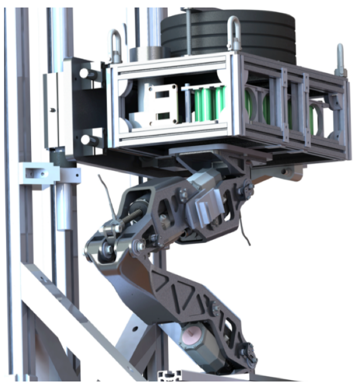
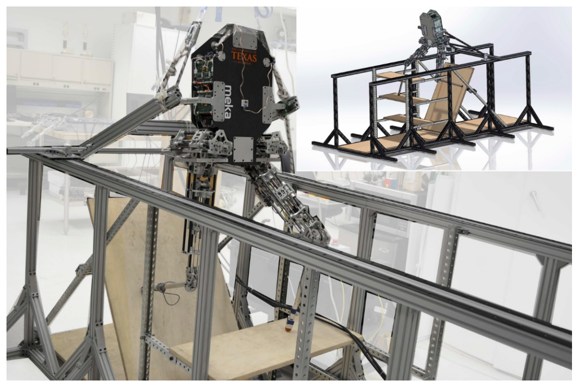
Stability and Control Performance Limits of Latency-Prone Distributed Whole-Body Operational Space Control





Ye Zhao

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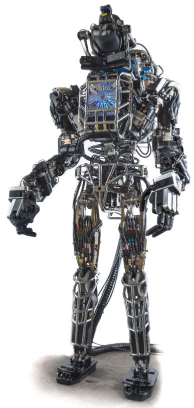
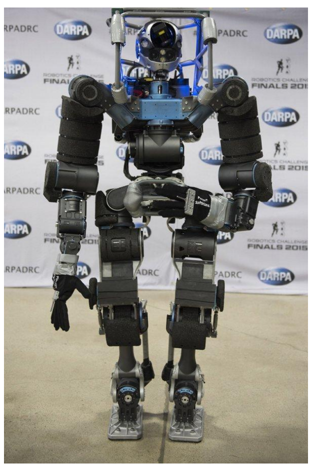
Human Centered Robotics Laboratory, The University of Texas at Austin

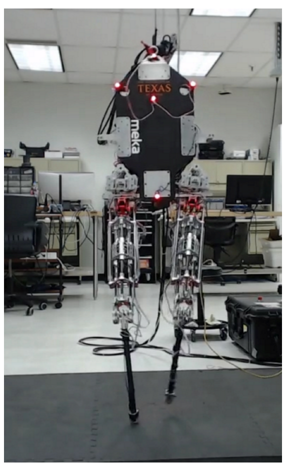
2016 Humanoid Workshop on Humanoid OS

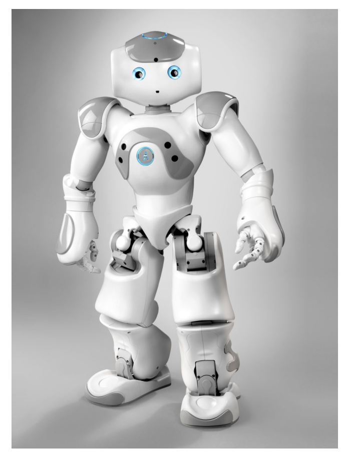
Motivation



Can humanoid robots achieve stability and real-time performance?







Fundamental Challenges

- Whole-Body Operational Space Control (WBOSC) with embedded actuator dynamics and feedback delays is an unsolved scientific problem
- **Actuator dynamics** and **time delays** are commonly ignored but play important roles in closed-loop system stability and control performance
- It is crucial to formulate and experiment control frameworks to achieve optimal, safe and real-time performance with environmental/human interaction.
- Existing impedance control methods lack performance measures.
- Stability/passivity of Whole-Body Operational Space Control require more investigations.

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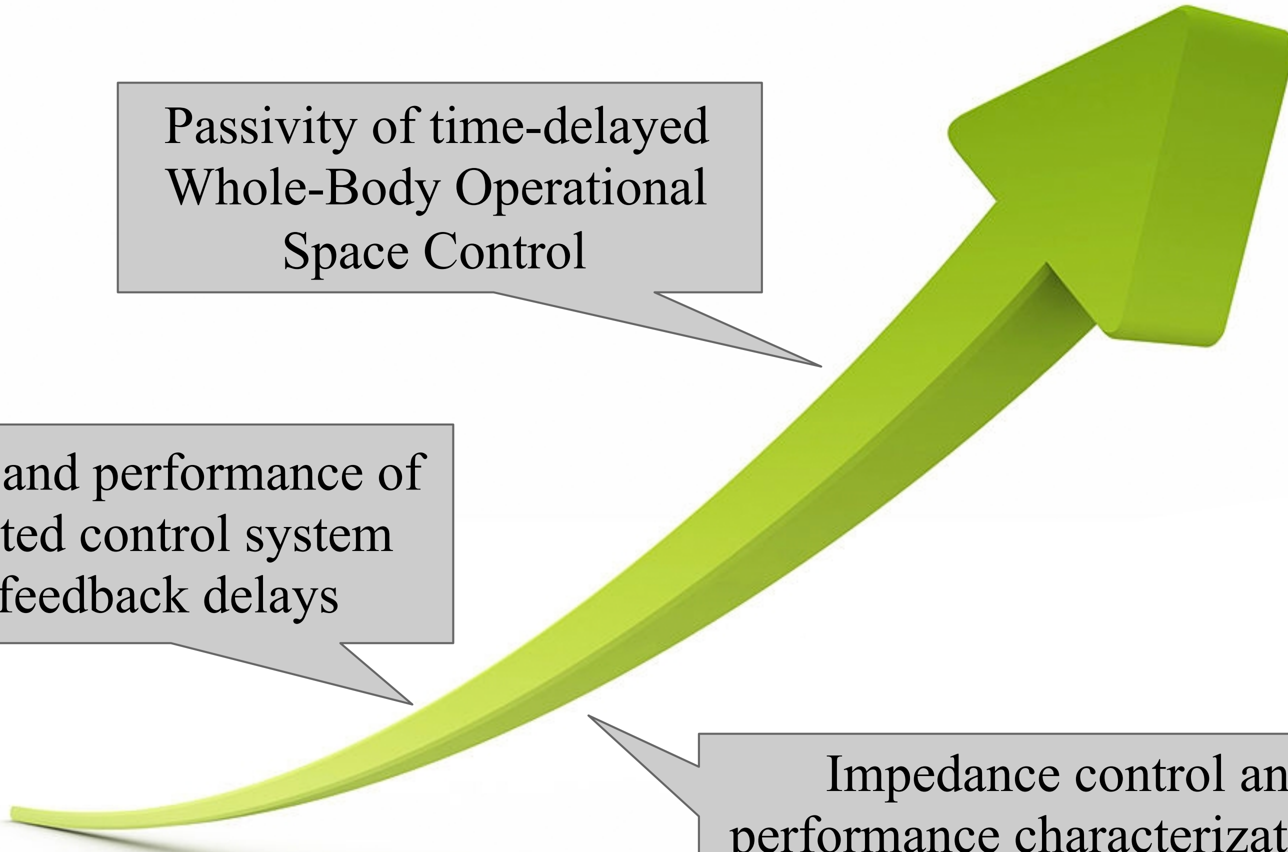
Objective

To formulate and reason about a distributed Whole-Body Operational Space Control framework with feedback delays and series elastic actuator dynamics for humanoid robots to achieve complex tasks.

Roadmap

Distributed Whole-Body Operational Space Control of humanoid robots in cluttered environments



