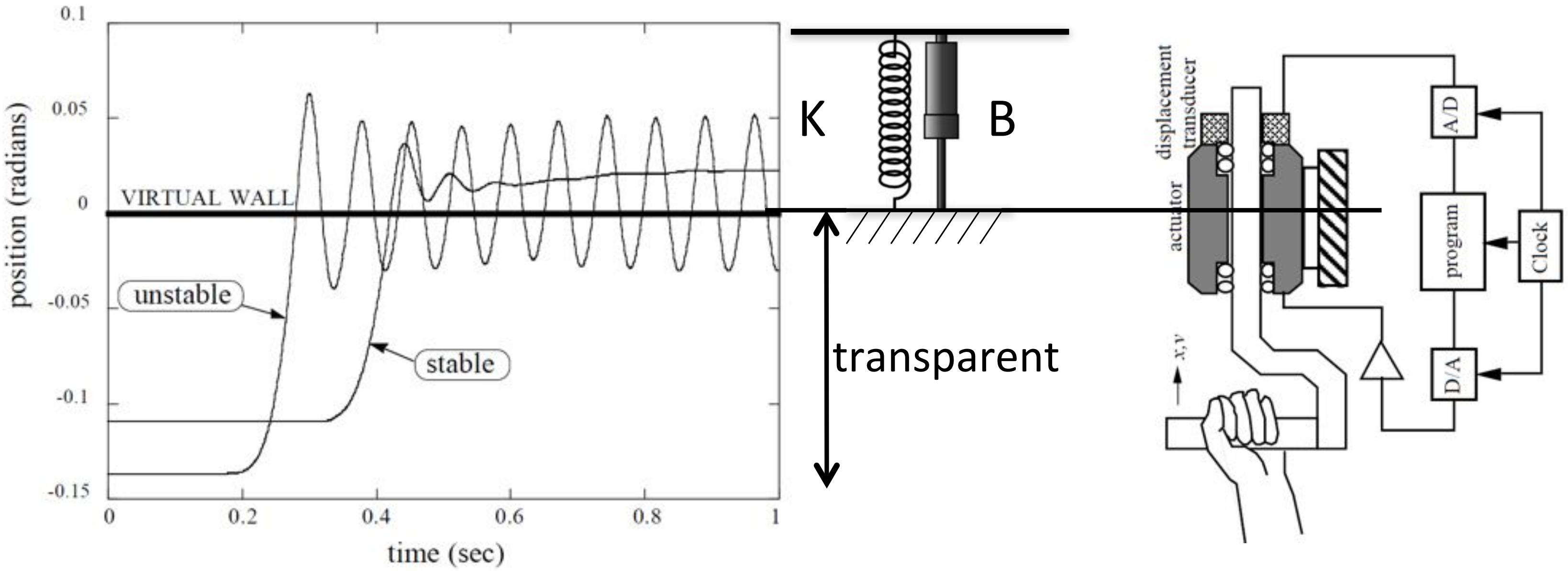
Large window when velocity is low produce more precise estimates.

(Janabi-Sharifi, 2000)

Colgate Paper - Experimental Setup

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



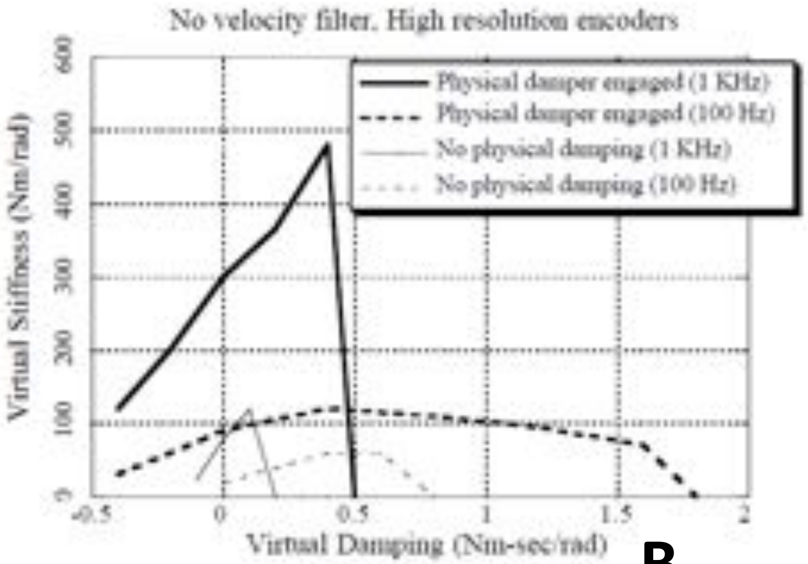
Factors Affecting the Z-Width of a Haptic Display, J. Edward Colgate, J. Michael Brown, 1994

