HS'12 Workshop on Hardware Evaluation

Guidelines for Haptic Interface Evaluation: Physical & Psychophysical Methods

Evren Samur, PhD

March 4th, 2012

Prosthesis Design & Control Lab
Center for Bionic Medicine
Rehabilitation Institute of Chicago

NORTHWESTERN UNIVERSITY

RIC Rehabilitation Institute of Chicago

Outline

- Physical Evaluation
  - Literature Review
  - Modeling Haptic Interaction
  - Experimental Methods
- Psychophysical Evaluation
  - Introduction
  - Haptic Interaction Tasks
  - Experimental Methods
- Conclusions
  - Synthesis

Physical Evaluation

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  - Modeling Haptic Interaction
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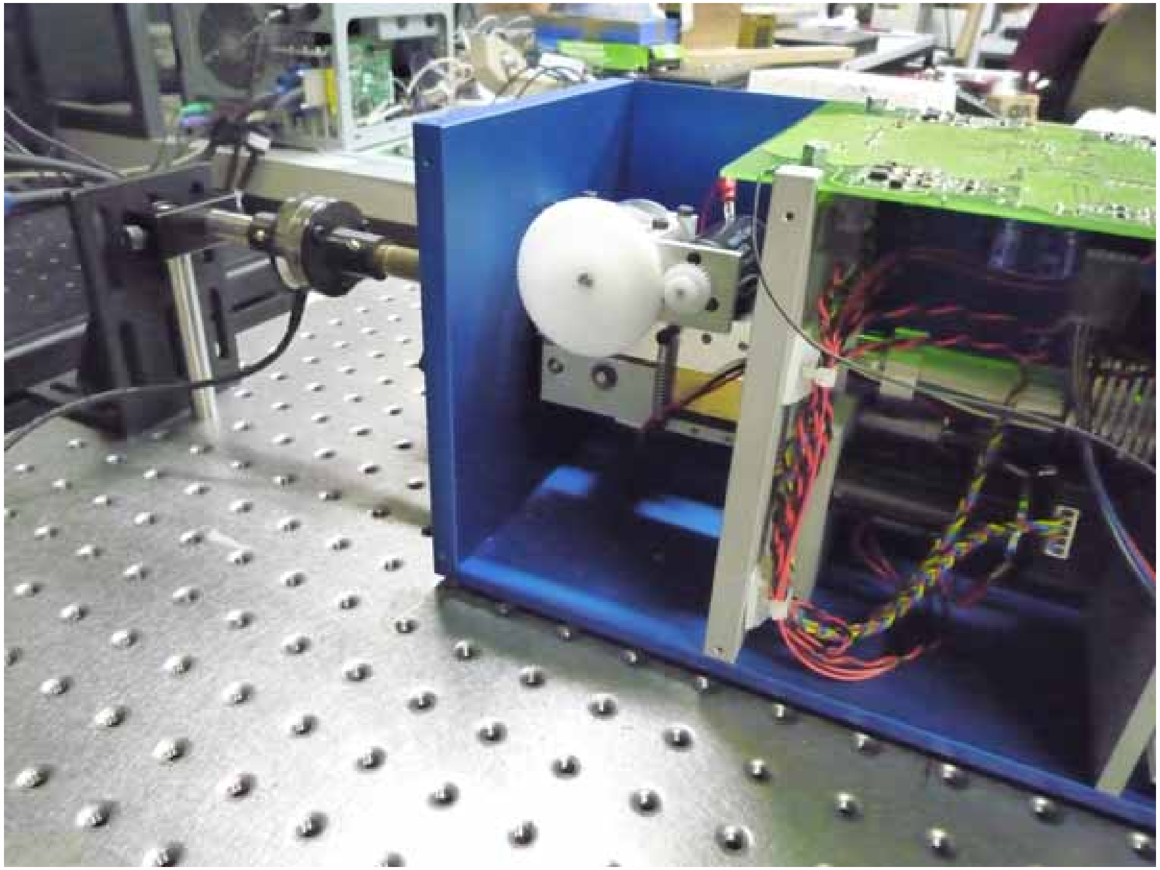
- Conclusions

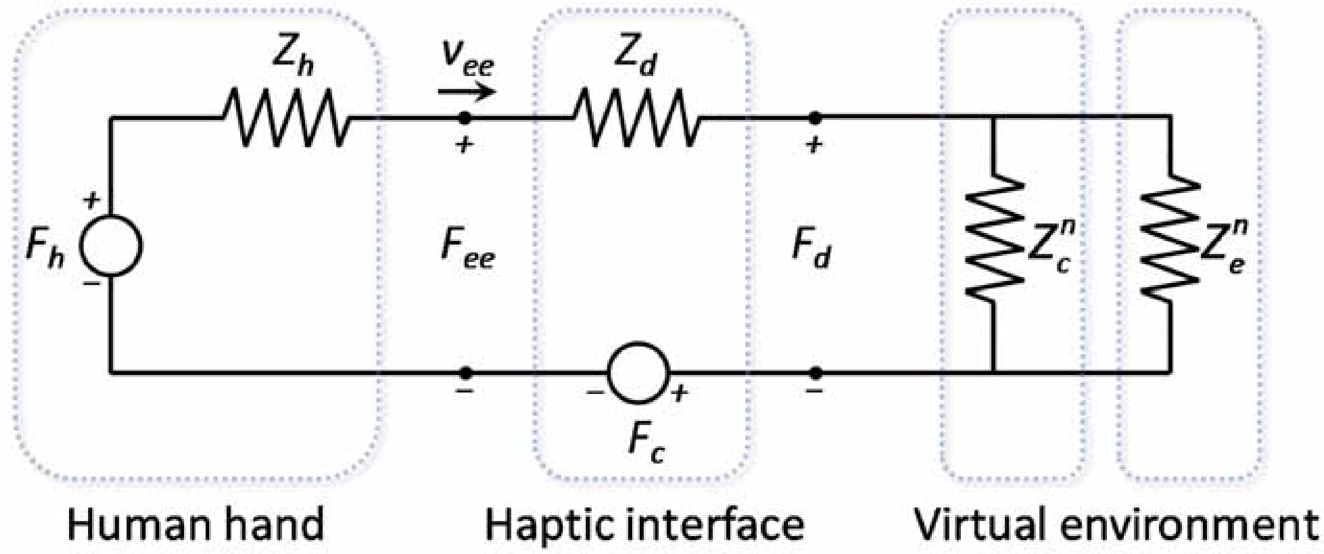


Literature Review

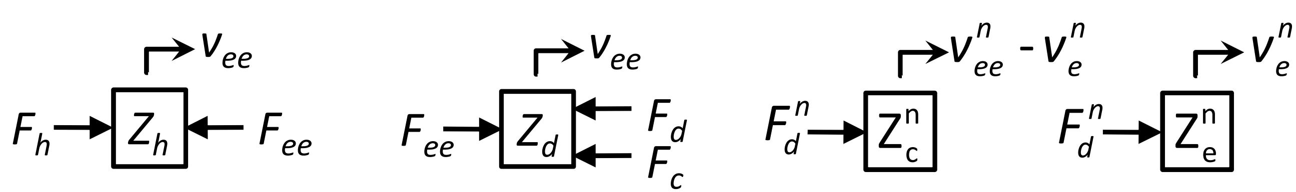
- Performance characteristics for teleoperation
  - Design requirements *Brooks (1990)*
  - Key characteristics *McAffee and Fiorini (1991)*
- Performance measures for haptic interfaces
  - Theoretically defined measures *Hayward and Astley (1996)*
  - Measures are formalized and demonstrated for coupled micro-macro actuators *Morrell and Salisbury (1998)*
  - Some practical measurement methods are experimentally demonstrated *Ellis et al. (1996),Frisoli & Bergamasco (2003), Ueberle (2006), Chapuis (2009), Samur (2011)*

Modeling

- Circuit representation



- Free body diagrams



- Dynamic equations
  - Uncompensated (Fc = 0) & without VE (Ze = 0)

$$\begin{bmatrix} F_h \\ F_{ee} \end{bmatrix} = \begin{bmatrix} Z_h + Z_d & H_f \\ Z_d & H_f \end{bmatrix} \begin{bmatrix} v_{ee} \\ F_d^n \end{bmatrix}$$