Passivity of time-delayed Whole-Body Operational Space Control

Stability and performance of distributed control system with feedback delays

Impedance control and performance characterization of series elastic actuators

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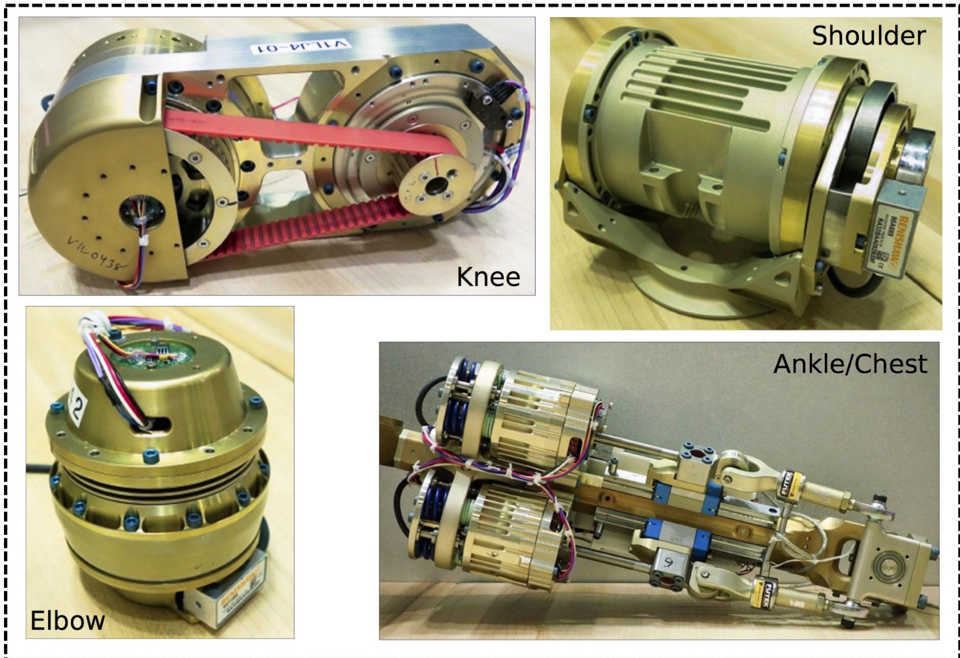
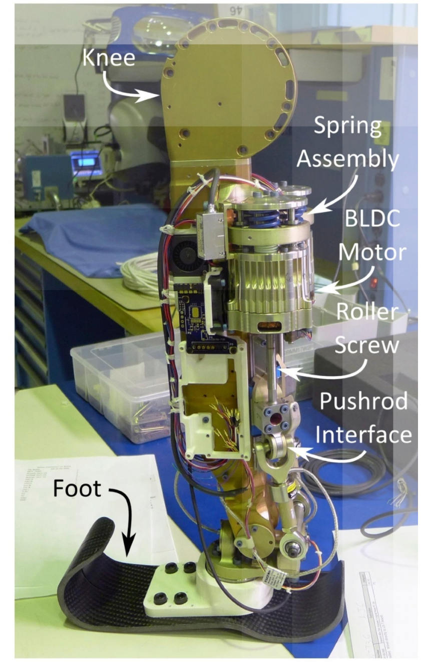
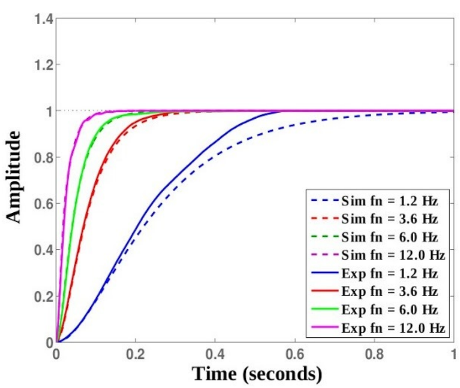
Physical Observation

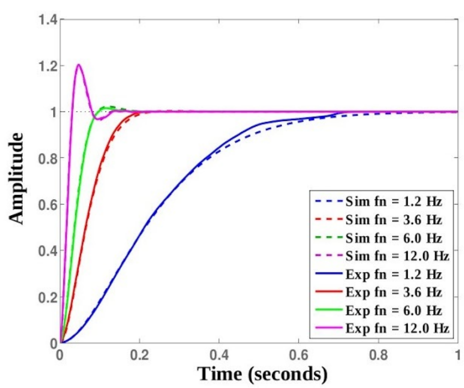




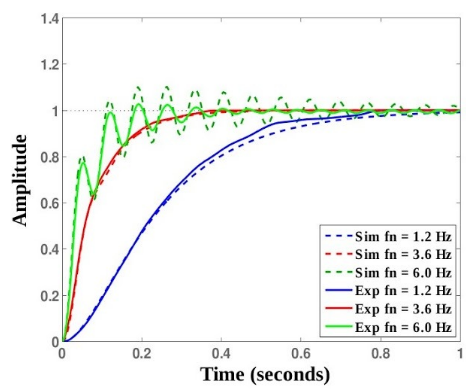
(a) Ts = 1 ms, Td = 1 ms



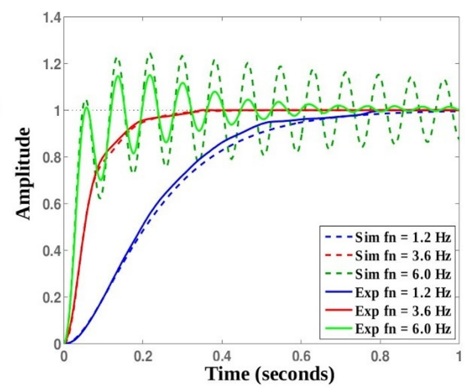
(b) Ts = 15 ms, Td = 1 ms



(c) Ts = 1 ms, Td = 15 ms



(d) Ts = 15 ms, Td = 15 ms



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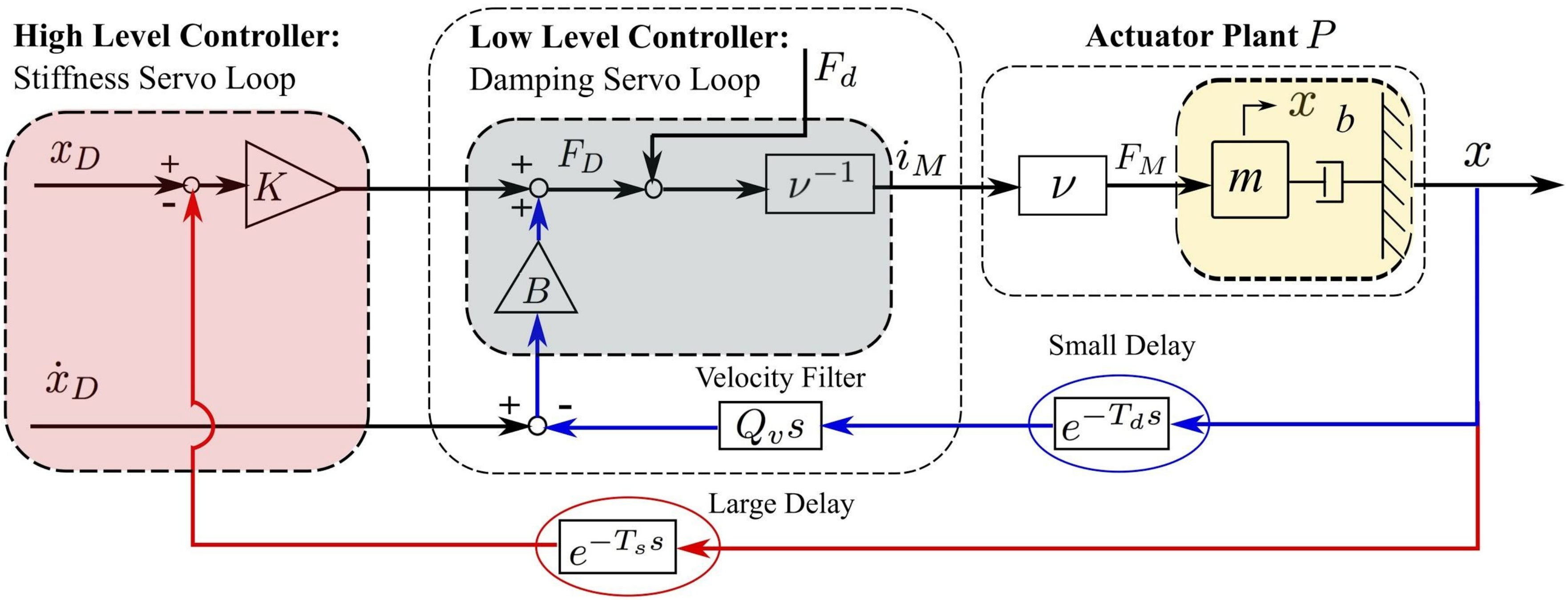
[Zhao, et. al, IEEE Trans. Industrial Electronics 2015]

Distributed Impedance Control Diagram

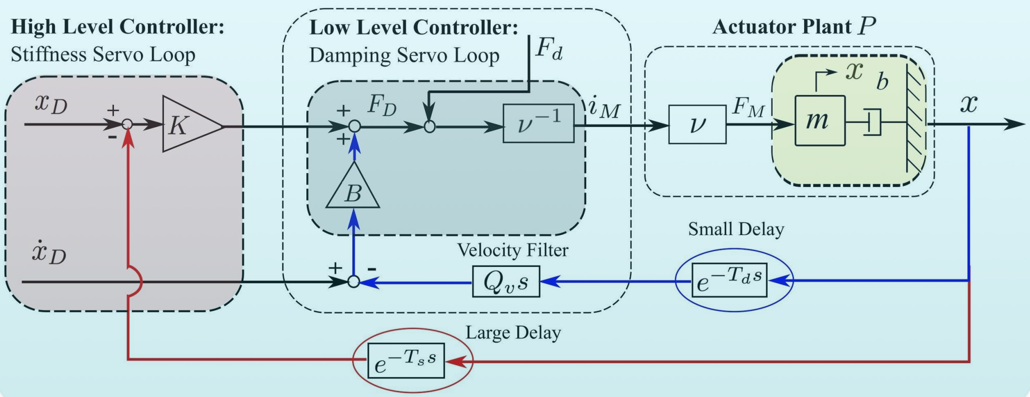


$$P_{CL}(s) = \frac{x}{x_D} = \frac{Bs + K}{ms^2 + (b + e^{-T_d s} B Q_v)s + e^{-T_s s} K}$$

