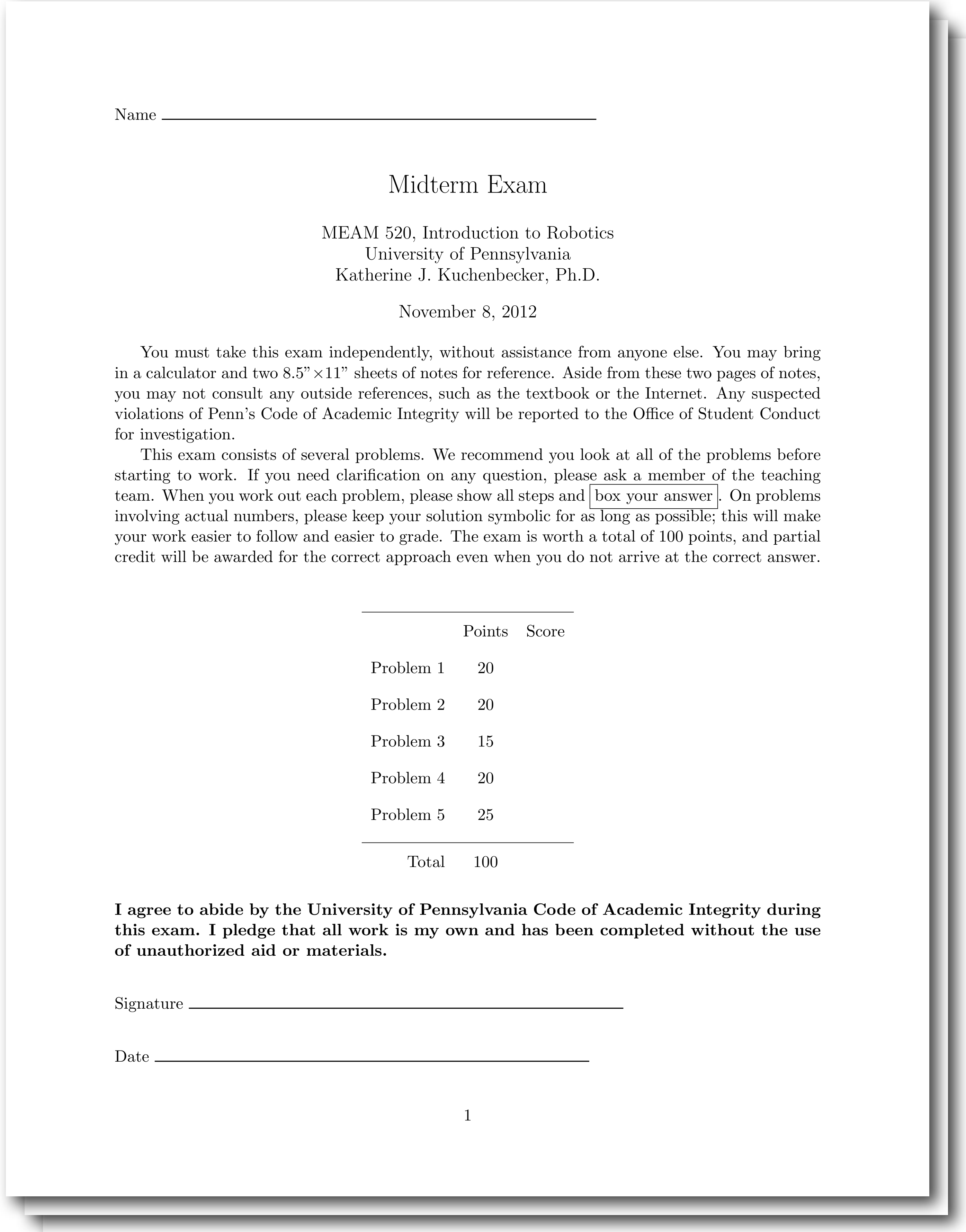
MEAM 520

More Teleoperation

Katherine J. Kuchenbecker, Ph.D.
General Robotics, Automation, Sensing, and Perception Lab (GRASP)
MEAM Department, SEAS, University of Pennsylvania

Lecture 18: November 20, 2012


Name ______________________________

Midterm Exam

MEAM 520, Introduction to Robotics
University of Pennsylvania
Katherine J. Kuchenbecker, Ph.D.

November 8, 2012

You must take this exam independently, without assistance from anyone else. You may bring in a calculator and two 8.5"×11" sheets of notes for reference. Aside from these two pages of notes, you may not consult any outside references, such as the textbook or the Internet. Any suspected violations of Penn's Code of Academic Integrity will be reported to the Office of Student Conduct for investigation.

This exam consists of several problems. We recommend you look at all of the problems before starting to work. If you need clarification on any question, please ask a member of the teaching team. When you work out each problem, please show all steps and box your answer. On problems involving actual numbers, please keep your solution symbolic for as long as possible; this will make your work easier to follow and easier to grade. The exam is worth a total of 100 points, and partial credit will be awarded for the correct approach even when you do not arrive at the correct answer.

	Points	Score
Problem 1	20	
Problem 2	20	
Problem 3	15	
Problem 4	20	
Problem 5	25	
Total	100	

I agree to abide by the University of Pennsylvania Code of Academic Integrity during this exam. I pledge that all work is my own and has been completed without the use of unauthorized aid or materials.

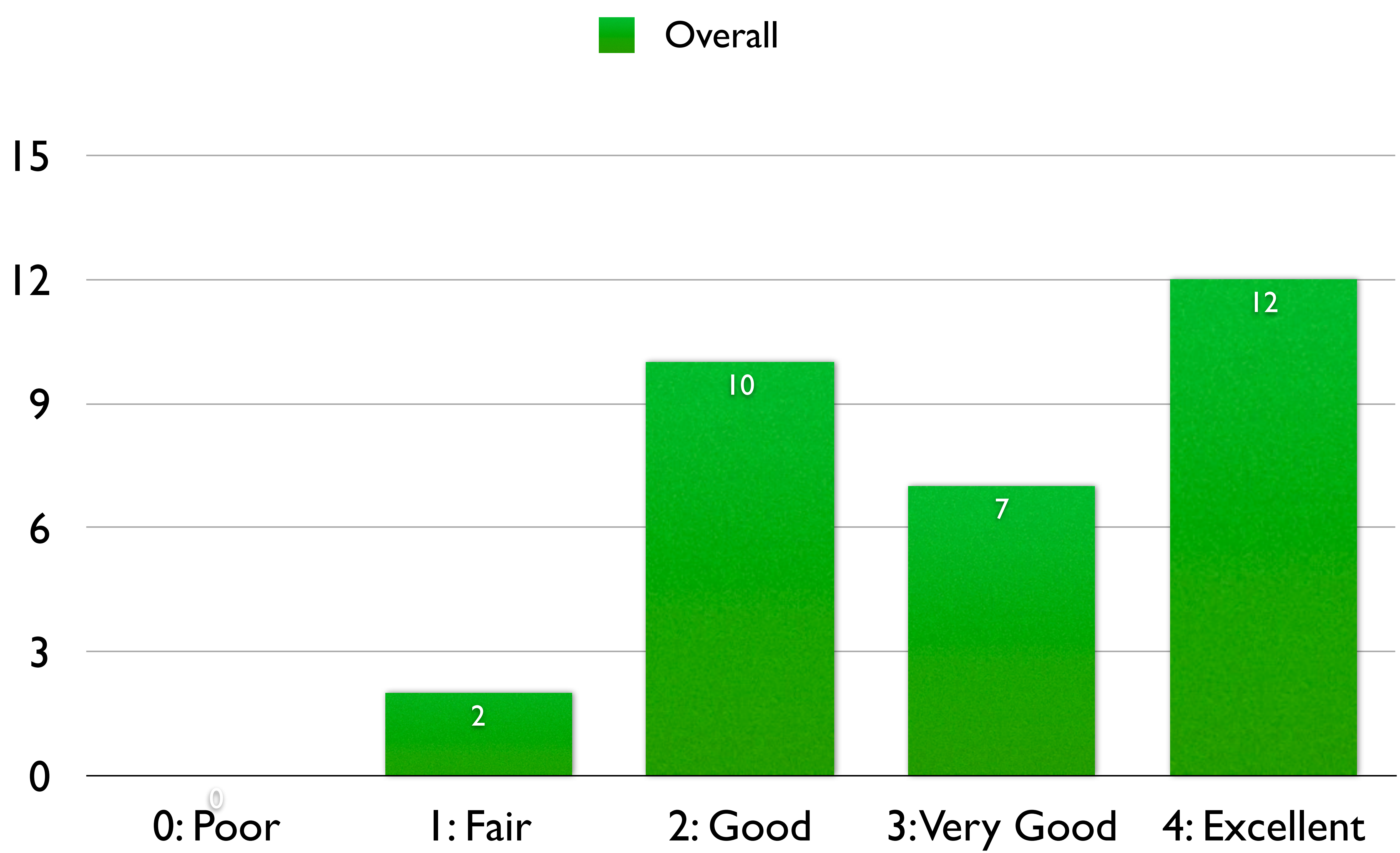
Signature ______________________________

Date ______________________________

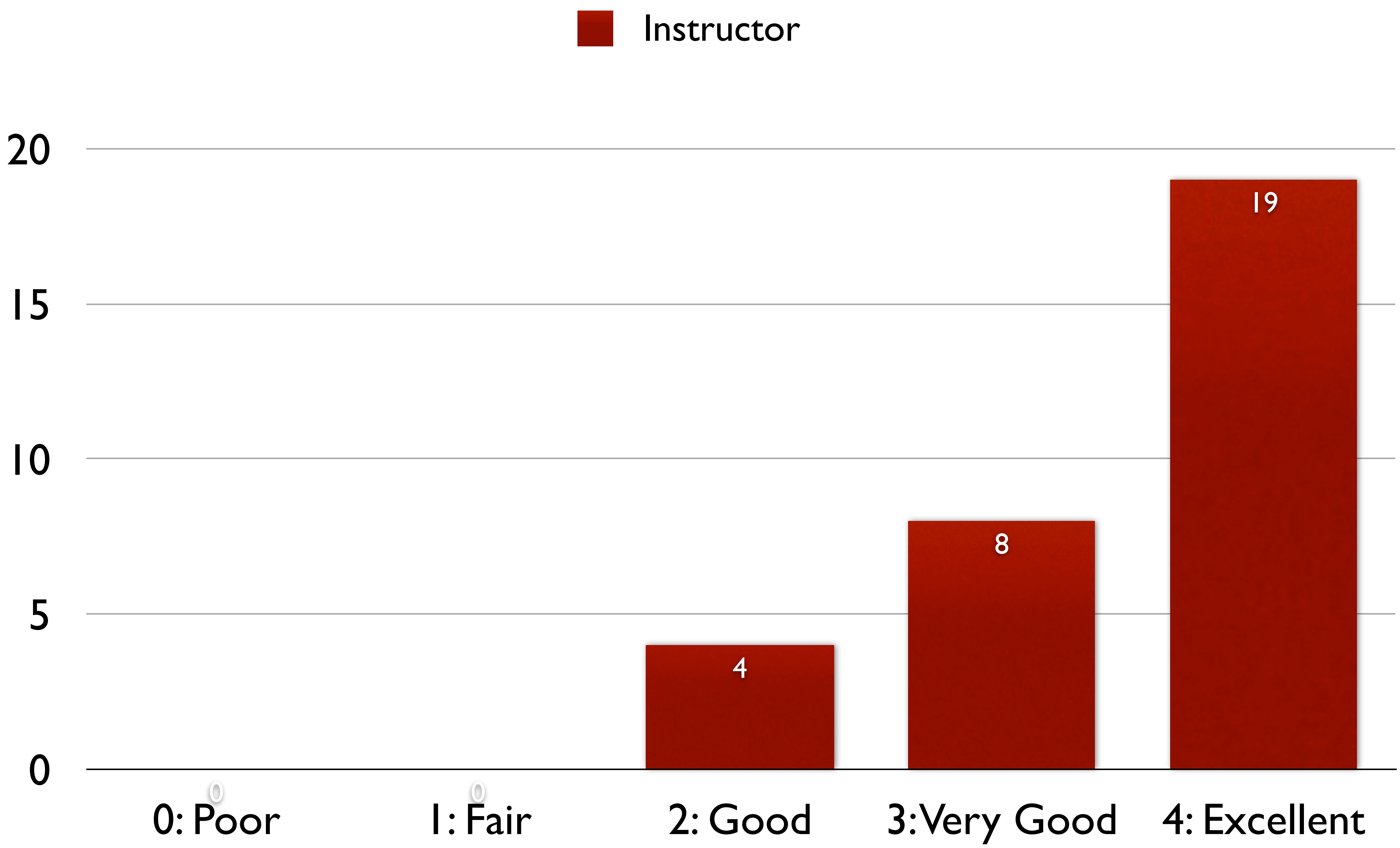
1

Regrades available. Making appointments.

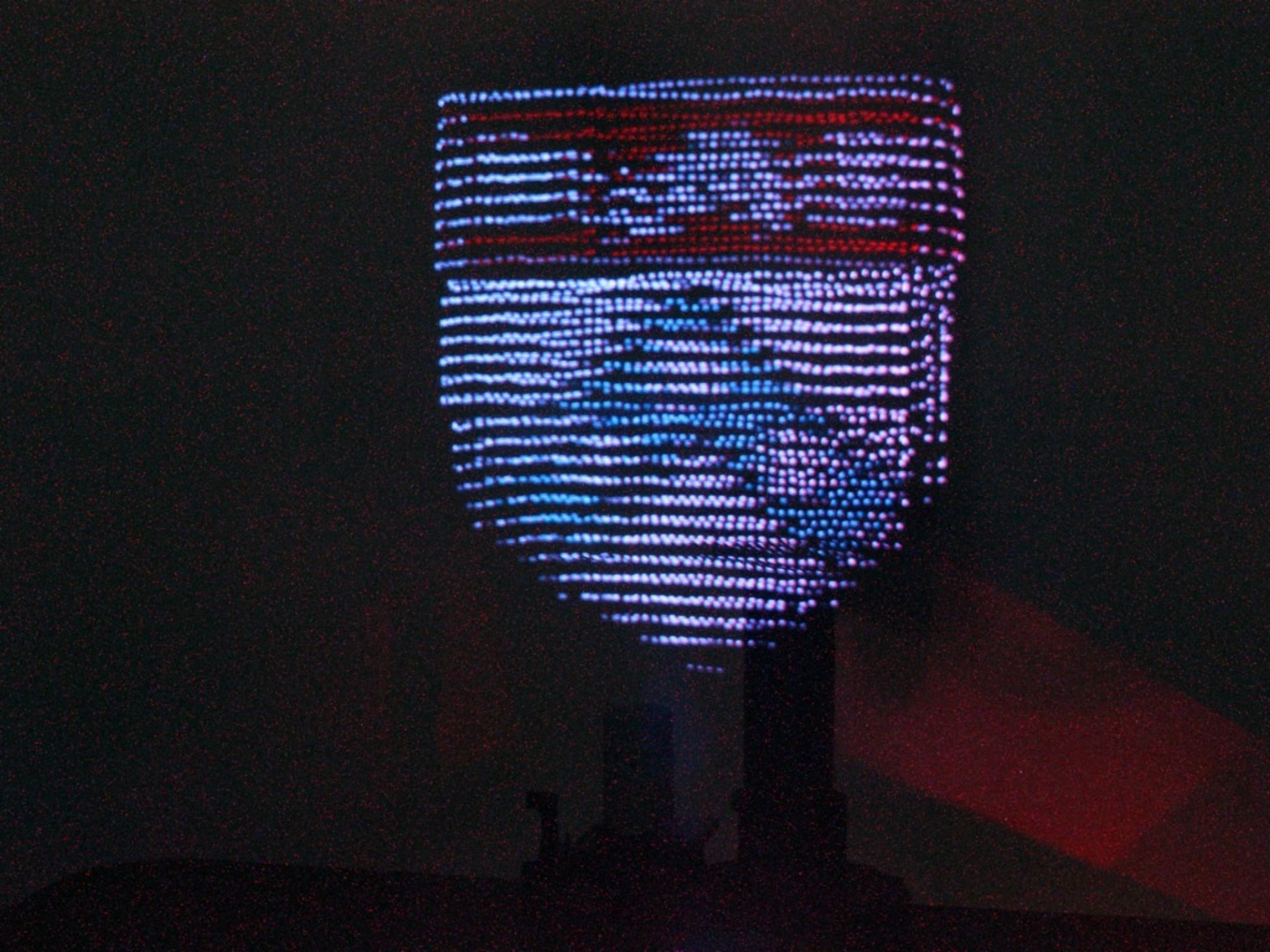
TEDYouth

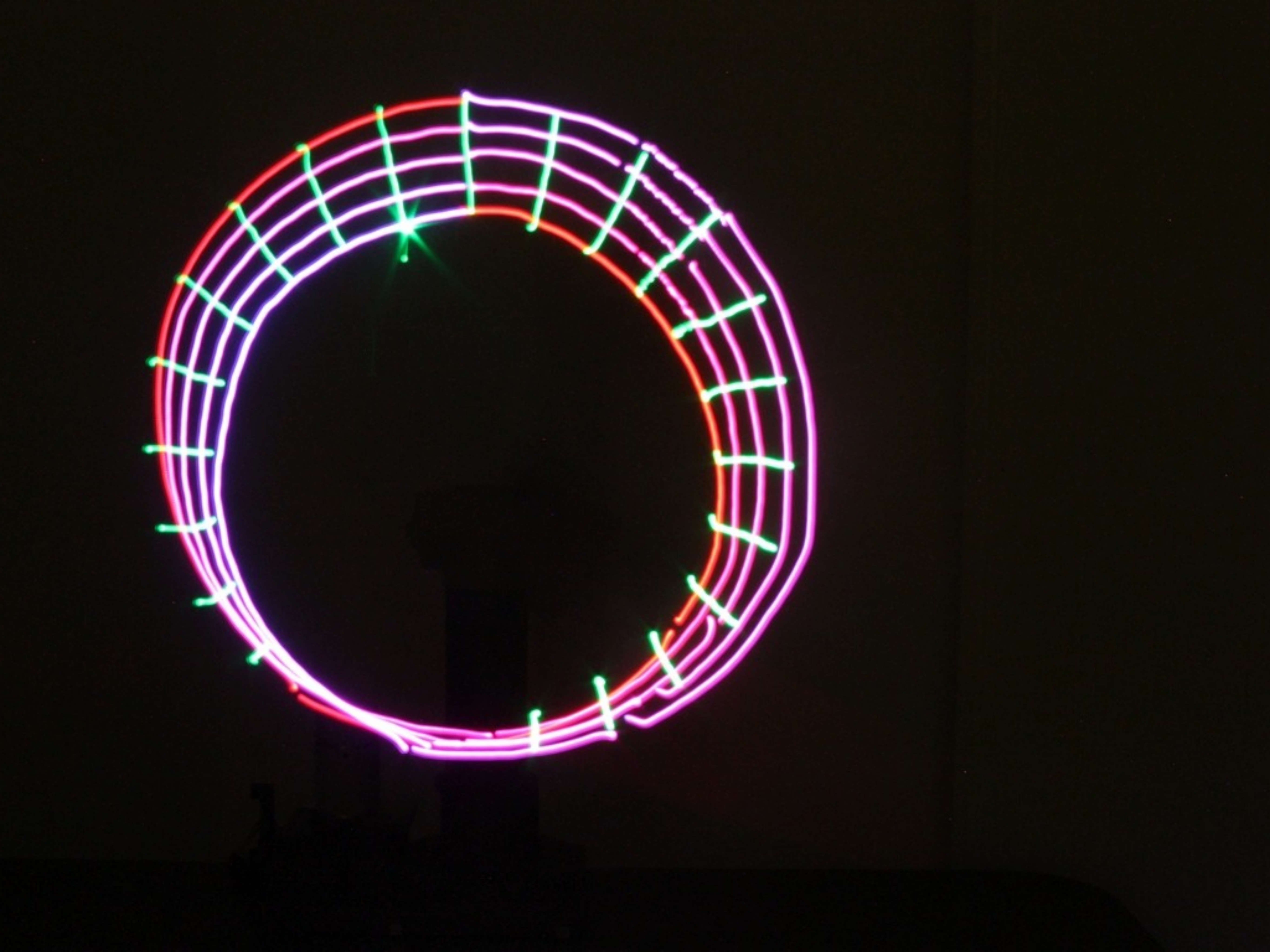


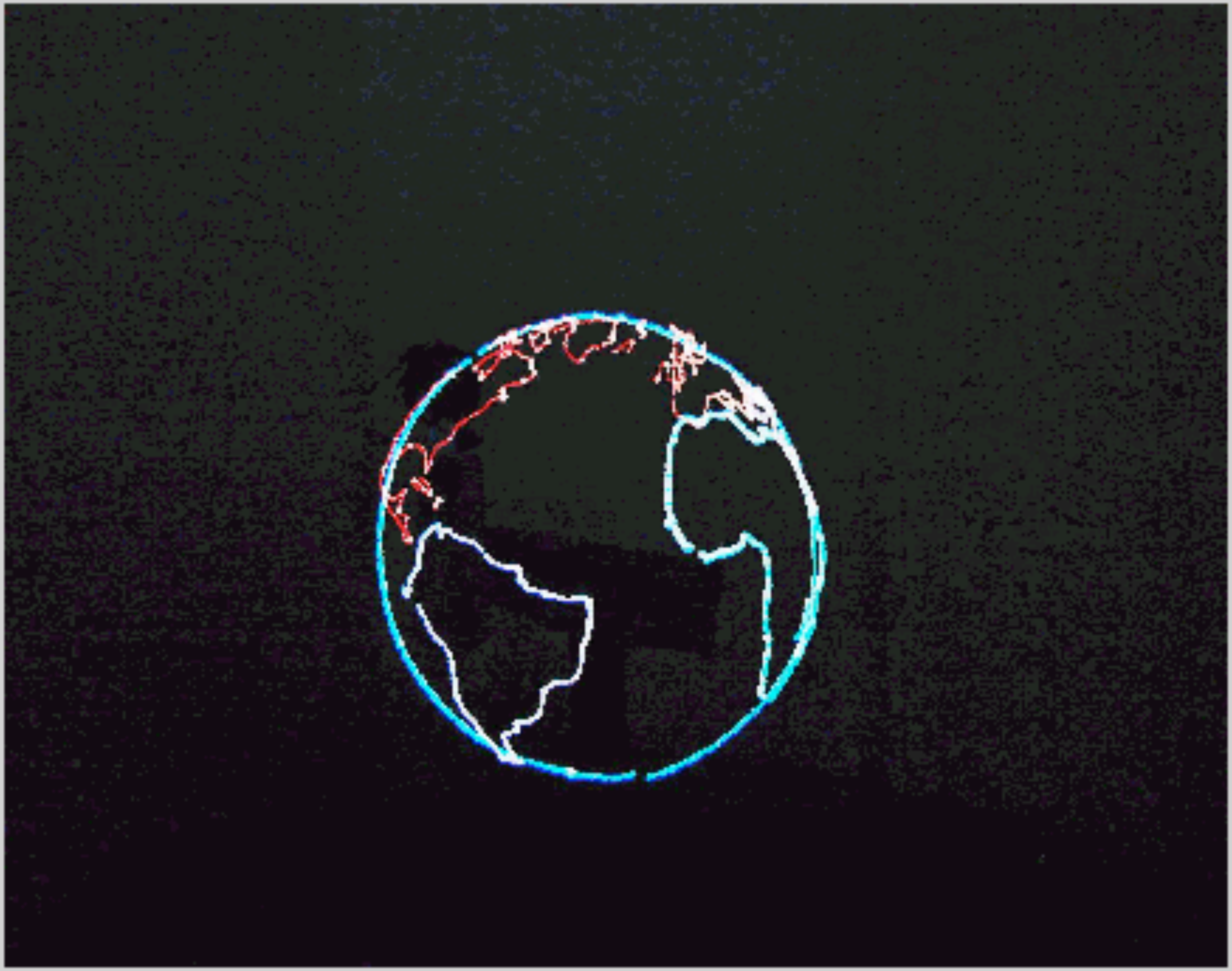
Overall
15
12
9
6
3
0
0
2
10
7
12
0: Poor
1: Fair
2: Good
3: Very Good
4: Excellent

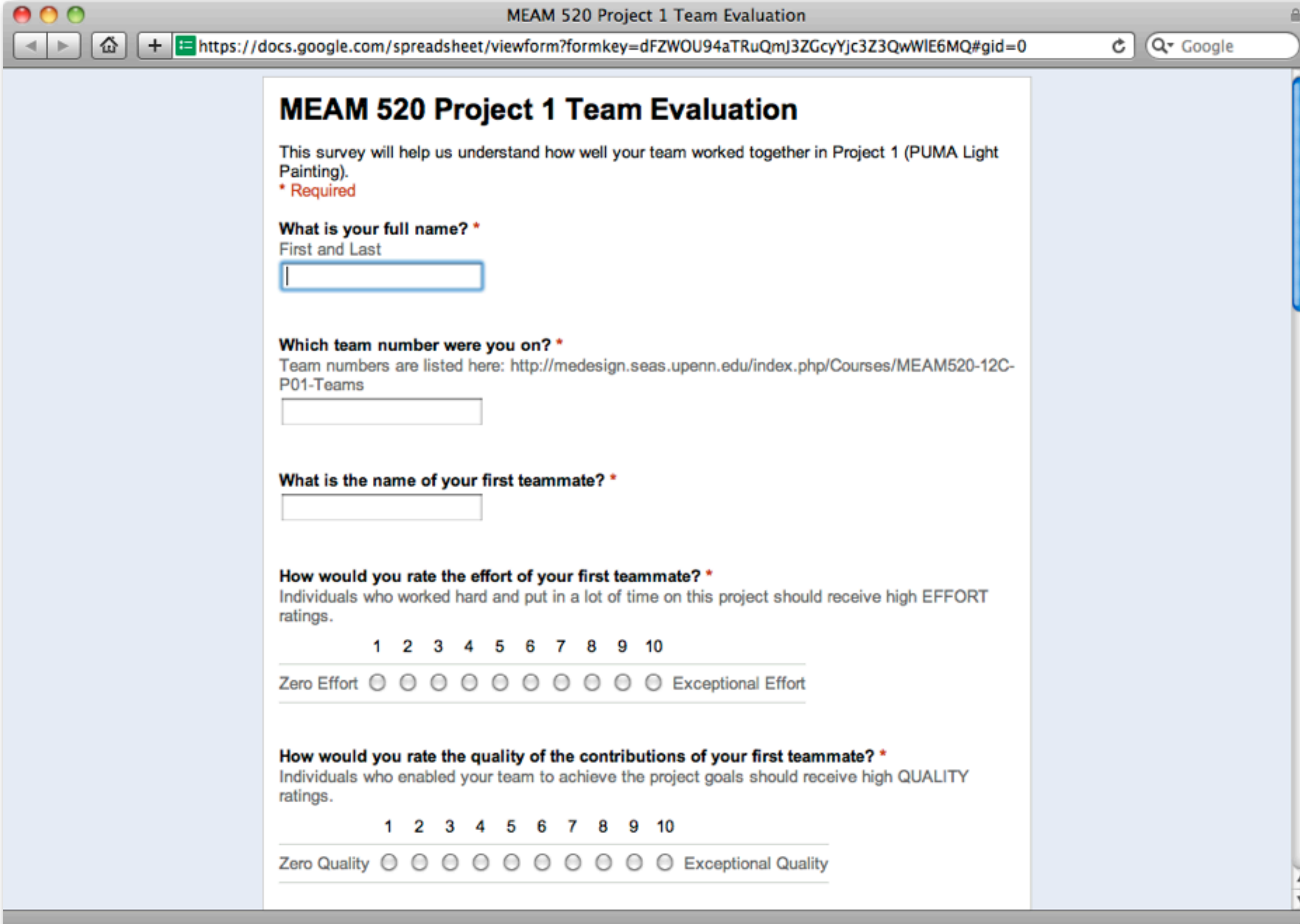

Instructor
20
15
10
5
0
19
8
4
0
0
0: Poor
1: Fair
2: Good
3: Very Good
4: Excellent

Project 1 : PUMA Light Painting









MEAM 520 Project 1 Team Evaluation

https://docs.google.com/spreadsheet/viewform?formkey=dFZWOU94aTRuQmJ3ZGcyYjc3Z3QwWlE6MQ#gid=0

MEAM 520 Project 1 Team Evaluation

This survey will help us understand how well your team worked together in Project 1 (PUMA Light Painting).

* Required

What is your full name? *

First and Last

Which team number were you on? *

Team numbers are listed here: http://medesign.seas.upenn.edu/index.php/Courses/MEAM520-12C-P01-Teams

What is the name of your first teammate? *

How would you rate the effort of your first teammate? *

Individuals who worked hard and put in a lot of time on this project should receive high EFFORT ratings.

	1	2	3	4	5	6	7	8	9	10	
Zero Effort	○	○	○	○	○	○	○	○	○	○	Exceptional Effort

How would you rate the quality of the contributions of your first teammate? *

Individuals who enabled your team to achieve the project goals should receive high QUALITY ratings.

	1	2	3	4	5	6	7	8	9	10	
Zero Quality	○	○	○	○	○	○	○	○	○	○	Exceptional Quality

Very useful comments. Please complete by Sunday.

Homework 5: Input/Output Calculations for a Real Robot

MEAM 520, University of Pennsylvania
Katherine J. Kuchenbecker, Ph.D.

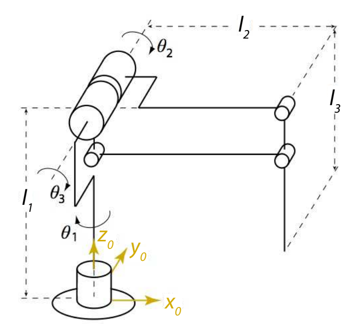
November 13, 2012

This assignment is due on **Tuesday, November 20**, by 5:00 p.m. sharp. You should aim to turn the paper part in during class that day. If you don't finish until later in the day, you can turn it in to Professor Kuchenbecker's office, Towne 224. Late submissions will be accepted until 5:00 p.m. on Wednesday, November 21, but they will be penalized by 25%. After that deadline, no further assignments may be submitted.

You may talk with other students about this assignment, ask the teaching team questions, use a calculator and other tools, and consult outside sources such as the Internet. To help you actually learn the material, what you write down should be your own work, not copied from a peer or a solution manual.

SensAble Phantom Premium 1.0 ***(60 points)***

This entire assignment is focused on a particular robot – the SensAble Phantom Premium 1.0. As shown in the photo below left, the Phantom is an impedance-type haptic interface with three actuated rotational joints. Designed to be lightweight, stiff, smooth, and easily backdrivable, this type of haptic interface enables a human user to interact with a virtual environment or control the movement of a remote robot through the movement of their fingertip while simultaneously feeling force feedback.