K-B-Plot

Z-Width

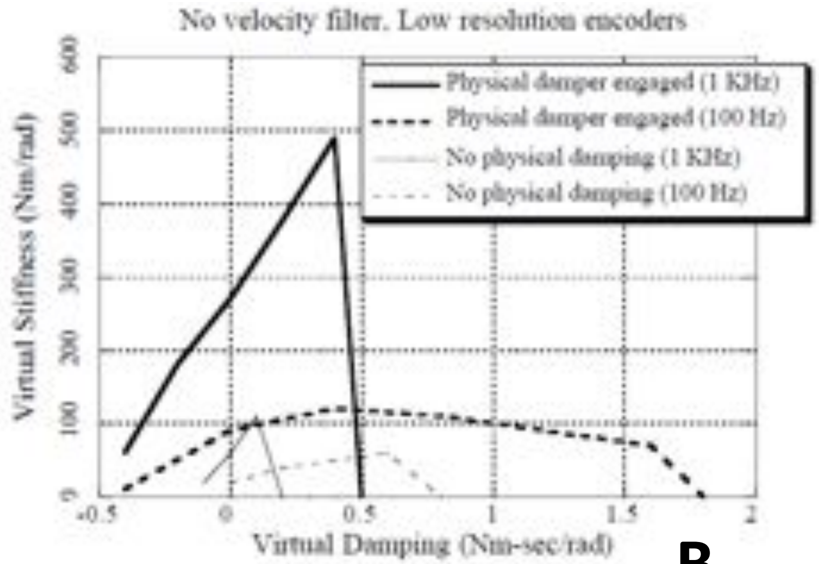
Experimental Results. Plots indicate Z-Width (area beneath the curves)