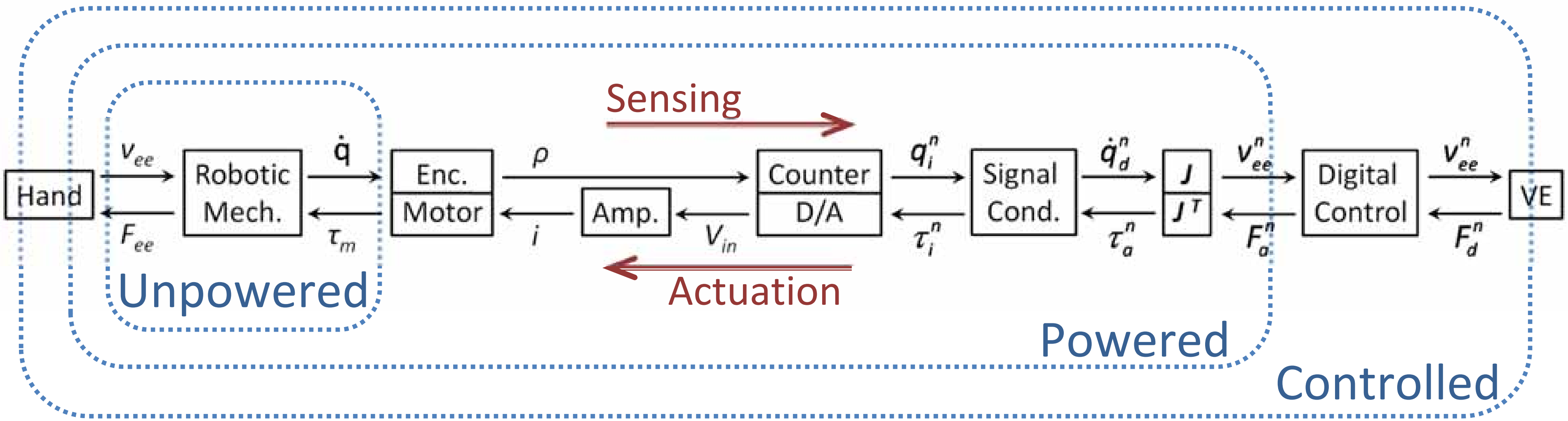
  - For a transparent system, device dynamics is compensated

$$F_{ee} = (Z_d - H_f Z_d^n H_v) v_{ee} + H_f F_d^n$$

  - Haptic system as a whole including VE

$$F_{ee} = (Z_d - H_f Z_d^n H_v + H_f Z_e^n H_v) v_{ee}$$

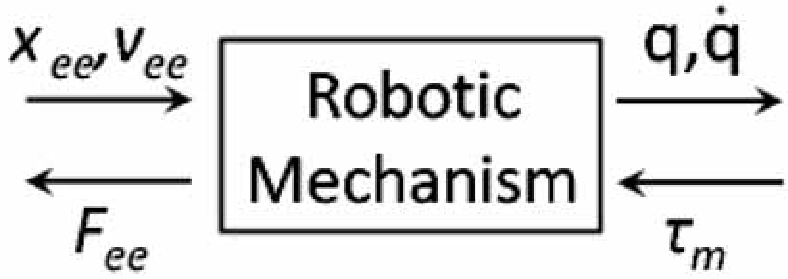
Categorization



- Kinematics, elastostatics, dynamics
- Actuation, sensing
- Impedance range, control bandwidth

Unpowered System Properties

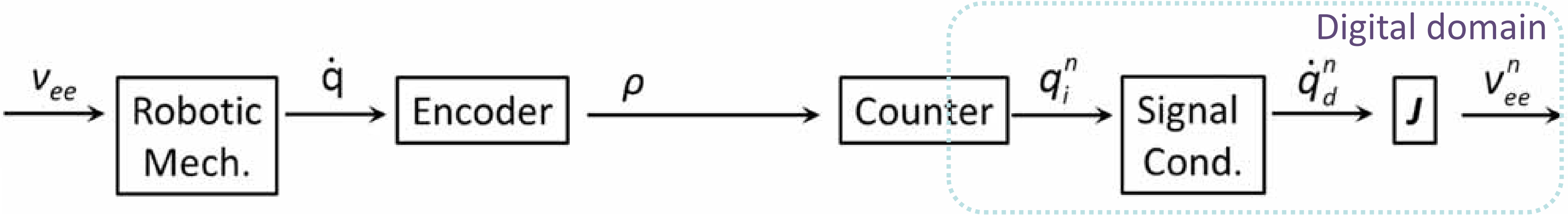
- Kinematics
  - Workspace
  - DOF
    - Passive
    - Active
  - Structure
  - Dexterity



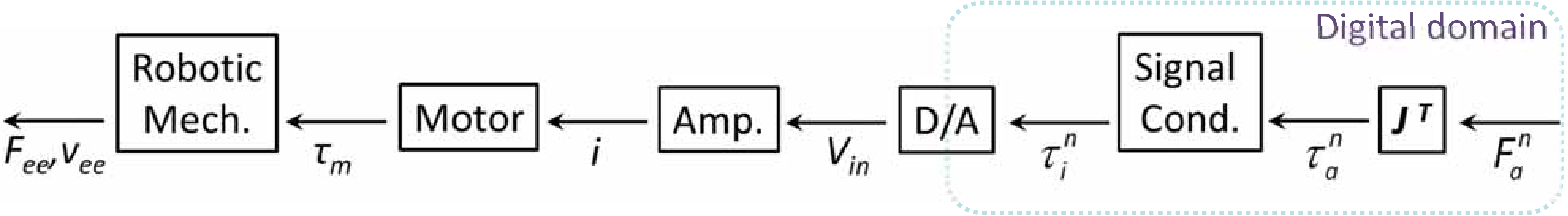
- Elastostatics
  - Stiffness
- Dynamics
  - Structural dynamics

Powered System Properties

- Sensing capabilities
  - Static & Frequency responses



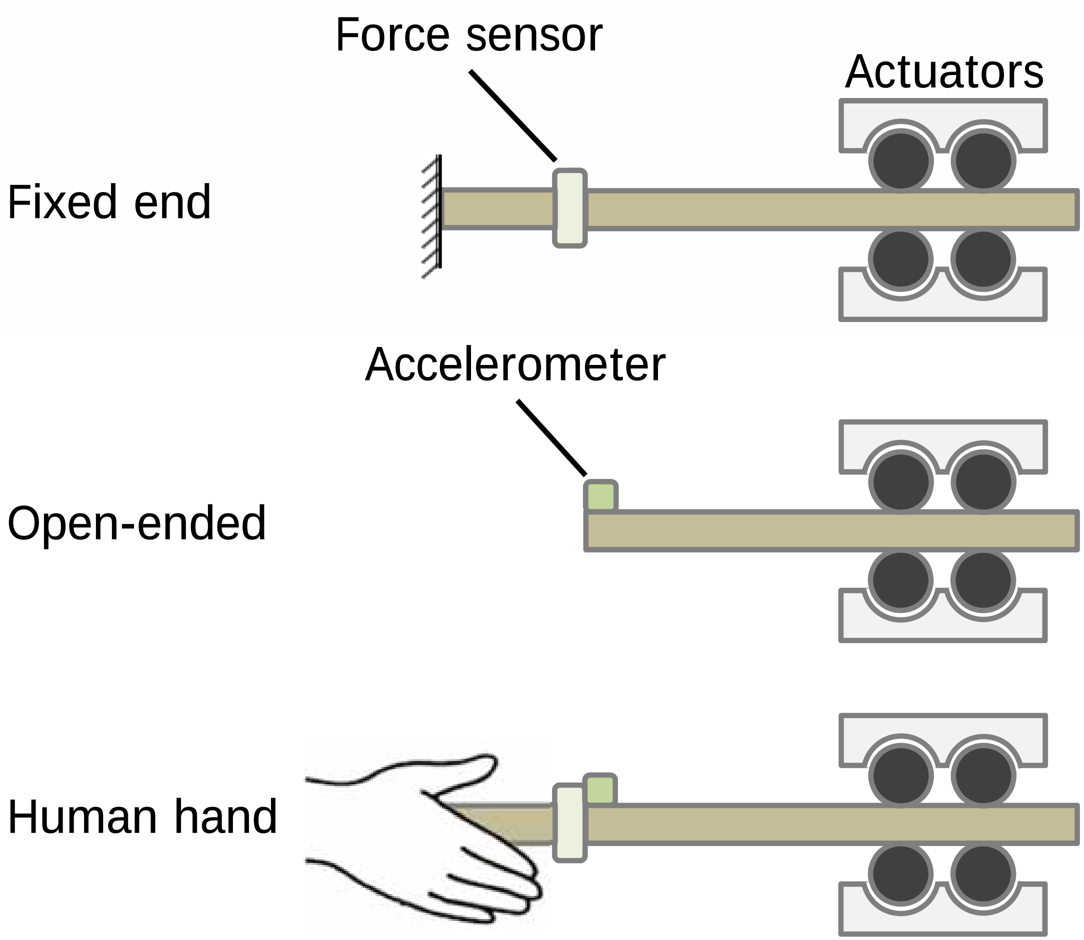
- Actuation capabilities
  - Static, Impulse & Frequency responses