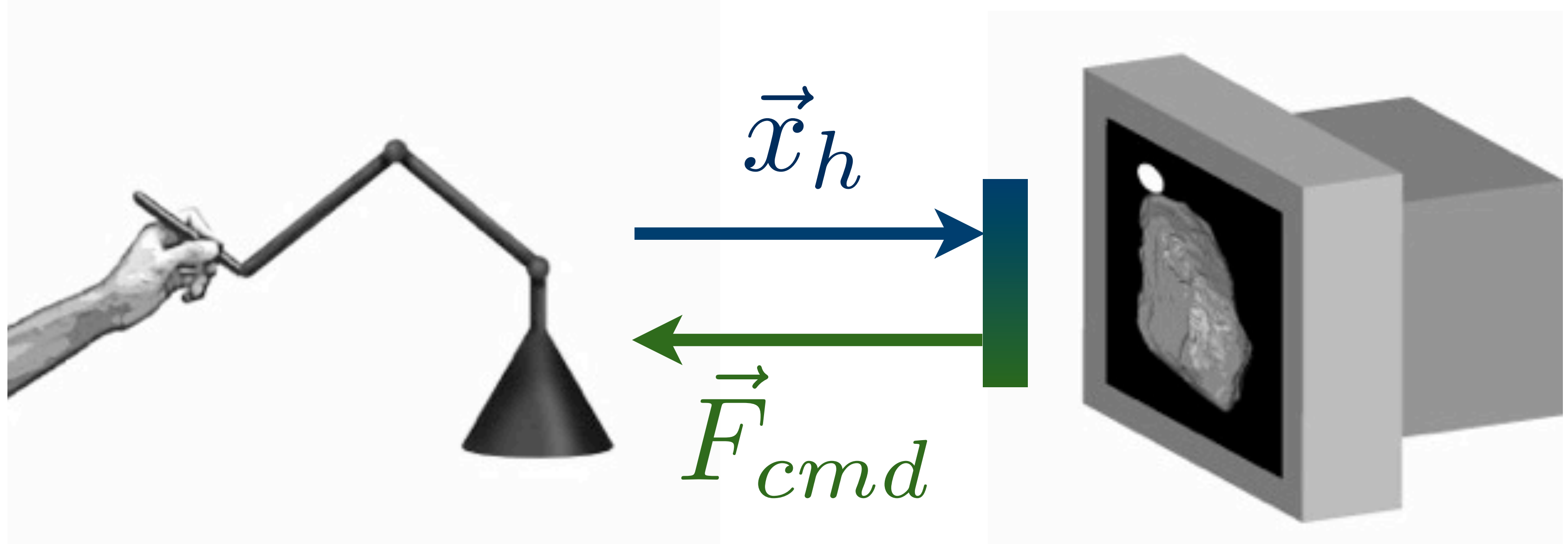


A thimble is attached to the tip of the robot via a passive non-encoded three-axis gimbal to allow the user to move the robot around while freely rotating their fingertip. As shown in the diagram above right, the Phantom haptic device looks similar to the standard RRR articulated manipulator base, but it uses a unique four-bar mechanism to co-locate the shoulder and elbow joints while also keeping the upper arm and forearm in the plane that intersects the axis of the waist joint.

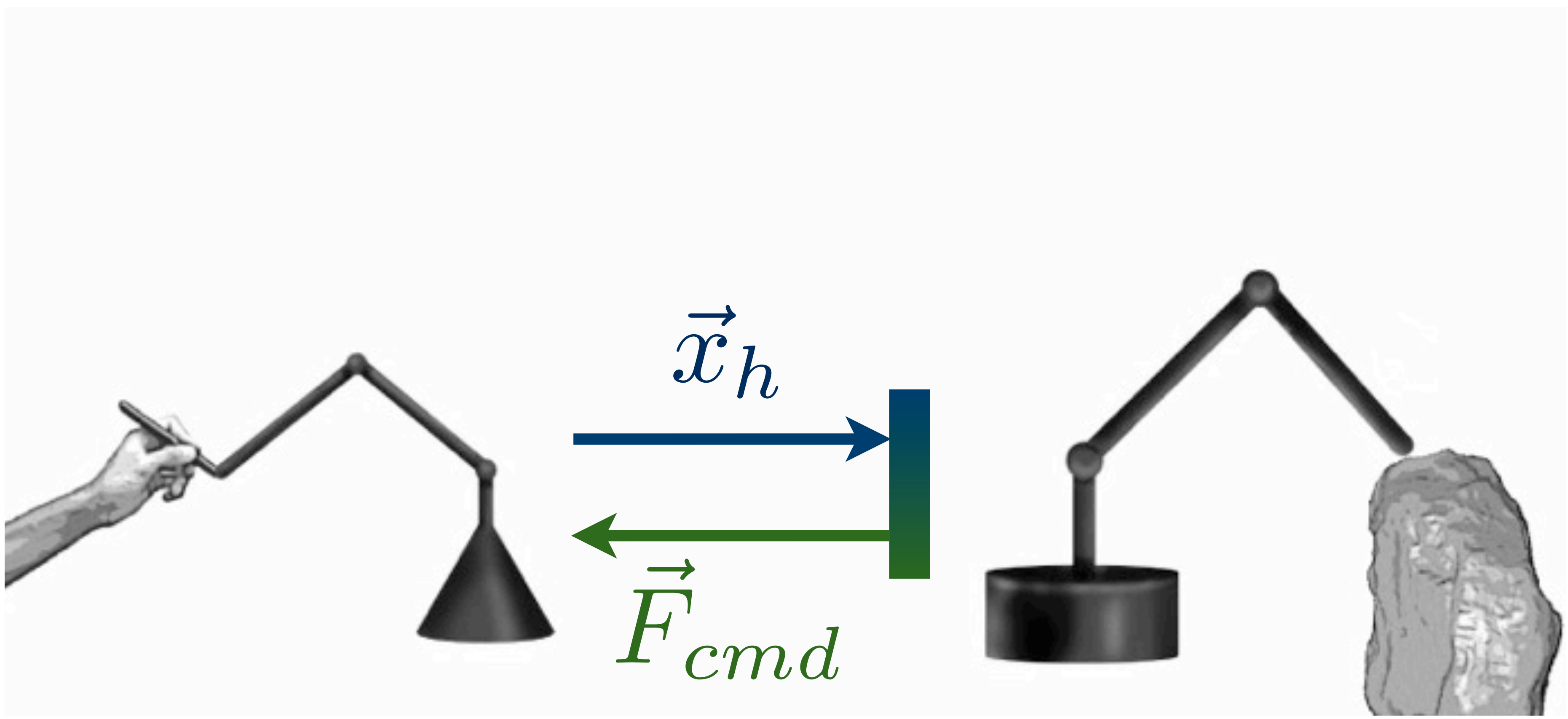
Each of the four questions below includes both a written explanation and the programming of a specific Matlab function. For the paper parts, write in pencil, show your work clearly, $\boxed{\text{box your answers}}$, and staple your pages together. For the programming, download the starter code from this assignment's page on the class wiki, change all function and file names to include your PennKey, comment your code, and follow the instructions at the end of this document to submit all of your Matlab files.

Due today by 5pm. -25% tomorrow. (Some extensions.)

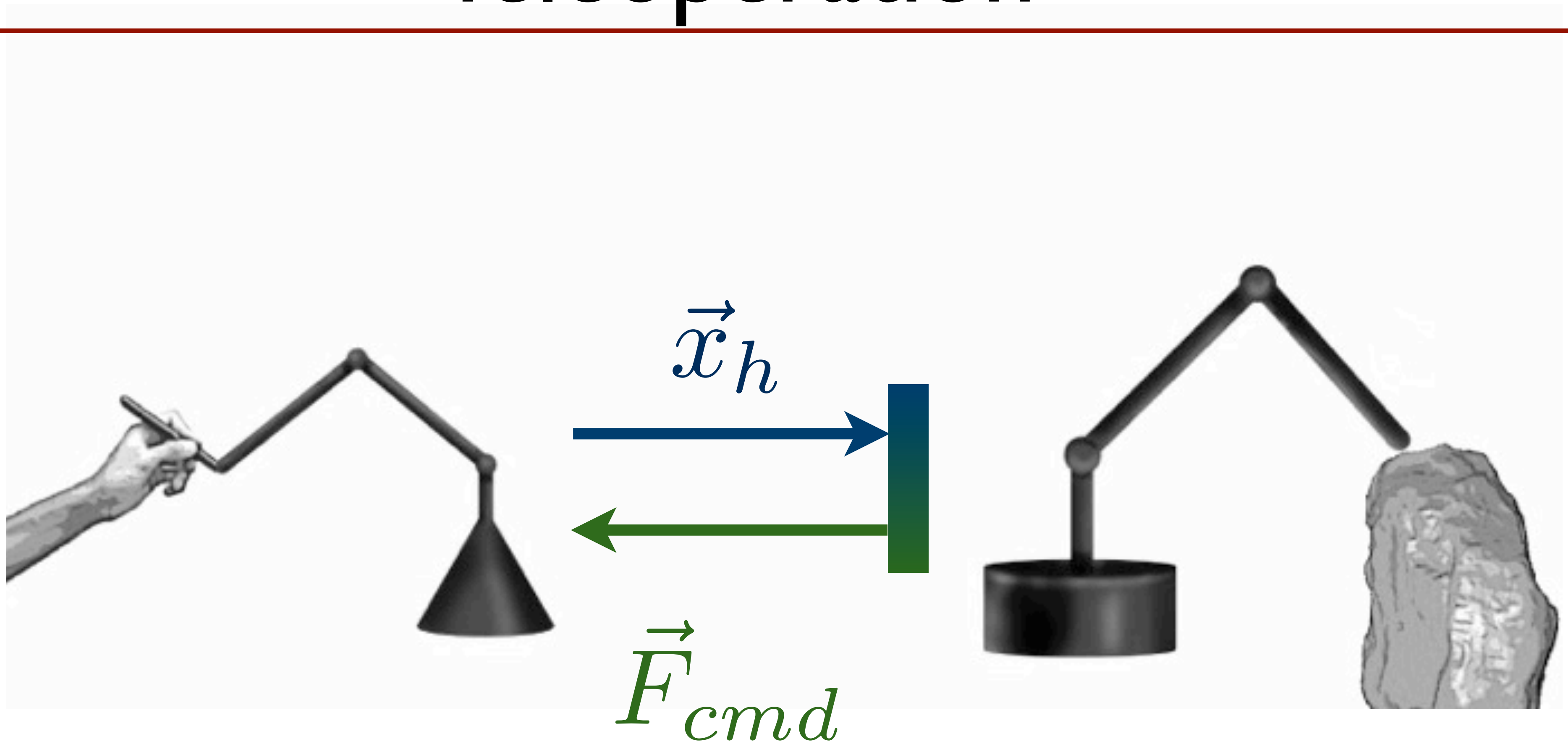
Haptic Virtual Environment



Haptic Remote Environment

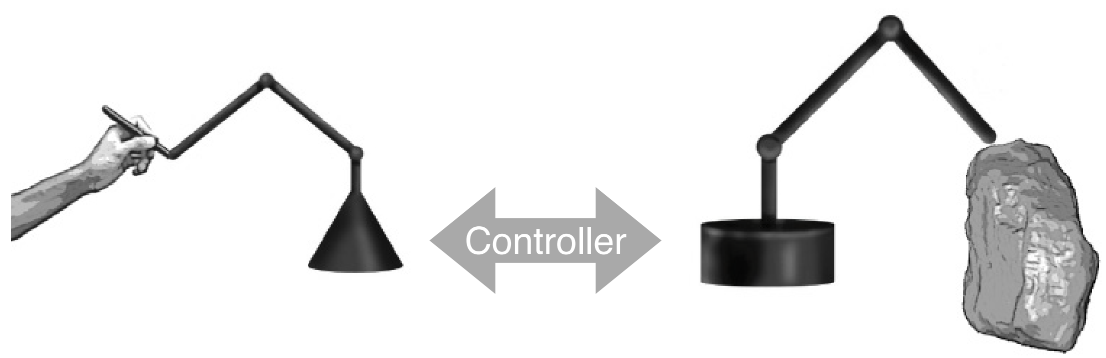


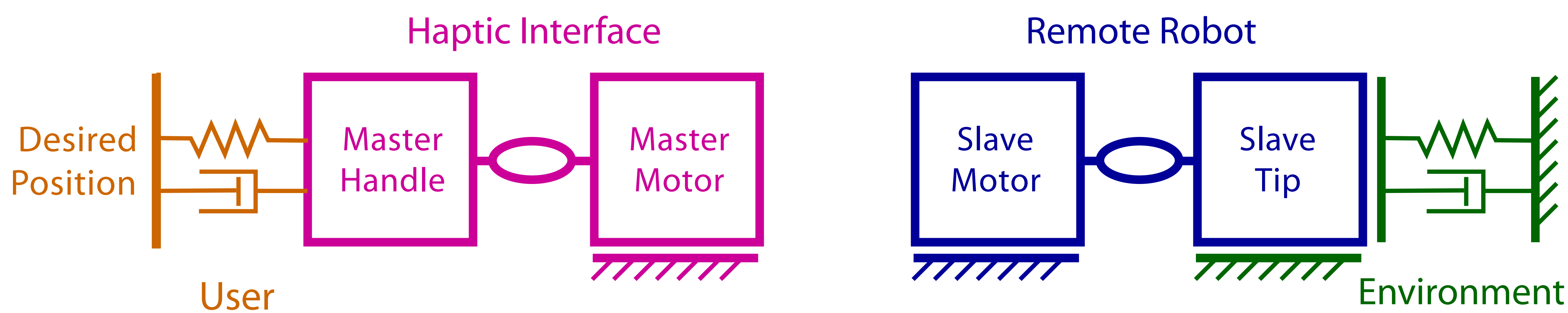
Teleoperation



- Teleoperation has always been tightly intertwined with robotics, especially manipulators.
- Control system design is a primary concern:
  - Stability
  - Transparency

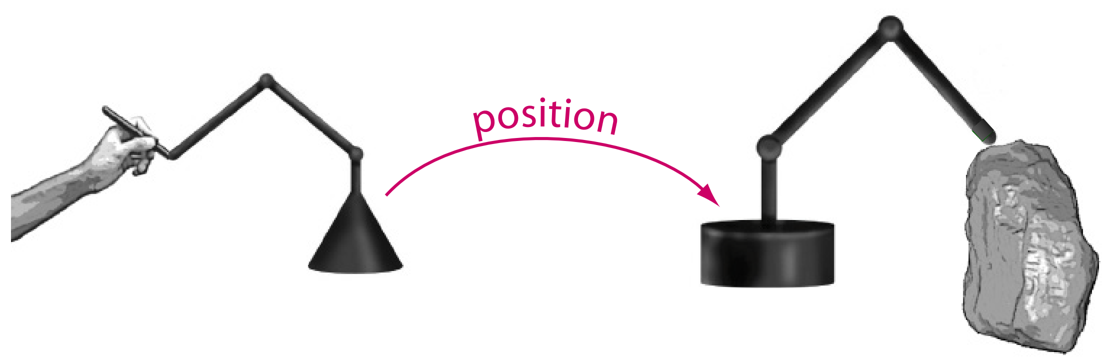
Teleoperation

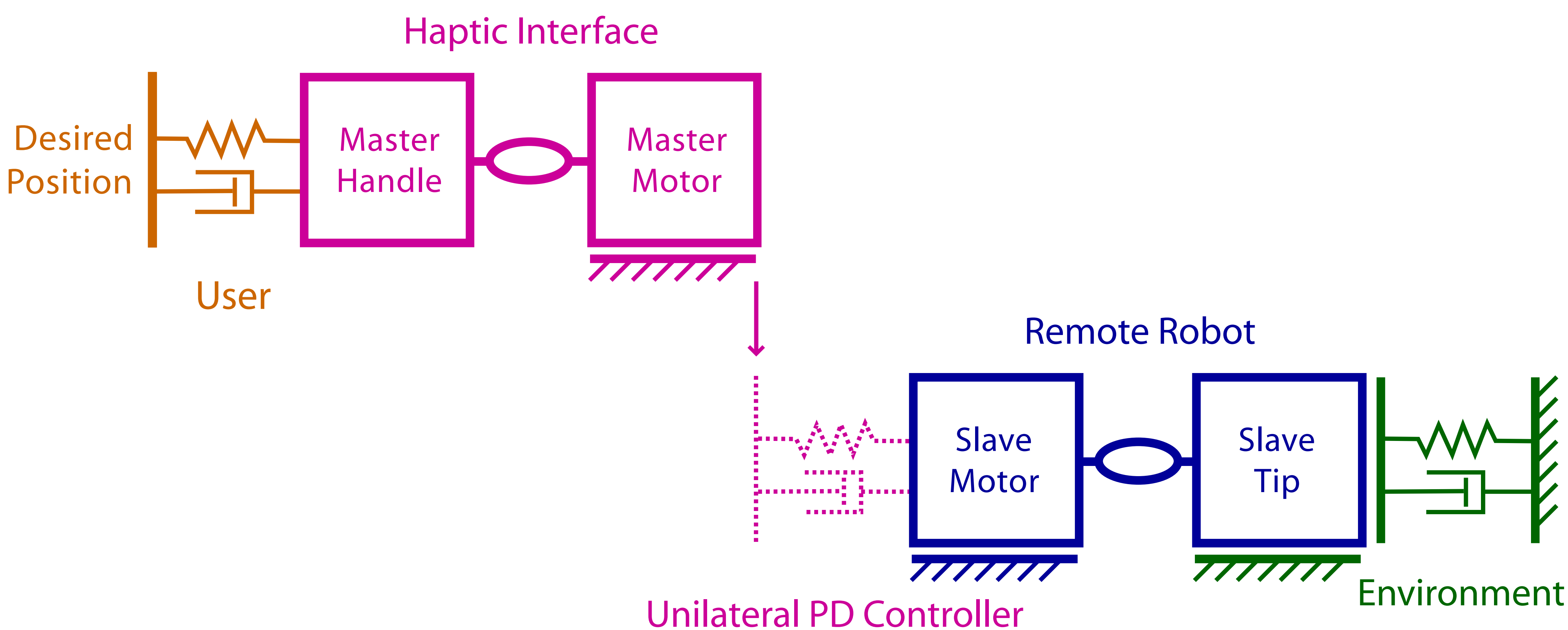




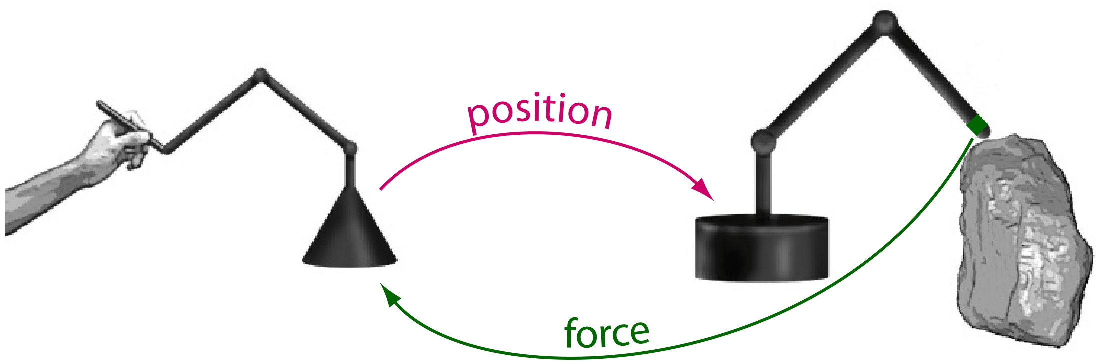
How should we connect the sensors and actuators of the master and slave to make the system behave well?

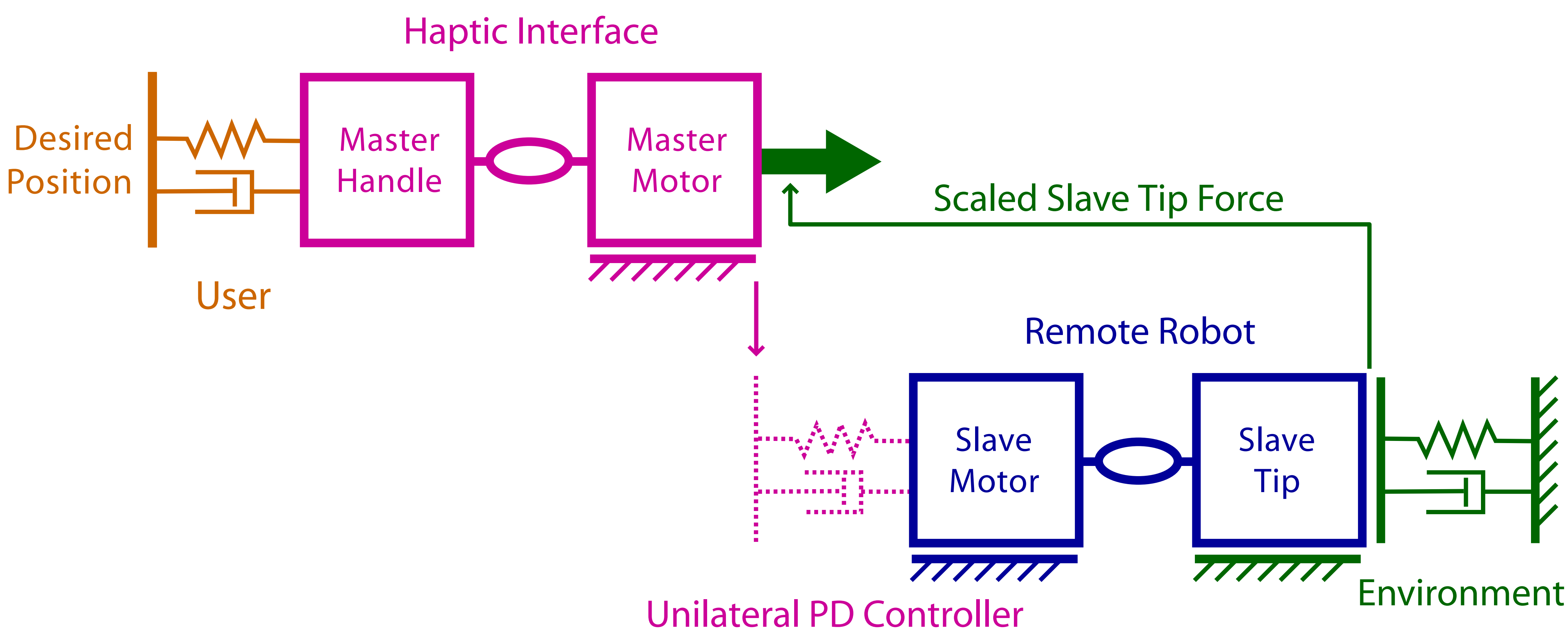
Position-Forward Control



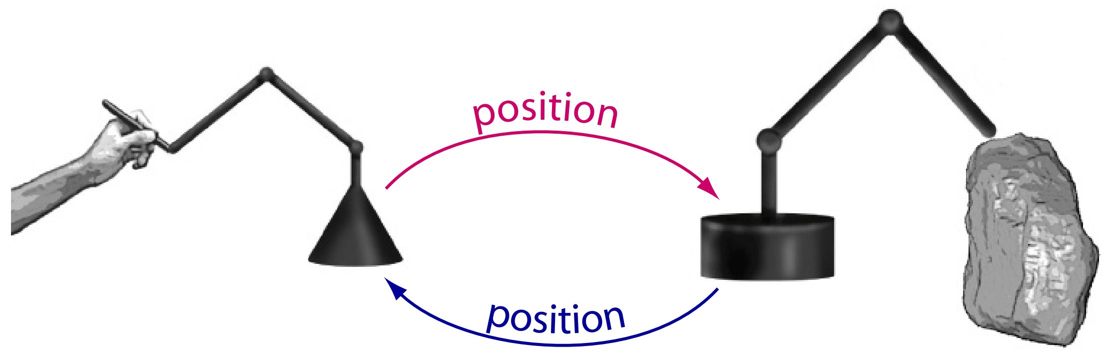


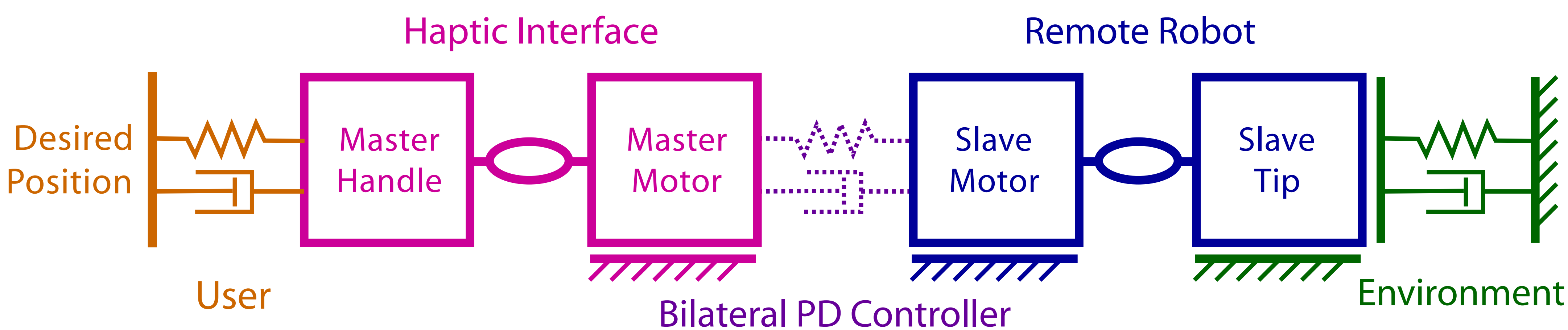
Position-Force Control



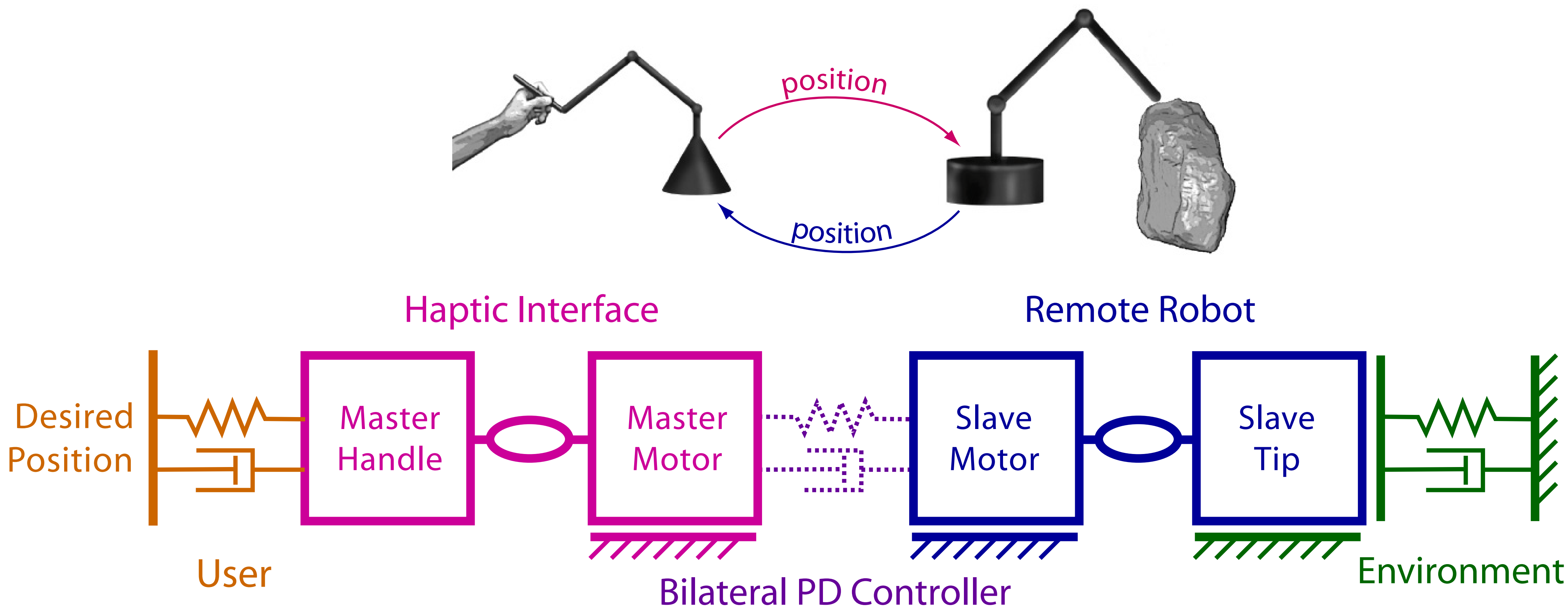


Position-Position Control



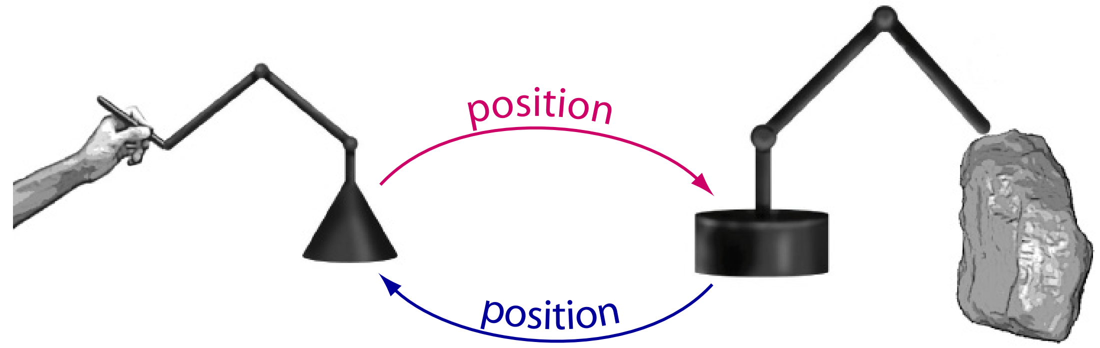


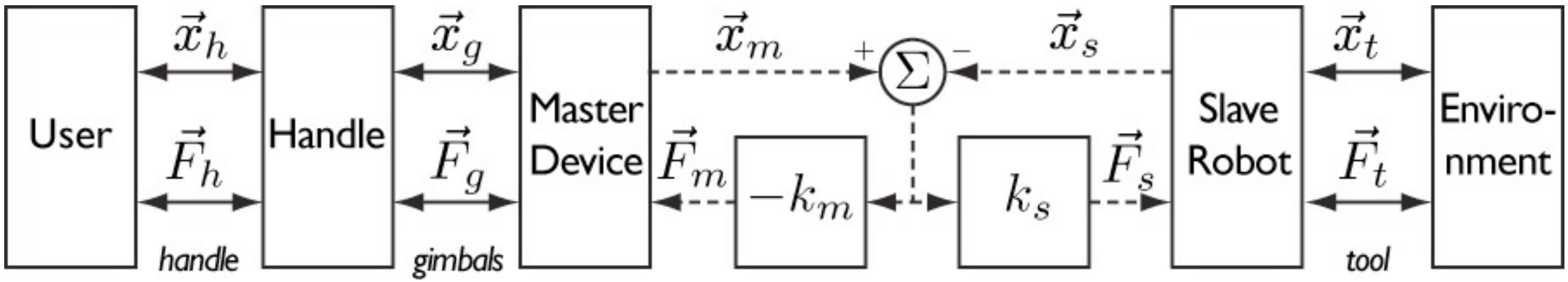
Position-Position Control



- With two impedance-type (backdrivable) devices, the most common controller is position-position, also known as position exchange.
- Each device has a desired state (position and velocity), which is computed from measured states.
- Separate controllers try to make each device achieve its desired state by using the motors to output forces.