K



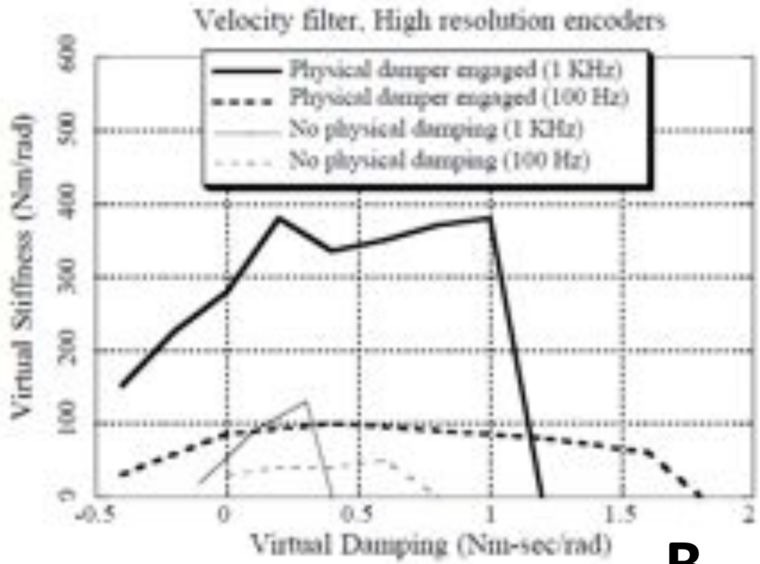
B

K



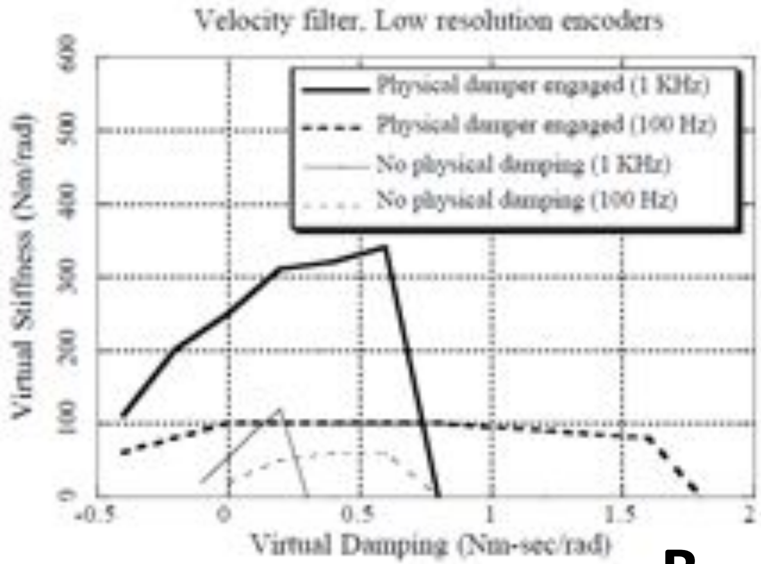
B

K



B

K



B

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

Performance Metrics

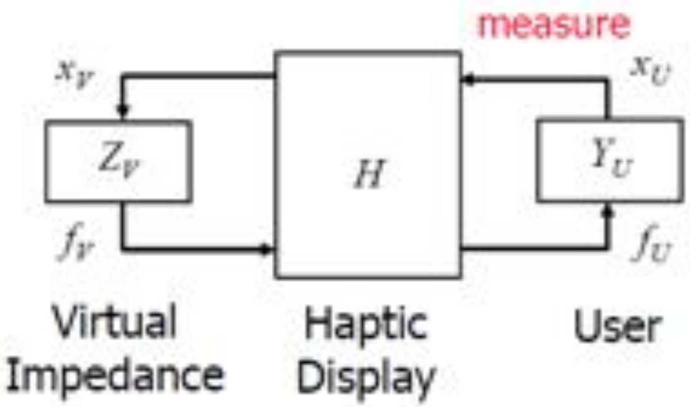
- V. Hayward and O. Astley. Performance measures for haptic interfaces. Robotics Research, pages 195–207, 1996.
- E. Samur, “Systematic Evaluation Methodology and Performance Metrics for Haptic Interfaces,” Ph.D. dissertation, Ecole Polytechnique Fédérale de Lausanne, Lausanne, 2010. [Online]. Available: http://library.epfl.ch/theses/?nr=4648
- J.ColgateandJ.Brown,“Factorsaffectingthez-widthofahapticdisplay,”inRoboticsandAutomation,1994.Proceedings., 1994 IEEE International Conference on, may 1994, pp. 3205 –3210 vol.4.
- D.Weir,J.Colgate,andM.Peshkin,“Measuringandincreasingz-widthwithactiveelectricaldamping,”inHapticinterfaces for virtual environment and teleoperator systems, 2008. haptics 2008. symposium on, march 2008, pp. 169 –175.

