Admittance-based Haptic Interface Performance Evaluation and Associated Challenges



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Why? What?

Performance Evaluation and Associated Challenges

Device Types



Admittance-based Devices
 Generally non-backdrivable
 Requires a task-space force/torque sensor Requires closed-loop controller
HapticMaster
Admittance-based
rendering high inertia
high stiffness
rce / power high
omplexity high

THE UNIVERSITY **Effect of Actuation Characteristics** Haptic device actuation dominant **EM** actuators 1.0 Normalized Torque Power efficiency Efficiency nax power 0.5 Overview: [Hollerbach et al 1992] low torque density max maximum power / efficiency at high velocity $\omega_{NI} \sim 1k - 10k RPM$ 0.0 Angular velocity Commonly paired with gear reduction **Amplifies motor dynamics** increases output torque as seen at output motor inertia x N² for high torque applications but ... motor friction = coulomb x N deceases output velocity viscous x N^2 \rightarrow operate closer to P_{max} torque amplification т $\tau_o = N \tau_m$ -**Actuation characteristics** $au_m heta_m$ constrain $=\frac{\theta_a}{\dot{\theta}}$ reflected inertia: **Device characteristics** $I_o = N^2 I_m -$



Simplified Device Model:



Output Impedance:

$$Z_{out}(s) = \frac{\mathcal{T}_a(s)}{\theta(s)}$$

alternative definition $\frac{\tau_a(s)}{\omega(s)}$



Output Impedance (Uncompensated)





Output Impedance (Uncompensated)







Output Impedance (Uncompensated)



Equivalent Viscous-Coulomb Friction

Coulomb Friction \Box **Equivalent Viscous Friction Model**



Equate work done over 1-cycle

$$W = \int_{0}^{T} P dt - \begin{cases} \text{Viscous:} \\ W = \pi A^{2} \omega c_{m} \\ \text{Coulomb:} \\ W = 4A\tau_{f} \end{cases} c_{m} = \frac{4\tau_{f}}{\pi A\omega} \quad \text{Equivalent viscous friction} \end{cases}$$



Output Impedance (Uncompensated)





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Output Impedance (Uncompensated)



Control Approach



Admittance-based systems require feedback

- feedback is required to overcome device characteristics:
 - o non-backdriveable
 - o high reflected inertia

- Numerous control strategies have been adopted
 - explicit force control virtual impedance

example control architecture – explicit force control



Control Approach



Admittance-based systems require feedback

- feedback is required to overcome device characteristics:
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- Numerous control strategies have been adopted
 - explicit force control virtual impedance
 - inner position loop virtual admittance

example control architecture – inner position loop



Closed-Loop Output Impedance





- Low frequency transparency can approach zero
 - Only limited by sensor and controller limitations
 - Quantification of transparency at DC may not be well defined
- BUT ... rendering *low inertia* is *hard* for admittance devices ... why?

Rendering Challenge: Low Inertia

Simplified system model:



Rendering Challenge: Low Inertia

Simplified system model:



Evaluation using human subjects



Device-user evaluation of rendering limits:



Evaluate range of stable virtual impedance via direct user-device interaction

$$Z_{des}(s) = ms^2 + cs + k$$

Advantages:

- Direct determination of rendering limits / stability bounds including minimum inertia (for admittance systems)
- end-to-end system evaluation

Disadvantages:

- Subjective evaluation of stability limits
- Human subject variability and grasp variability
- Difficult to measure robustness

Emulated human-impedance



Passive impedance emulation



Active impedance emulation



- Active emulation of impedance
- e.g. Series Elastic Actuation (SEA) or its derivatives

Evaluate range of stable virtual impedance using emulation of human impedance

Advantages:

- good repeatability
- Allows evaluation of robustness

Disadvantages:

- no commonly accepted human impedance model
- complexity of hardware setup
- difficulty evaluating complete device workspace

THE UNIVERSITY W WISCONSIN Measurement of Output Impedance Force $\mathbf{F}_d(s) = 0$ $\mathbf{F}_{o}(s)$ Control D(s) $\mathbf{X}_{o}(s)$ **Minimum inertia** via Output impedance -Force Sensor with explicit Virtual Impedance force control $\mathbf{Z}_{v}(s)$

$$\mathbf{F}_{o}(s) = \mathbf{T}_{f/d}(s)\mathbf{F}_{d}(s) + \mathbf{T}_{f/x}(s)\mathbf{X}_{o}(s)$$

$$\mathbf{F}_{o}(s) = \mathbf{T}_{f/x}(s)\mathbf{X}_{o}(s)$$
set desired force, $\mathbf{F}_{d} = 0$
Generally simplify to 1 DOF (ignore coupling)
output impedance

$$\frac{F_{o}(s)}{X_{o}(s)} = \overline{T_{f/x}(s)} = Z_{o}(s) - determine transparency and I_{min} \text{ from } Z_{o}(s)$$

Output impedance Measurement – systems *with explicit* force control

$$Z_o(s) = \frac{F_o(s)}{X_o(s)}$$

Measurement options:

Position input **Force** measurement Force input **Position measurement**

Position input:

- Typical method for impedance based device
- Use of high impedance position/velocity source
- Challenging for admittance-based devices
 - Not useable above ω_{Cl} of haptic device controller
 - Can reduced position controller gains for testing [Ueberle, Buss 2002]

Force input:

- Well suited to admittance-based devices
- Force sources are challenging to implement
 - Ideal source has zero output impedance
 - Source dynamics can distort and destabilize system

Measurement of Output Impedance W

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Indirect measurement of output impedance – *with explicit force control*

[Chapius 2009]	$F_o(s) = T_{f/d}(s)F$	$T_d(s) + T_{f/x}(s)X_o(s)$
Fixed end-poin	input: $F_d(s)$	output impedance
	$X_o(s) = 0$ $K_o(s) = 0$ output: $F_o(s)$	$\frac{F_o(s)}{F_d(s)}\Big _{X_o=0} = T_{f/d}(s)$
Free end-point		
	input: $F_d(s)$ output: $X_o(s) = 0$	$\frac{X_o(s)}{F_d(s)}\Big _{F_o=0} = -\frac{T_{f/d}(s)}{T_{f/x}(s)}$

Measurement of Output Impedance W

Indirect measurement of output impedance – *with explicit force control*





Systems without explicit force control:



Partition system and evaluate via modeling & experiment

- Position controlled device
- Human-impedance
- Virtual impedance (or admittance)



Systems without explicit force control:





high bandwidth position controller

- high output impedance
- loading effects negligible







Systems without explicit force control:



Partition system and evaluate via modeling & experiment

- Position controlled device
- Human-impedance
- Virtual impedance (or admittance)

• Evaluate stable virtual admittances (e.g. stability margins)



Advantages / Disadvantages: stability margins to estimate range of stable virtual impedances

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Relies on human impedance model

Summary



- Admittance-based devices are fundamentally different than impedance-based devices
 - High open-loop output impedance
 - Characteristics are unavoidable
 - Rendering capabilities are different (opposite) than impedance-based devices
 - Low inertia is difficult
- Evaluation of rendering capability is challenging
 - High output impedance limits techniques
 - Various techniques used / suggested ... but more work is required

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