Position-Position Control



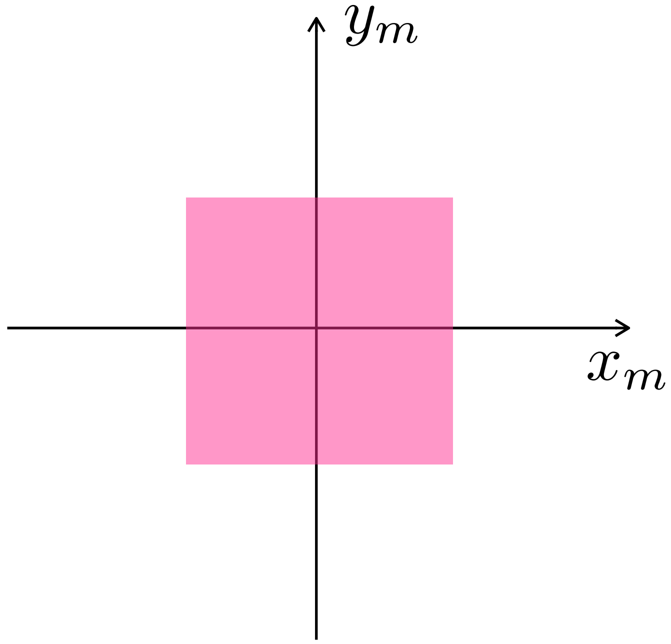


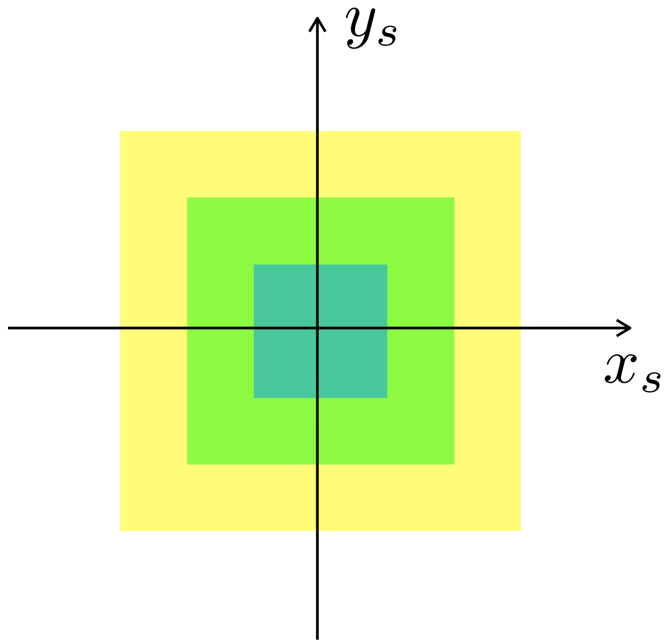
- When there is no motion scaling and no derivative feedback, a position-position controller can be diagrammed as above.
- What happens when one or both of the k's are zero?
- If both k's are positive, it's a bilateral feedback controller. Does the designation of master/slave matter?
- Why not use an integral term in the controllers?

Position Scaling

$$\vec{x}_{s,des} = \mu \, \vec{x}_m$$

$$\vec{x}_{m,des} =$$





- You can use a position scaling factor, μ, to scale how the master's workspace maps into the slave workspace.

- Usually use the same gain in all Cartesian directions.

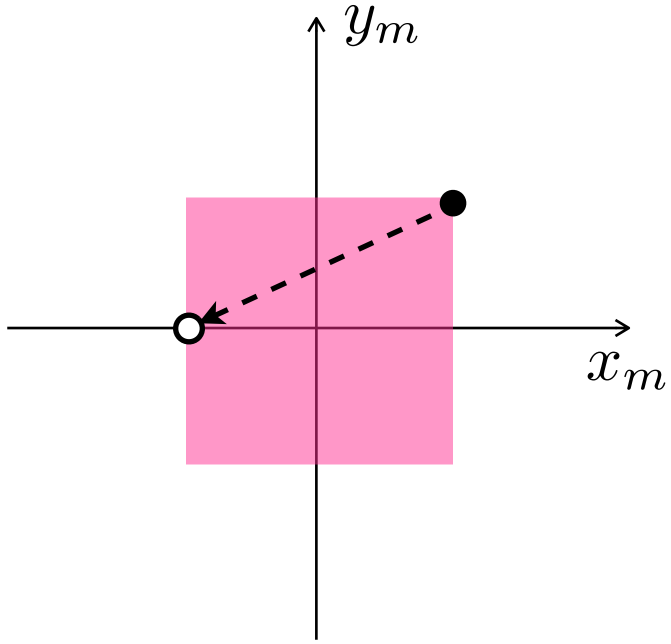
- Should we scale rotational motion?

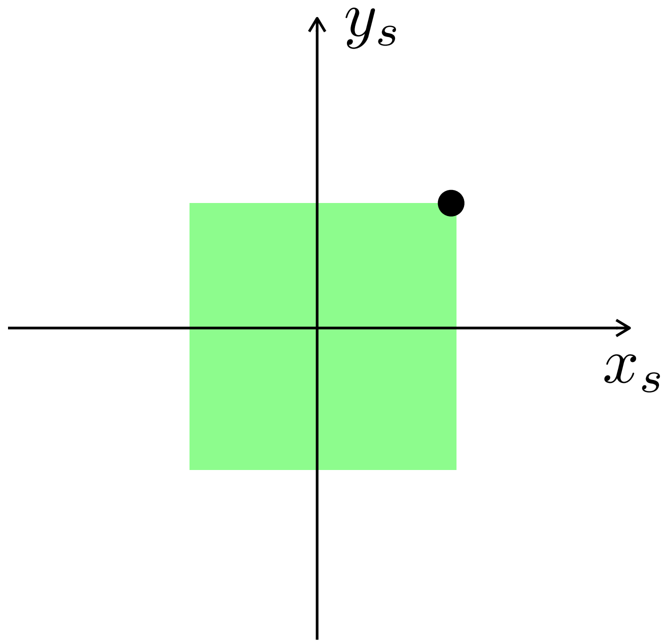
Clutching (also called Indexing)

$$\vec{x}_{s,des} = \mu\,(\vec{x}_m - \vec{x}_{clutch})$$

$$\vec{x}_{s,des} = \mu\,\vec{x}_m + \vec{x}_{offset}$$

$$\vec{x}_{m,des} =$$





- You can use let the user disengage the master from the slave to change the offset between their respective workspaces.

- The offset starts at zero and accumulates during the interaction.

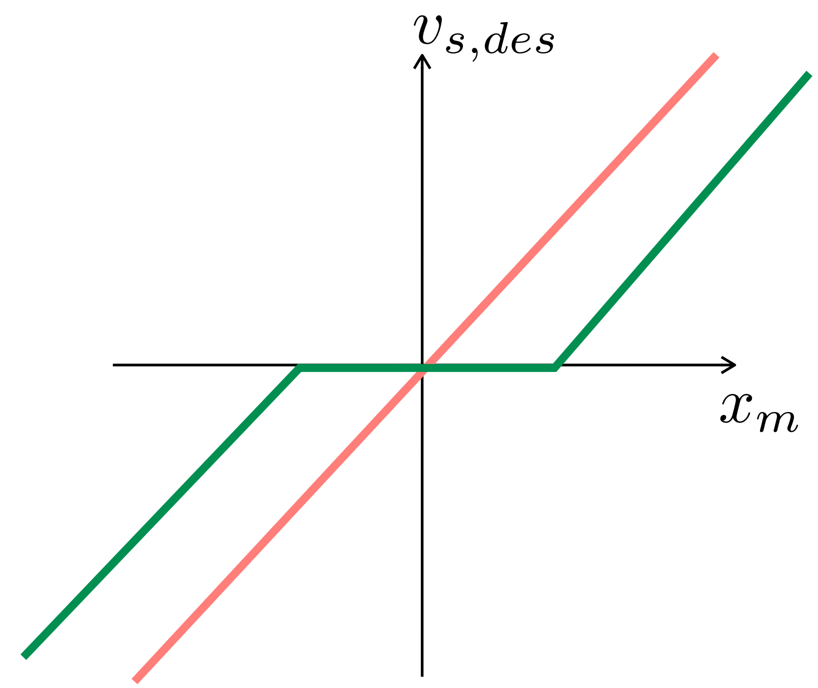
- Usually allow clutching in all Cartesian directions.

- Should we clutch rotational motion?

Rate Control

$$\vec{v}_{s,des} = \gamma\, \vec{x}_m$$

$$\vec{F}_m = -k\, \vec{x}_m$$



- If the slave workspace is very large or even infinite, you can use a different type of controller: rate control.
- Use a centering spring to push the user's hand back to zero.
- But ... the operator often wants to be able to stop the remote robot easily, so add a deadband.

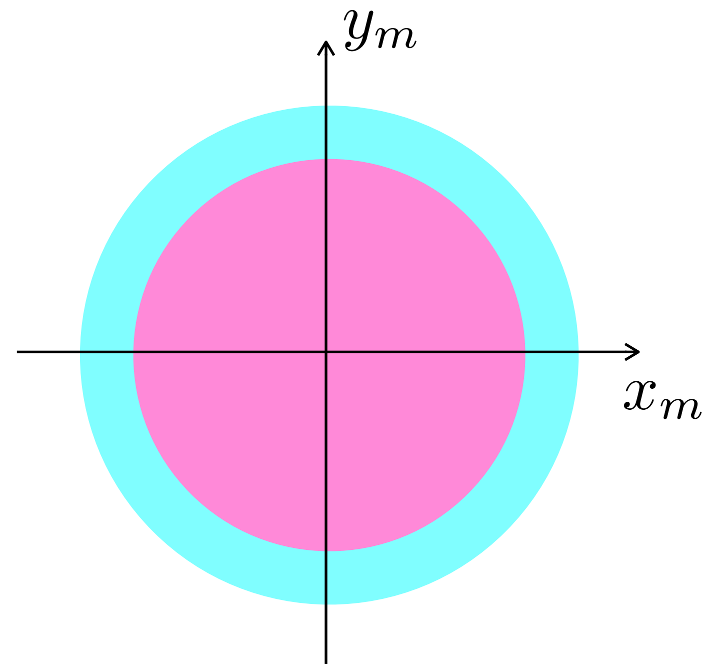
$$\text{if } x_m > \delta, v_{s,des} = \gamma(x_m - \delta)$$

$$\text{else if } x_m < -\delta, v_{s,des} = \gamma(x_m + \delta)$$

$$\text{else } v_{s,des} = 0$$

- Should we use rate control for rotational motion?

Hybrid Position and Rate Control

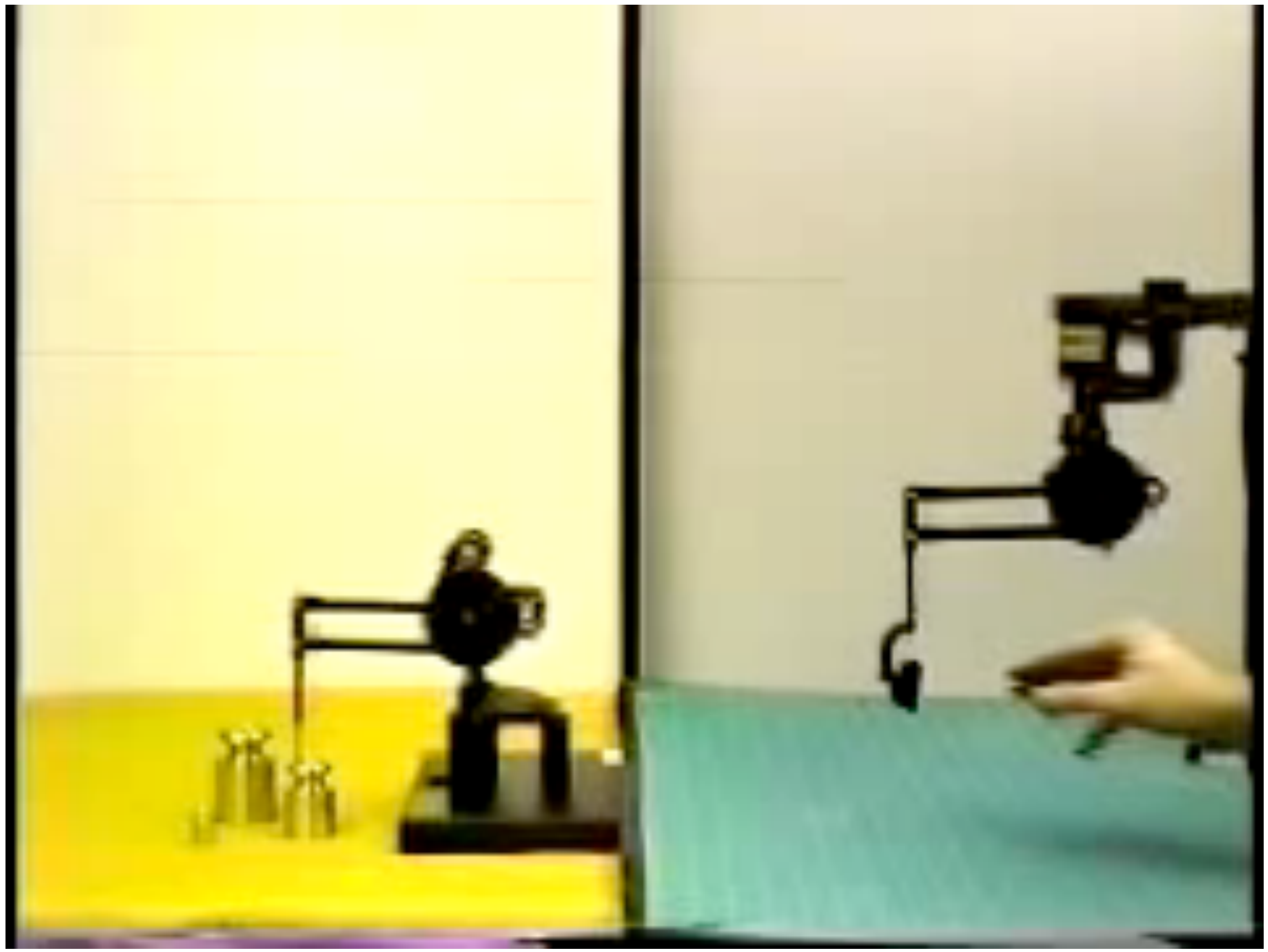


- Use a position-position controller in a zone that's centered in the master's workspace.
- When the user gets to the edge of this zone, transition to rate control, which moves the master's workspace around in the remote environment.
- This approach avoids the distinct mode switching that comes with clutching.
- What should the user feel if the remote robot hits something under rate control?

Time Delay

- Time delays between master and slave will make position-position control unstable; time delays are unavoidable when the master and slave are in separate locations.
- When delays are fixed and known, you can use alternative encoding methods, such as wave variables, to avoid instability.
- People then won't notice delays of about 200 milliseconds, but the feel will be deteriorated.
- Can use a predictor to estimate where the user is moving the master, to improve responsiveness.
- Can build a model of the remote environment and use that to provide haptic feedback locally.
- When time delays become large, operators adopt a "move and wait" approach - give the slave more autonomy.

Teleoperation with Time Delay



(Niemeyer and Slotine, 1998)

Questions ?

A teleoperation assignment is
being planned for homework 6...


The Ben Franklin
Racing Team

Homework 6

(tentative plan)

Test out the Intuitive da Vinci robot in small groups.
(Dates and times will be announced).

Answer a series of questions about the da Vinci.
(Done individually).

A haptics assignment is
being planned for project 2...


PHANToM

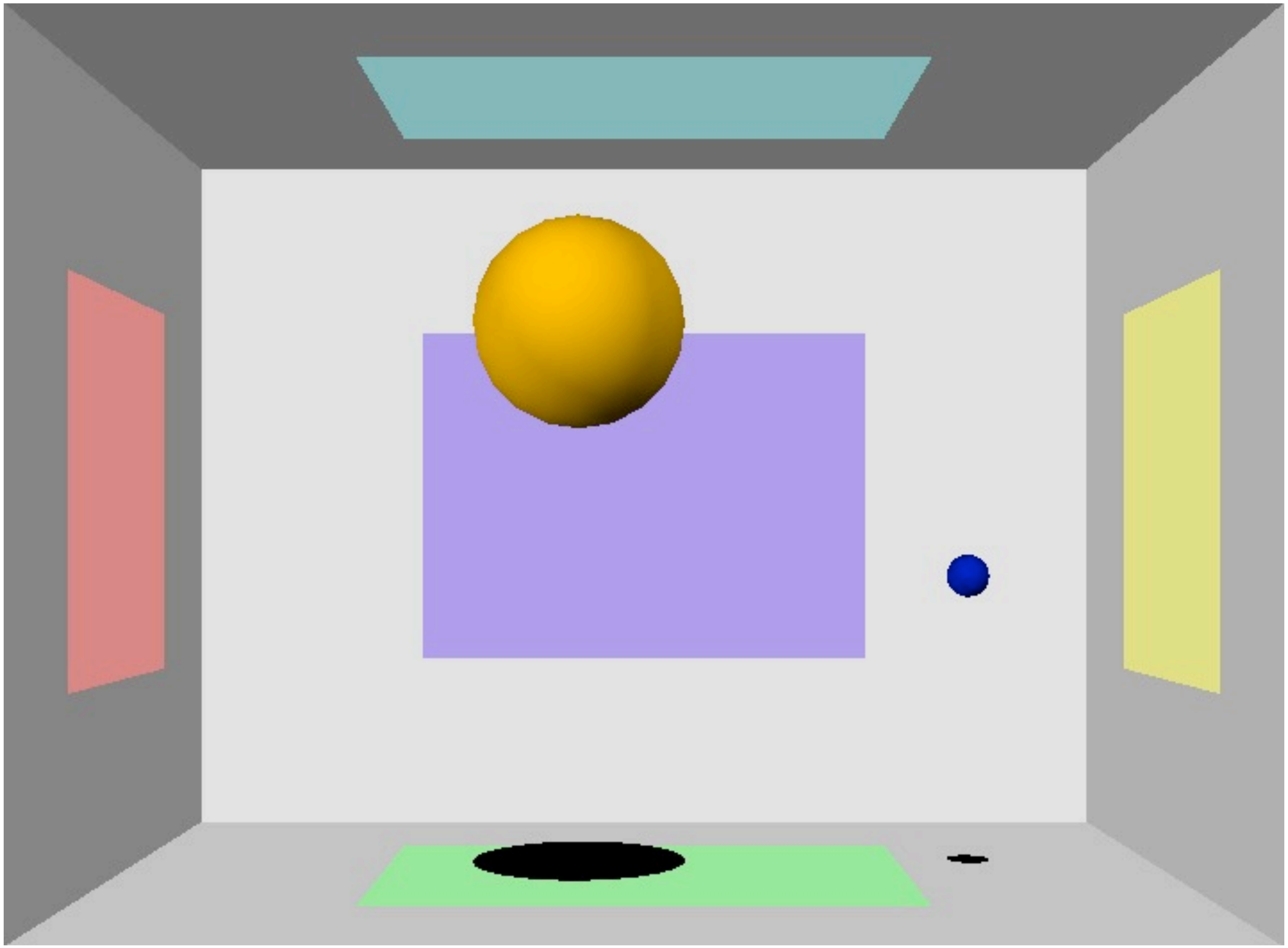
Project 2

(tentative plan)

Program a simple haptic virtual environment that can be touched with the Phantom.

(Details will be announced).

(Done in teams of three).



Something like a box with a stationary ball...

Team Formation

You will work in a team of 3
(33 teams of 3, only one team of 4)

You may not keep the same team as for project 1.
I strongly encourage you to work with all new people.

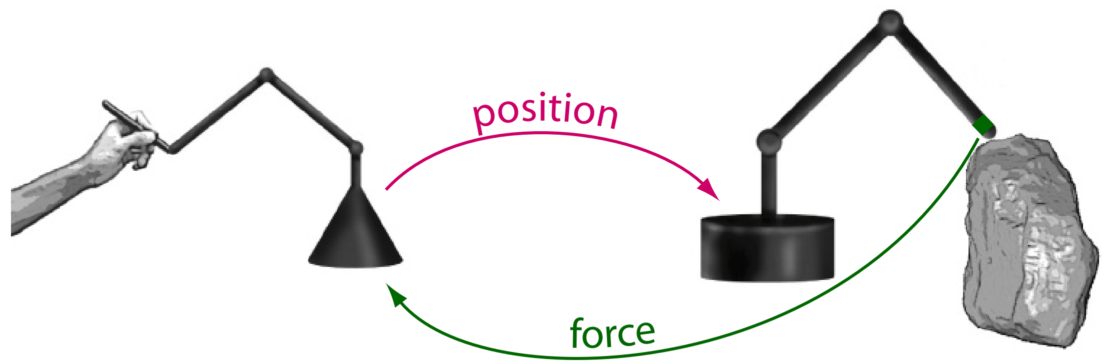
If you insist, you can stay with one other person, but beware the negative effects this may have on the dynamics of your subsequent team.

I encourage you to mix undergrad and grad, MEAM and non-MEAM, but this is not required.

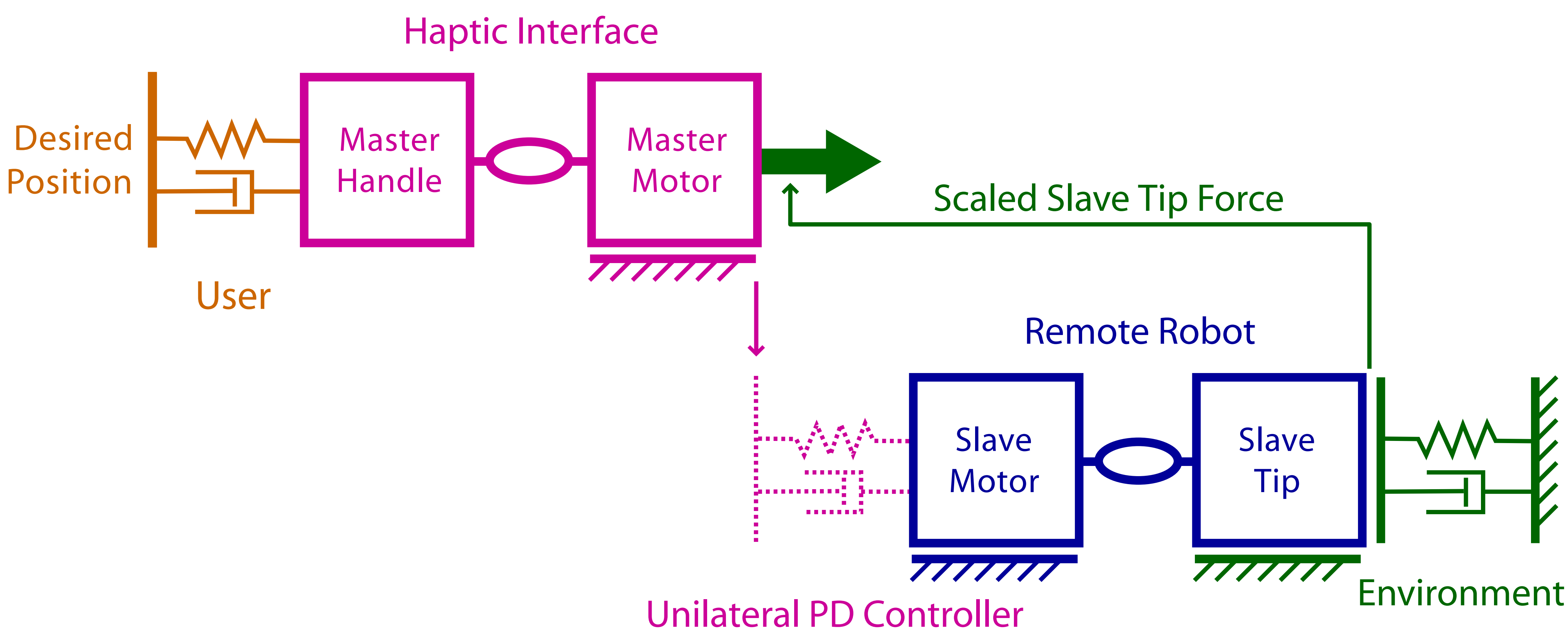
Please pick your team soon.   Details out ASAP.
We will randomly assign people who do not select a team.

Questions ?

Position-Force Control



How can you scale the slave tip force more?

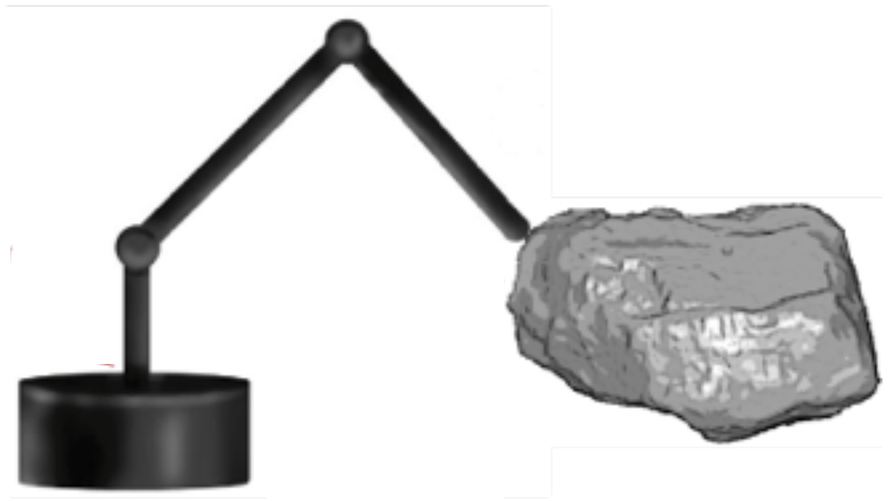


Canceling Induced Master Motion

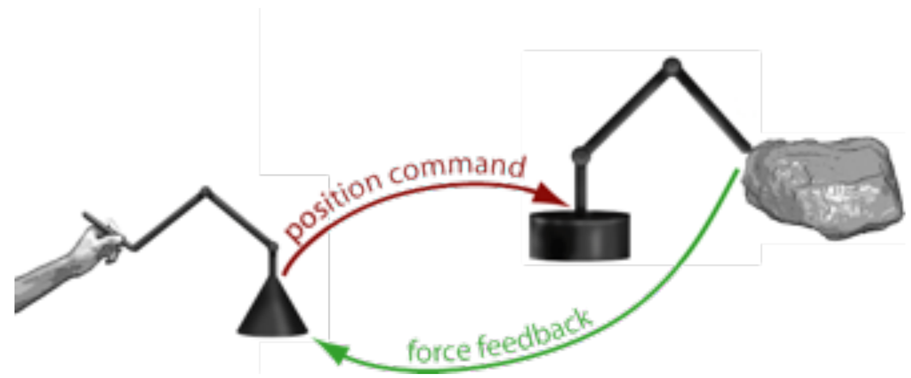
in Force-Reflecting Teleoperation

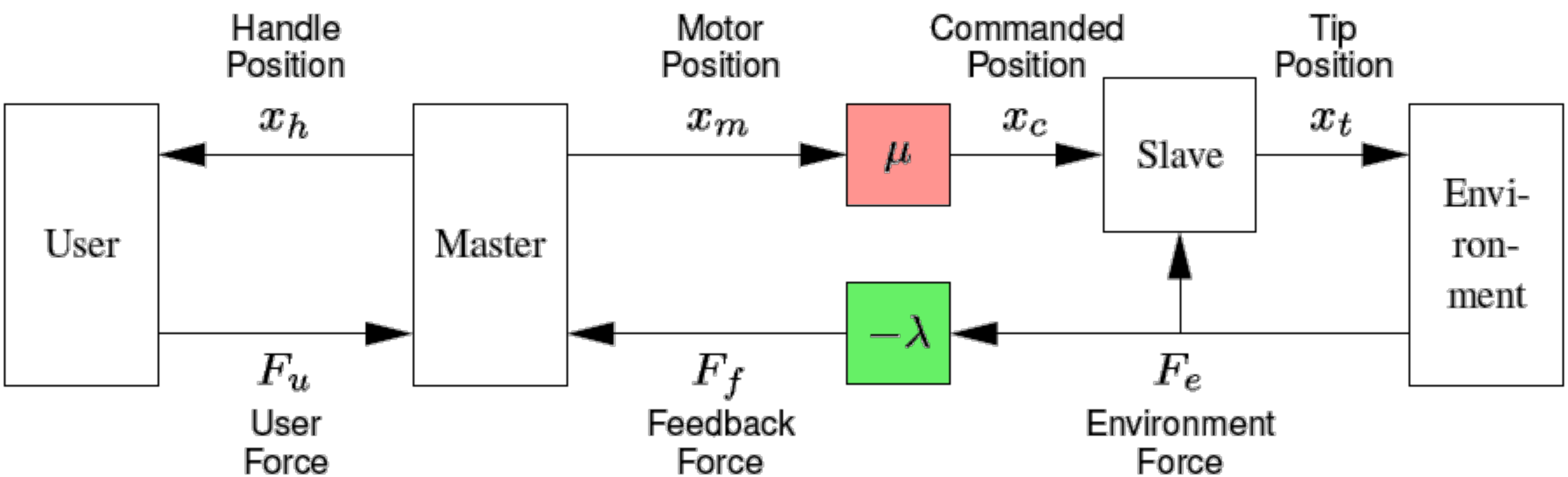
Katherine J. Kuchenbecker
Günter Niemeyer
Telerobotics Lab
Stanford University