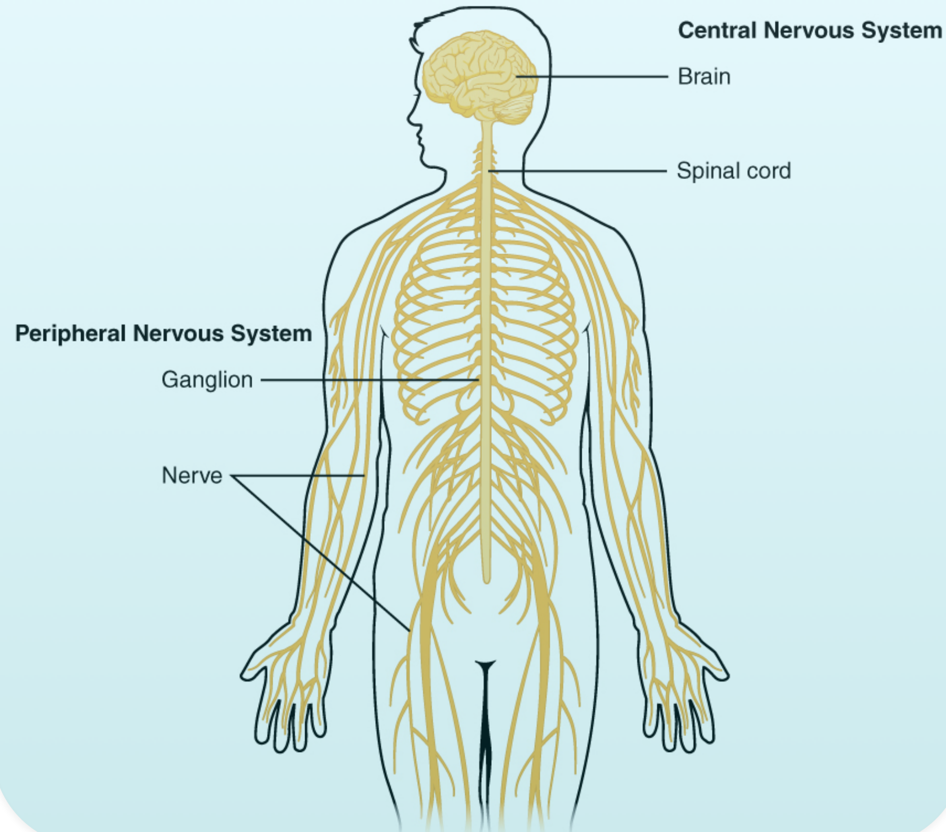
[Zhao, et. al, IEEE Trans. Industrial Electronics 2015]

Distributed Control Analogy: Robot and Human Nervous System

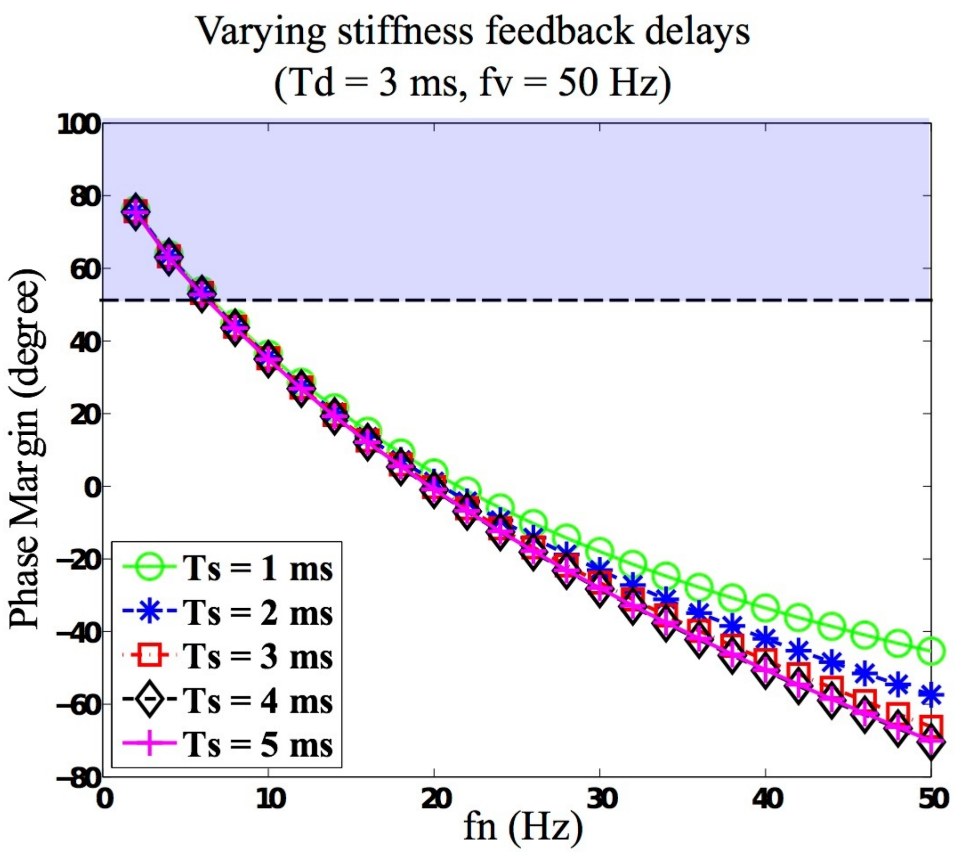
Distributed Robot Control System

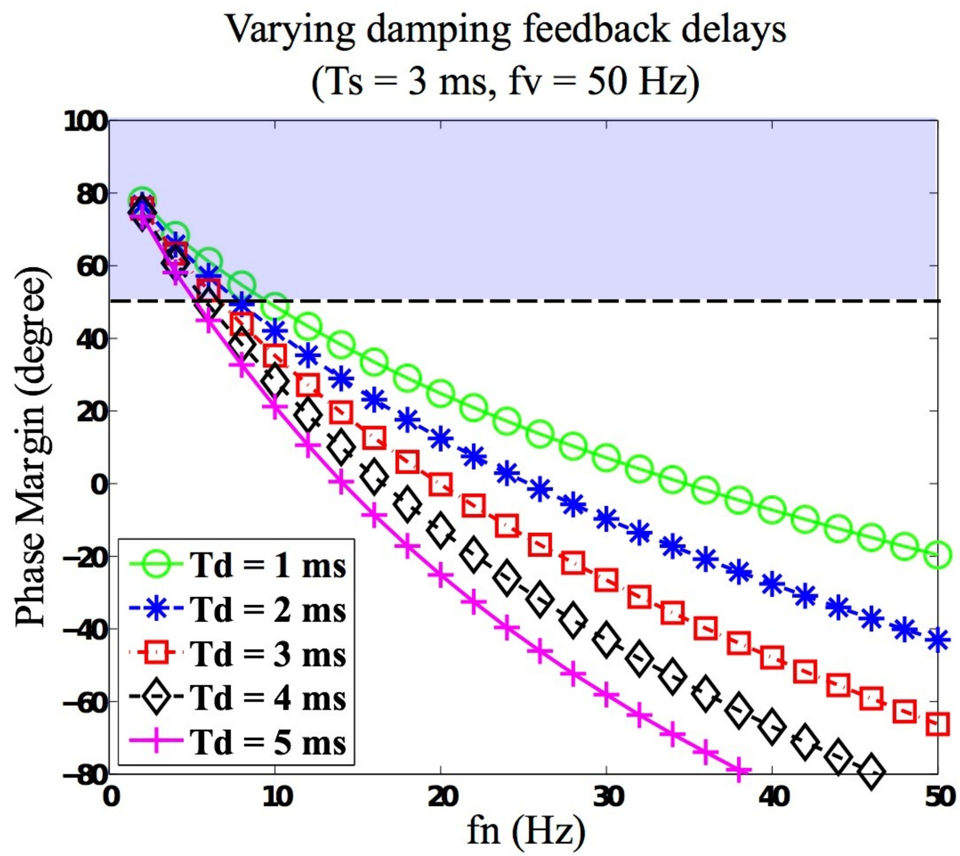


Human Nervous System



Stability Sensitivity to Different Time Delays





Sensitivity to damping delay > Sensitivity to stiffness delay

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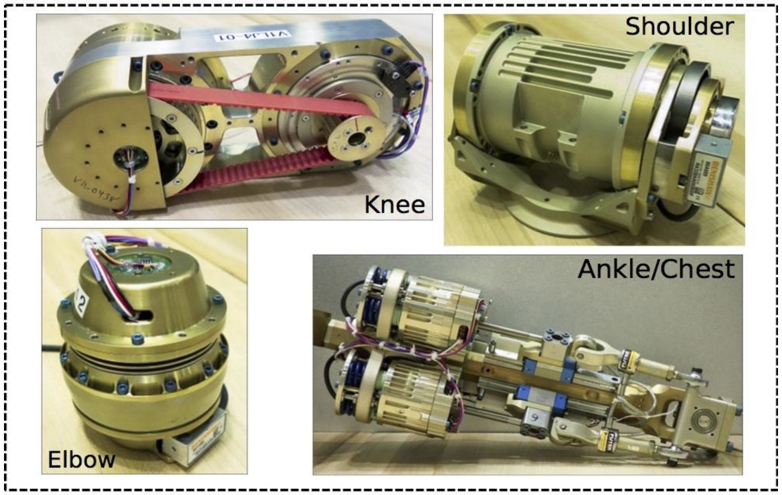
[Zhao, et. al, IEEE Trans. Industrial Electronics 2015]

