Strength Amplification through a Virtual Inertia and System Identification

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Introduction & Motivation

Cobots (collaborative robots):

- Usually autonomous
- Task specific
- Limited dexterity and assistance

Exoskeletons:

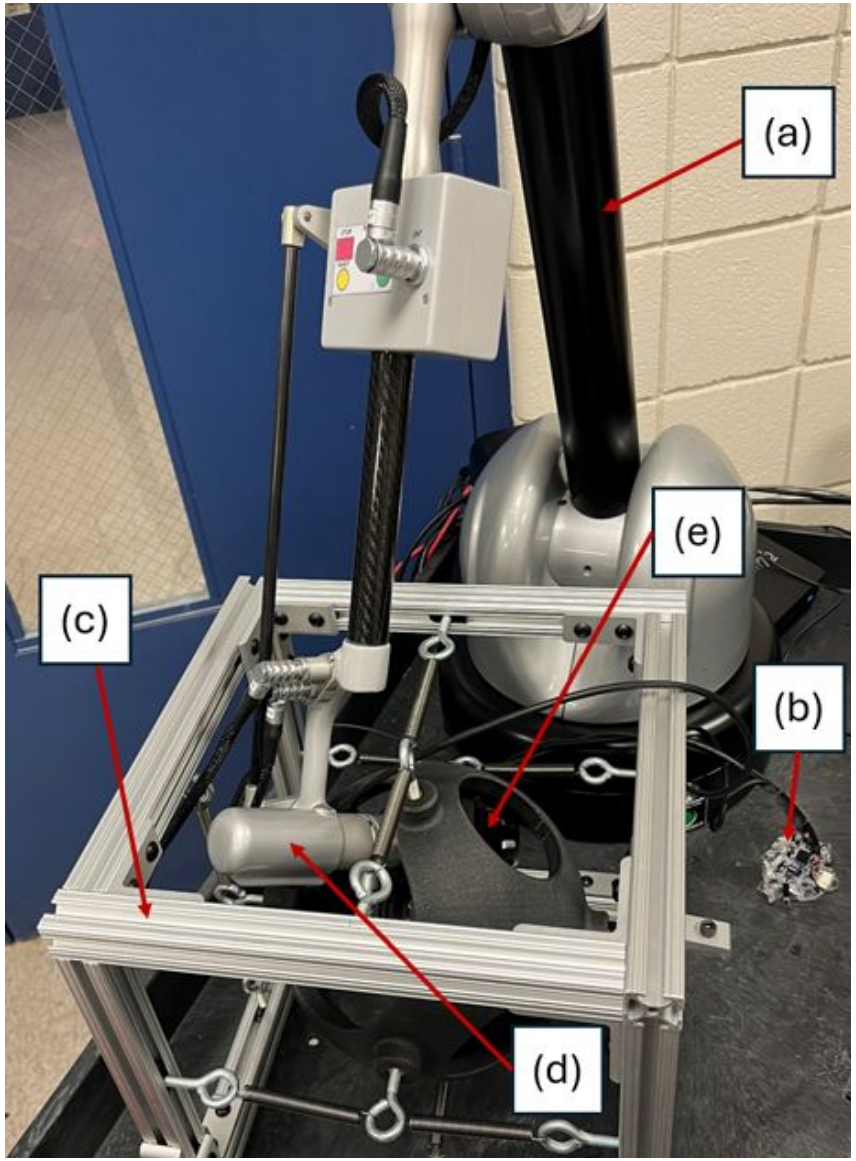
- Shine in physical, less-structured tasks
- Not suited for general environment interaction.

Is there an in-between?

Hardware

The experimental setup consists of:

(a) Haption Virtuose 6D TAO™ High Force Robotic Manipulator
(b) Sunrise Instruments (SRI) 6 axis force/torque sensor breakout board
(c) Spring-box frame, as well as the springs that attach the black sphere to the frame
(d) The end-effector of the robot arm, attached in the center of the spring-box to the black sphere
(e) The handle of the robot arm. Not shown is the force/torque sensor, which is located between the handle and the end-effector of the robot arm.