Telerobotics



Controller Architecture



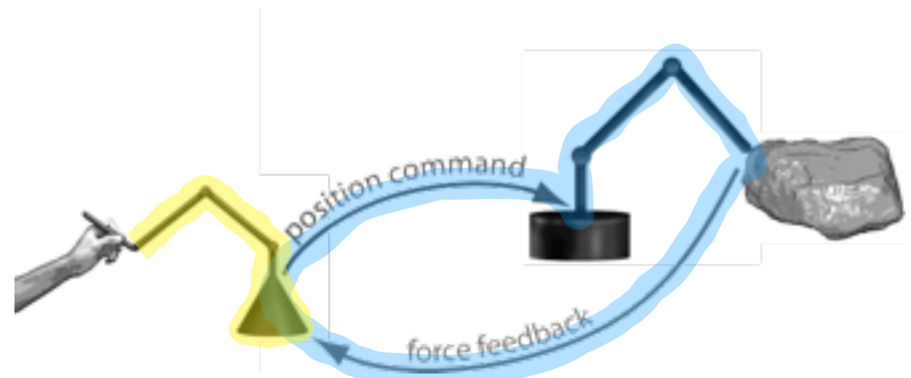


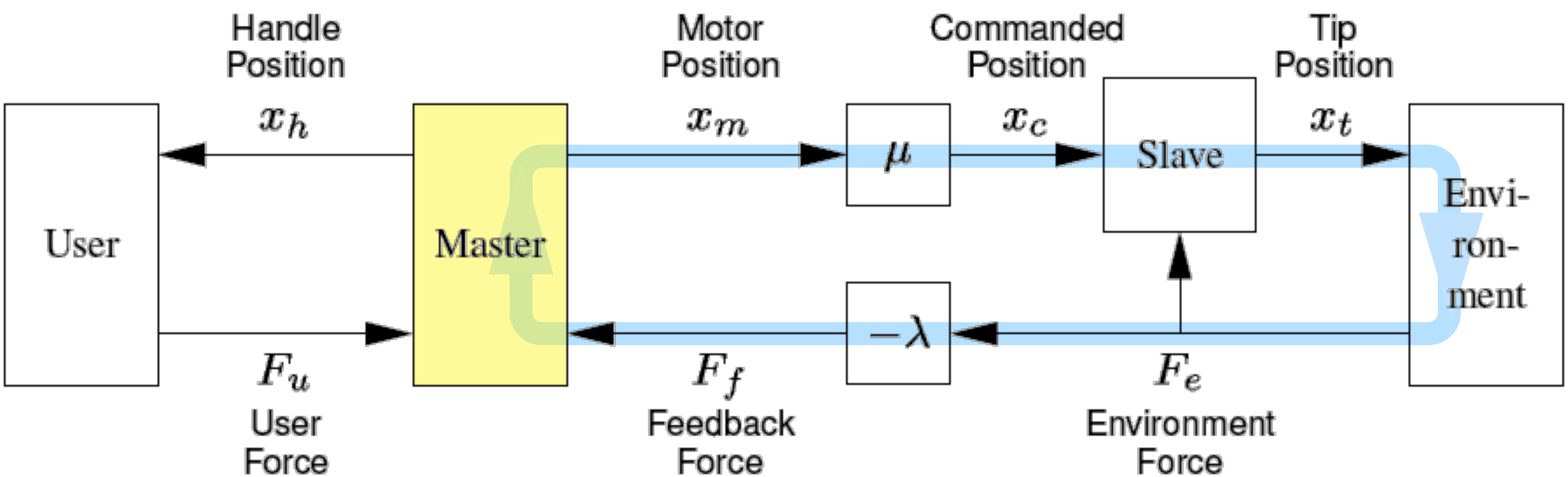
Position-Force Testbed

Position-Force, lambda = 20

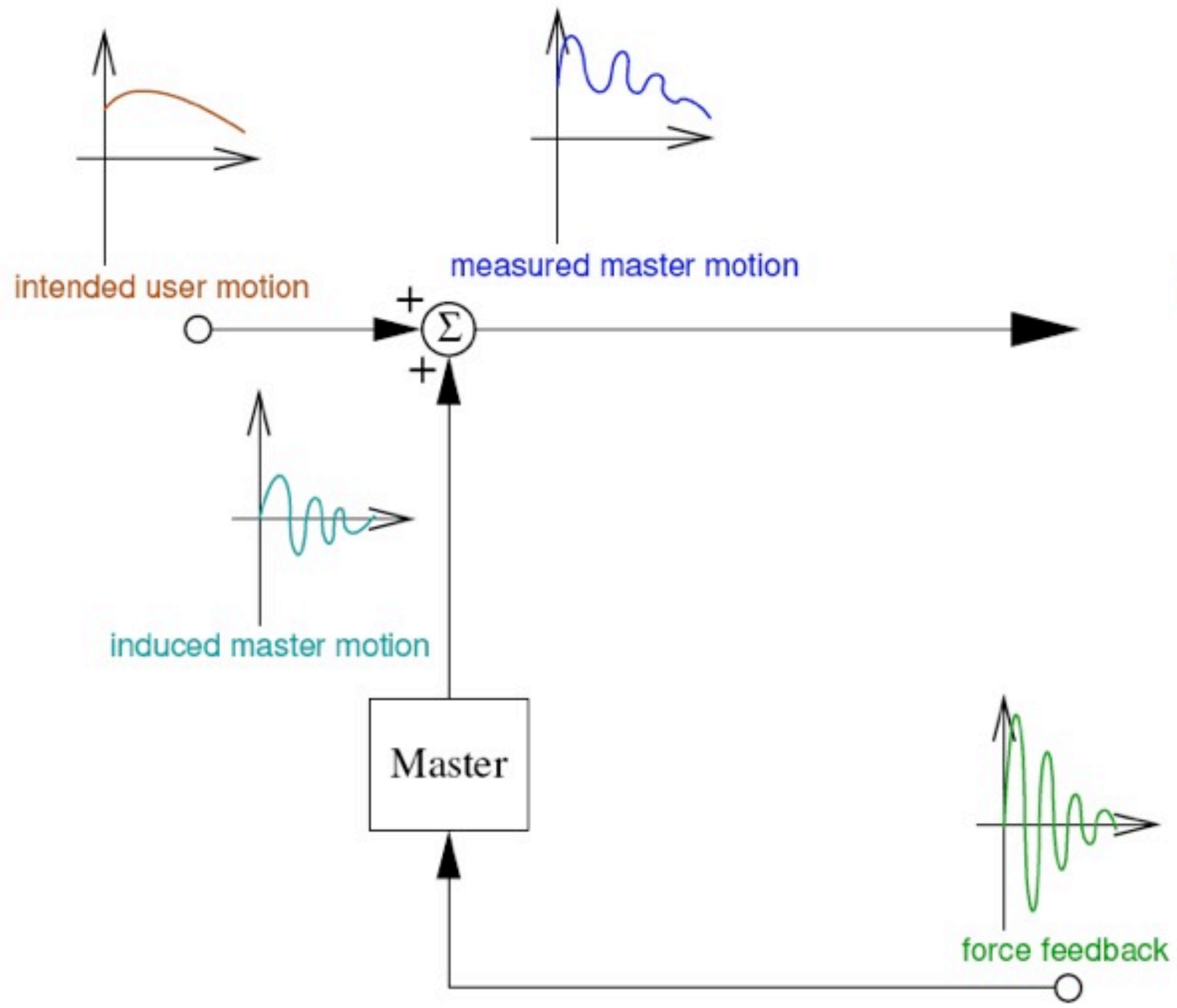
Position-Force, lambda = 10

Internal Controller Loop

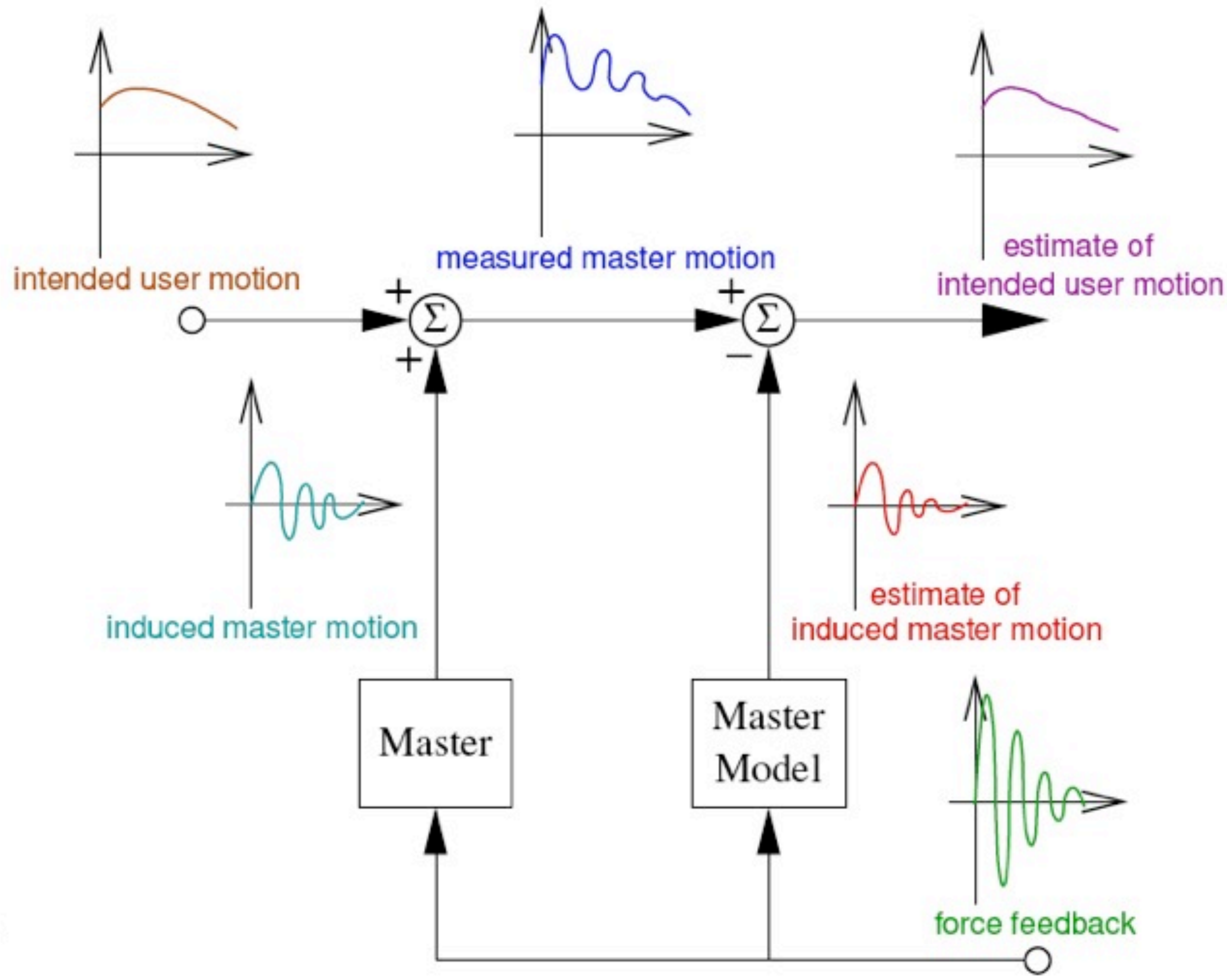




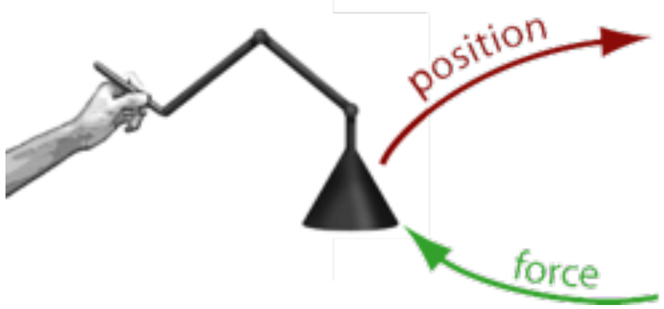
Induced Master Motion

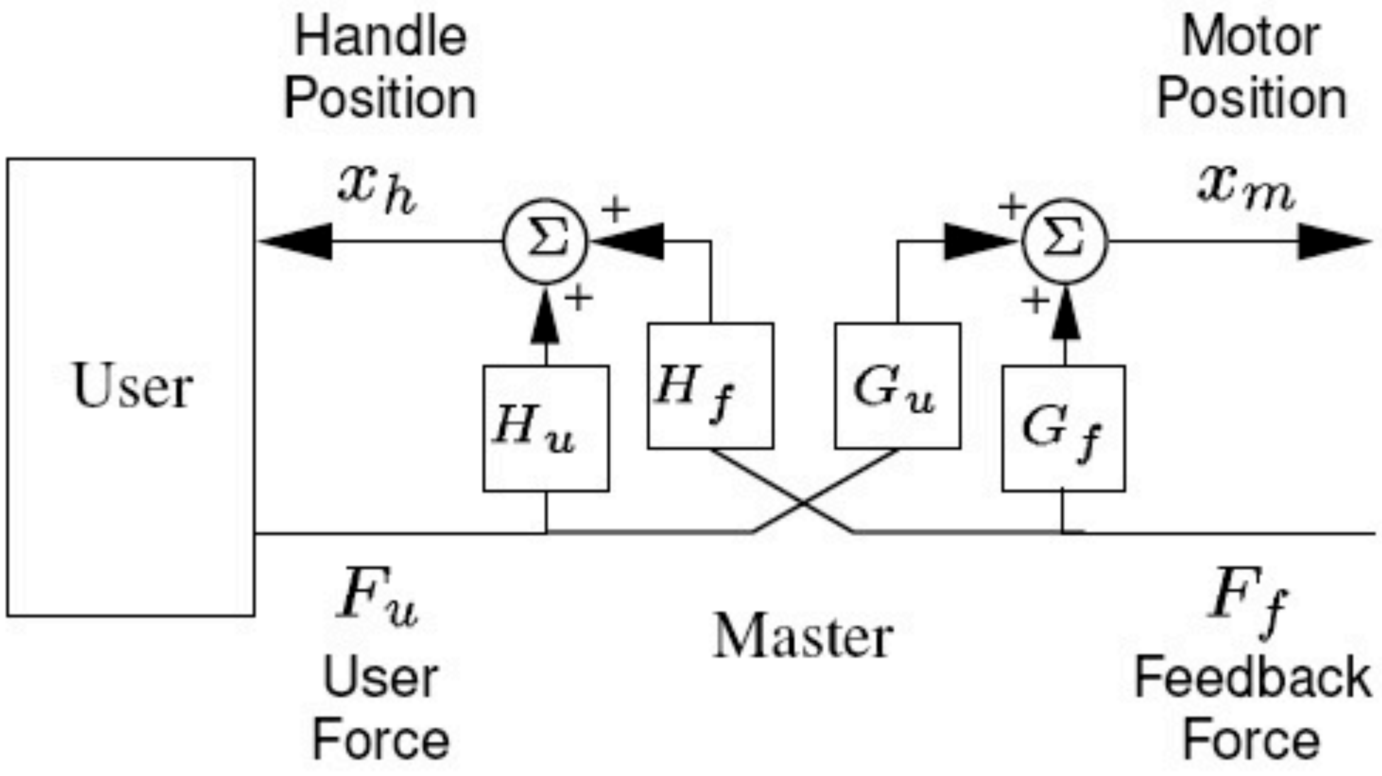


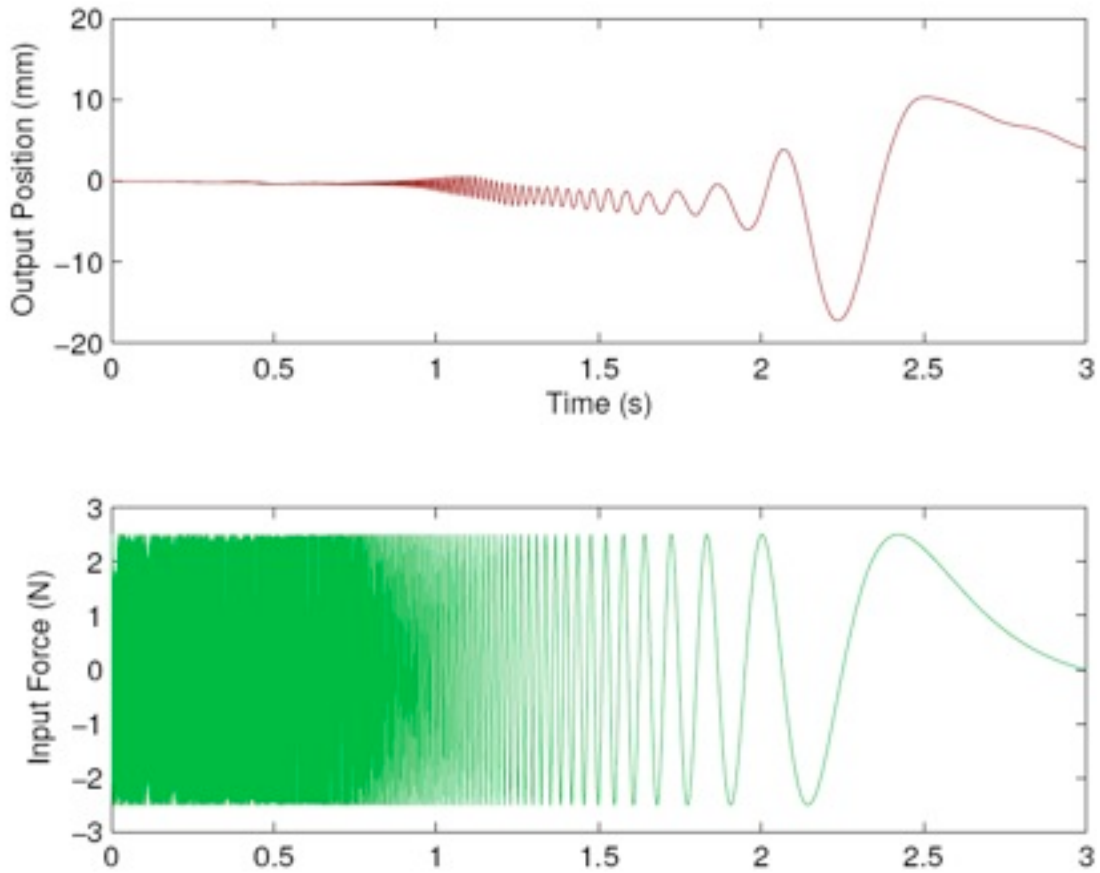
Canceling Induced Master Motion



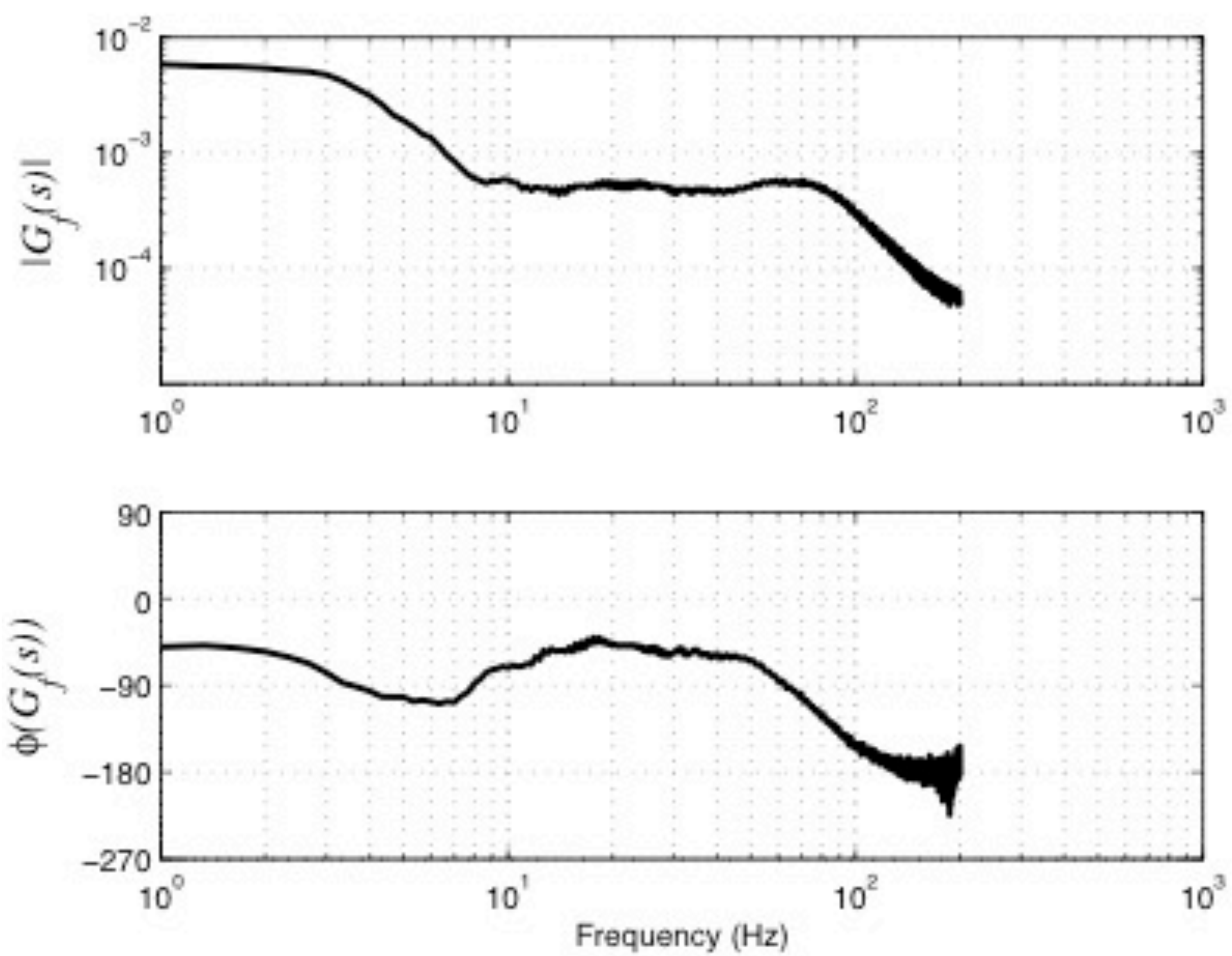
Master System Identification



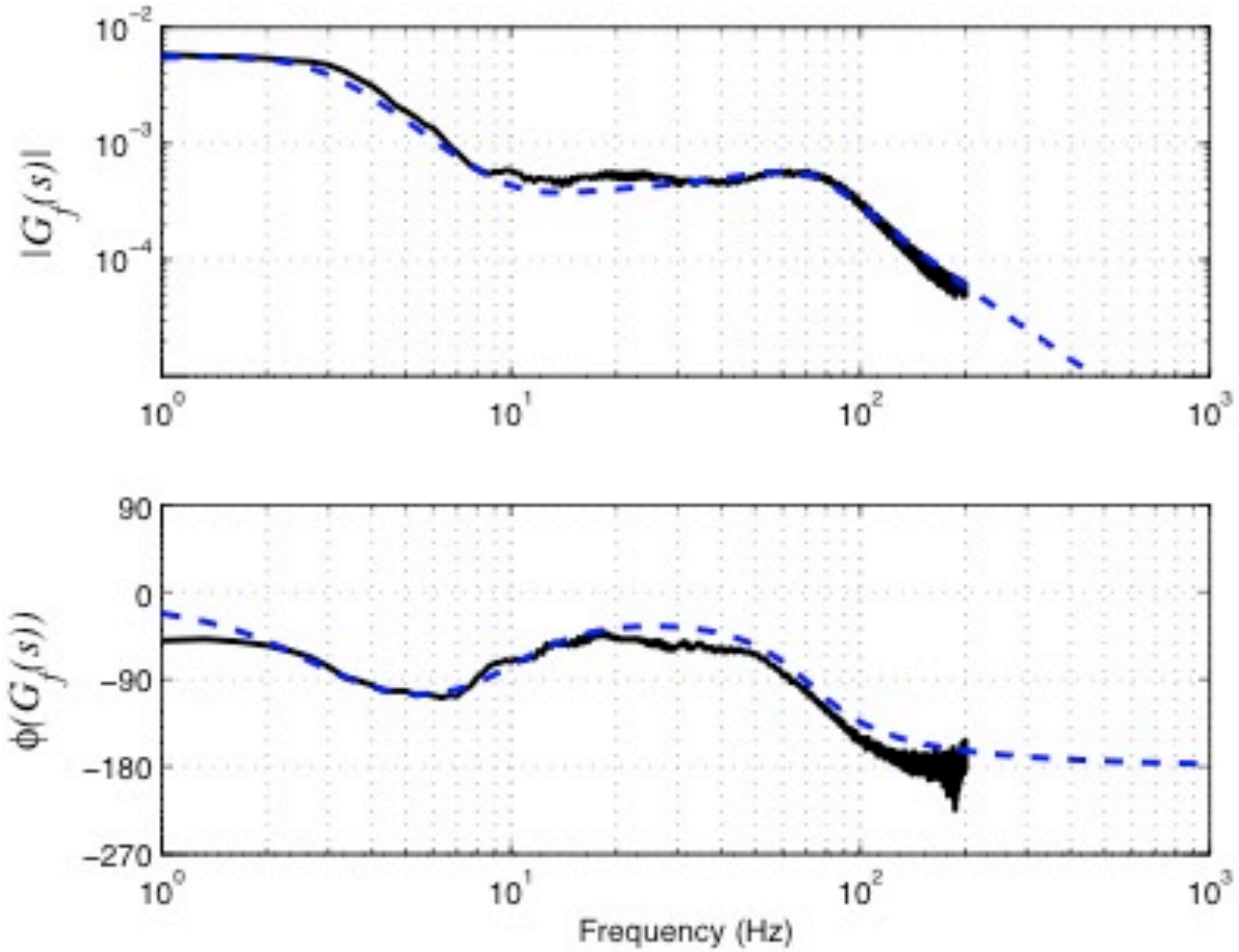


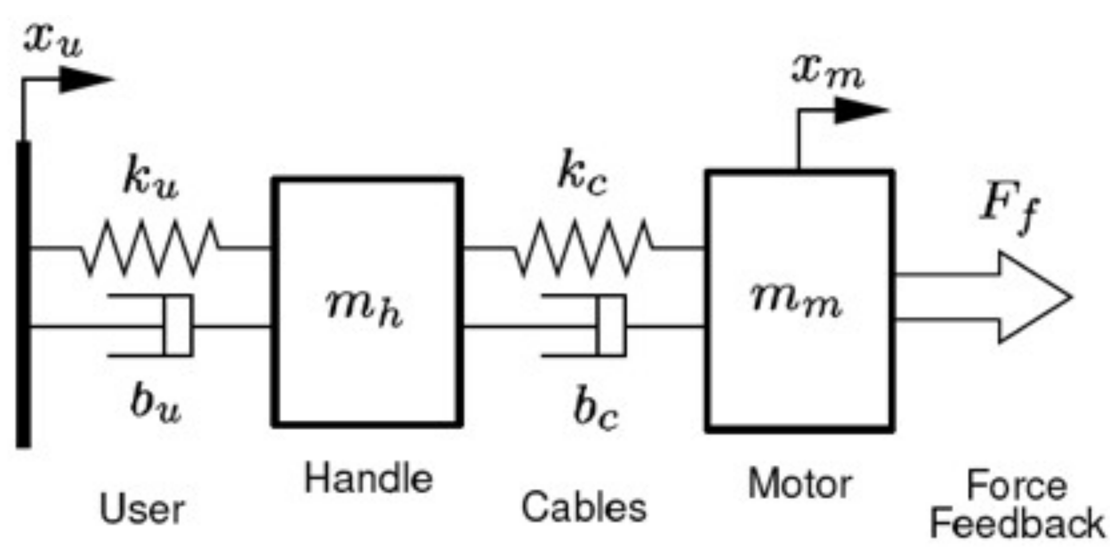


Master Model

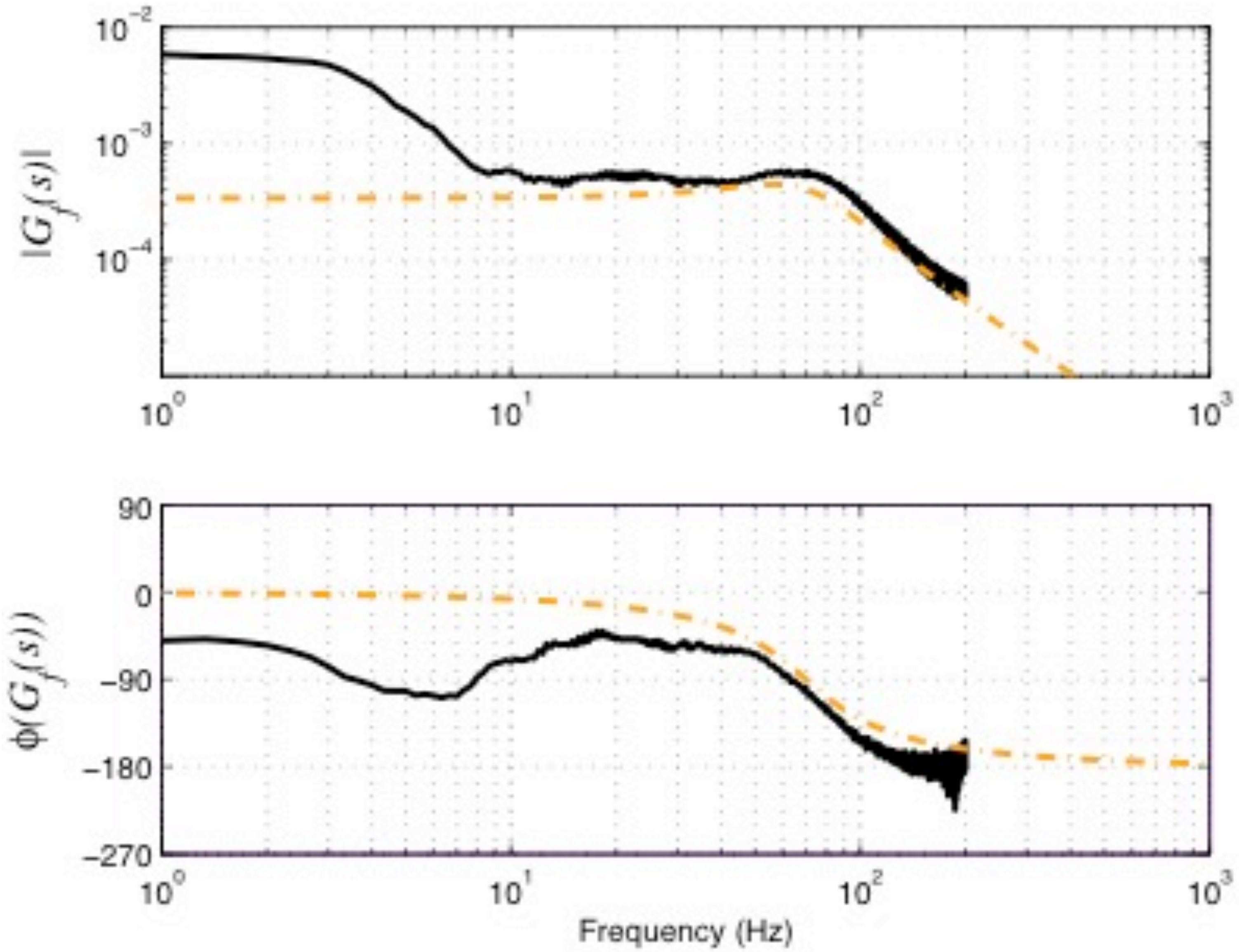


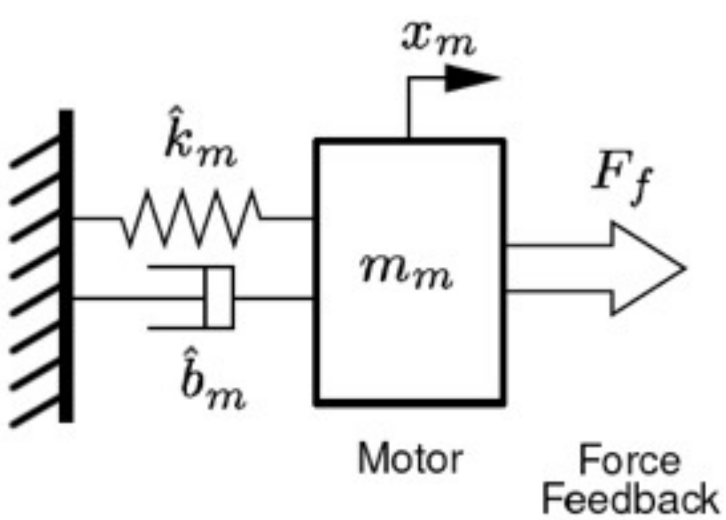
Master Model



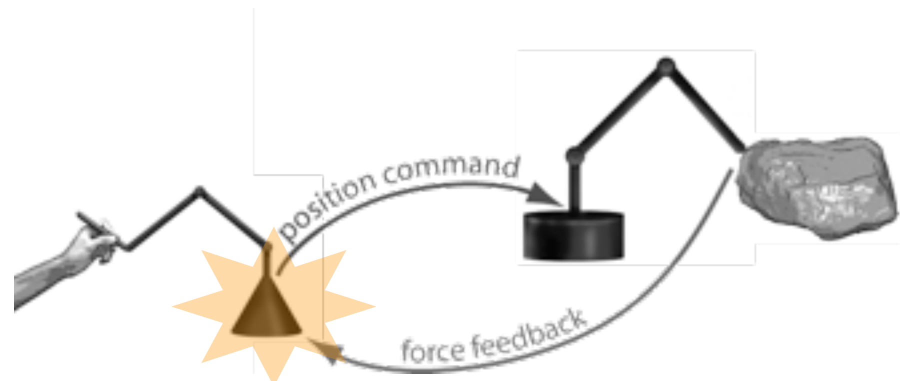


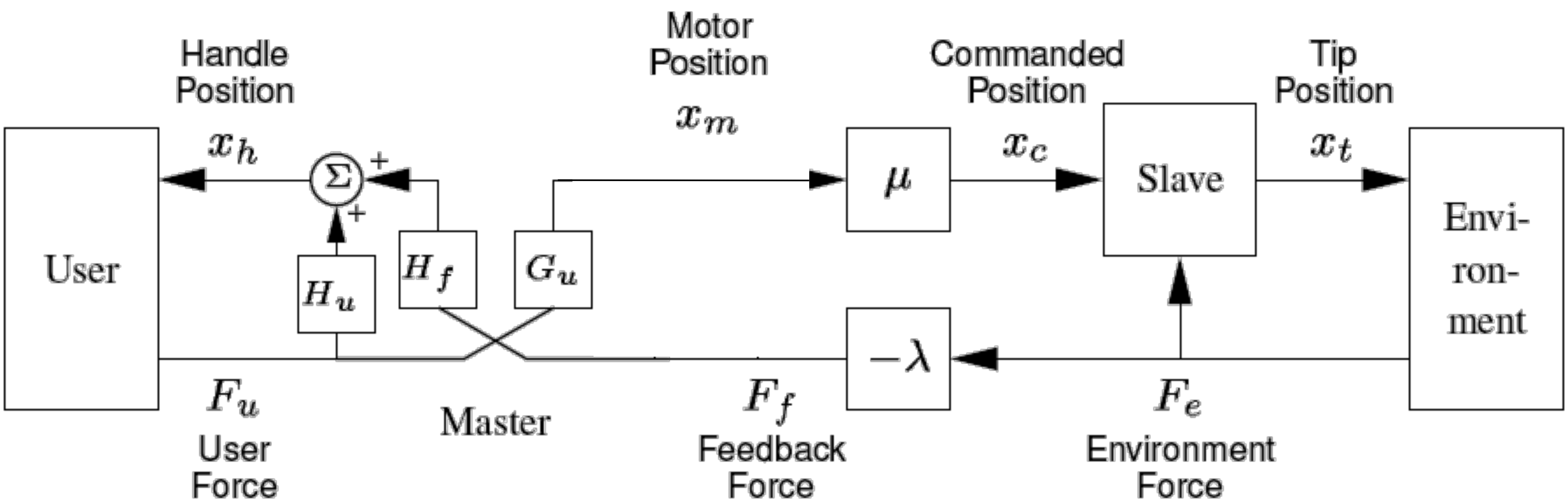
Master Model





Cancellation Strategy

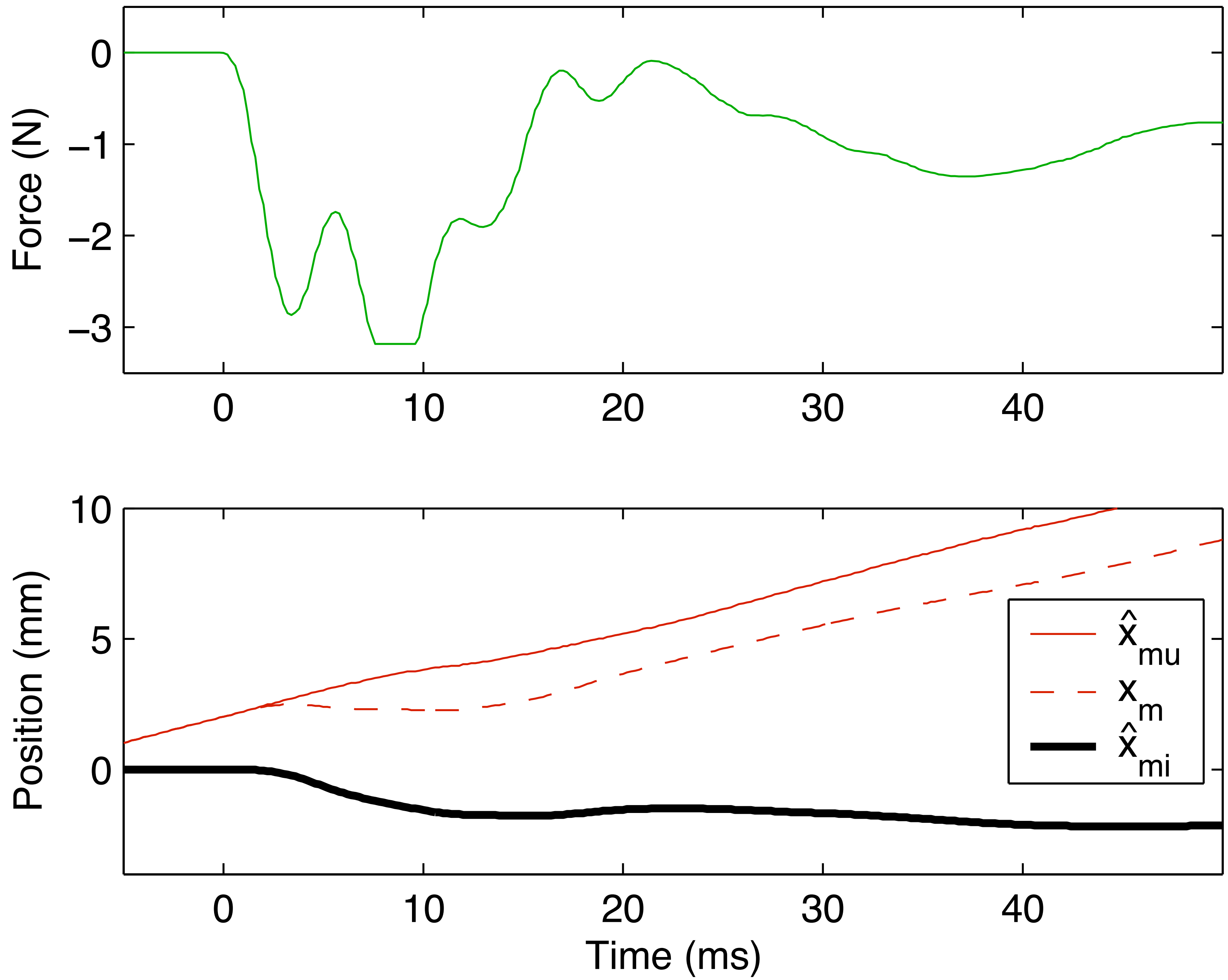




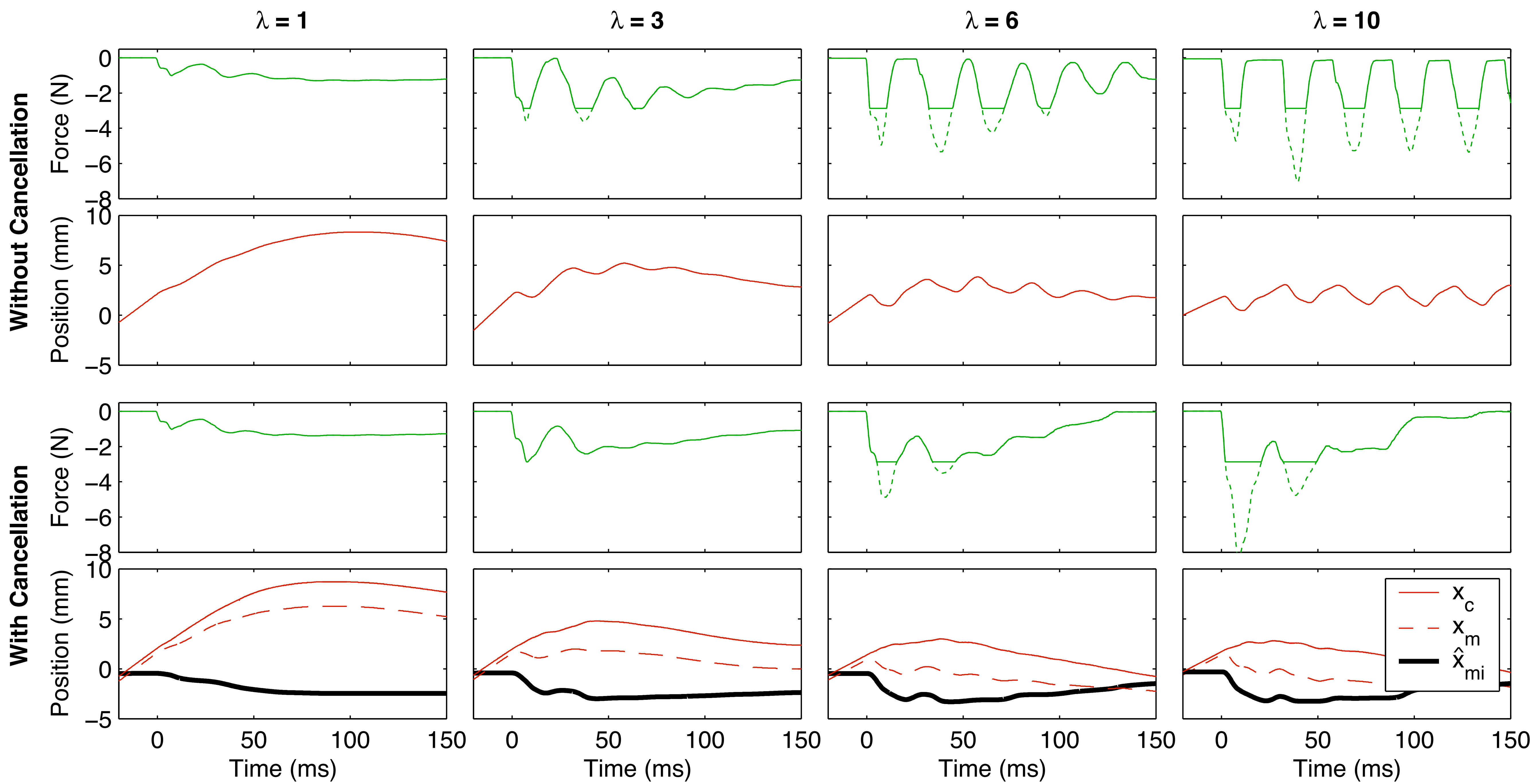
Position-Force Control with CIMM

Position-Force with CIMM, lambda = 20
Position-Force with CIMM, lambda = 20

Canceling Results

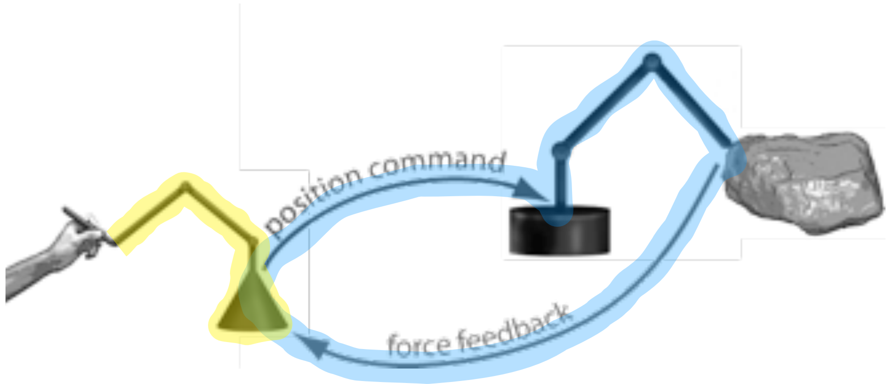


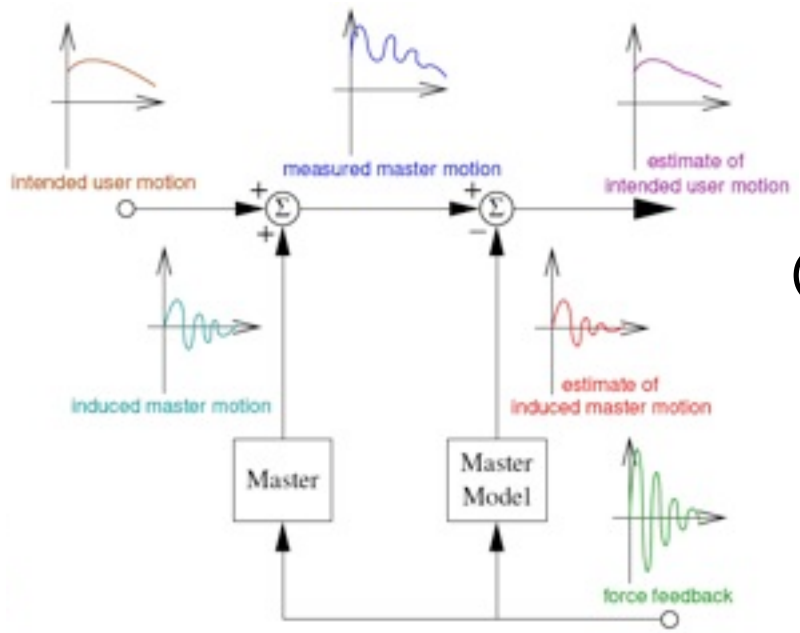
Additional Results



Conclusions

Controller's inner loop limits stability

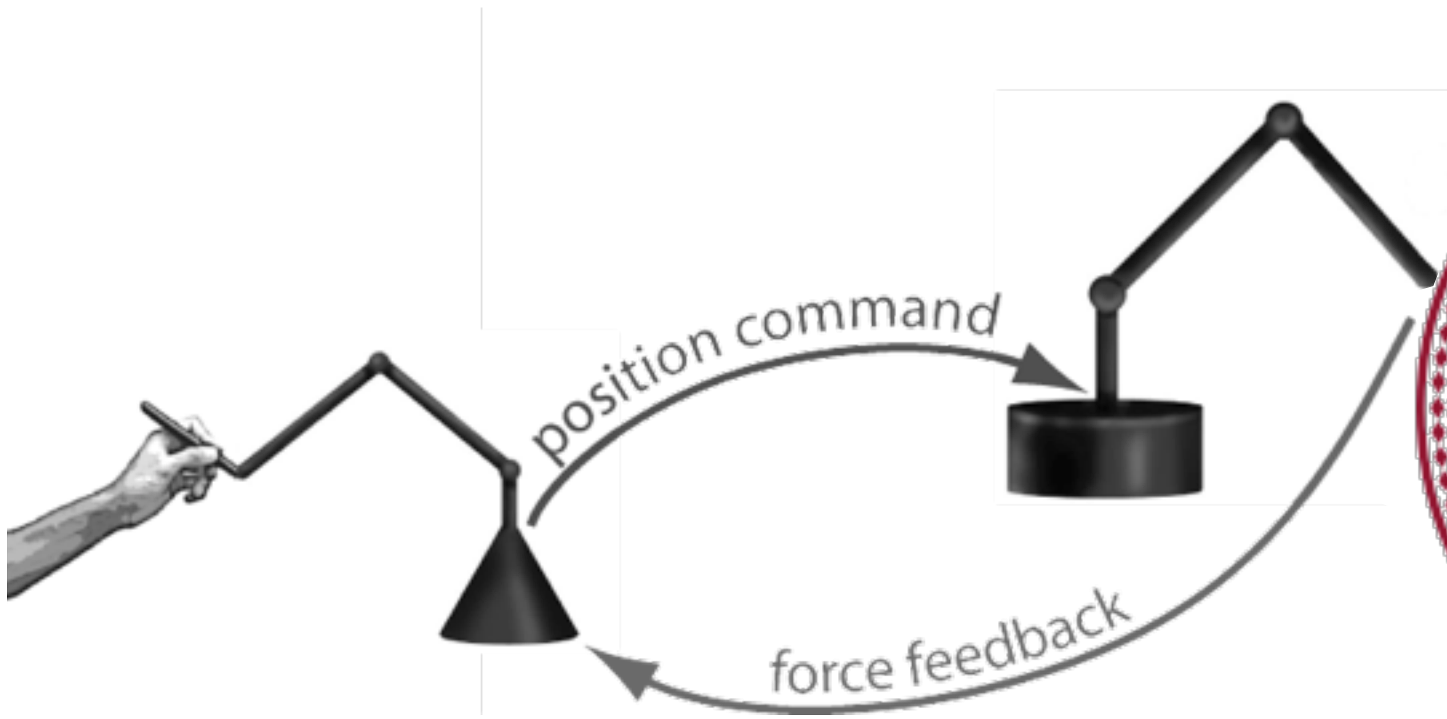