Sensitivity Discrepancy Analysis

Valkyrie Actuators



Maximum Allowable Damping Gains for Effective Delays of 0.5ms

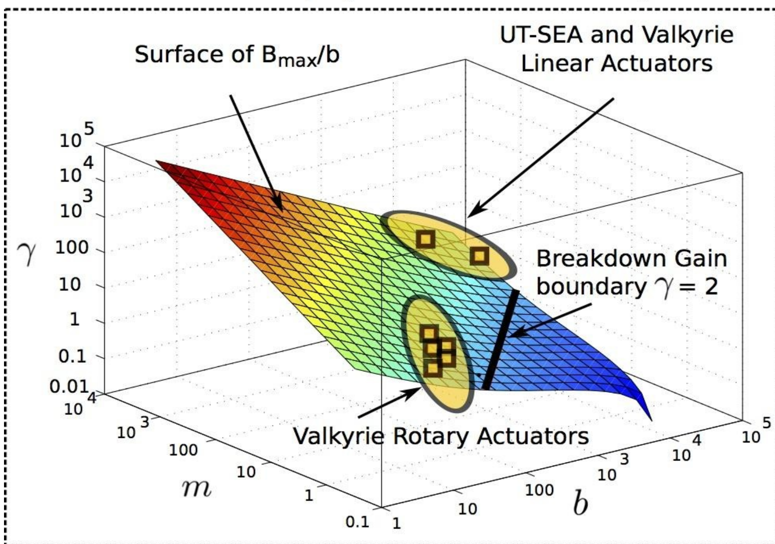


TABLE I: UT-SEA/Valkyrie Actuator Parameters

Actuator Type	output inertia m	passive damping b	damping gain B	ratio γ
UT-SEA	360 kg	2200 N·s/m	50434 N·s/m	22.92
Valkyrie 1	270 kg	10000 N·s/m	46632 N·s/m	4.66
Valkyrie 2	0.4 kg·m^2	15 Nm·s/rad	68 Nm·s/rad	4.55
Valkyrie 3	1.2 kg·m^2	35 Nm·s/rad	196 Nm·s/rad	5.60
Valkyrie 4	0.8 kg·m^2	40 Nm·s/rad	145 Nm·s/rad	3.61
Valkyrie 5	2.3 kg·m^2	50 Nm·s/rad	360 Nm·s/rad	7.20
Valkyrie 6	1.5 kg·m^2	60 Nm·s/rad	259 Nm·s/rad	4.32

- Phase margin sensitivity to time delays

$$\frac{\partial PM}{\partial T_d} < \frac{\partial PM}{\partial T_s}$$

- Servo breakdown gain rule

$$B > 2b$$

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[Zhao, et. al, IEEE Trans. Industrial Electronics 2015]

UT Actuator Tracking

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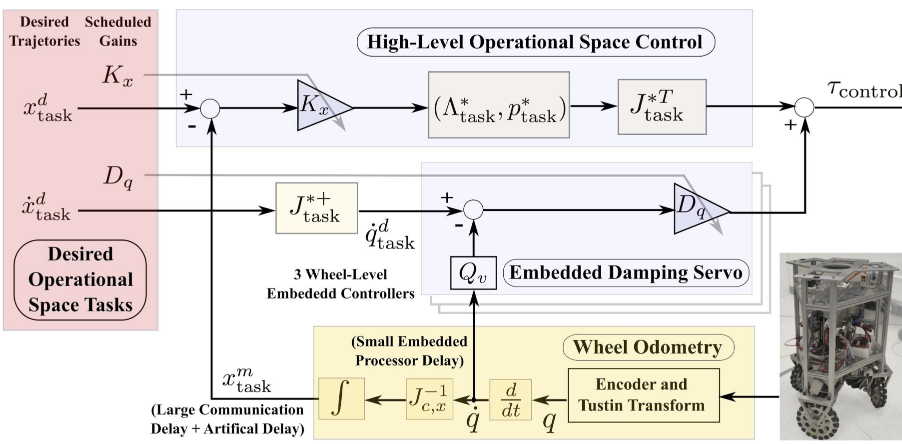
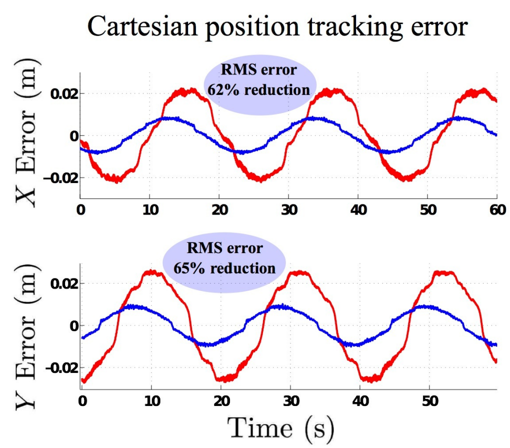
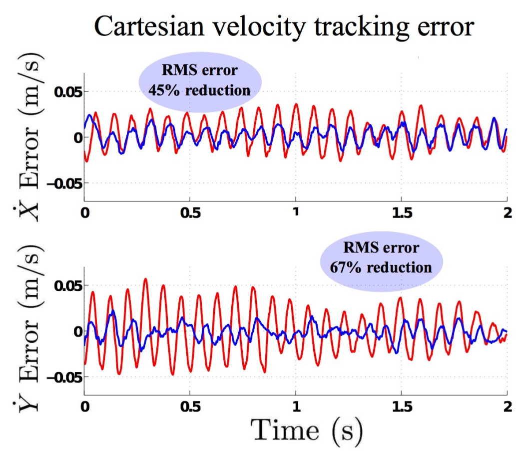
[Zhao, Paine, Sentis, DSCC 14]

How about MIMO systems?

Distributed Operational Space Control





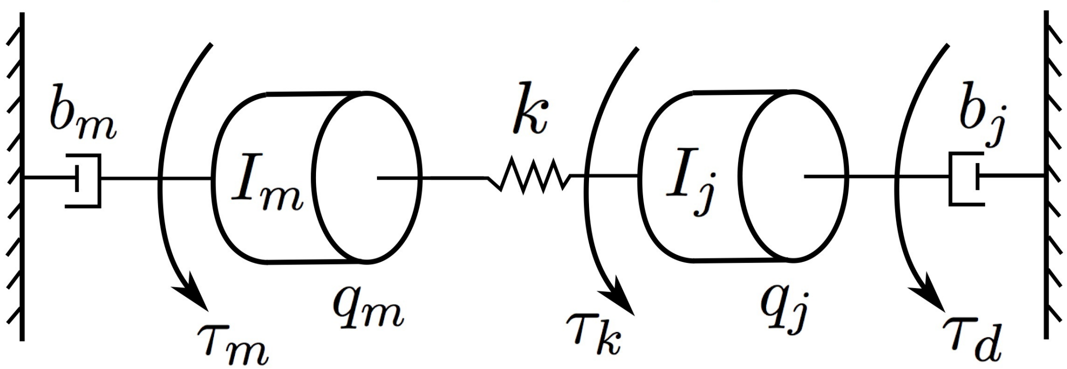


[Zhao, et. al, IEEE Trans. Industrial Electronics 2015]

How about actuators with high-order dynamics?

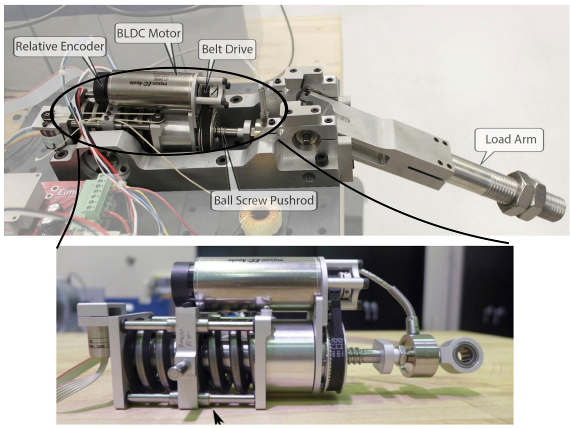
e.g., series elastic actuator.