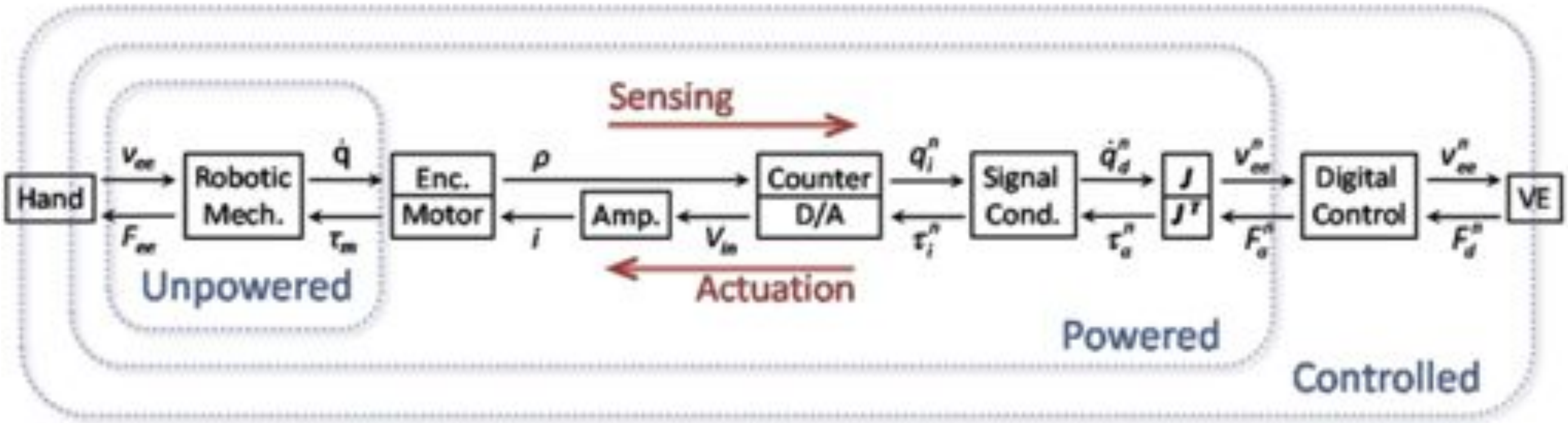
Performance Metrics

- Gross features: DOF, interface, motion range, inertia (not easily reduced by feedback) and damping, power density
- Detailed features: resolution, precision, bandwidth, structural response
- Saturation:
    - maximal velocity and acceleration
    - peak force and rate of change
- Dynamic precision: crosstalk, distortion
- K-B plots