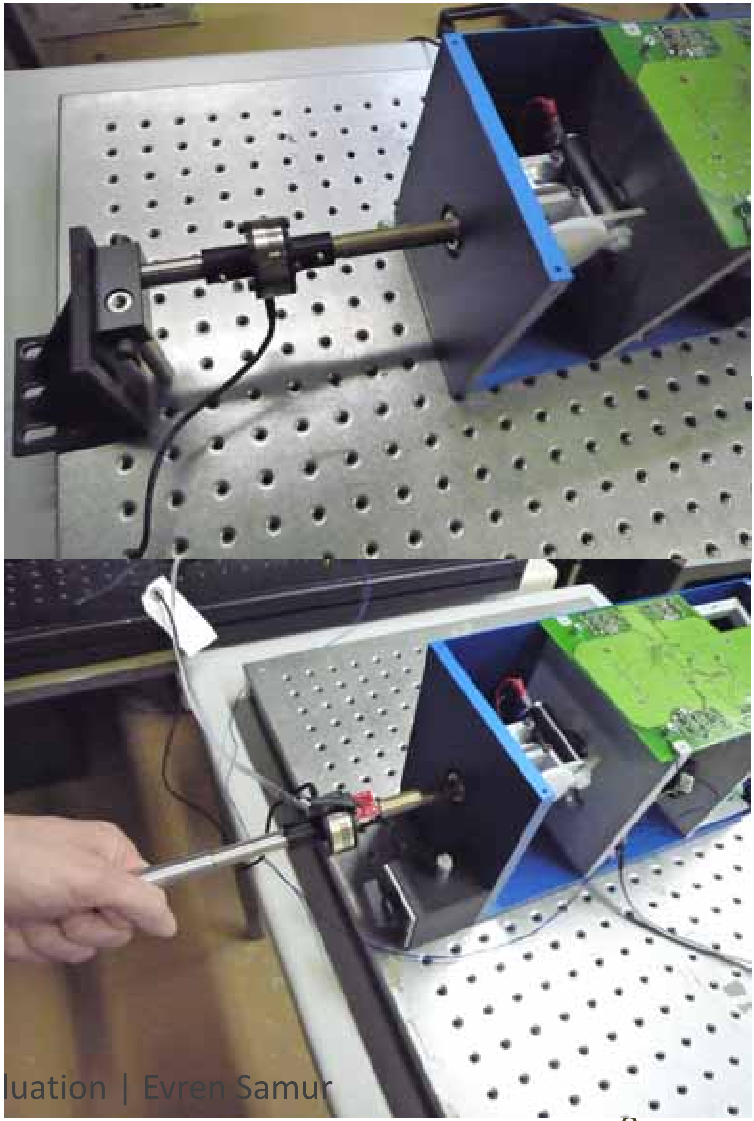


Powered System Properties

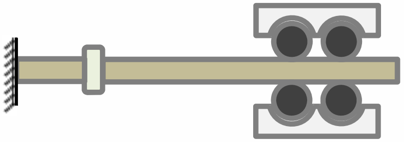
- Sensing
  - Static response
    - Sensitivity
    - Hysteresis
    - Position resolution
    - Dynamic range
    - Position measurement accuracy
    - Precision
  - Frequency response
    - Sensor bandwidth

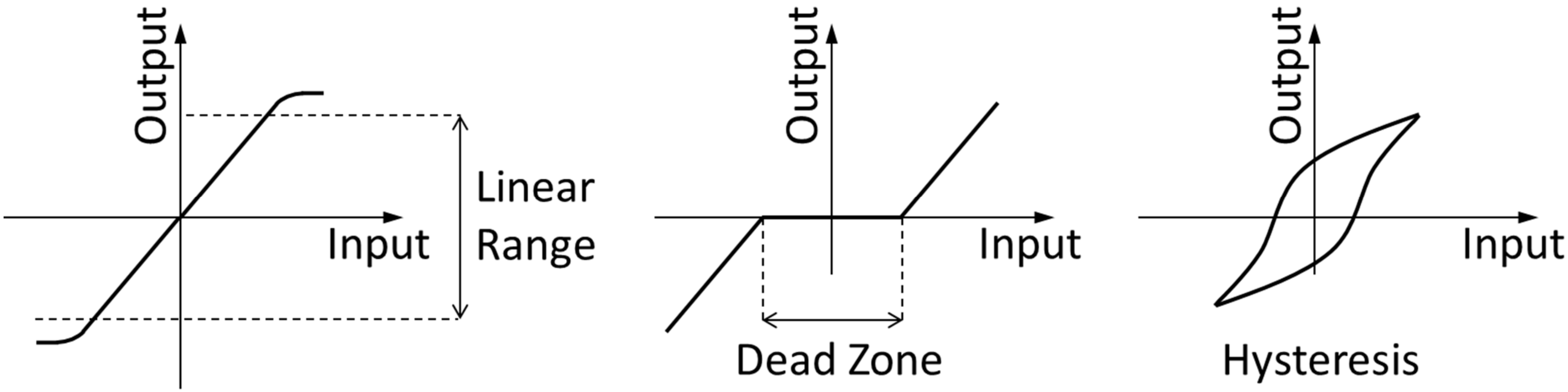
Measurement Setup





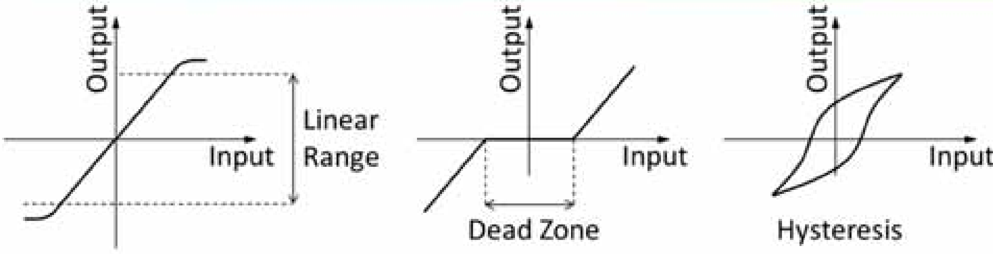
- Input-output (calibration) curve
  - Input: slowly increasing and decreasing ramp
  - Measured: force output
  - Shows any nonlinear behavior

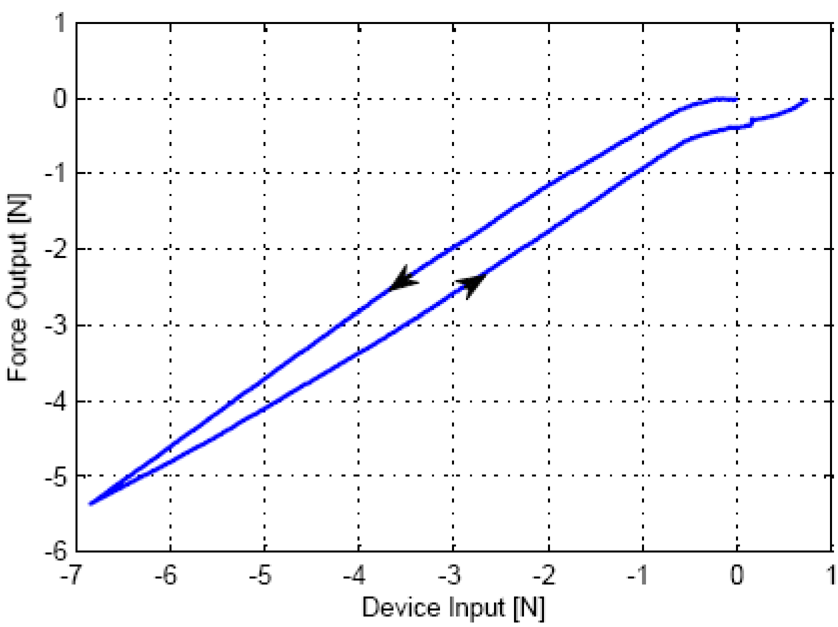


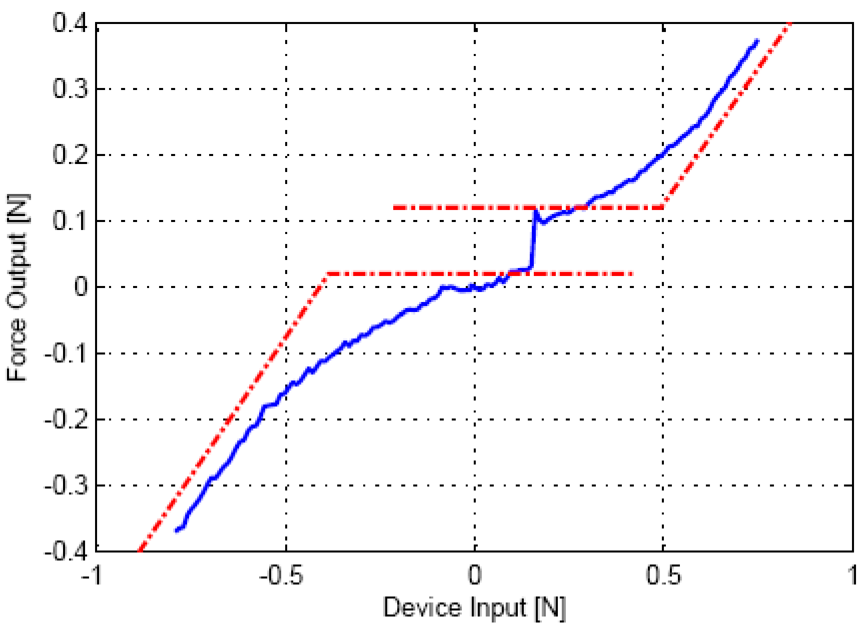


Static Response

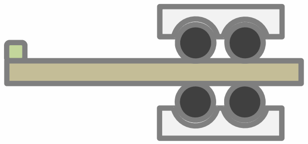
- Max continuous force 5.4 N
- Min force 0.5 N
- Dynamic range 20 dB
- Output force resolution 9 mN