SEA Plant (P_F)

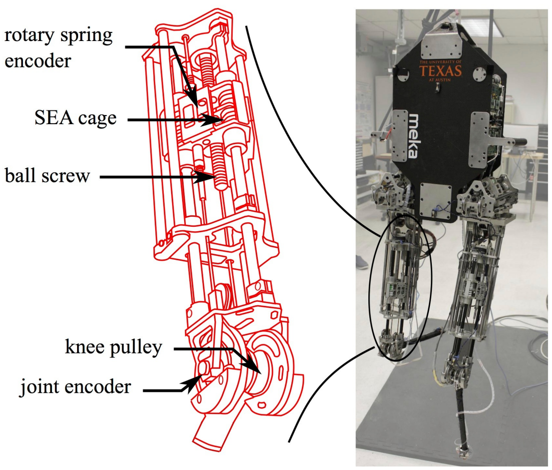


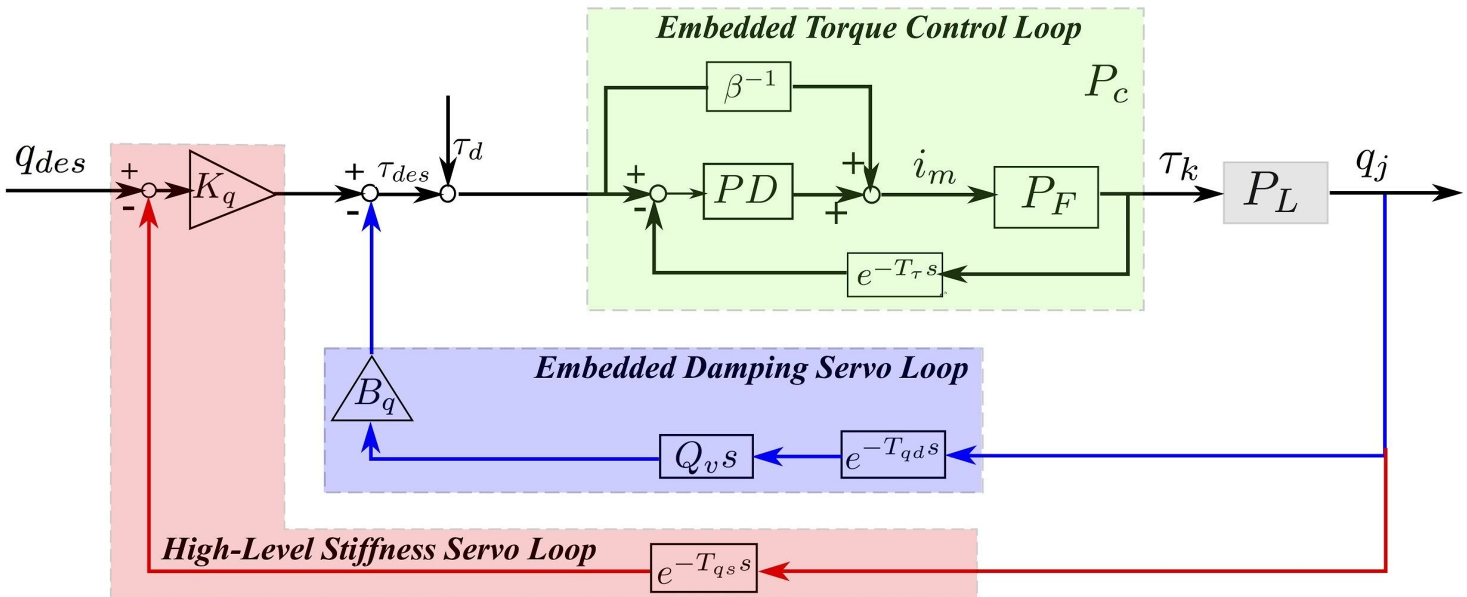
SEA Control Diagram

UT-SEA



Hume-SEA





$$P_{CL}(s) = \frac{q_j(s)}{q_{des}(s)} = \frac{K_q P_C P_L}{1 + P_C P_L (e^{-T_{qd}s} B_q Q_{qd} s + e^{-T_{qs}s} K_q)}$$

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[Zhao, Paine, Sentis, Humanoids 2014]

Critically-damped Gain Selection Criterion

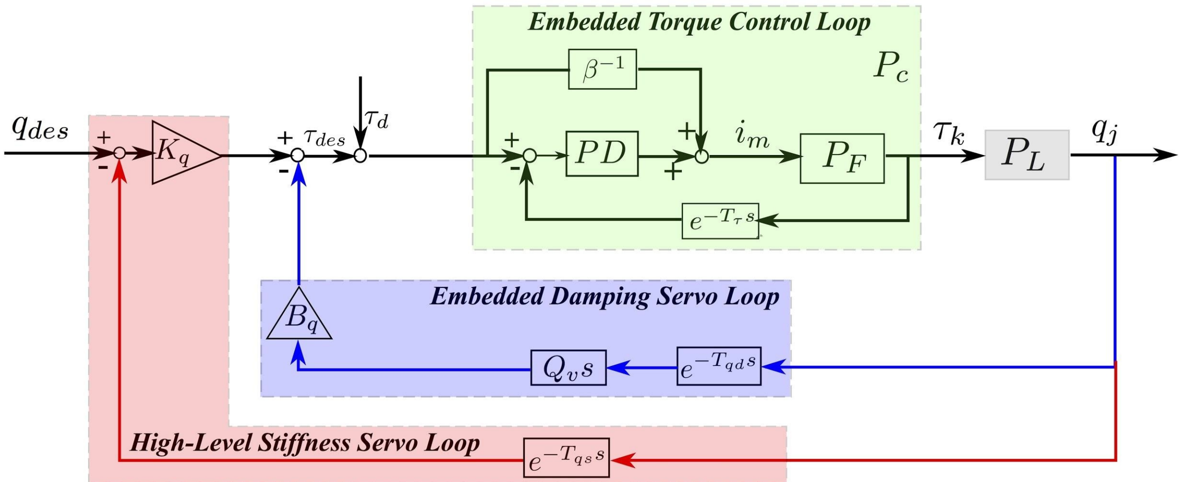


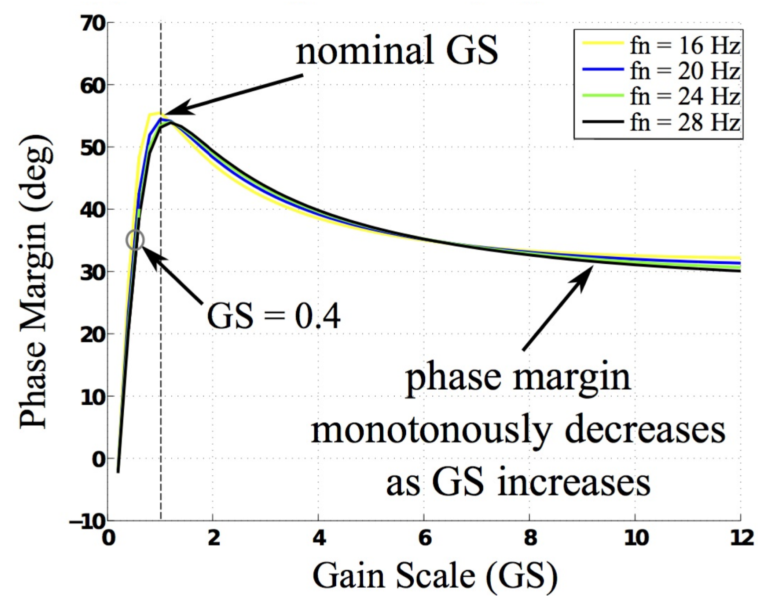
TABLE I
CRITICALLY-DAMPED GAIN SELECTION RULE

Frequency (Hz)	Impedance Gains (Nm/rad, Nms/rad)	Torque Gains (A/Nm, As/Nm)	Phase Margin
$f_n = 12$	$K_q = 65$ $B_q = 0.46$	$K_\tau = 1.18$ $B_\tau = 0.057$	49.1°
$f_n = 14$	$K_q = 83$ $B_q = 0.76$	$K_\tau = 1.80$ $B_\tau = 0.067$	47.0°
$f_n = 16$	$K_q = 103$ $B_q = 1.02$	$K_\tau = 2.56$ $B_\tau = 0.077$	43.6°
$f_n = 18$	$K_q = 124$ $B_q = 1.26$	$K_\tau = 3.45$ $B_\tau = 0.087$	39.9°
$f_n = 20$	$K_q = 148$ $B_q = 1.49$	$K_\tau = 4.48$ $B_\tau = 0.097$	36.4°

- A **critically-damped** gain selection criterion is designed to deterministically solve all the gains.
- There exists a **trade-off** between torque and impedance feedback gains.
- A gain scale GS is proposed

$$GS = \frac{K_{\tau_a}}{K_{\tau_n}} = \frac{K_{q_n}}{K_{q_a}} \qquad GS = \frac{B_{\tau_a}}{B_{\tau_n}} = \frac{B_{q_n}}{B_{q_a}}$$

Optimal performance



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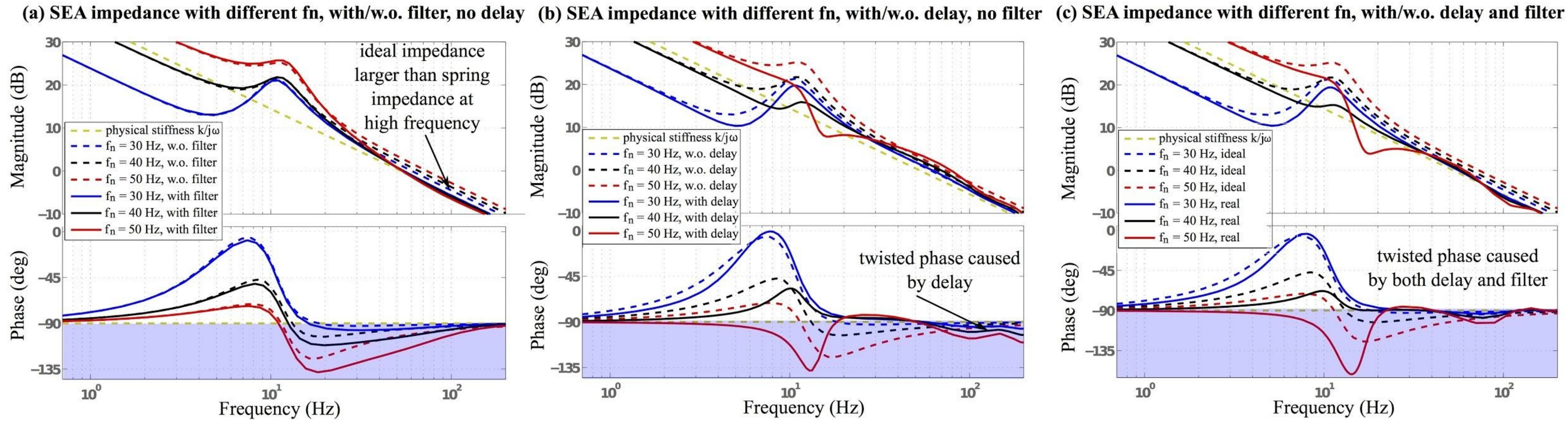
SEA Impedance Analysis with Time Delays and Filtering



- What type of metric can be used to quantify SEA impedance performance?