Control Problem: Plant Model

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Consider a 1-DOF linearized translational model with:

- Robot inertia, J
- Supported mass, J'
- External force, F_{ext}
- Human interaction force, F_h
- Robot force, F_{rob}

$$(J + J')\ddot{\theta} = F_{rob} + F_{ext} + F_H \quad (1)$$

$$\eta(s) = e^{-sT}\frac{\omega}{s+\omega} \quad (2)$$

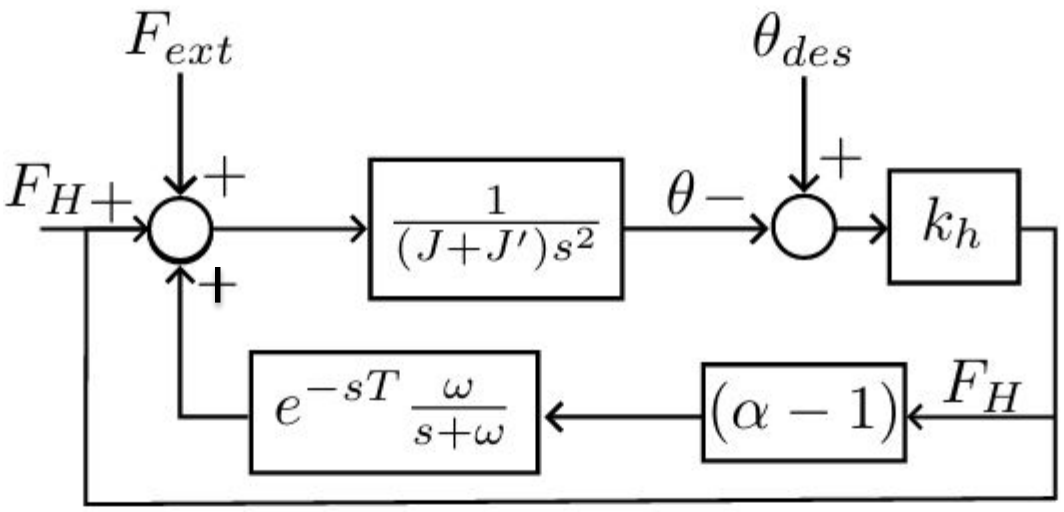
$$F_{rob} = \eta(s)u \quad (3)$$

$$F_H = k_h(\theta_{des} - \theta) \quad (4)$$

Control Problem: Naïve Force Feedback

Implementing Naïve Force Feedback results in:

- Instability at low α
- Instability in high frequency, stiff motion
- Inflexibility in human-interaction