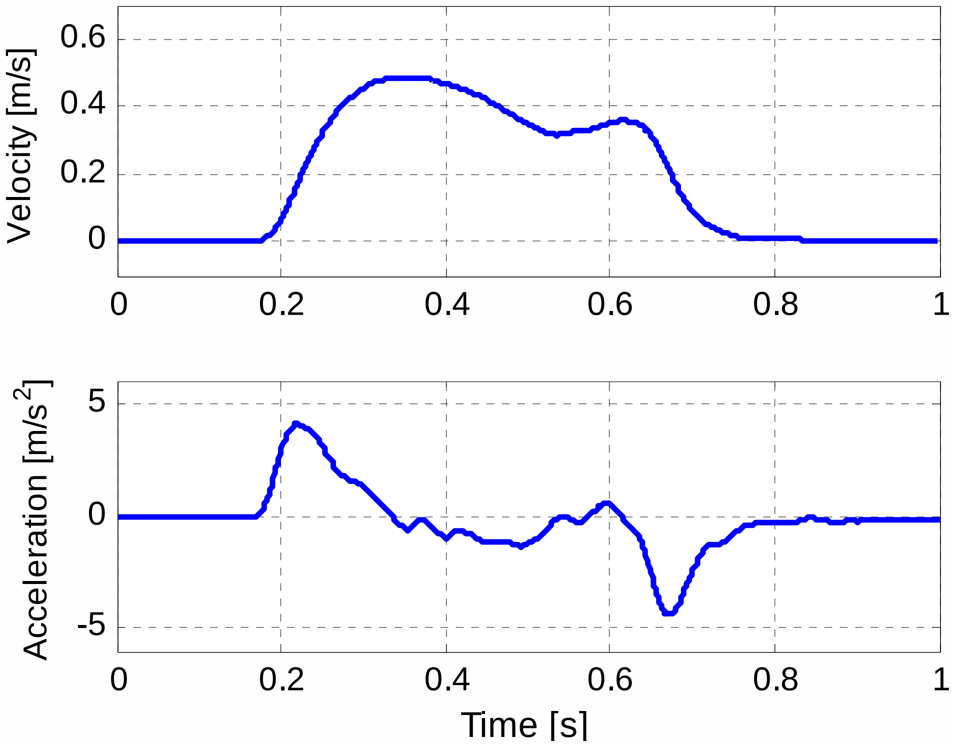




Impulse Response

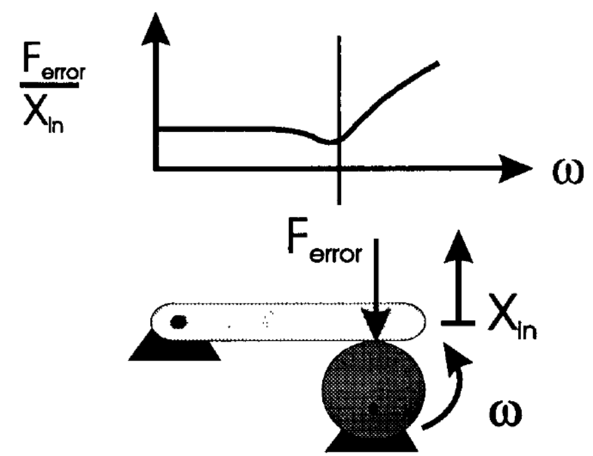


- Speed of a device
  - Input: an approximate impulse (square wave) with a magnitude of max force
  - Peak speed
    - 0.5 m/s
  - Max acceleration
    - 4 m/s2

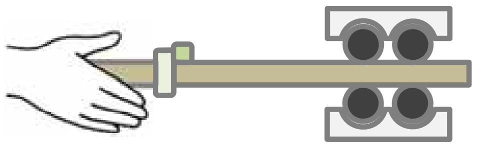


Frequency Response

- Transfer functions
- Output Impedance
  - External excitation
    - Shaker

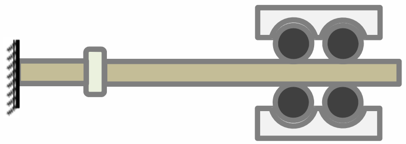


    - Human hand (limited to 10 Hz)