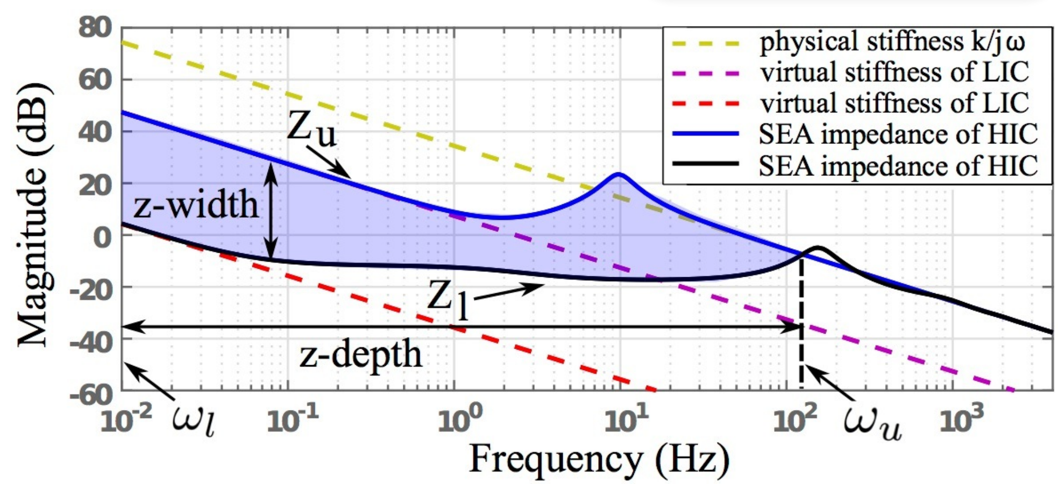
Z-width?

limited to magnitude range!

SEA Z-region

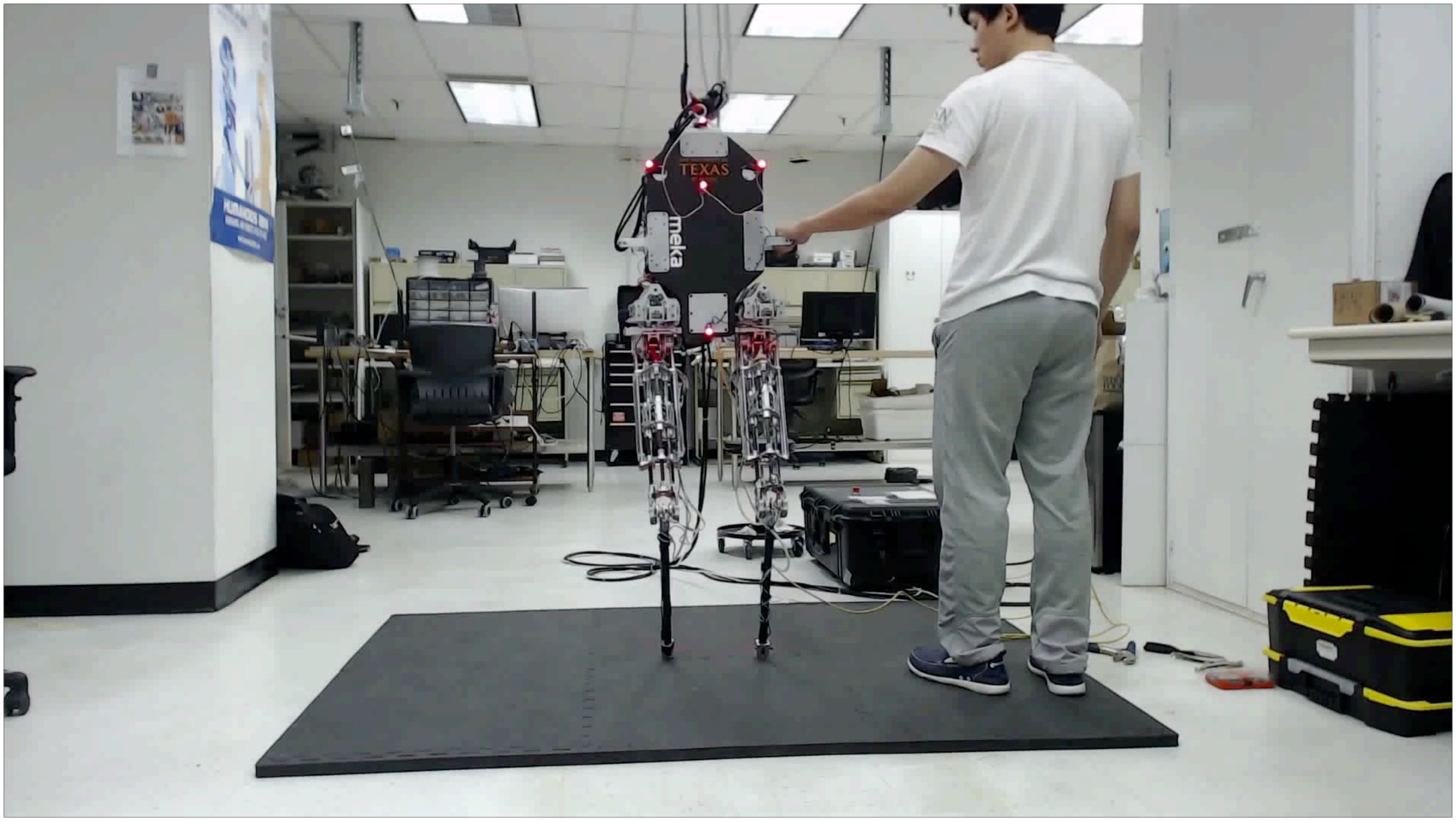
The SEA impedance performance can be measured by a Z-region, which is a frequency domain region composed of the achievable impedance magnitude range (Z-width) over a particular frequency range (Z-depth).

$$Z_{\text{region}} = \int_{\omega_l}^{\omega_u} W(\omega) \Big| \log|Z_u(j\omega)| - \log|Z_l(j\omega)| \Big| d\omega.$$



[Zhao, et. al, Sentis, IEEE Trans. Ind. Electron. 2016, in revision]

Dynamic Balancing on Hume Bipedal Robot



(Experiment lead by Donghyun)

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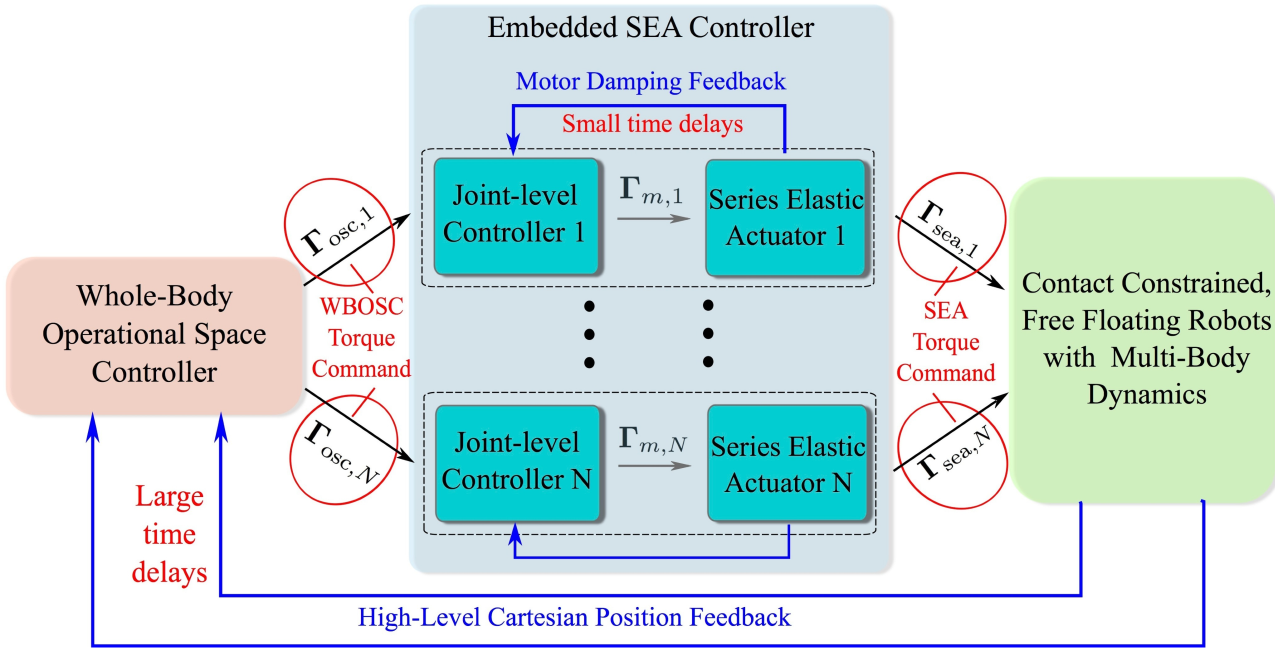
[Kim, Zhao, et, al, and Sentis, IEEE Trans. on Robotics 2016]

How about SEA + MIMO system?