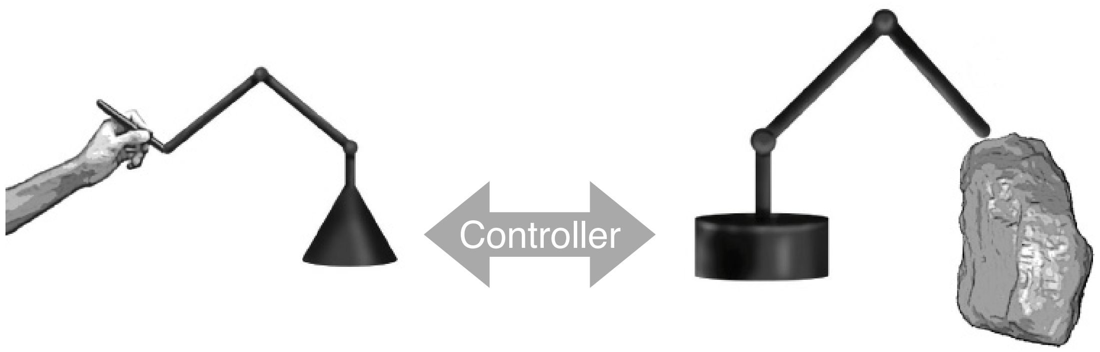
Canceling induced master motion stabilizes contact

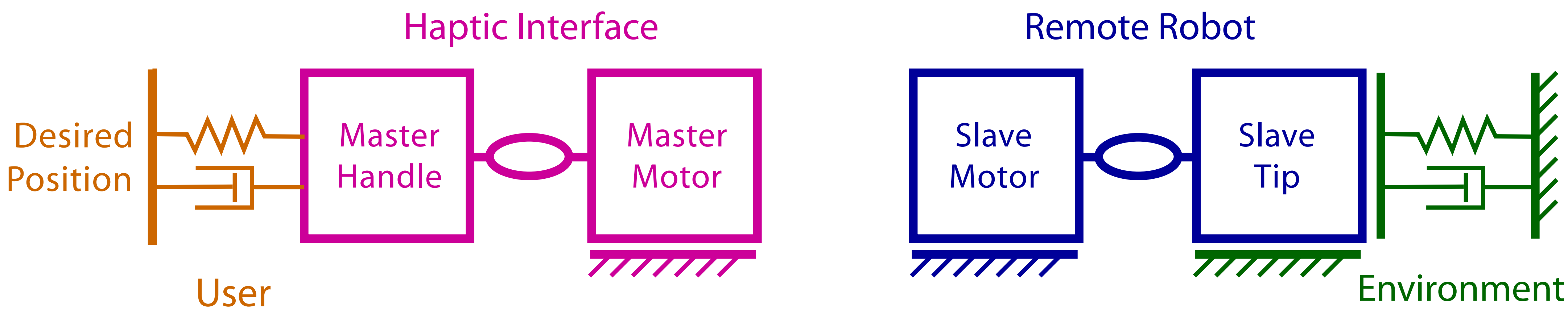
Enable strong, realistic force feedback

Questions?



Teleoperation



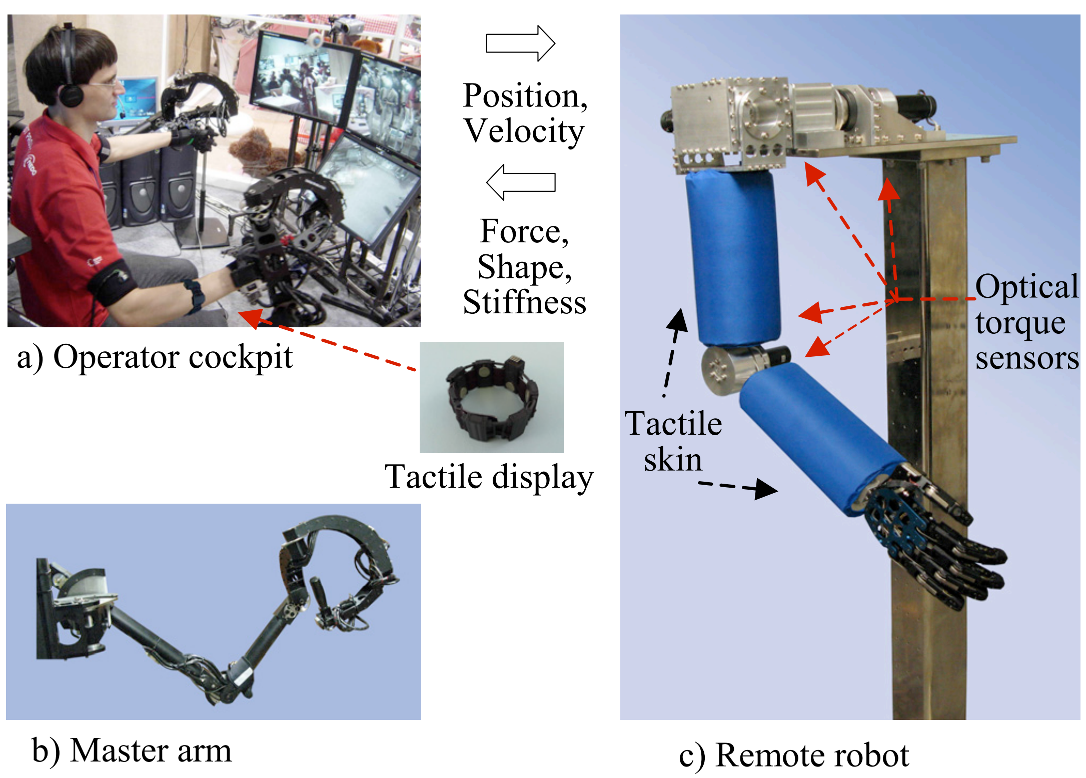


Forward Path Alternatives

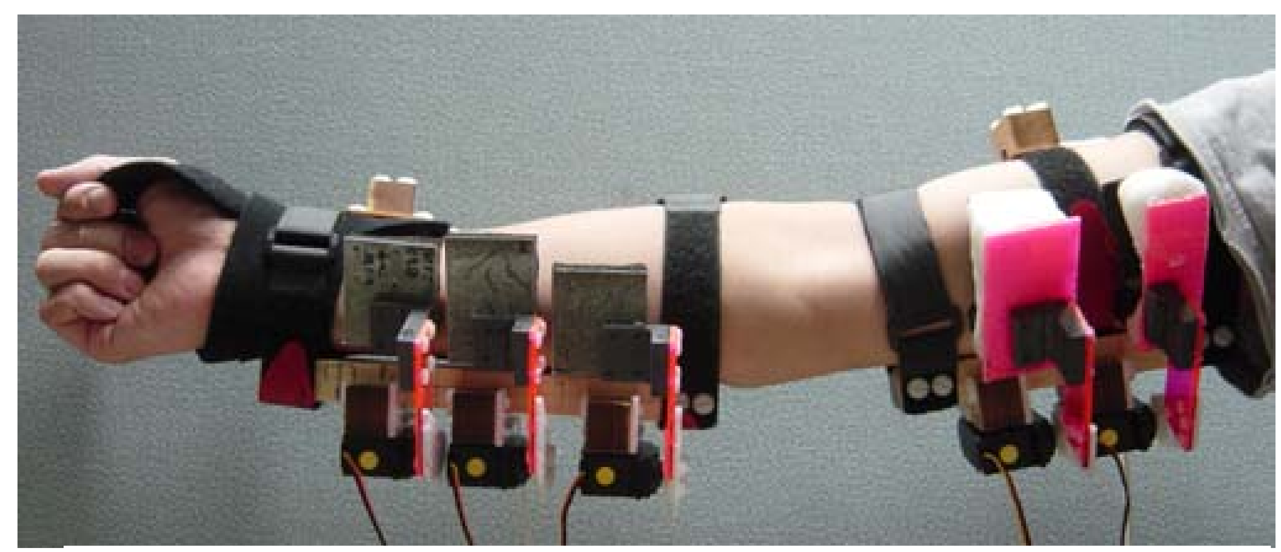
- Cancel induced master motion to keep the system stable for high gain force feedback.
- Use a virtual slave to impose constraints such as joint limits, maximum velocities, and singularity avoidance.
- Change the apparent dynamics of the slave through local force-feedback: pseudo-admittance.
- Measure and send the impedance of the user's hand, so that the slave robot responds as the human hand would: stiff for precise position control and loose for imprecise movement.

Feedback Channel Alternatives

- Historically, there has been so much attention paid to position and force.
- It's important to remember the capabilities and preferences of the human user.
- Tactile feedback is starting to be used more for teleoperation.

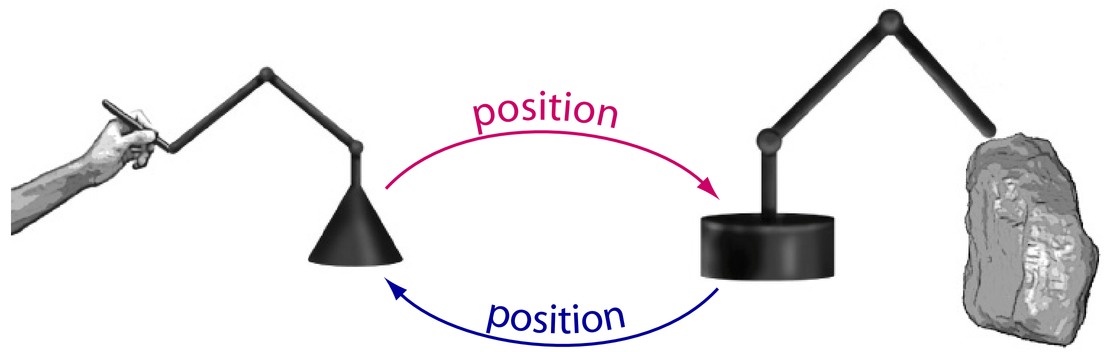


Tsetserukou and Tachi, WHC 2009

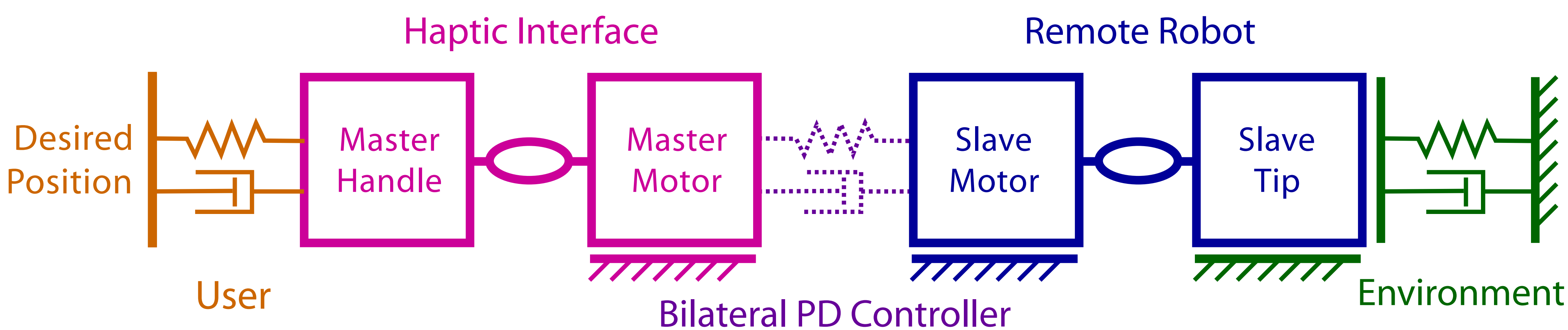


Howe and Tadakuma, WHC 2009

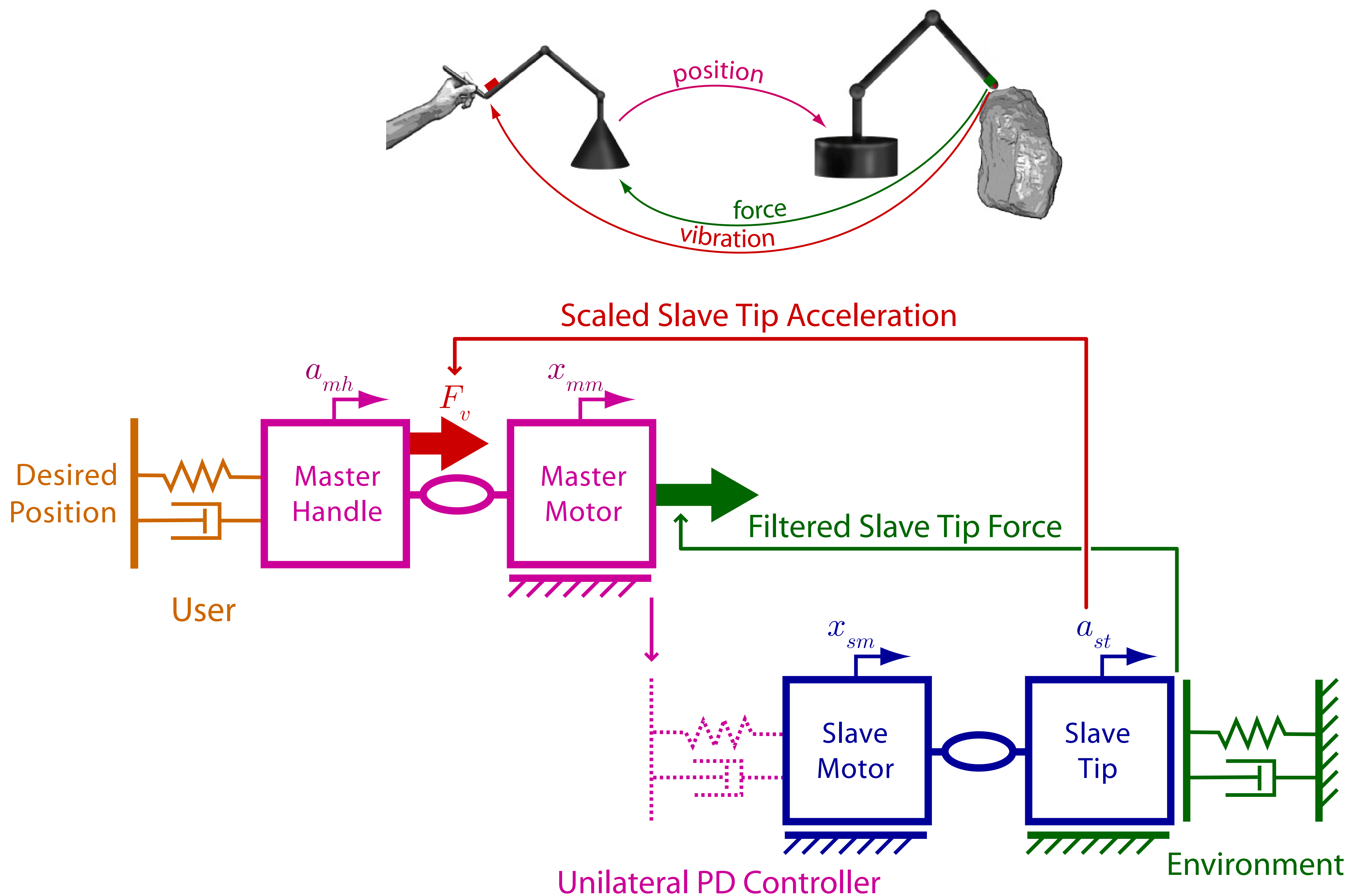
Position-Position Control



How can you give the user a better feel for the environment?