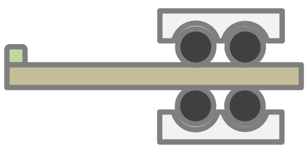
Frequency Response

- Fixed end



$$\frac{F_{ee}}{F_d^n} = H_f$$

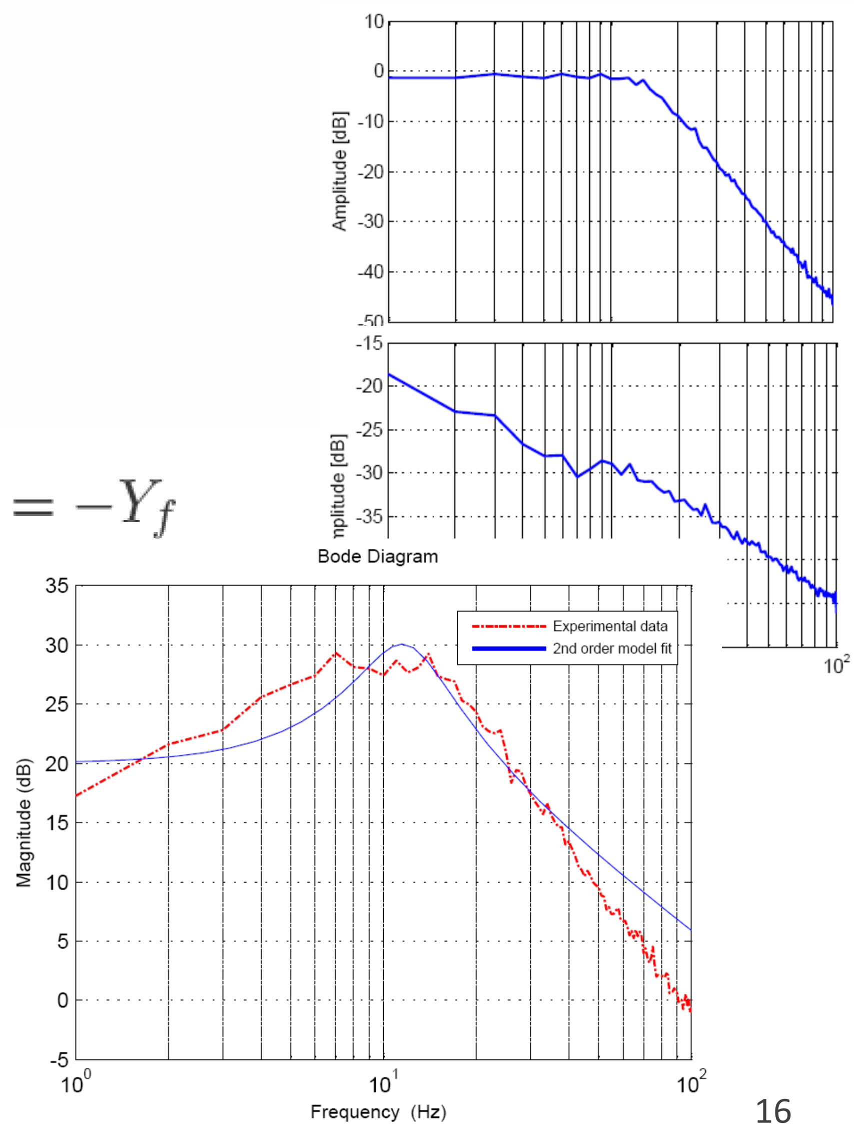
- Open end



$$\frac{v_{ee}}{F_d^n} = -\frac{H_f}{Z_d} = -Y_f$$

→ Output Impedance

$$Z_d = \frac{F_{ee}}{v_{ee}}$$

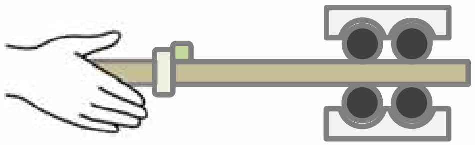


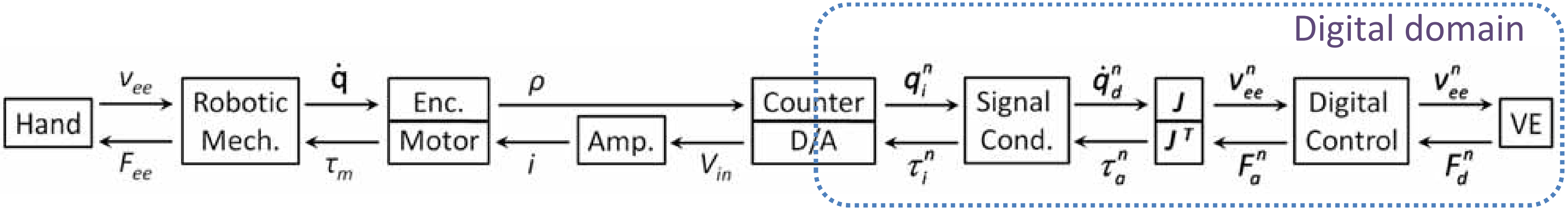
Powered System Properties

- Actuation
  - Peak force
  - Continuous force
  - Minimum force
  - Hysteresis
  - Sensitivity
  - Output force resolution
  - D/A resolution
  - Dynamic range
  - Force bandwidth
  - Useful freq range
  - Amplifier bandwidth
  - Output impedance
  - Force fidelity
  - Rise time
  - Settling time
  - Overshoot
  - Output force accuracy
  - Force precision
  - Peak speed
  - Peak acceleration

Controlled System Properties

- Control Bandwidth
- Impedance range (Z-width)
  - Min impedance
  - Max impedance





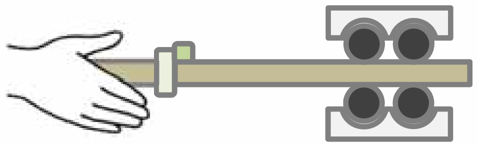
Controlled System Properties

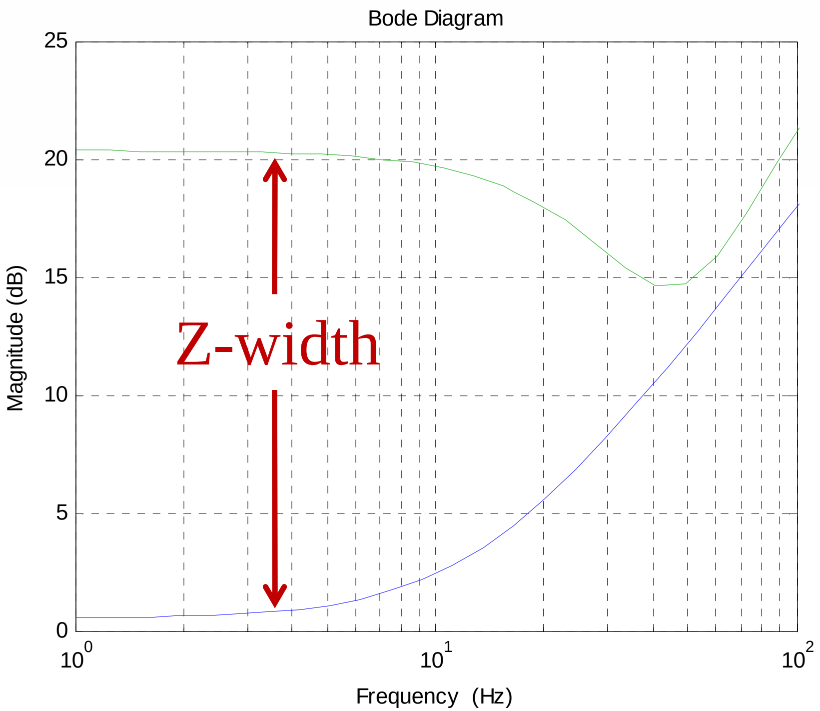
- Impedance range
  - Min impedance

$$\frac{F_{ee}}{v_{ee}} = Z_d - H_f Z_d^n H_v$$

  - Max impedance

$$\frac{F_{ee}}{v_{ee}} = Z_d + H_f Z_c^n H_v$$



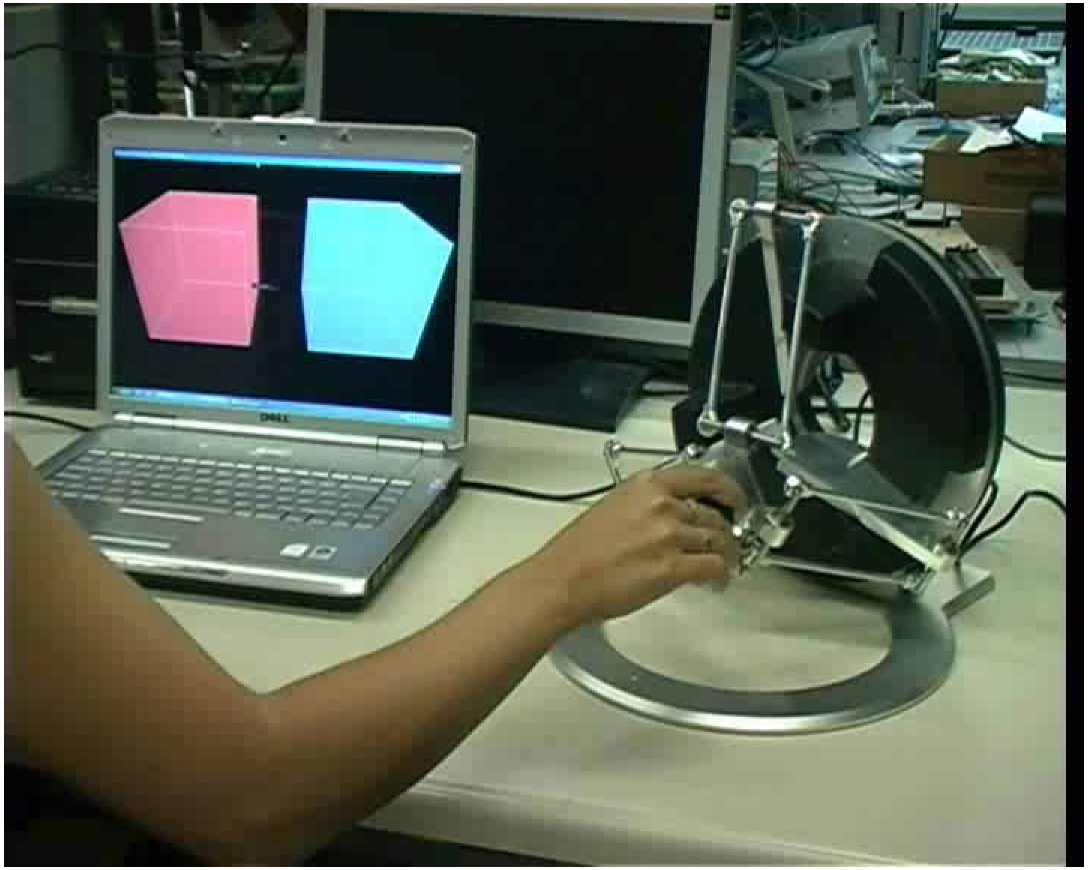


References:

Colgate & Brown (1994)
Weir et al. (2008)

Psychophysical Evaluation

- Physical Evaluation
- Psychophysical Evaluation
  - Introduction
  - Haptic Interaction Tasks
  - Experimental Methods
- Conclusions