Time-delayed Whole-Body Operational Space Control with SEA dynamics

SEA-aware Whole-Body Dynamics



Proposition: SEA-aware whole-body dynamics

Given an Euler-Lagrangian formalism, the following whole-body dynamics with the SEA model can be derived

$$\boldsymbol{A}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{N}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{J}_s^T \boldsymbol{F}_r = \boldsymbol{U}^T \boldsymbol{\Gamma}_{\text{sea}}, \tag{1}$$

$$\boldsymbol{B}\ddot{\boldsymbol{\theta}} + \boldsymbol{\Gamma}_{\text{sea}} = \boldsymbol{\Gamma}_m, \tag{2}$$

$$\boldsymbol{\Gamma}_{\text{sea}} = \boldsymbol{K}(\boldsymbol{\theta} - \boldsymbol{q}_j), \tag{3}$$

where $\boldsymbol{N}(\boldsymbol{q},\dot{\boldsymbol{q}}) = \boldsymbol{b}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q})$.

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[Zhao, and Sentis, Humanoids 2016] (ThPos.74)

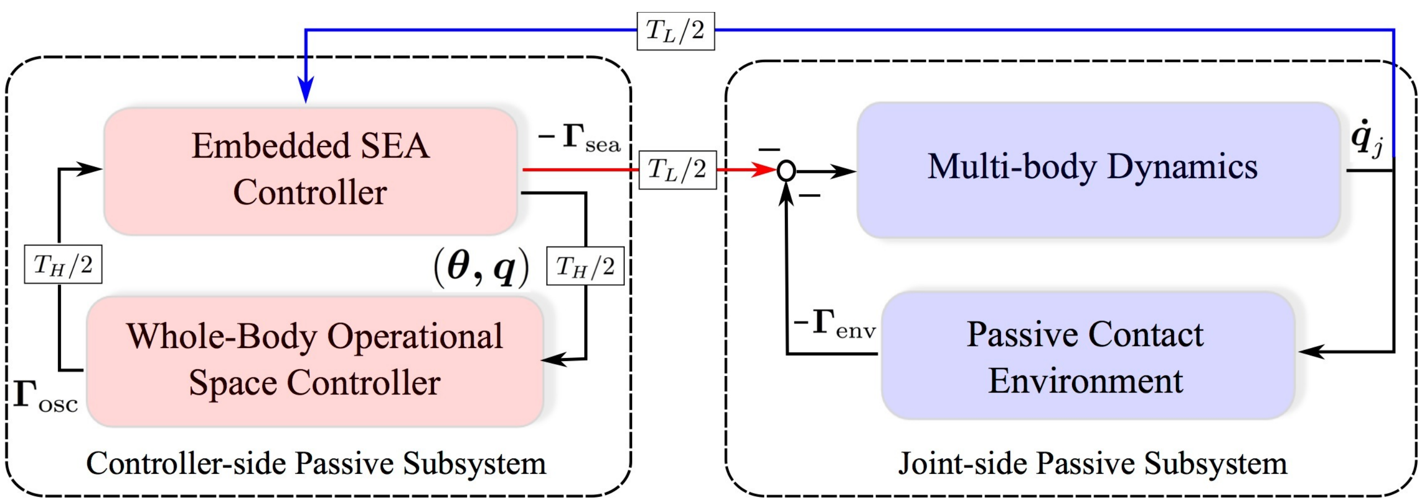
Time-Delayed Whole-Body Operational Space Control

Theorem: Time-delayed Operational Space Control

For contact-free motion control (i.e., $\boldsymbol{F}_c = 0$), the SEA torque command $\boldsymbol{\Gamma}_{\text{sea}}$ at the embedded level is

$$\boldsymbol{\Gamma}_{\text{sea}}(t) = \boldsymbol{J}^{*T}_{(-d_0)}\Big(\boldsymbol{\Lambda}_{t|s,(-d_0)}\boldsymbol{K}_x\big(\boldsymbol{x}_d(t - \frac{T_H + T_L}{2}) - \boldsymbol{x}(t - T_H - \frac{T_L}{2})\big)\Big) - \boldsymbol{B}_s\ddot{\boldsymbol{\theta}}(t) - \boldsymbol{D}_\theta\dot{\boldsymbol{\theta}}(t) + \bar{\boldsymbol{g}}(\boldsymbol{\theta})_{(-d_0)},$$

where the matrices with subscript $-d_0$ are evaluated at the instant $t - d_0 = t - T_H - T_L/2$.



[Zhao, and Sentis, Humanoids 2016] (ThPos.74)

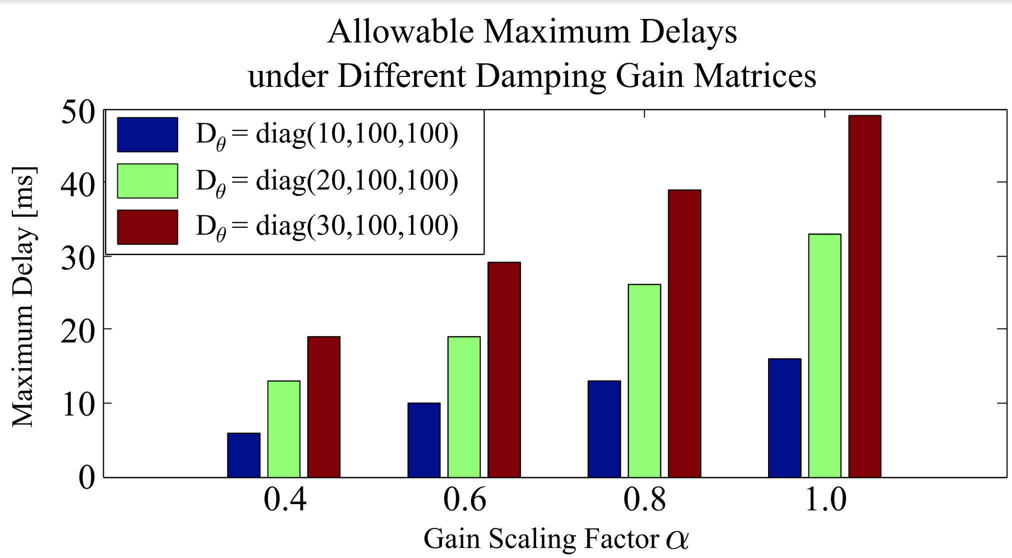
LMI-based Passivity Criterion of Time-Delayed WBOSC

Theorem: Passivity criterion of prioritized multi-task control

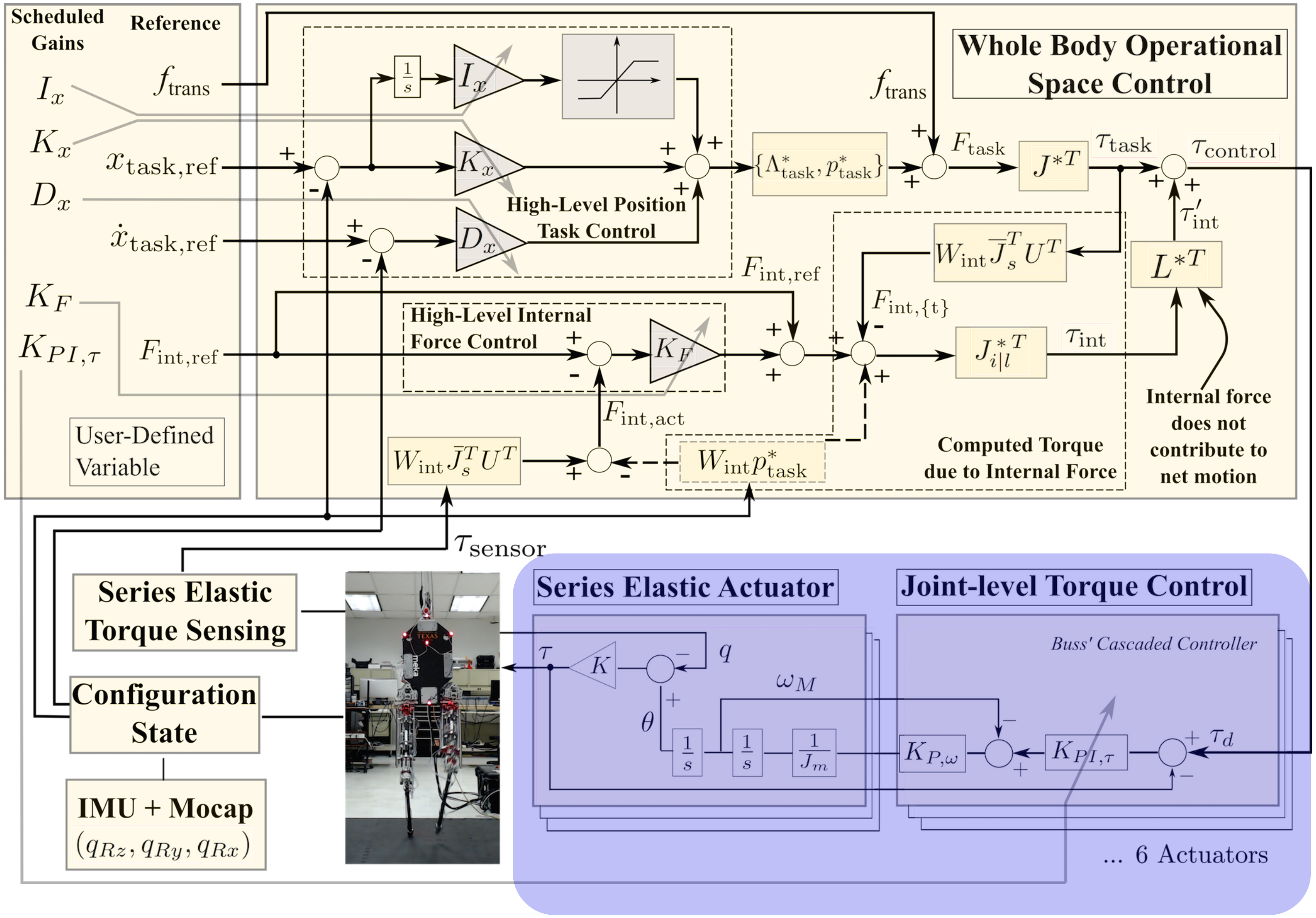
Consider N prioritized Whole-Body Operational Space tasks. If there exists a set of positive-definite matrices $\boldsymbol{Q}_i, i \in [1, N]$ and a positive time delay scalar $\bar{d}_1$ such that the following LMI holds,