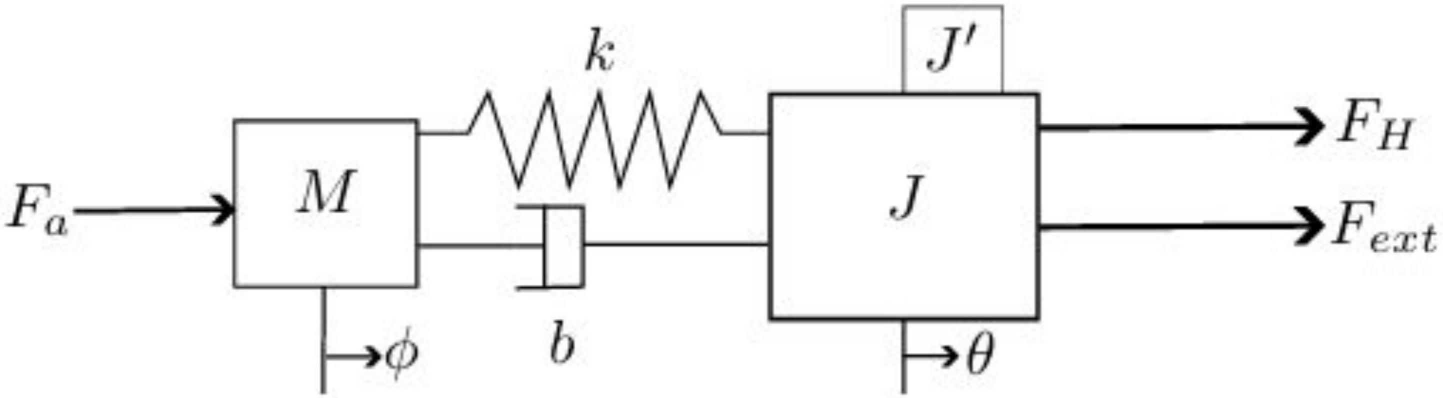
$$u = (\alpha - 1)F_H \qquad (5)$$

$$(J + J')\ddot{\theta} = F_H + (\alpha - 1)F_H + F_{ext} = \alpha F_H + F_{ext} \qquad (6)$$

Control Problem: Virtual-Mass Controller

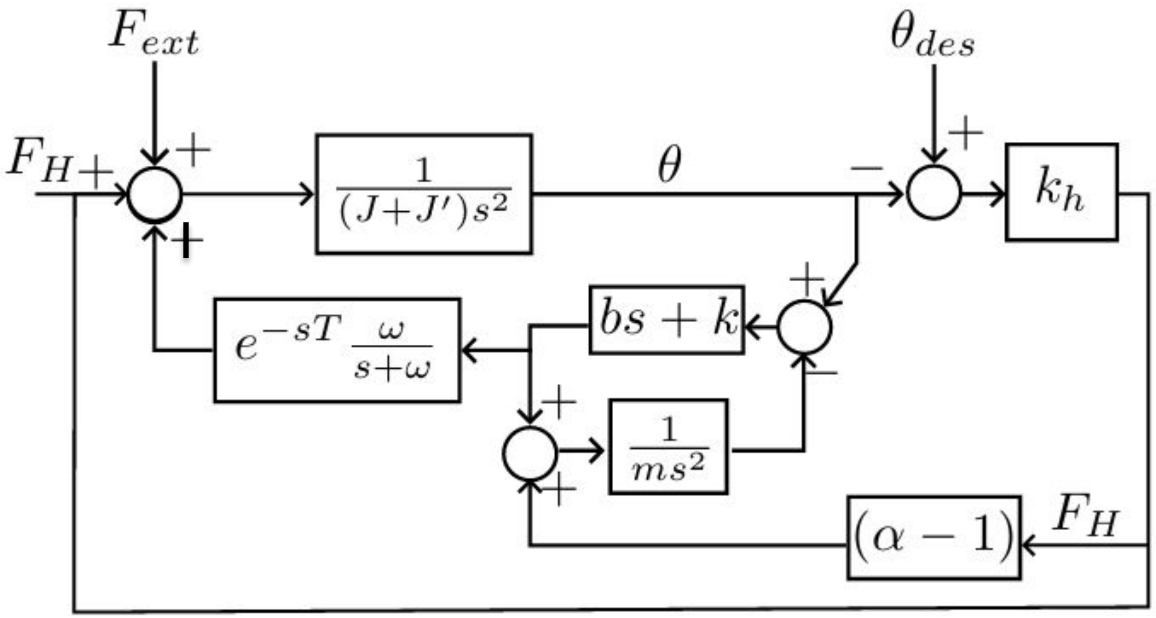
Consider simulating virtual dynamics to introduce an amplified version of the human force:

$$F_a = (\alpha - 1)F_h$$



$$M\ddot{\phi} = F_a + k(\theta - \phi) + b(\dot{\theta} - \dot{\phi}) \qquad (7)$$

The Virtual-Mass Controller introduces simulated inertia, stiffness, and damping.