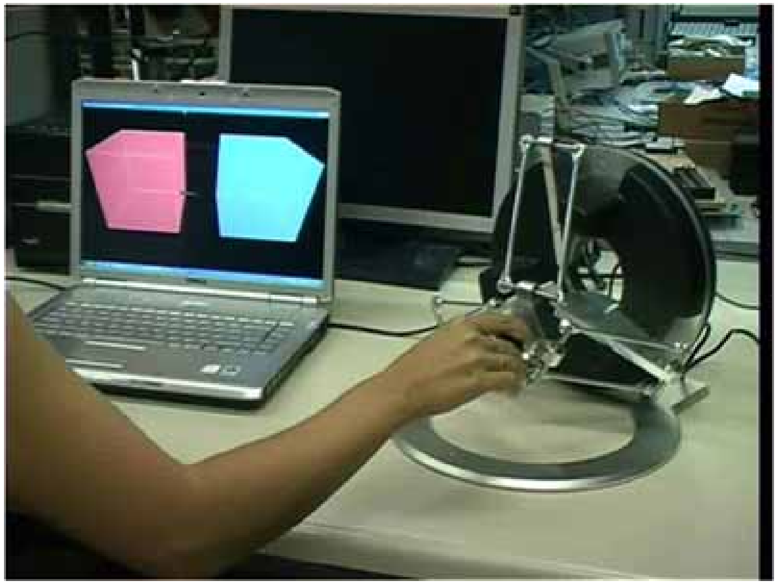


Psychophysical Evaluation

- Redoing psychophysical tests with haptic interfaces
  - Human perception as an evaluation tool

Human perception limits are well studied by psychologists

Psychophysical testbeds



human-in-the-loop experiments

Haptic Interaction Tasks

- Motor Control →
  - Travel
  - Selection
  - Manipulation
- Perception →
  - Detection → Stimulus
  - Discrimination → Stimulus, Material
  - Identification → Geometry
- Stimulus →
  - Position
  - Velocity
  - Force
  - Pressure
  - Stiffness
  - Viscosity
- Material →
  - Texture
  - Hardness
  - Weight
- Geometry →
  - Size
  - Shape

References:

Jandura & Srinivasan (1994)

Bowman & Hodges (1999)

Kirkpatrick & Douglas (2002)

Jones & Lederman (2006)

Psychophysical Testbeds

- Travel & Selection
- Selection & Manipulation

– to assess kinematic and dynamic quality

- Detection
- Discrimination
  - Force
  - Texture

– to find resolution limits associated with a device

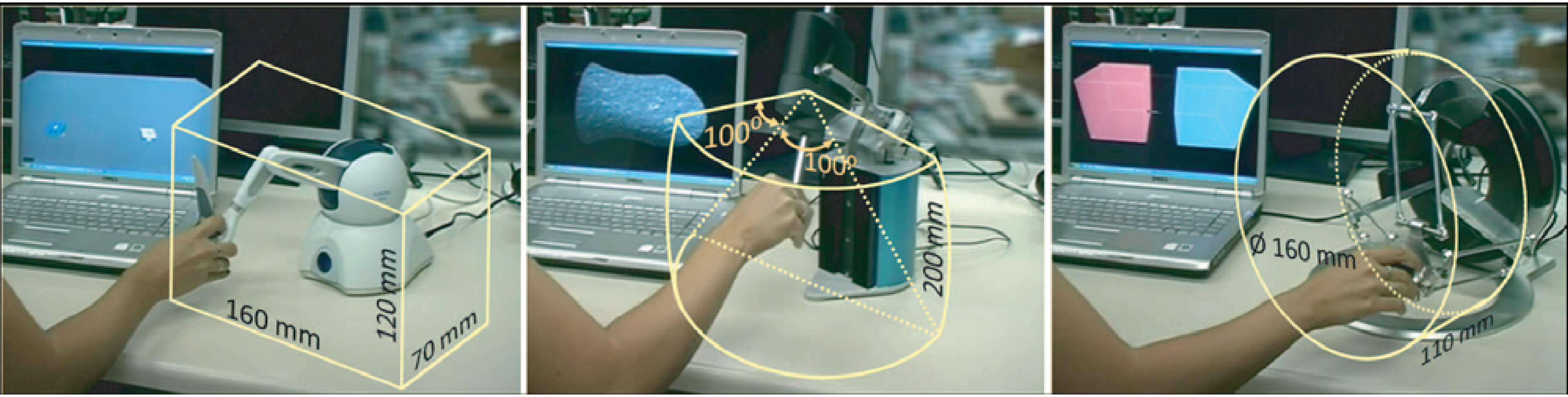
- Object Identification
  - Size
  - Shape

– to evaluate how well a device supports geometric identification of an object

References: Samur et al. (2007), Samur (2012)

Experiments

- Standard multi-threaded VE
- Three force feedback devices
  - diverse characteristics
- 15 subjects (5 per device)
- Overall 7 experiments (321 trials) per device



Psychophysical Testbeds

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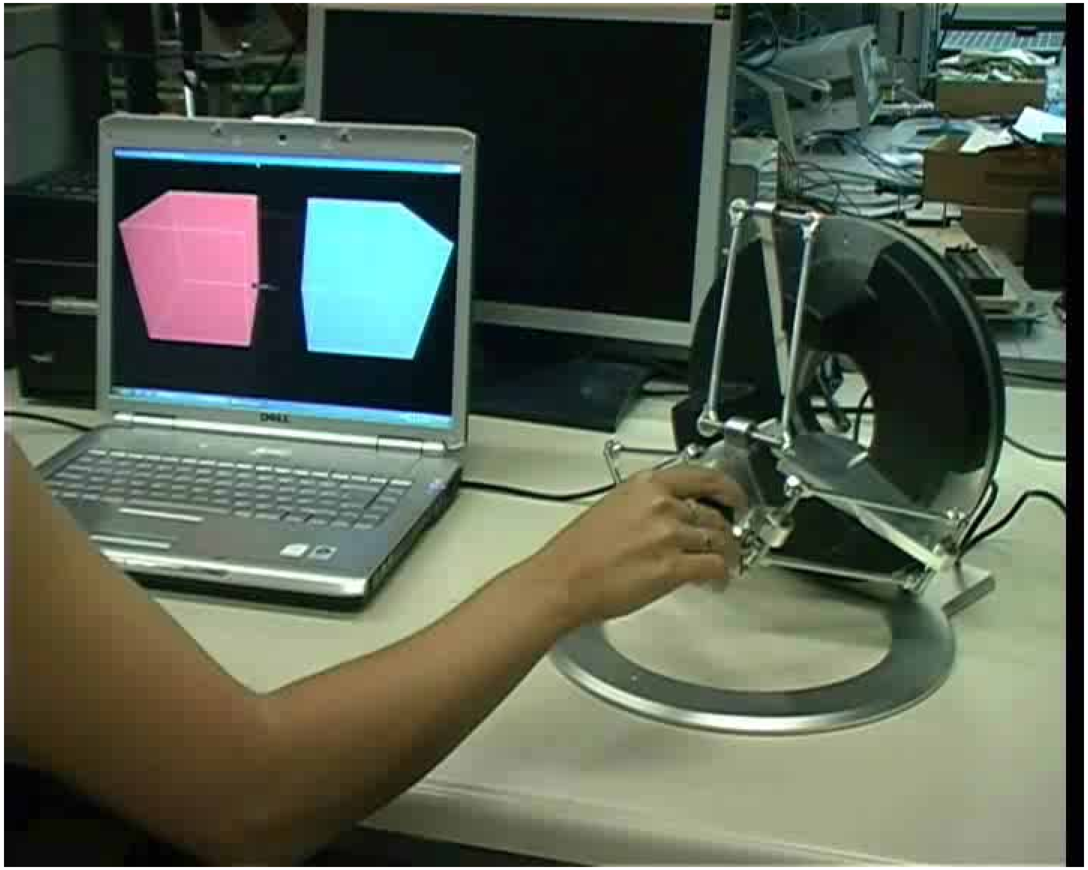
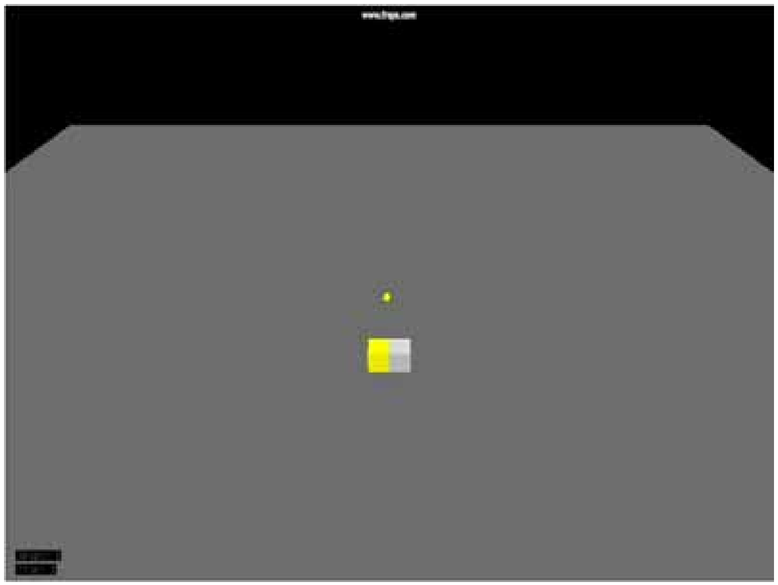