$$\begin{pmatrix} -\boldsymbol{D}_\theta + \frac{1}{2}\bar{d}_1 \sum_{i=1}^{N} \boldsymbol{J}^{*T}_{i|\text{prec}(i)}(\overline{\boldsymbol{q}})\boldsymbol{Q}_i \boldsymbol{J}^{*}_{i|\text{prec}(i)}(\overline{\boldsymbol{q}}) & \frac{1}{2}\bar{d}_1\boldsymbol{M}_1 & \cdots & \frac{1}{2}\bar{d}_1\boldsymbol{M}_N \\ * & -\frac{1}{2}\bar{d}_1\boldsymbol{Q}_1 & \boldsymbol{0} & \boldsymbol{0} \\ * & * & \ddots & \boldsymbol{0} \\ * & * & * & -\frac{1}{2}\bar{d}_1\boldsymbol{Q}_N \end{pmatrix} \preceq \boldsymbol{0},$$

where $\boldsymbol{M}_i = \boldsymbol{J}^{*T}_{i|\text{prec}(i)}(\overline{\boldsymbol{q}})\boldsymbol{\Lambda}_{i|\text{prec}(i)}\boldsymbol{K}_{x,i}$, then the interconnected feedback system is passive for prioritized multi-task control and motor velocity $\dot{\boldsymbol{\theta}}$ is bounded.



Distributed WBOSC on A Bipedal Robot



- Joint-level cascaded torque + motor damping controller
- Force sensing for internal force feedback control
- First time that the distributed WBOSC is implemented on a point-feet bipedal robot with series elastic actuators

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[Kim, Zhao, et. al, and Sentis, IEEE Transactions on Robotics 2016]

Conclusions

- Observed that system stability and tracking performance are more sensitive to damping than stiffness feedback delays.
  - Embedded dampping ⇨ Higher achievable impedance
  - Servo Breakdown Gain Rule: B > 2b
- Proposed a critically-damped gain selection criterion to achieve optimal performance
  - Analyzed effect of time delays and filtering
  - Devised an impedance performance measure: Z-region.
- Analyzed the passivity of time-delayed WBOSC with SEA dynamics via LMI technique
- Experimental validations

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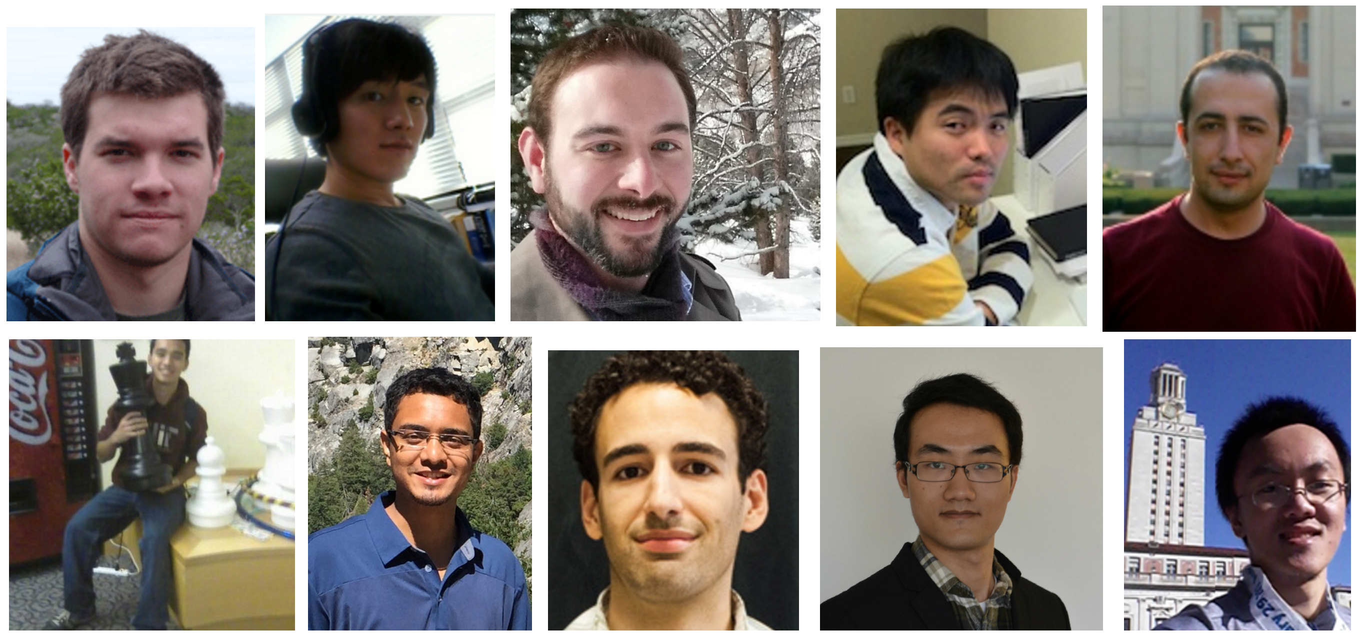
Acknowledgements

- Research Supervisor: Prof. Luis Sentis

- All Human Centered Robotics Lab members

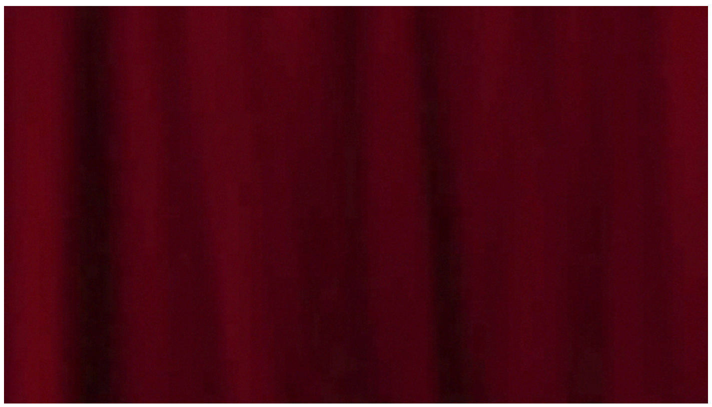


(et.al)

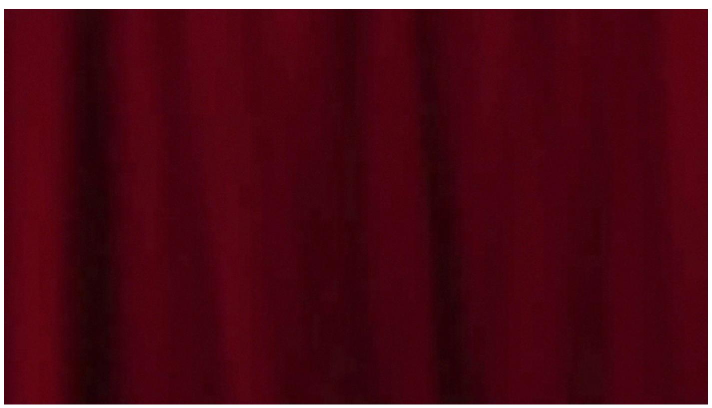
- Funding agency: ONR, NSF/NASA NRI, UT Austin

Summary of Contributions

- Trajectory Tracking under Different Feedback Delays
  - Tracking performance is more sensitive to damping feedback delays
  - Robustness to stiffness feedback delays



- Distributed Operational Space Control
  - Stability of delayed systems
  - High impedance control
  - Behavior reasoning and experimental validations



- Time-delayed Whole-Body Operational Space Control
  - Stability and passivity of overall feedback systems
  - Impedance and torque control