$$u = k(\phi - \theta) + b(\dot{\phi} - \dot{\theta}) \quad (8)$$

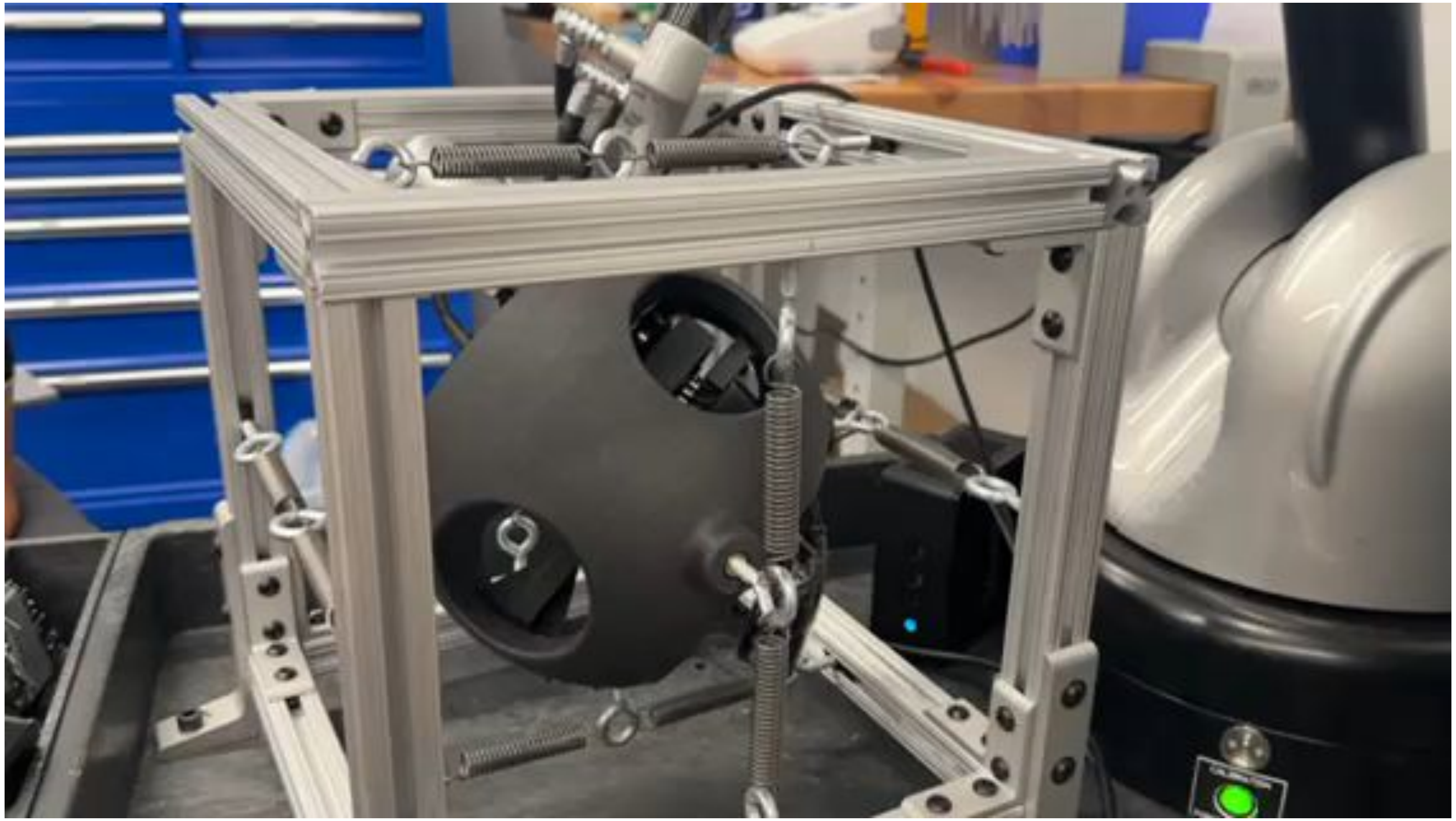
Resulting in:

- Responsiveness to operator input
- Stability over varying external forces

Methods

Sinusoidal chirp force tests conducted to characterize low frequency stiffness.

- Locked test to represent relative ground.
- Springbox test to represent human stiffness.