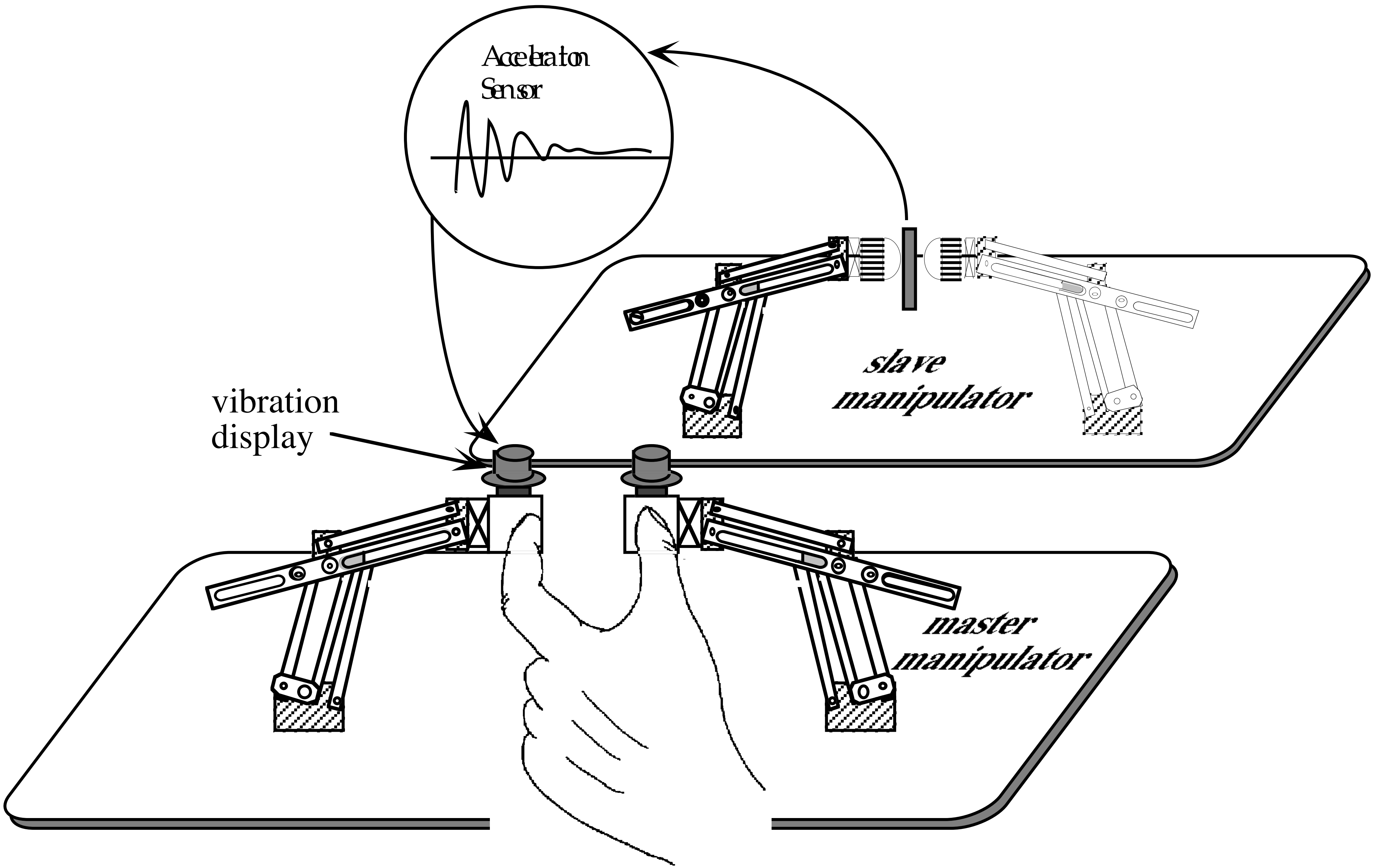


Position-Force Control + Vibrotactile Feedback



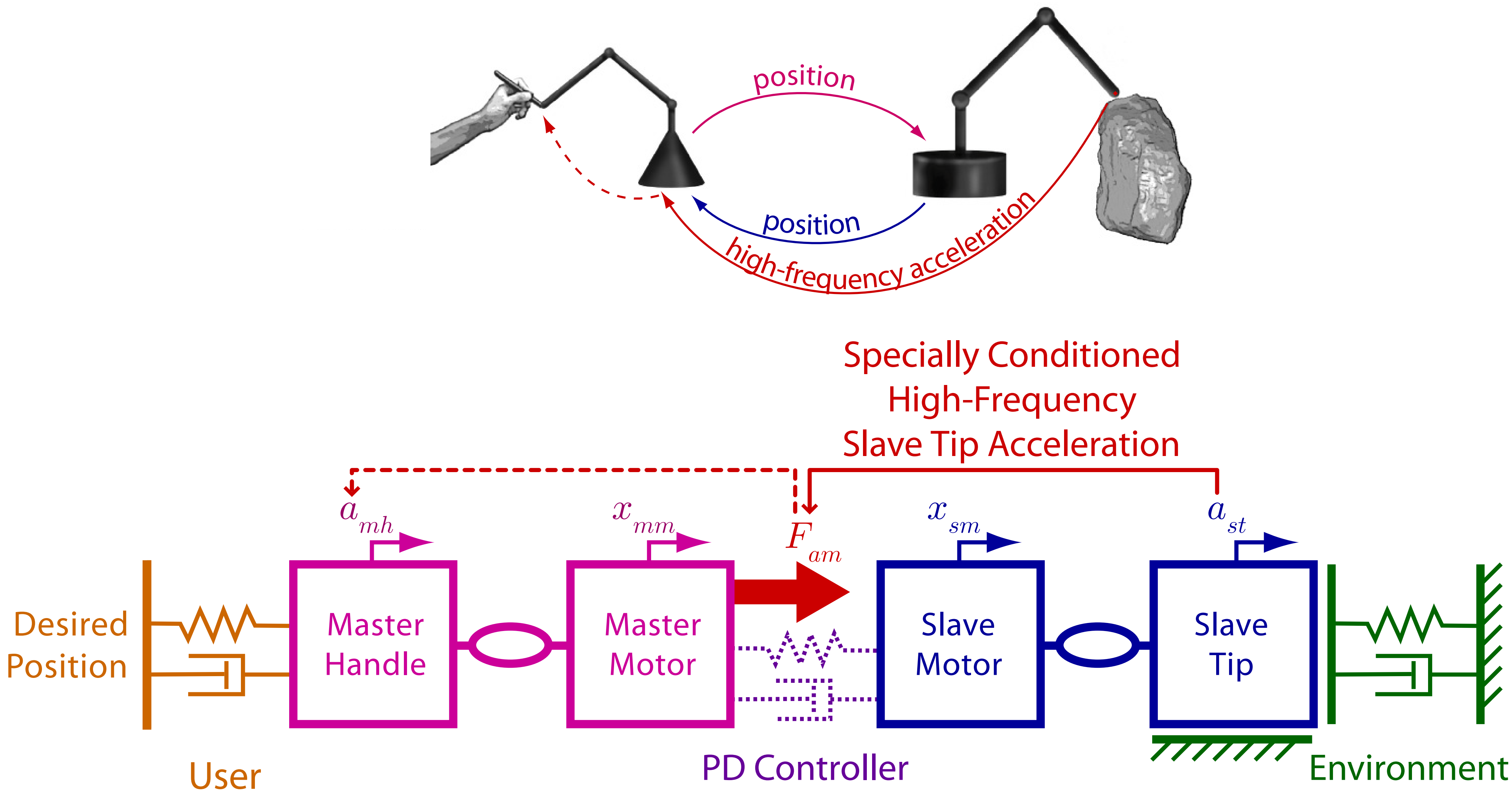
Kontarinis and Howe, 1995.

Kontarinis and Howe's System



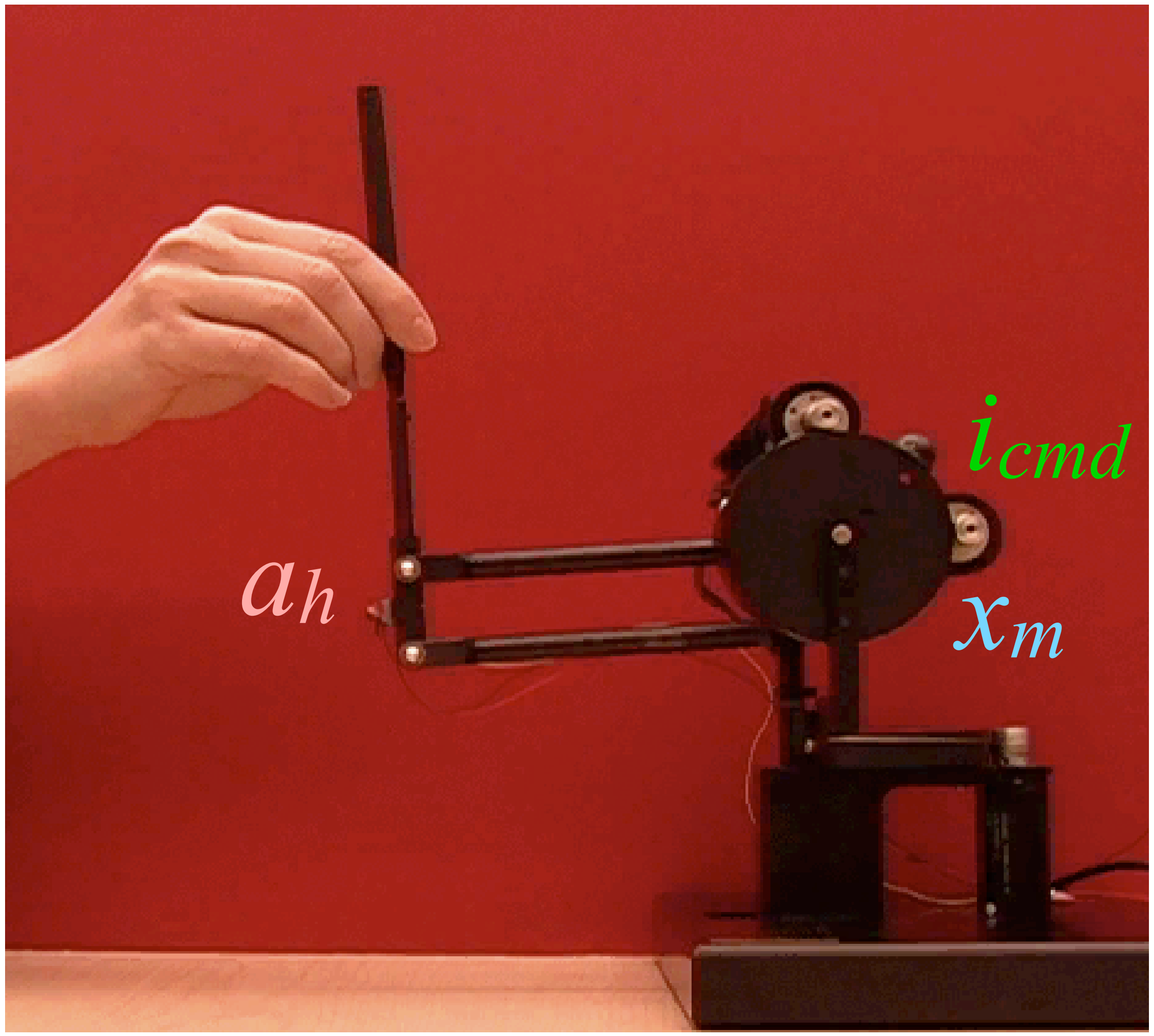
Kontarinis and Howe, 1995.

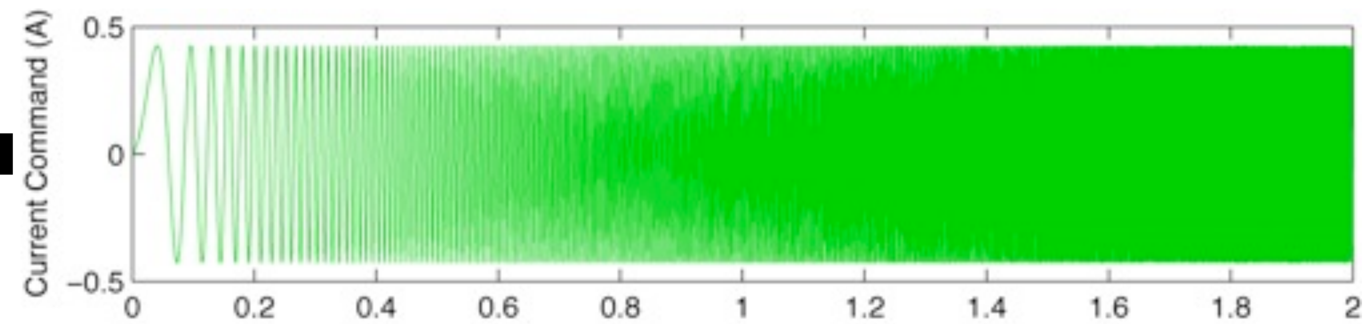
Position-Position Control + HFAM



Kuchenbecker and Niemeyer, 2006.