V. Hayward and O. Astley. Performance measures for haptic interfaces. Robotics Research, pages 195–207, 1996.

Impedance Controller Performance

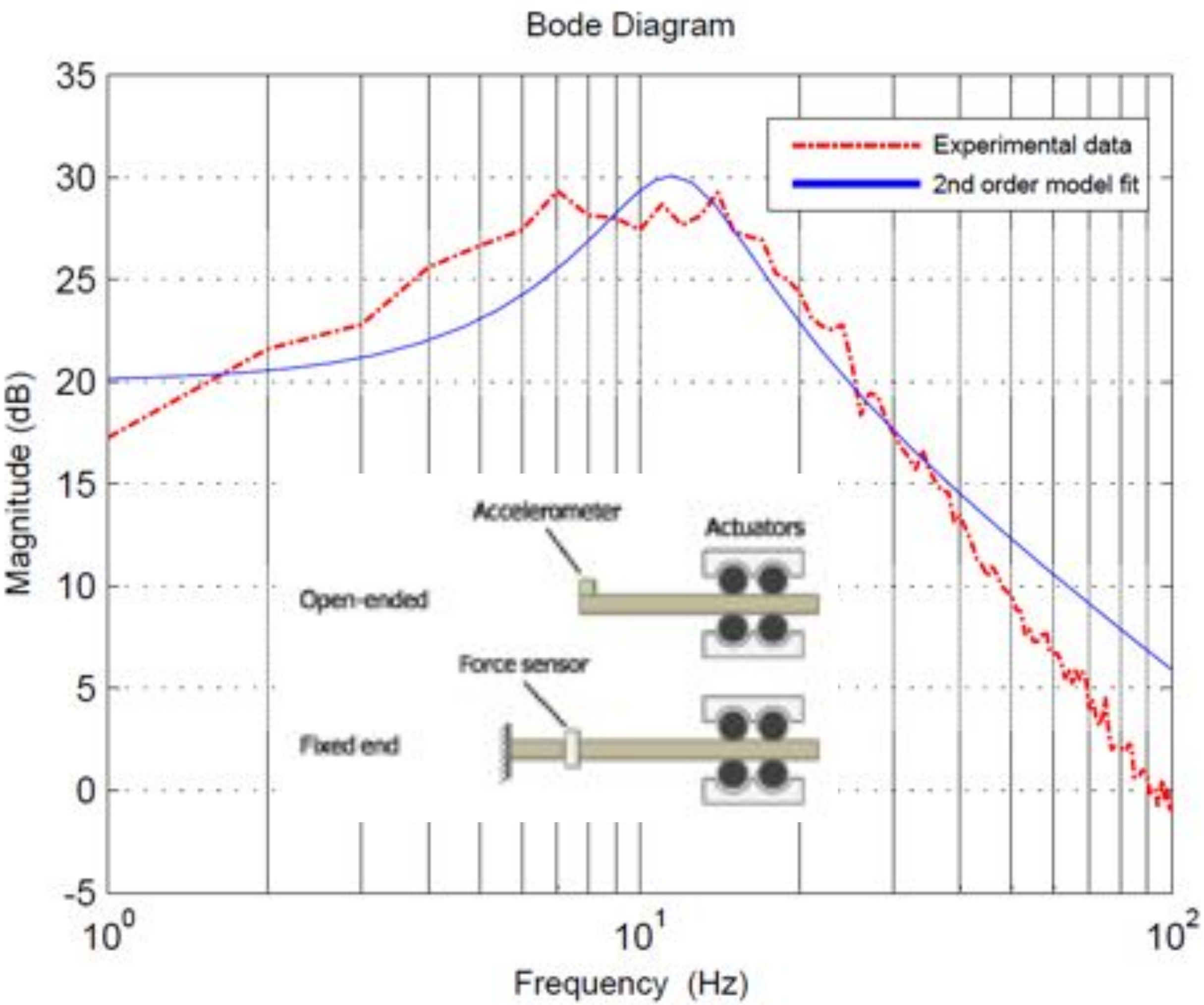




Powered system → output impedance
Controlled system → controlled impedance (Z-Width)

Output Impedance

Identify the force-velocity relationship of the powered (uncontrolled) system



$$\mathbf{f}(\omega) = \mathbf{Z}(\omega) \cdot \mathbf{v}(\omega) \qquad Z_{RHK} = \frac{F_{ee}}{\dot{q}}$$

1. *open-ended*: the velocity $\dot{q}$ of the end-effector is recorded when applying a sinusoidal input force F_{input} via the motor. The relation between applied force and measured velocity can be described by the following relation:

$$\dot{q} = \frac{H_f}{Z_{RHK}} \cdot F^n_{input} \tag{13}$$

where H_f represents the transfer function comprising all signal conversions and kinematic transformations from the real-time system to the end-effector, i.e. H_f maps a digital signal (denoted with a superscript n) to an analog signal.

2. *fix-end*: in this experiment the end-effector has to be blocked (as shown in figure 5) and the same sinusoidal input force F_{input} needs to be applied via the motor.