Results

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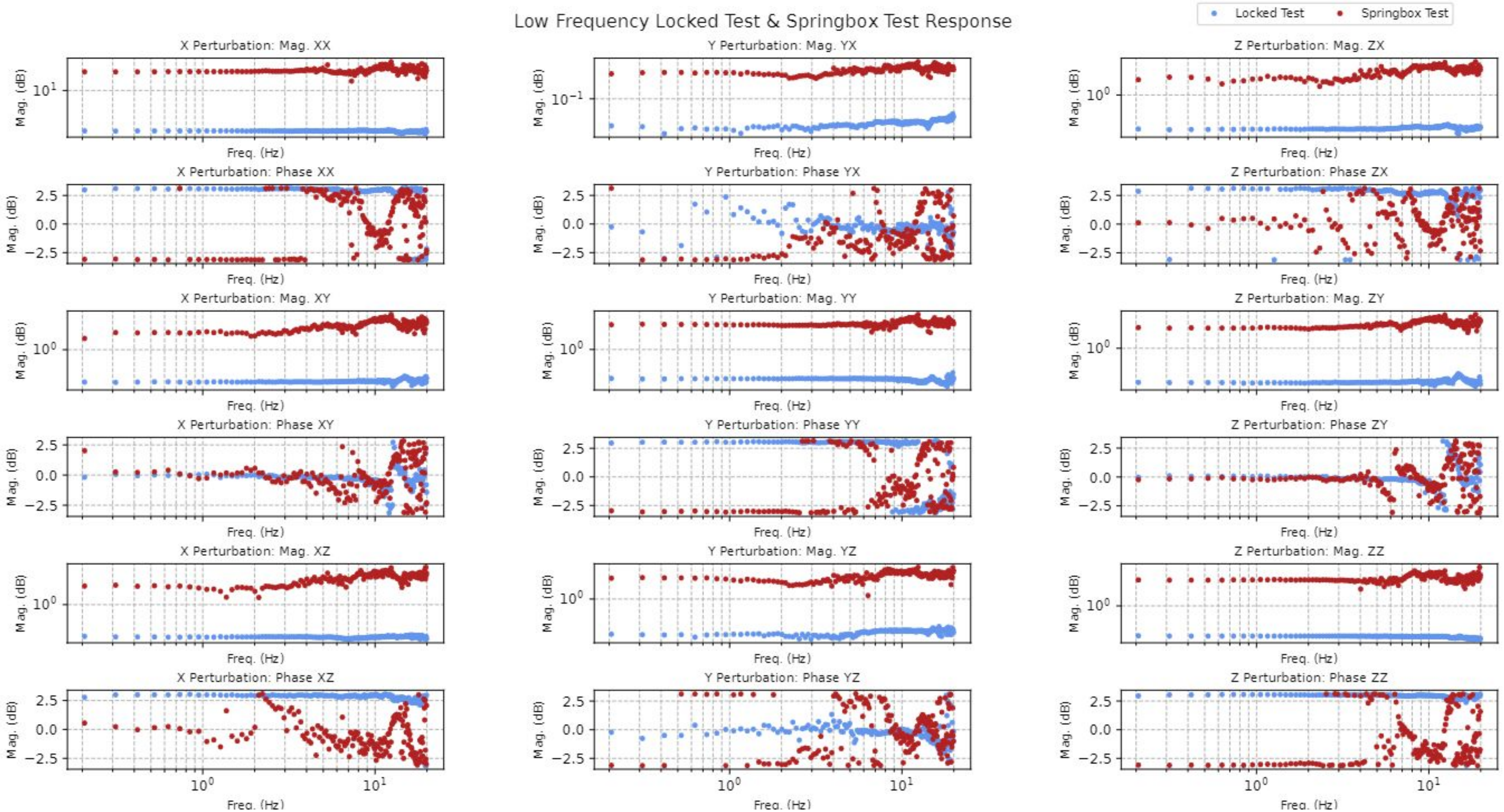


Results cont.

Taking the complex difference between the locked and springbox test yields stiffness matrices.