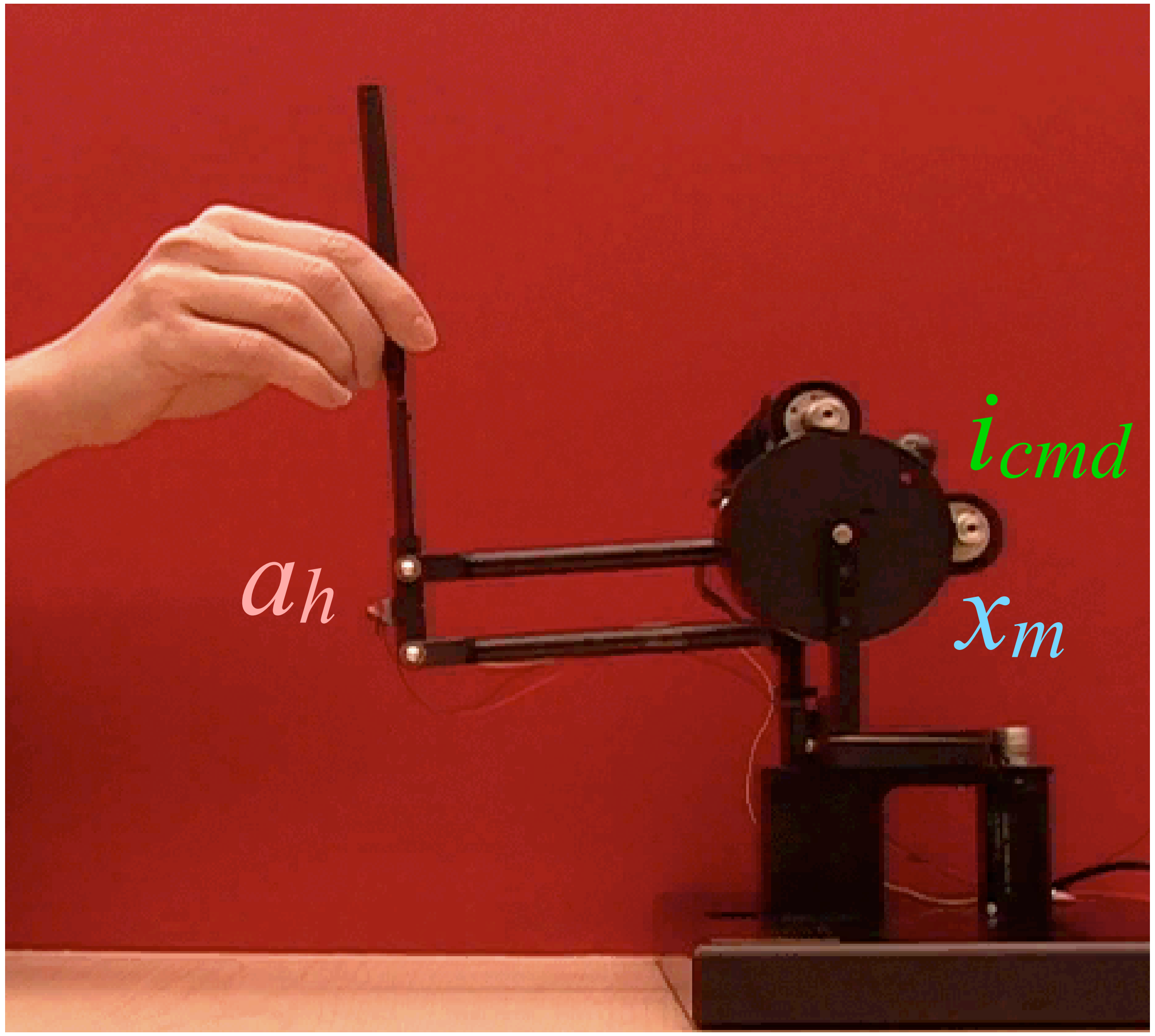
Comprehensive Evaluation

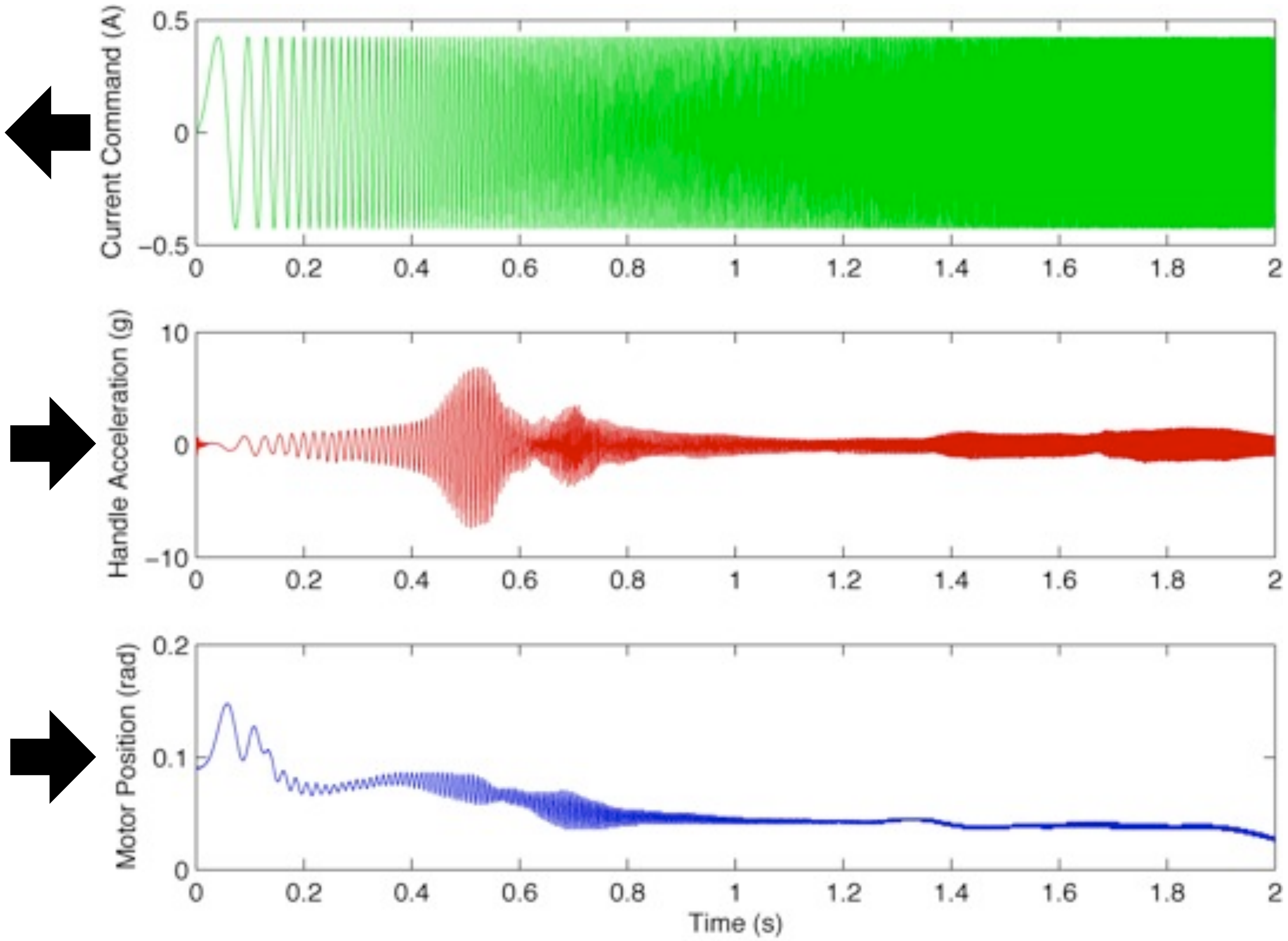




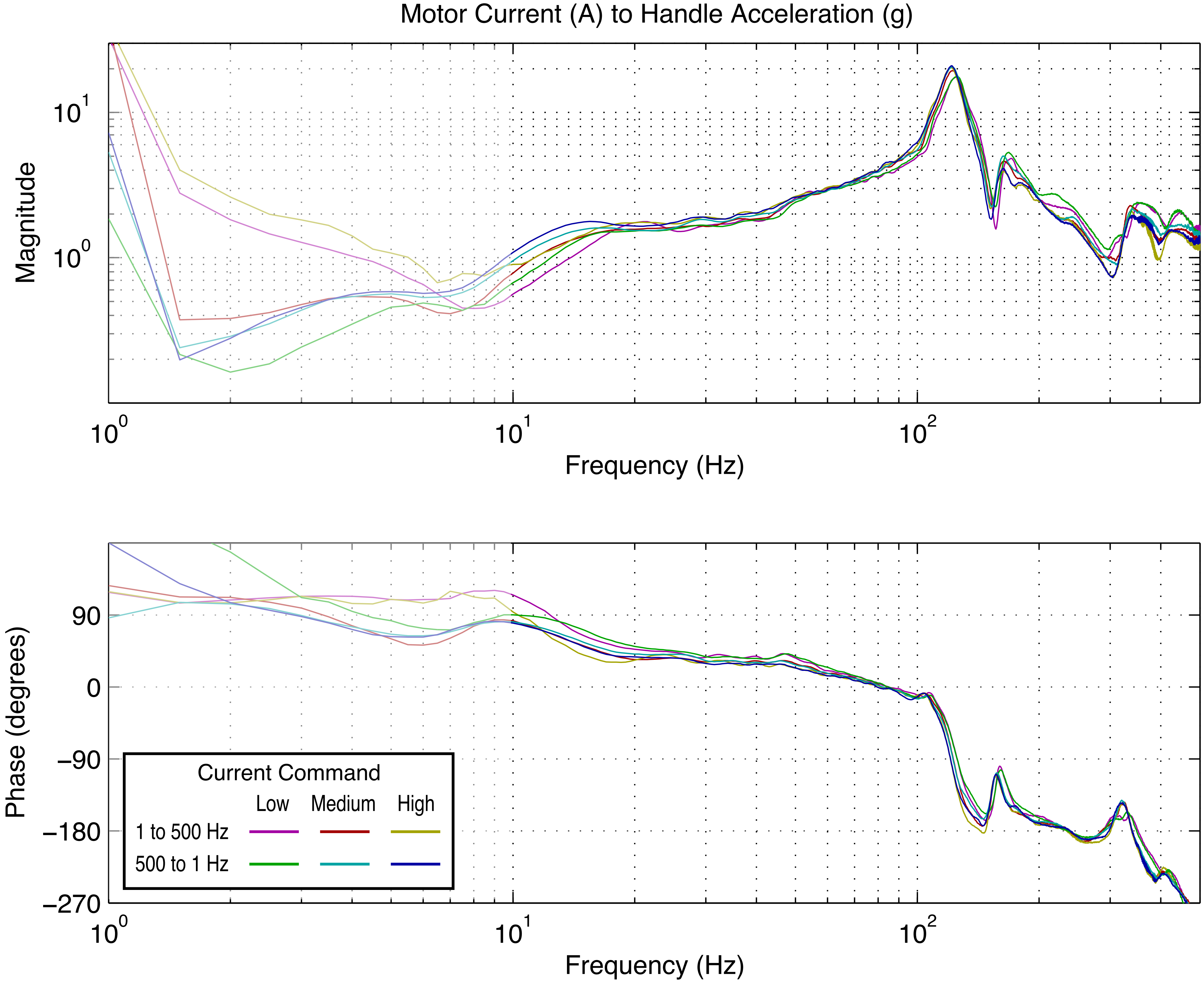
Comprehensive Evaluation Trial

Comprehensive Evaluation

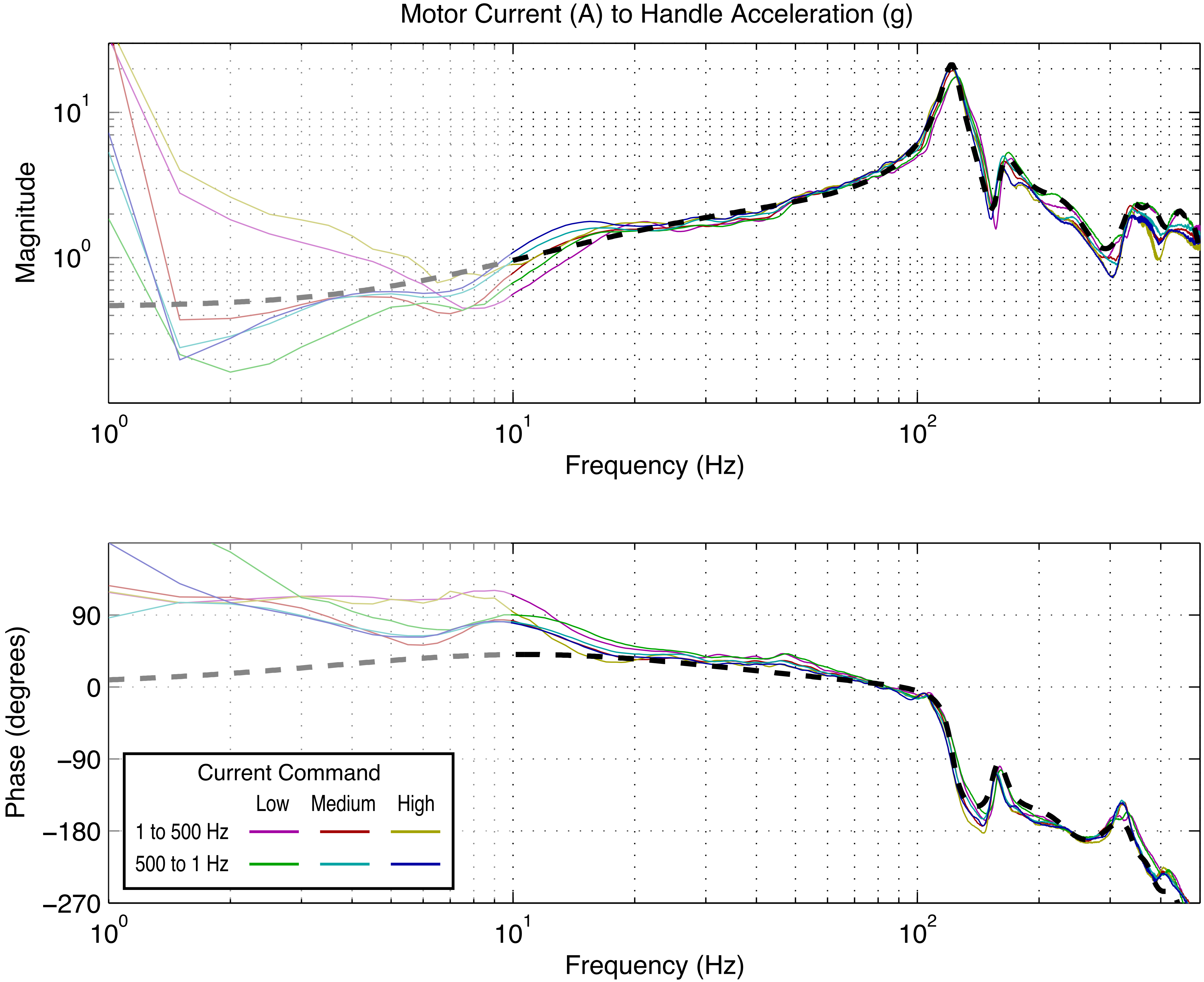




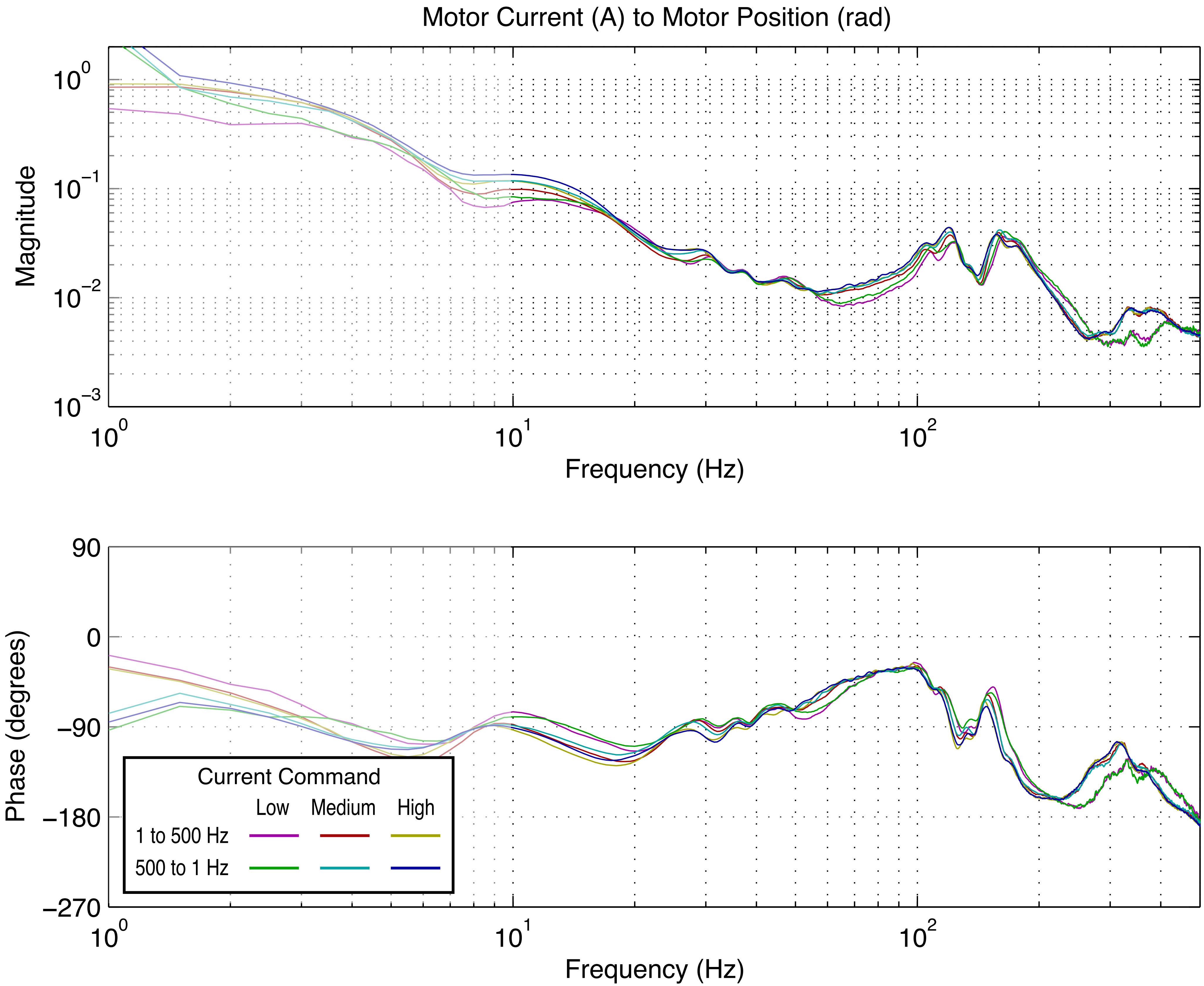
Handle Acceleration



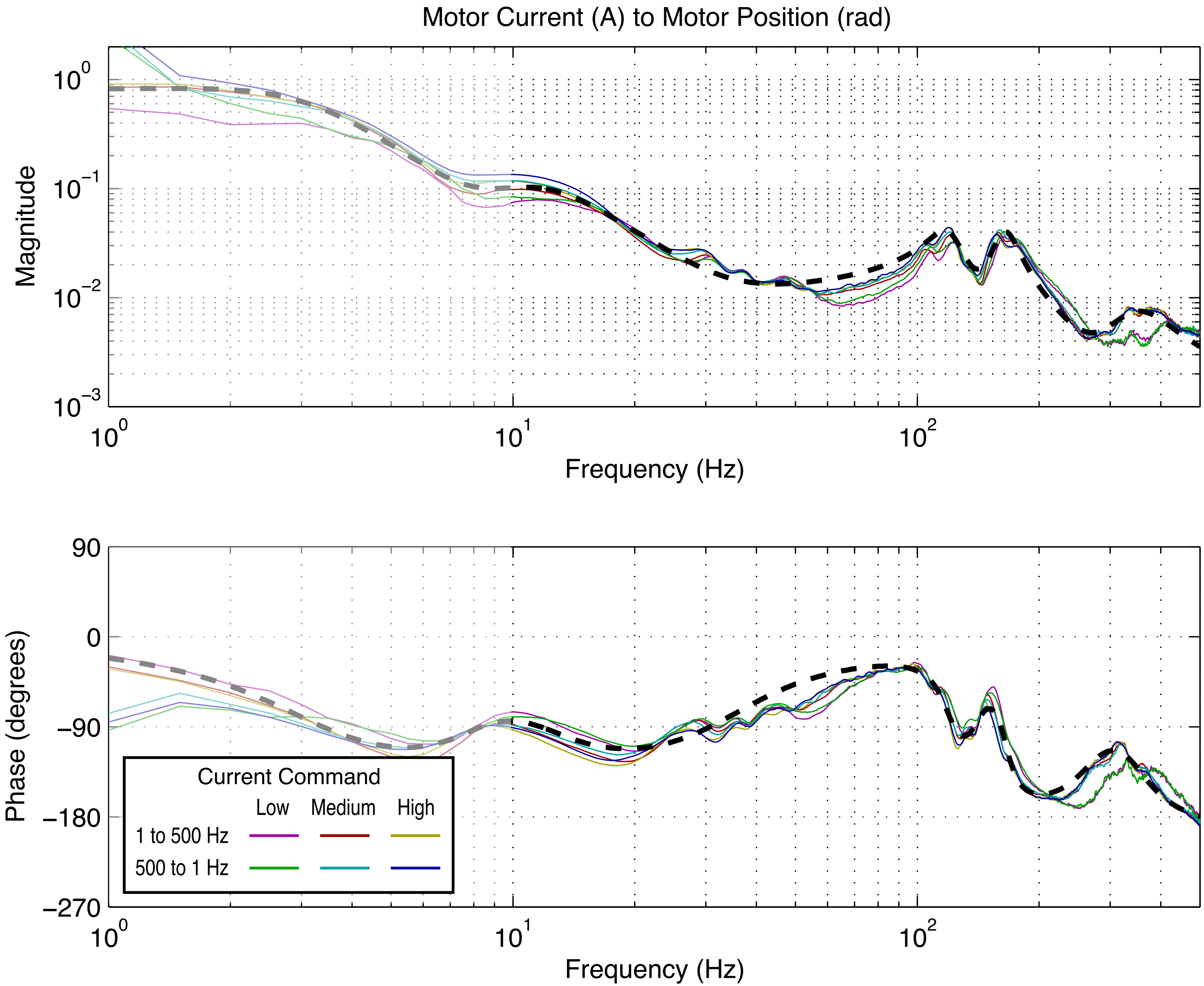
Handle Acceleration



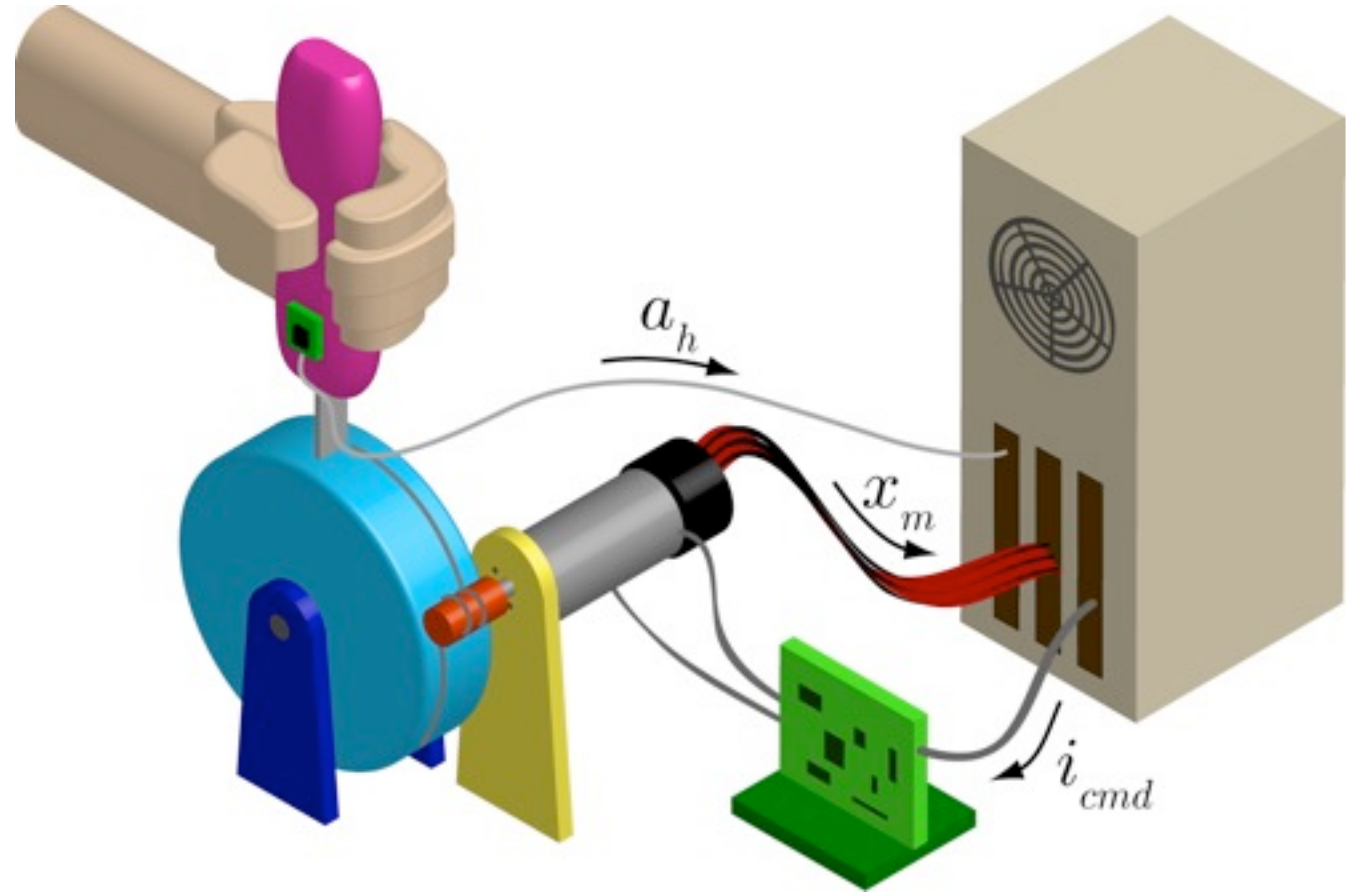
Motor Position



Motor Position

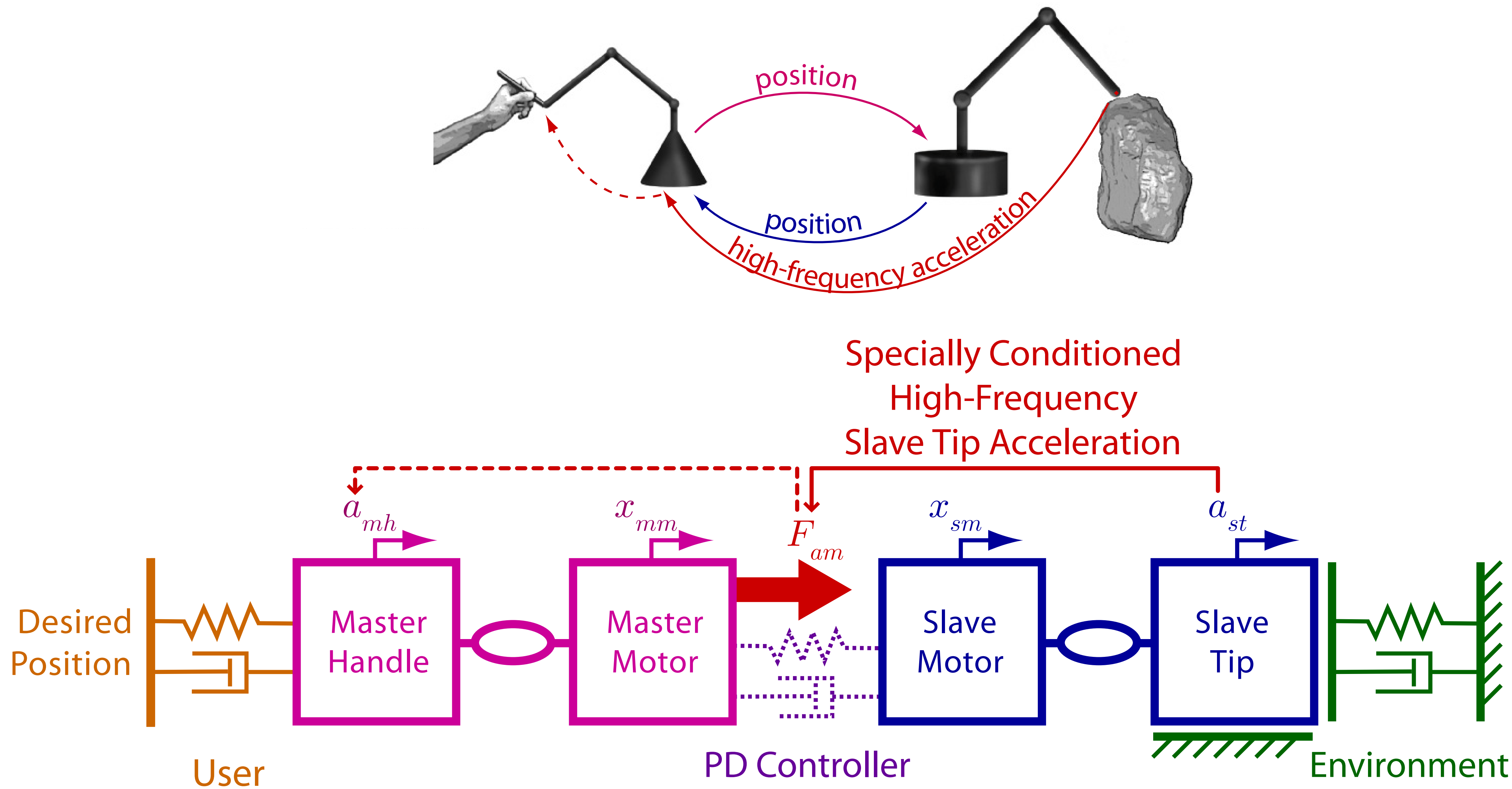


Comprehensive Evaluation



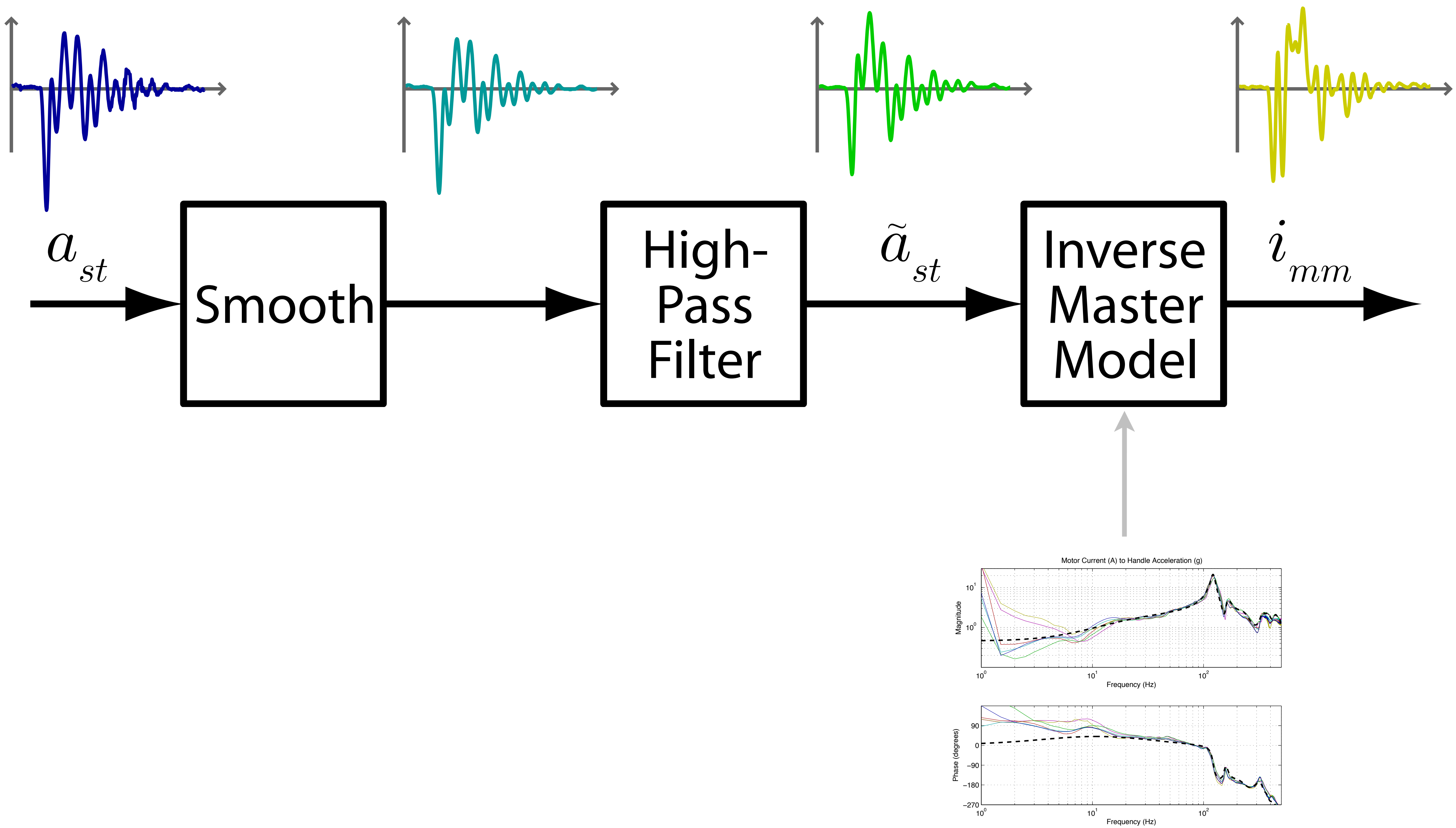
- Characterizes the entire system at once.
- Elucidates the linearity and time invariance of the user-device system.
- Can yield a high-order linear model that captures the dynamics but lacks physical significance.

Position-Position Control + HFAM

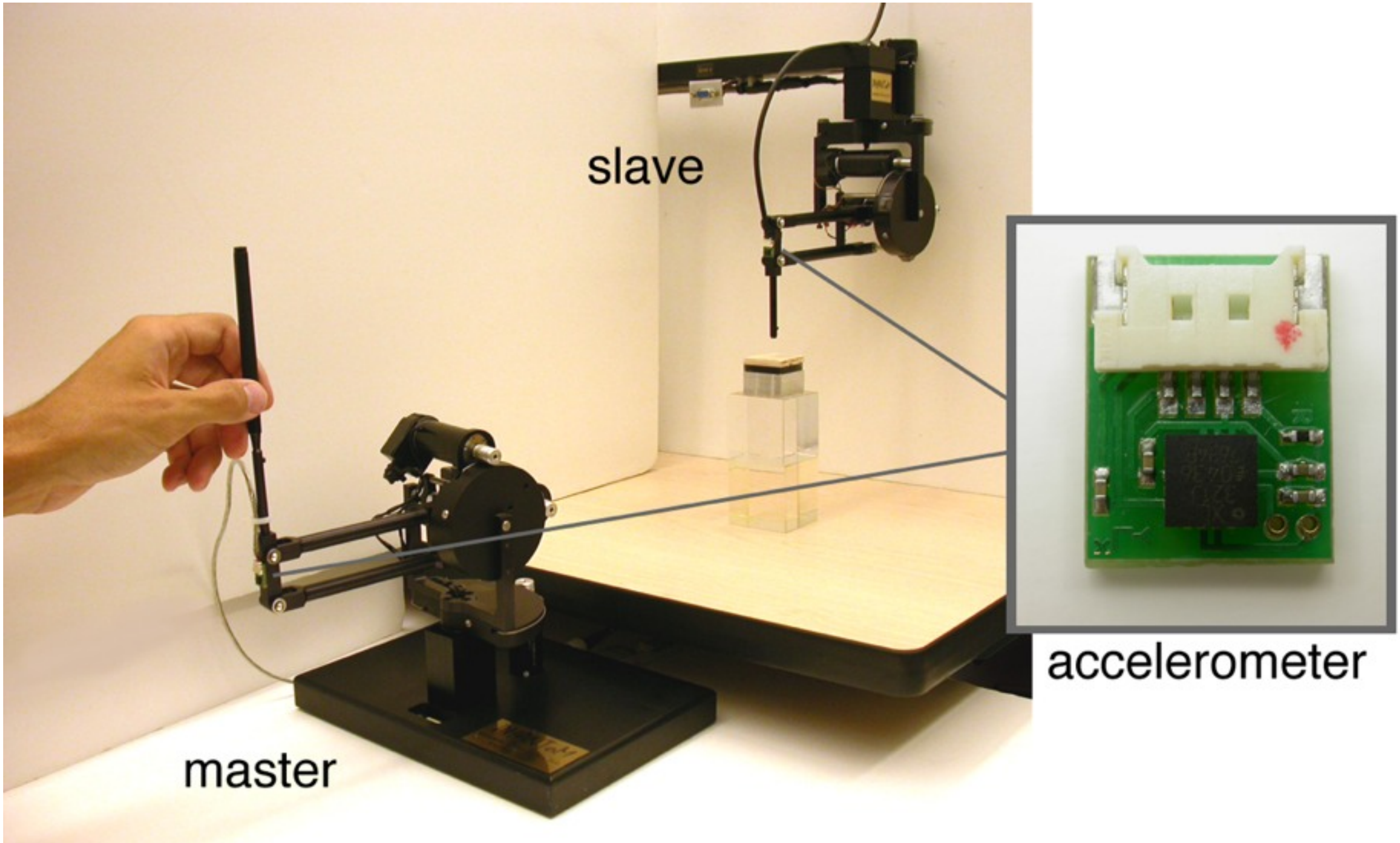


Kuchenbecker and Niemeyer, 2006.