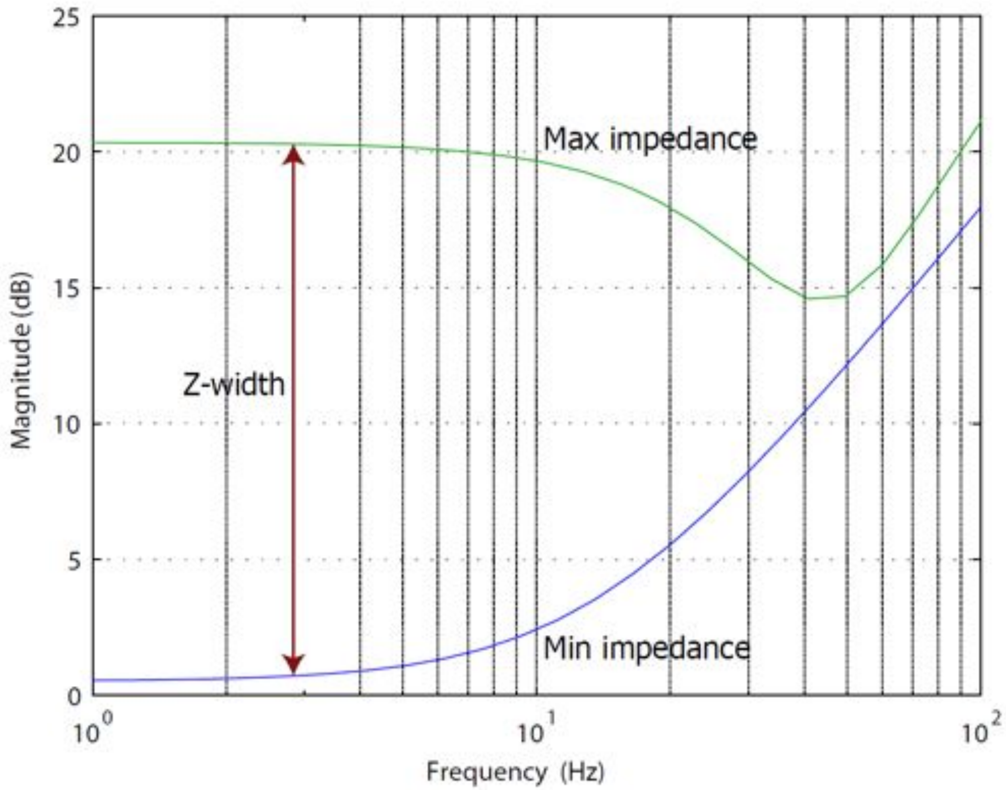
Then the resulting force at the end-effector F_{ee} has to be measured with the force sensors. As the end-effector is blocked ($\dot{q} = 0$) and therefore the device dynamics do not have an influence on the measurements, this experiment can capture the above described transfer function H_f:

$$F_{ee} = H_f \cdot F^n_{input} \tag{14}$$

Equation (13) can be solved for F^n_{input} and set into equation (14). Then H_f cancels down and the output impedance - as described in equation (12) - can be calculated with the measurements of the two above described experiments.

Evren Samur, EPFL PhD thesis 2010 ; Metzger et al., Haptic Symposium 2012

Controlled Impedance: Z-Width in Frequency Domain



Calculate:

$$Z(\omega) = \frac{f(\omega)}{v(\omega)}$$ measured

- Display low and high impedance with the controller (controlled system)
- Measure the interaction force and motion while perturbing the system at different frequencies (by hand: frequencies up to 10Hz possible or larger frequency spectrum with an external shaker (motor))
- Transform the measured data (f and v) into frequency space (fft) and calculate impedance $Z(\omega)$

(Evren Samur, phd thesis 2010)