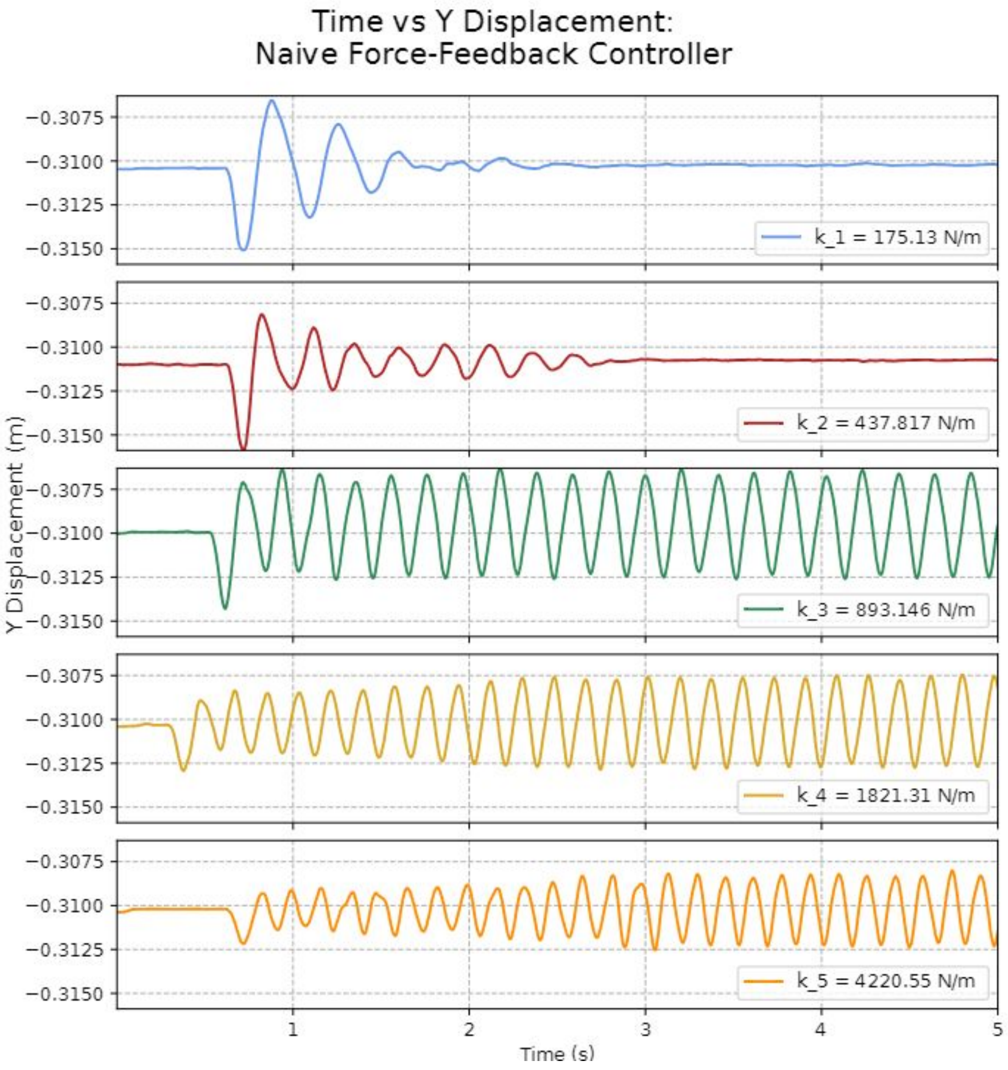
$$K_{1\,(N/m)} = \begin{bmatrix} 171.55 & 43.275 & 15.240 \\ 8.87 & 214.37 & 43.4172 \\ 36.11 & 87.028 & 217.57 \end{bmatrix}$$