#1 Travel & Selection

- Fitts' tapping task



References:

Fitts (1954)
Hannaford et al. (1991)
MacKenzie (1992)
Wall & Harwin (2000)
Chun et al. (2004)

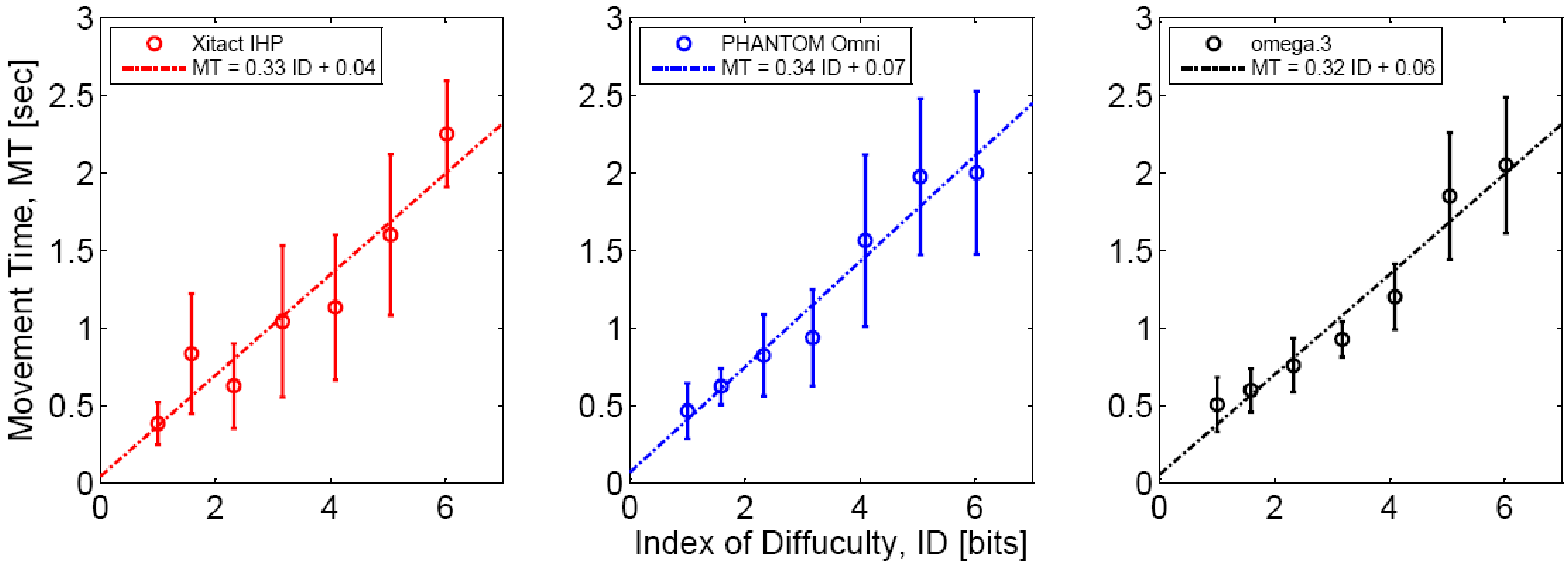
– Users are asked to tap alternately two virtual plates
  - Different size & distance
  - # of tabs are recorded
– Fitts' law:

$$MT = a + b\log_2(A/W + 1)$$

– Index of Difficulty (ID)
  - in *bits*
– Performance metrics:
  - IP (1/b) in *bit/s*
  - Intercept (a)

#1 Travel & Selection

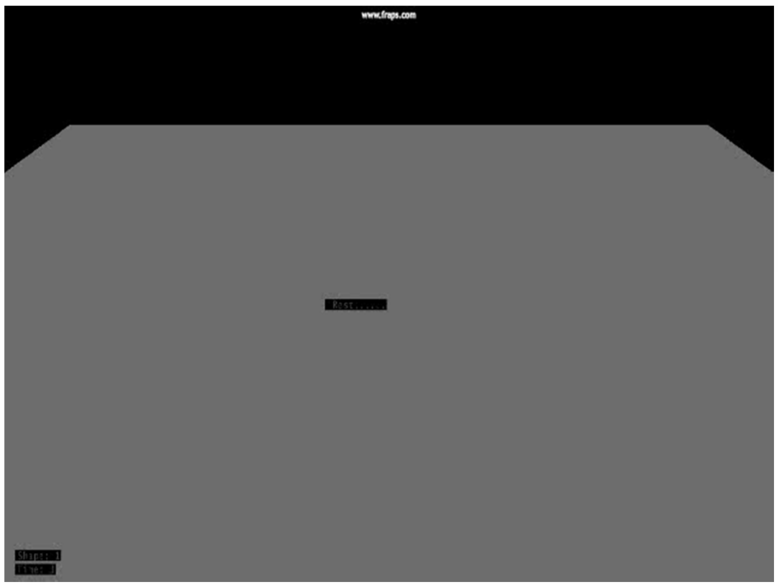
- Experimental Results



  - No significant difference between groups' mean and std
  - Same performance: IP ≈ 3 and the intercept a ≈ 0.06
  - Fitts' original experiment IP = 8 & Computer mouse IP = 4.5

#2 Selection & Manipulation

- Peg-in-hole test



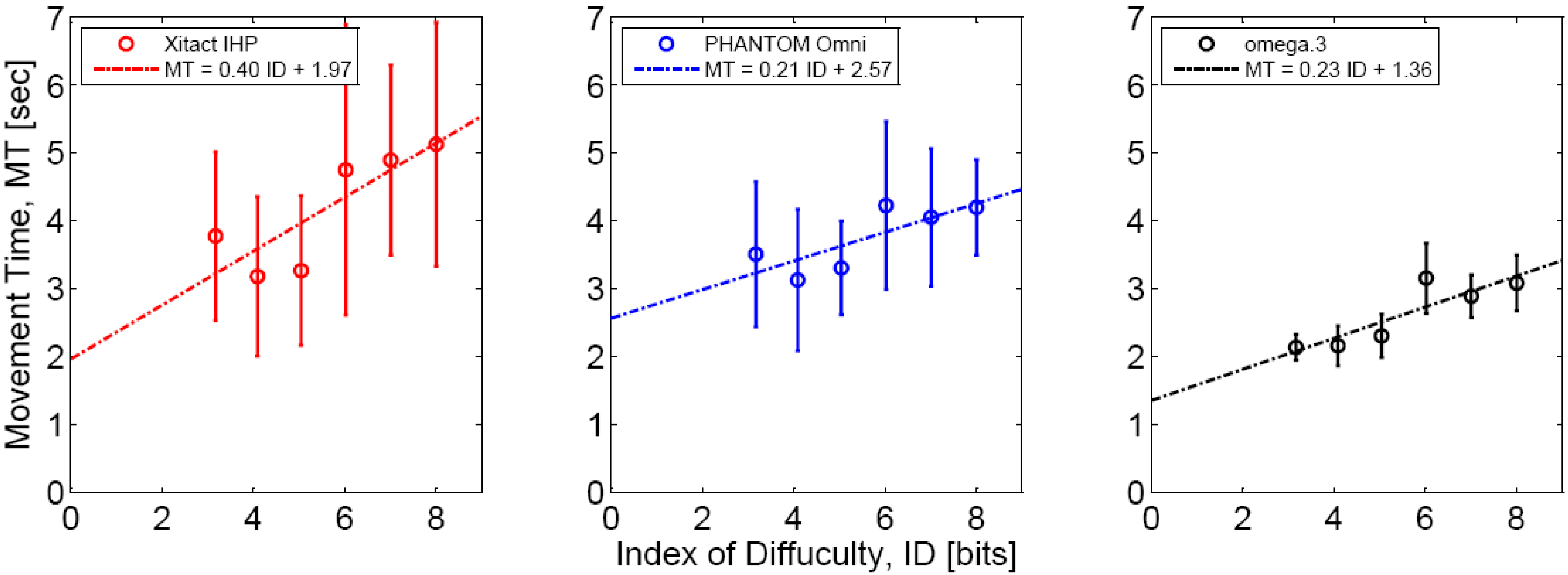
References:

Fitts (1954)
Hannaford et al. (1991)
MacKenzie (1992)
Harders et al. (2006)
Unger et al. (2001)

- Users select an object from a group and place it within a target area
  - Time is recorded
- Fitts’ law
- Index of Difficulty (ID)
  - Different precision & distance
- Performance metrics:
  - IP (1/b) in *bit/s*
  - Intercept (a)

#2 Selection & Manipulation

- Experimental Results



  - Mean differences are statistically significant
  - Phantom Omni & omega.3 enables faster movements IP ≈ 4.5
  - Haptic feedback by omega.3 is more appropriate a = 1.36