Output Impedance and Z-Width

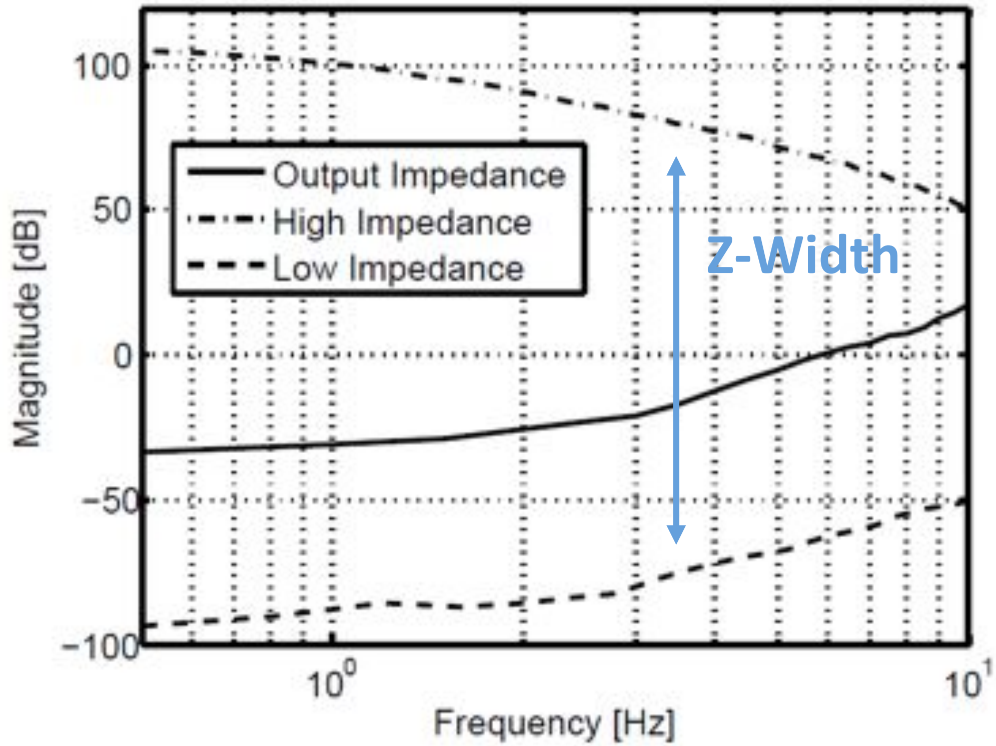
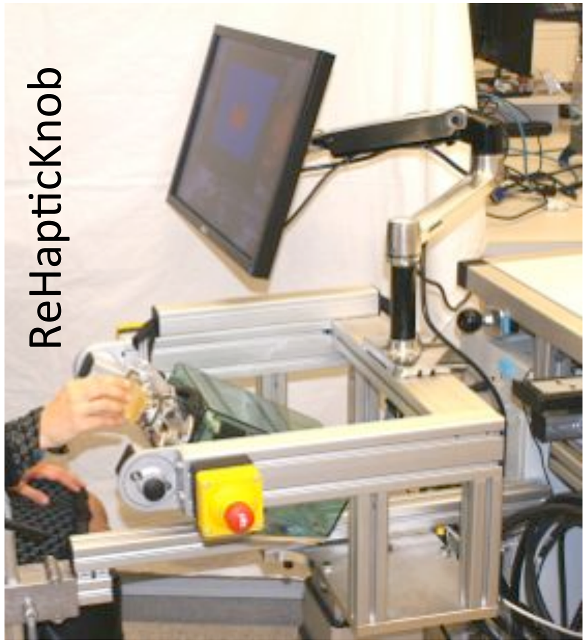
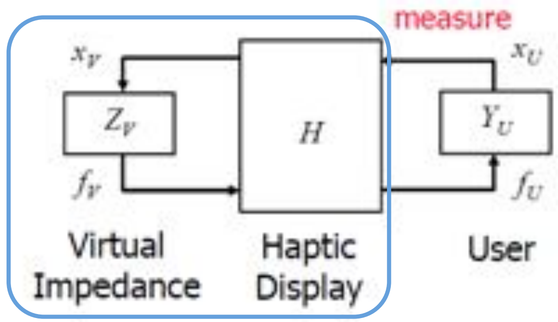


Figure 8: The output impedance reflects the dynamic behavior of the *ReHapticKnob* as a function of different frequencies and relates the overall force applied by the human at the end-effector and the actuation force from the motor to the velocity (motion) of the end-effector. With the impedance controller the apparent impedance at the end-effector can be reduced by setting the desired impedance parameters to zero ($K = 0$, $B = 0$, dashed line) or the apparent impedance can be increased by choosing the desired impedance parameters high ($K = 40$, $B = 0.1$, dash-dotted line). The range between the two controlled curves reflects the Z-Width of the *ReHapticKnob*.



$$f_U(\omega) = Z_{apparent}(\omega) \cdot v_U(\omega)$$



* apparent impedance:
felt impedance at the end-effector

Thank you for your attention!

Roger Gassert

Rehabilitation Engineering Lab, ETH Zurich

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

RELAB
Rehabilitation Engineering Lab