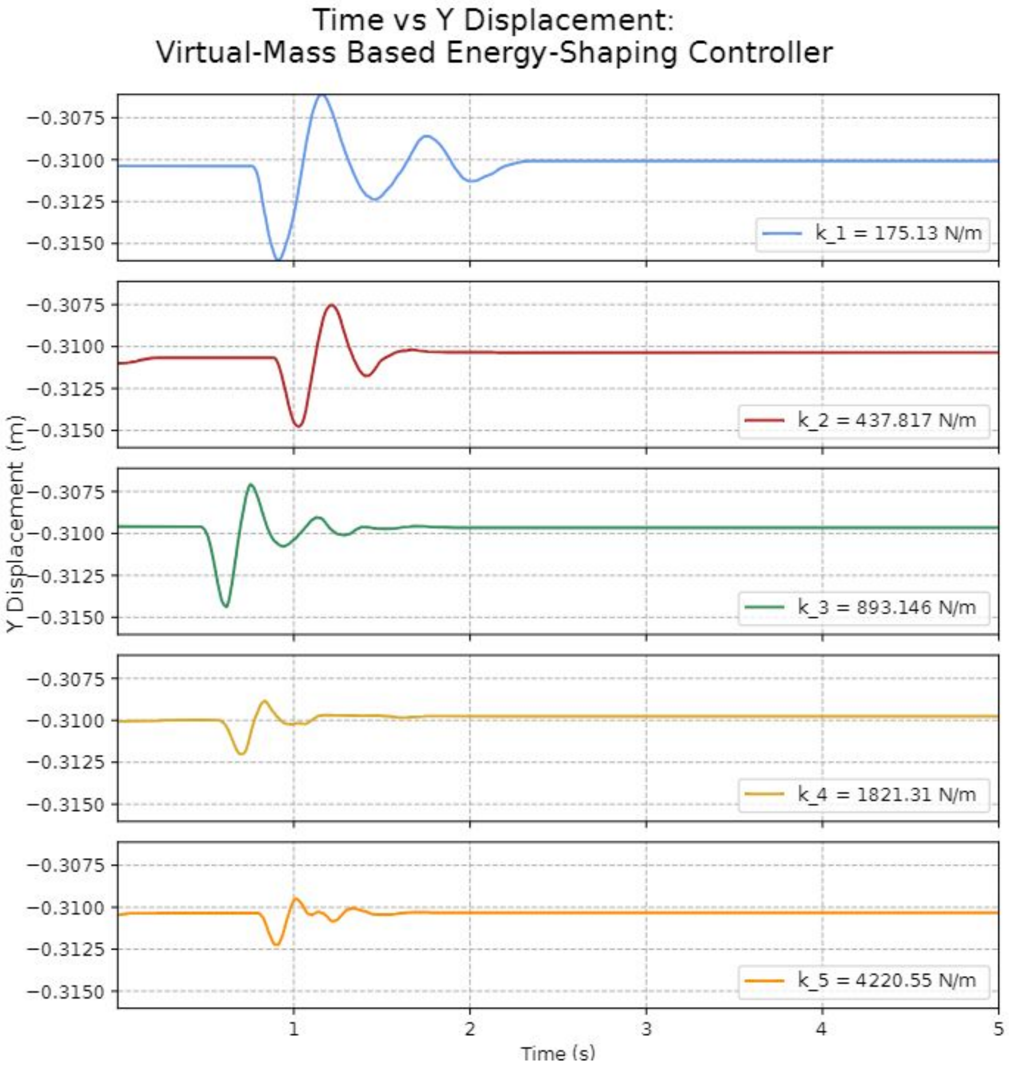
$$K_{1\_ratio\,(N/m)} = \begin{bmatrix} 0.991 & 0.247 & 0.087 \\ 0.051 & 1.22 & 0.25 \\ 0.21 & 0.497 & 1.242 \end{bmatrix}$$

$$K_{2\,(N/m)} = \begin{bmatrix} 257.392 & 64.877 & 63.574 \\ 125.749 & 526.829 & 137.478 \\ 282.815 & 71.431 & 538.710 \end{bmatrix}$$

$$K_{2\_ratio\,(N/m)} = \begin{bmatrix} 0.588 & 0.148 & 0.145 \\ 0.287 & 1.203 & 0.314 \\ 0.646 & 0.163 & 1.230 \end{bmatrix}$$

Experimental Stability





Conclusion

Safe human-robot interaction in the real world requires compliant and aware control methodologies.

The Human-Empowering Robotics and Controls lab achieves this by:

- Demonstrating the performance and stability of a novel virtual inertia-based feedback controller.
- Proposing methods for estimating human stiffness.
- Demonstrating the above through experimental validation.

Acknowledgements

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Questions?