#3 Detection

- Force detection
  - Method of constant stimuli
  - Users response whether the stimulus detectable or not
  - Performance metric:
    - Absolute threshold for force
  - Force stimuli
    - 0.1 to 0.6 N with 0.1 increments
    - Three axis (X,Y and Z) and two directions (+ & -)

References:

Salisbury et al. (2011)

#3 Detection

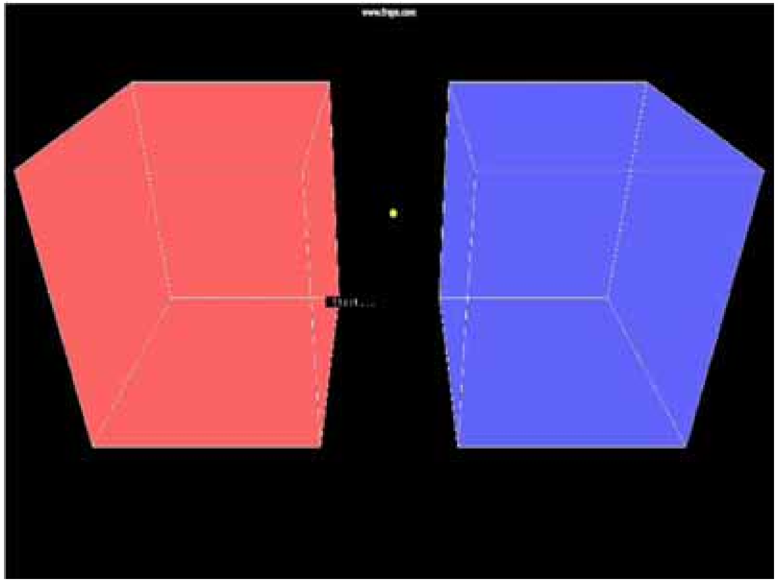
- Experimental Results

Performance Metric	Axis	Xitact IHP	PHANTOM Omni	omega.3	Unit
Absolute Threshold	X (+, -)	0.6, 0.6	0.3, 0.2	0.3, 0.2	N
	Y (+, -)	0.3, 0.2	0.4, 0.5	0.3, 0.2	N
	Z (+, -)	0.4, 0.5	0.2, 0.3	0.5, 0.4	N
Dynamic Range	X	19	13	36	dB
	Y	40	7	36	dB
	Z	20	13	30	dB

  - Only stimulus and direction were statistically significant
  - Xitact IHP cannot generate lower forces on the left-right axis due to the higher transmission ratio on this axis
  - Human's force sensitivity on fingertips is 0.06 N
  - Omni has considerably narrow force rendering range

#4 Discrimination

- Force

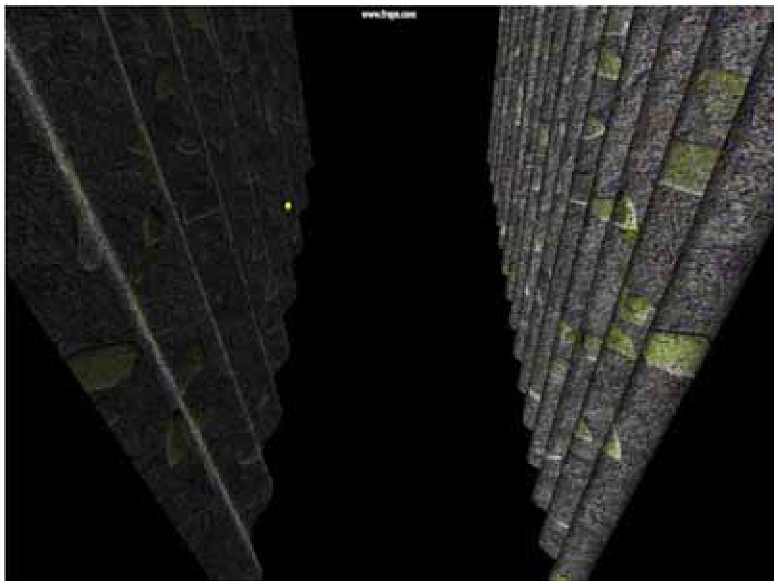


References:

– Method of constant stimuli
– Users response whether the stimulus perceived differently than the reference or not
– Performance metric:
  - Weber fractions
– Force stimuli
  - 1.0 to 6.0 N with 1.0 increments
  - Weber fractions from 0.1 to 0.6
  - Three axis (X,Y and Z) and two directions (+ & -)

#5 Discrimination

- Texture



References:

Weisenberger et al. (1991)
Wall & Harwin (2001)

– Periodic gratings
– Users determine whether they can distinguish difference between periods of gratings.
– Performance metric:
  - Weber fractions
– Sinusoidal stimuli
  - Spatial period 1.0 to 6.0 mm with 1.0 increments
  - Weber fractions up to 0.5

#4 & 5 Discrimination

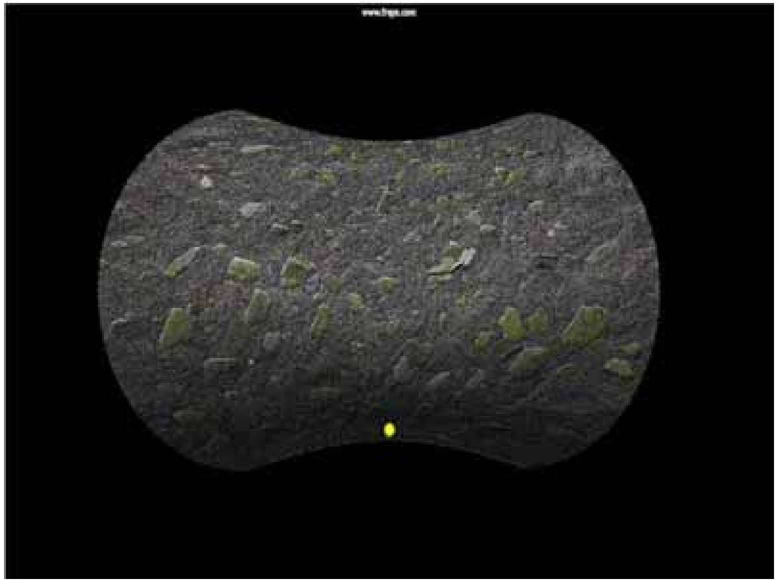
- Experimental Results

Variable	Axis	Xitact IHP	PHANTOM Omni	omega.3
Force	Y	0.5	0.4	0.3
	Z	0.4	0.5	0.3
Texture	Z	0.5	0.4	0.4

  – Omega has better force resolution and haptic transparency however it is still 3 times higher than human's force discrimination threshold for force (0.10 = Perfect transparency)
  – Weber fractions of the distinguishable spatial period are much higher than the one of humans (0.02) when touching real textured surfaces

#6 & 7 Identification

- Size & Shape



References:

Tan (1997)

Kirkpatrick & Douglas (2002)

O'Malley & Goldfarb (2002)

Murray et al. (2003)

- Size identification
  - A virtual sphere (no vision)
  - Haptically identifying four different sizes of spheres
- Shape identification
  - 4 quadratic shapes (no vision)
  - Haptically identifying 4 different quadratic shapes
- Performance metric:
  - Information transfer (IT) in *bits*

$$IT_{est} = \sum_{j=1}^{k}\sum_{i=1}^{k} \frac{n_{ij}}{n} \log_2\left(\frac{n_{ij}.n}{n_{i}.n_{j}}\right)$$

#6 & 7 Identification

- Experimental Results

Testbed	Xitact IHP	PHANTOM Omni	omega.3	Unit
Size	1.36	1.36	1.74	*bits*
Shape	1.12	1.30	1.65	*bits*

< 2 bits

  - Identification performance of human (3-4 categories)
  - Performance is degraded by the use of the haptic interfaces
  - Differences might be attributed to the device kinematics
    - Surgery specific kinematic design of Xitact IHP impedes geometric identification
    - Parallel kinematics of Omega (handle always parallel to the base) provides more natural exploration

Conclusions

- Literature
- Physical Evaluation
- Psychophysical Evaluation
- Synthesis

Conclusions

- Synthesis of Physical and Psychophysical methods

Psychophysical Testbeds			Physical Evaluation			
Aim	#	Metric	Kinematics	Actuation	Sensing	Impedance
Motor Control	1 2	IP, a	Workspace DOF			Min Max
Force Perception	3 4	Abs. threshold Force JND		Min force Resolution Max force		
Texture Perception	5	Position JND		Bandwidth	Resolution	
Geometry Perception	6 7	IT	Structure DOF			Max

References - Physical Evaluation (1)

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References - Physical Evaluation (2)

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Thank you for your attention!

QUESTIONS?

RIC
Rehabilitation Institute *of* Chicago

Evren Samur
e-samur@northwestern.edu