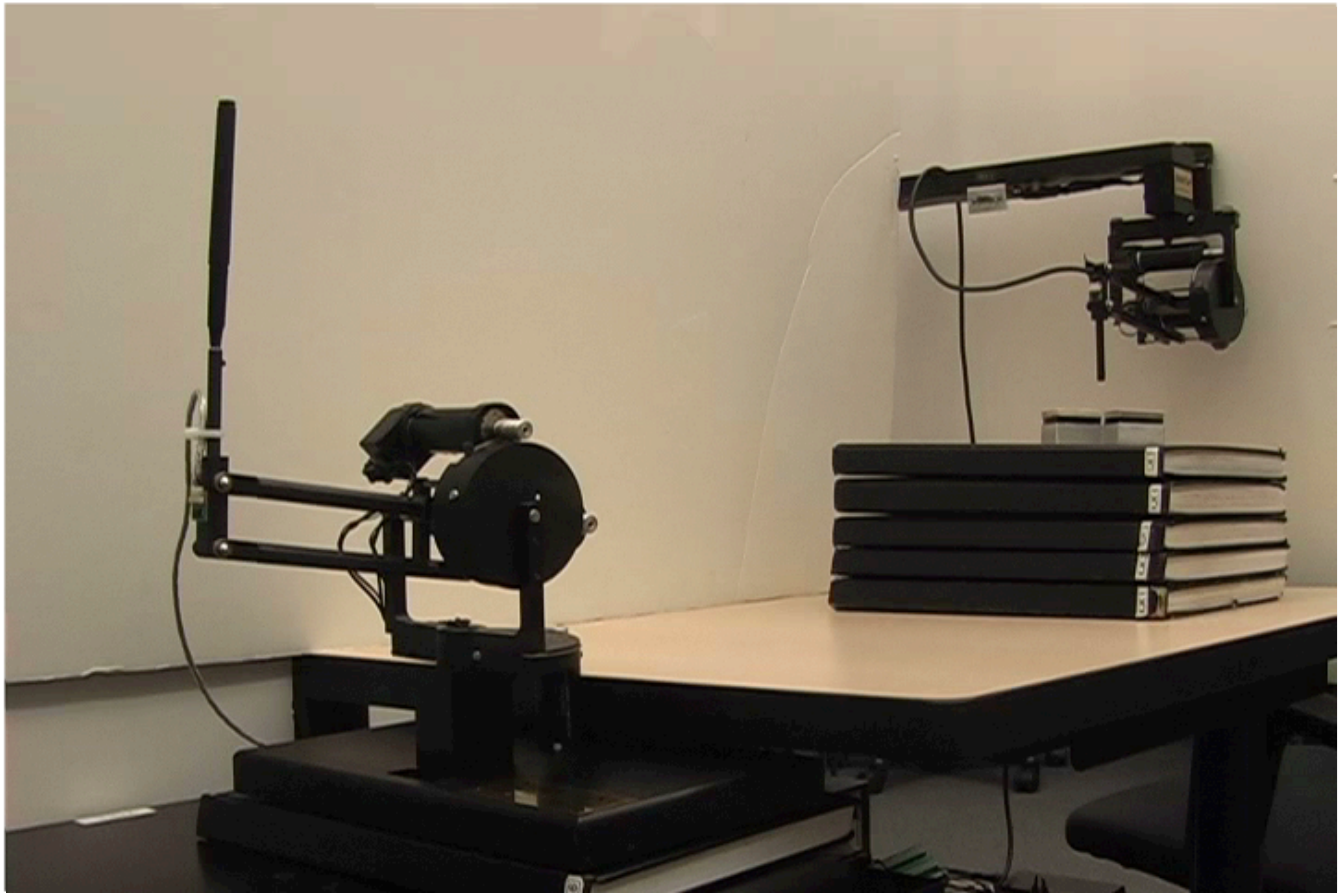
Real-Time Signal Processing



Teleoperation Testbed



Teleoperation Results: Tapping

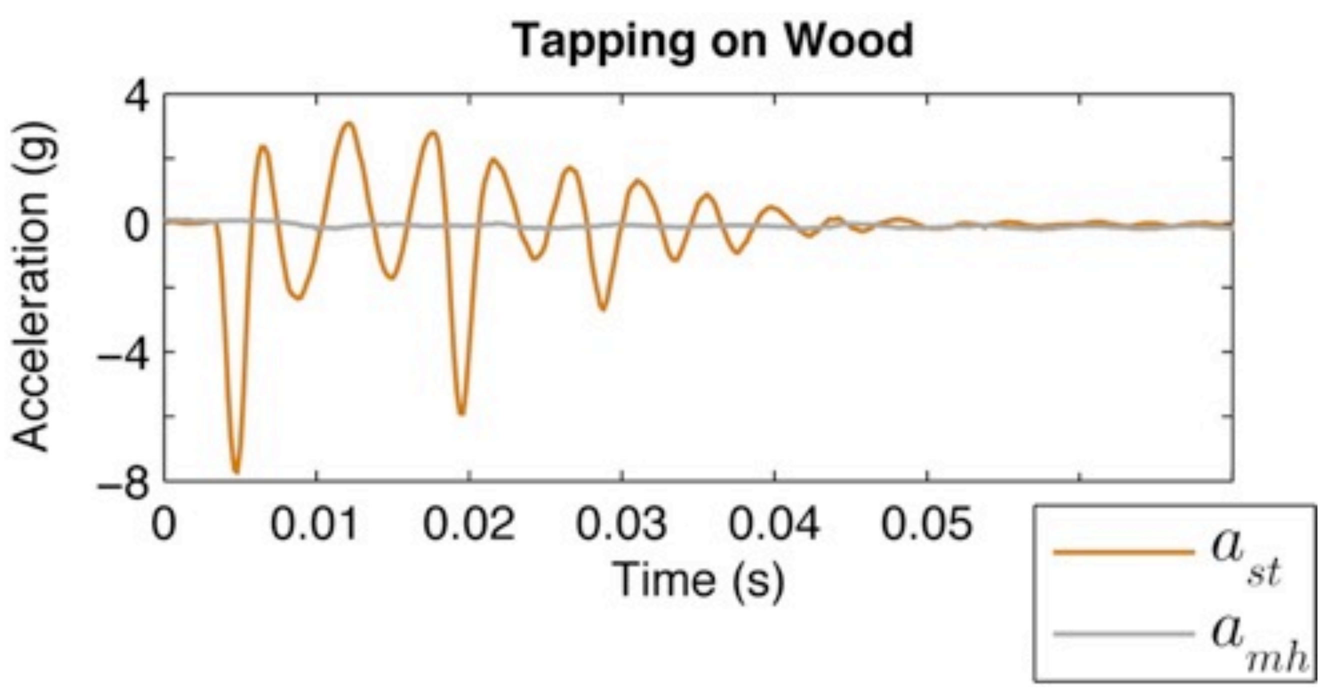


Position-Position with HFAM

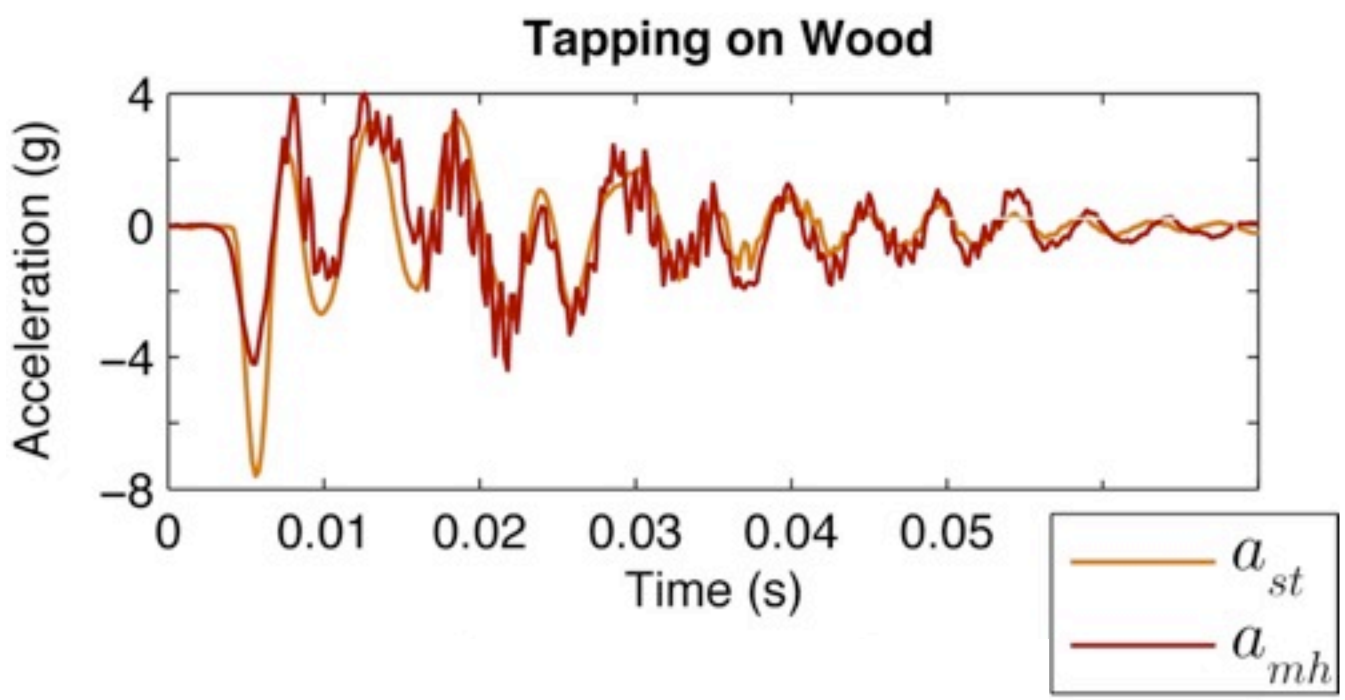
Position-Position

Teleoperation Results: Tapping

Position-Position Control



With Acceleration Matching



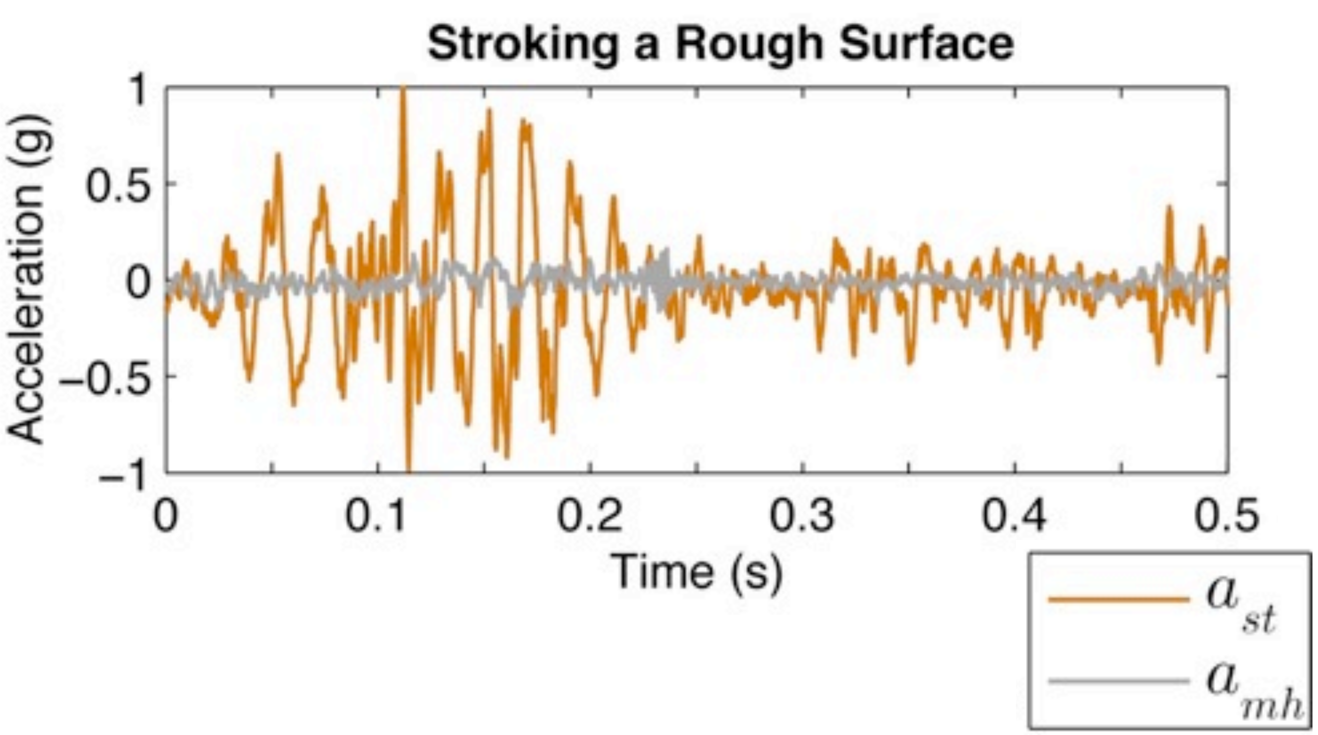
Teleoperation Results: Texture

Position-Position with HFAM

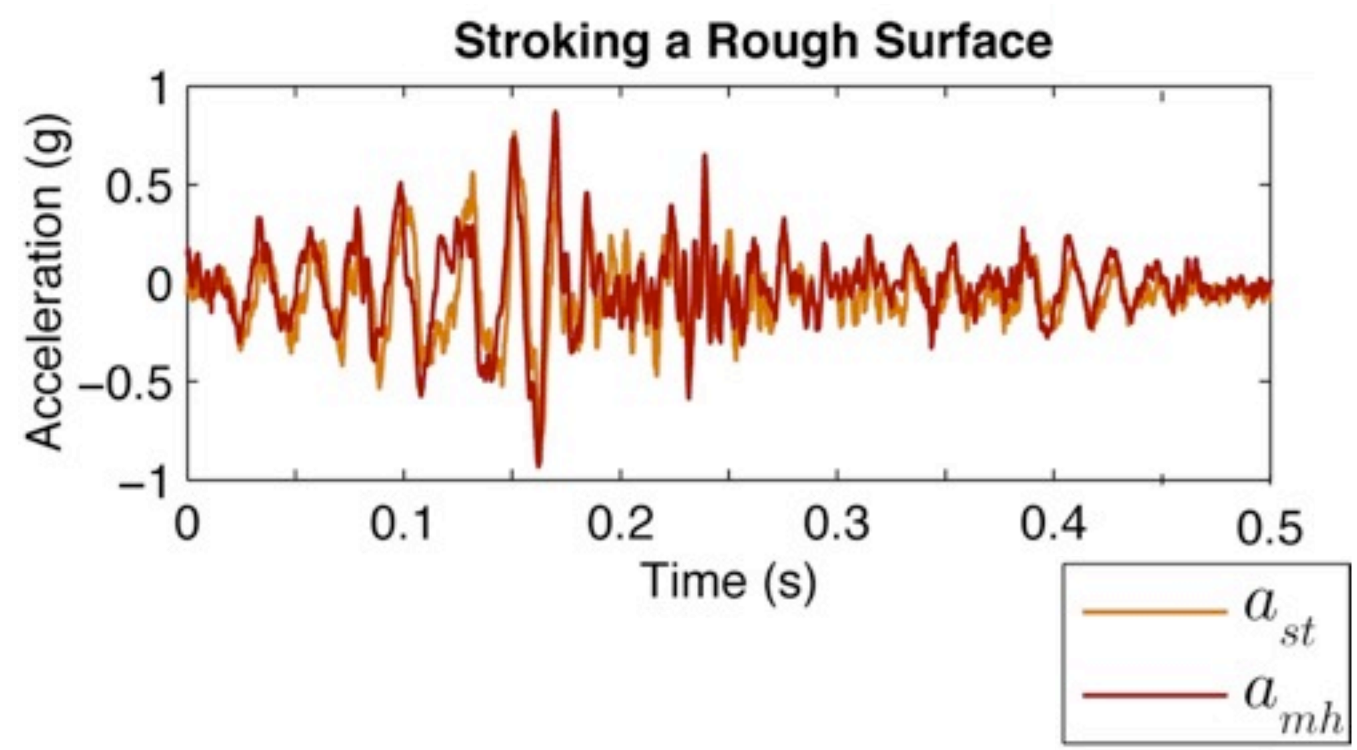
Position-Position

Teleoperation Results: Texture

Position-Position Control

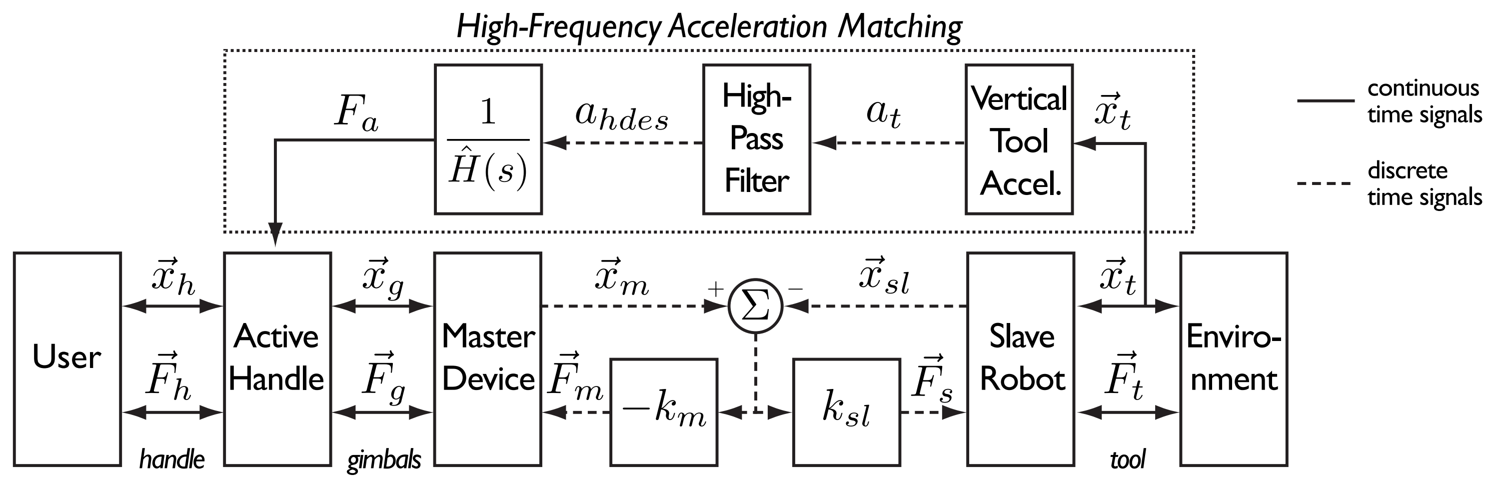


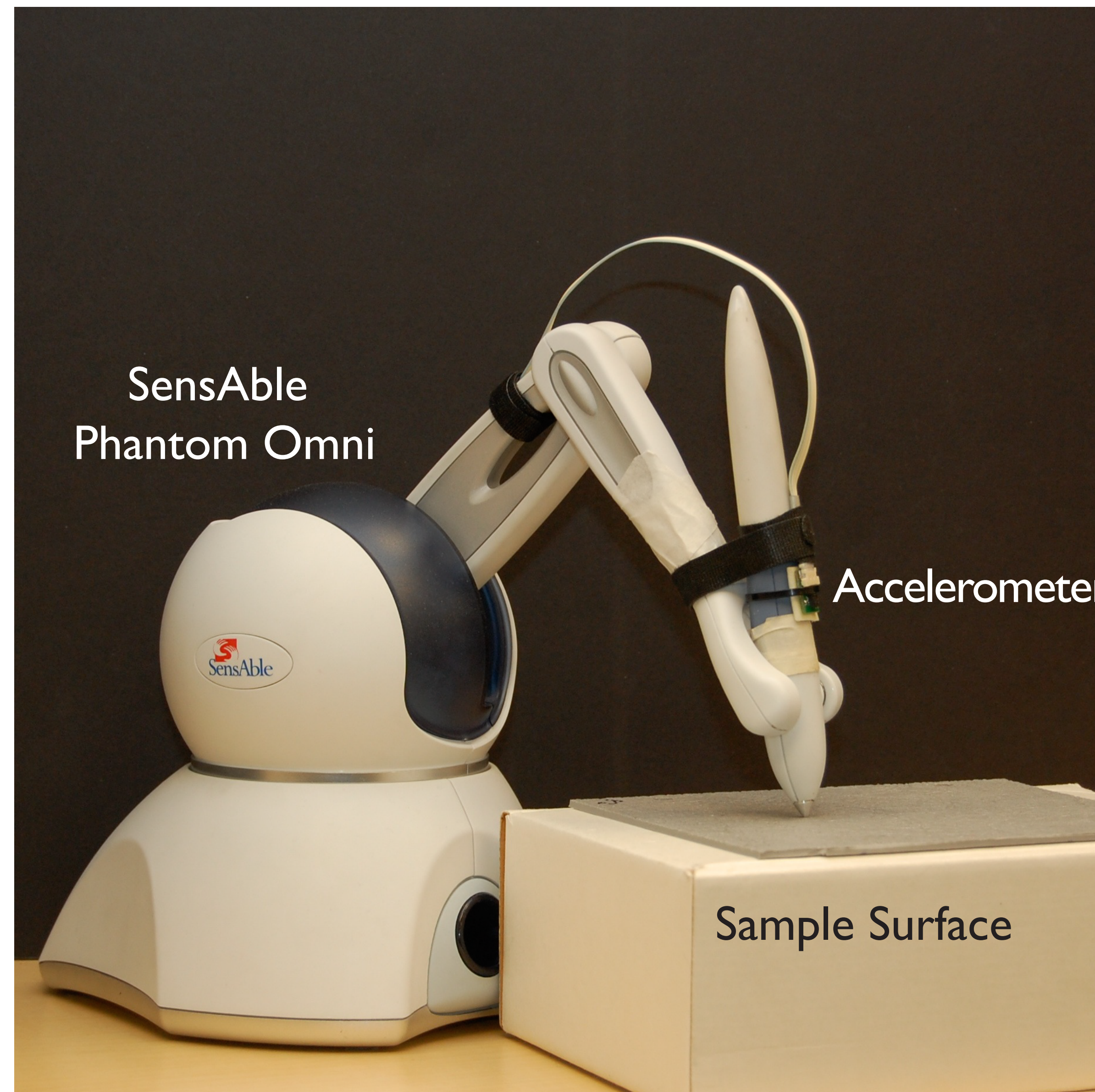
With Acceleration Matching



Interesting, except:
Not totally robust, easy to destabilize
Dynamic model changes a lot with configuration

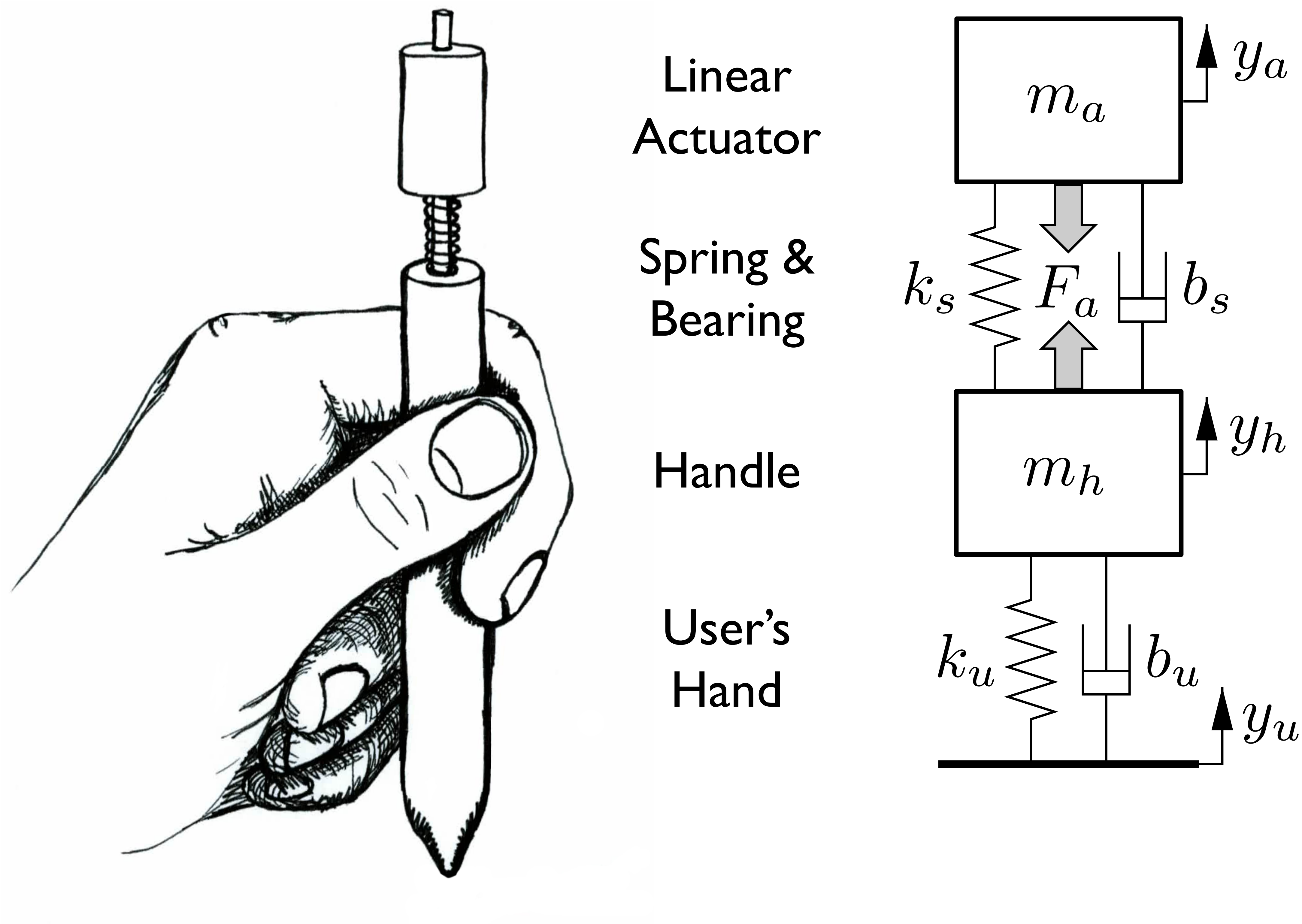
Penn Research





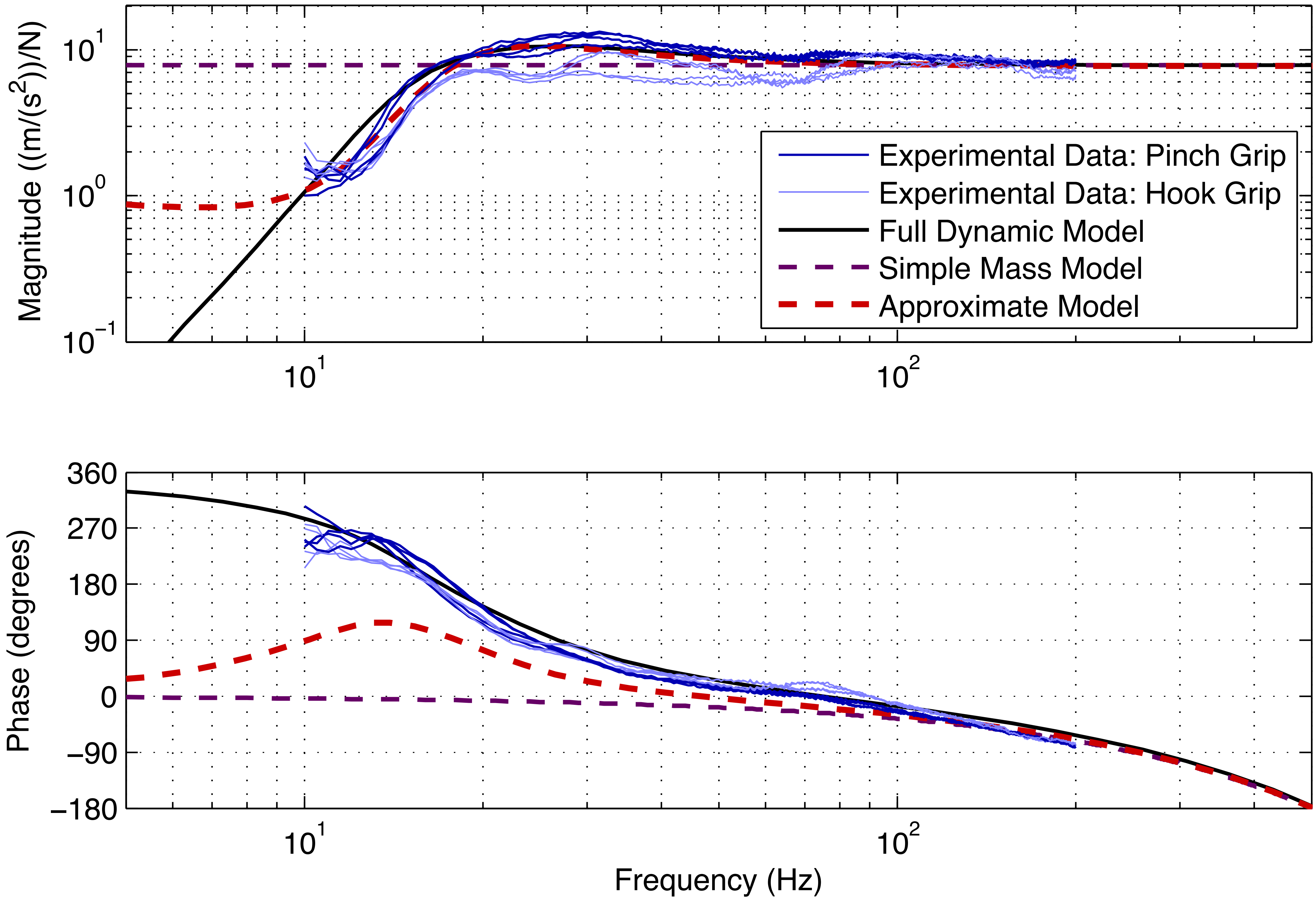
McMahan and Kuchenbecker, 2009.

Penn Research



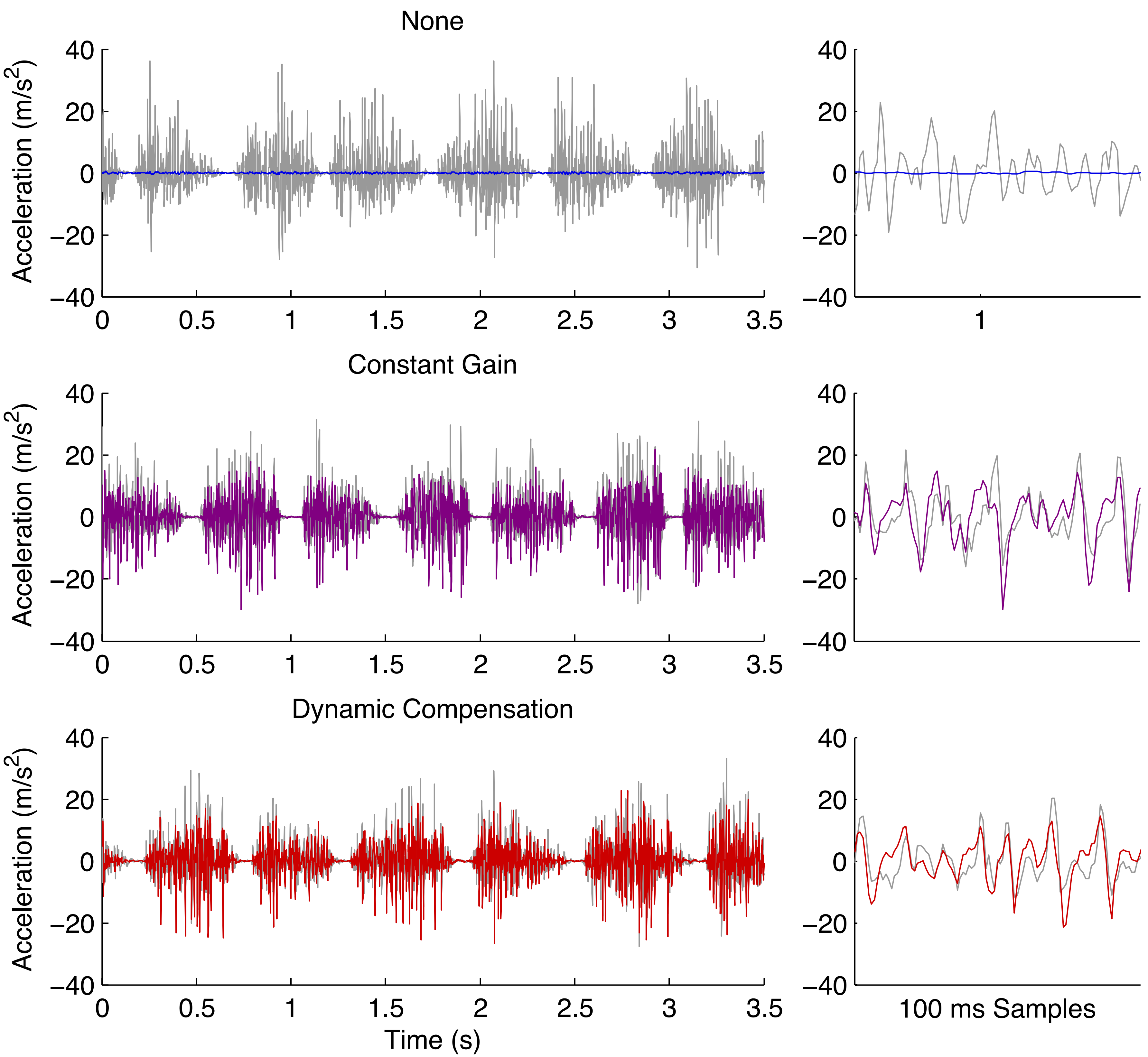
McMahan and Kuchenbecker, 2009.

Penn Research



McMahan and Kuchenbecker, 2009.

Penn Research



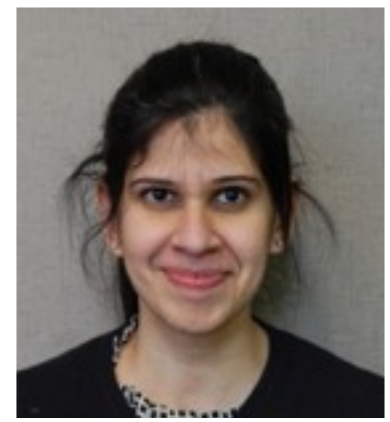
McMahan and Kuchenbecker, 2009.


Without Acceleration Matching
With Acceleration Matching
world HAPTICS 2009

Coulter Translational Research Award

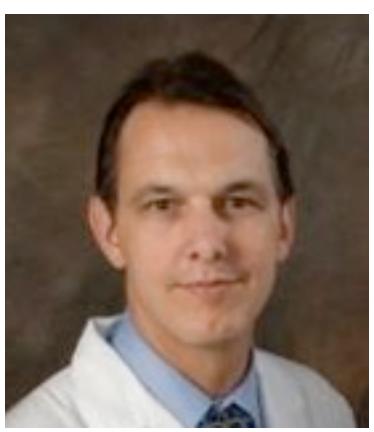
Katherine J. Kuchenbecker, Ph.D.
Bioengineering Faculty PI

David I. Lee, M.D.
Clinical Co-PI



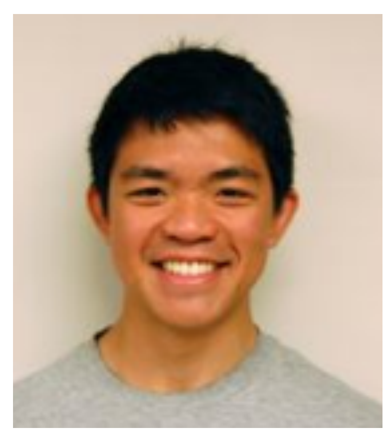
Shilpa Bhansali, Ph.D.
Technology Transfer Representative

Michael Whitman
Business Advisor



Kris Dumon, M.D.
Bariatric Surgeon

Noel Williams, M.D.
Bariatric Surgeon



Ted Gomez
M.D. / M.T.R. Student

Karlin Bark, Ph.D.
Postdoc

Will McMahan
Ph.D. Student

We have discovered and refined a practical way to add high-quality touch feedback to robotic surgery.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Haptic Feedback For Telerobotic Surgical Systems
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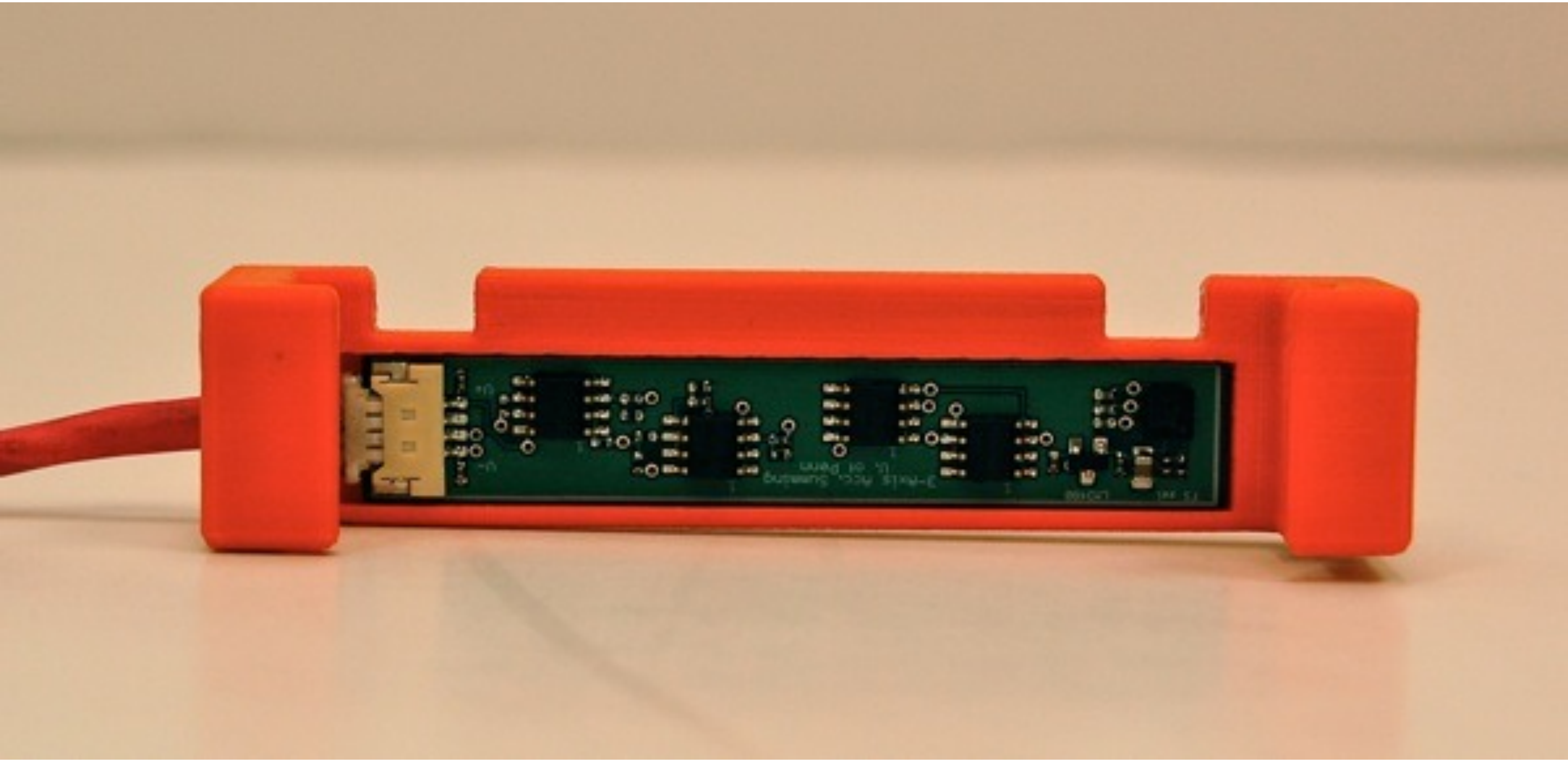
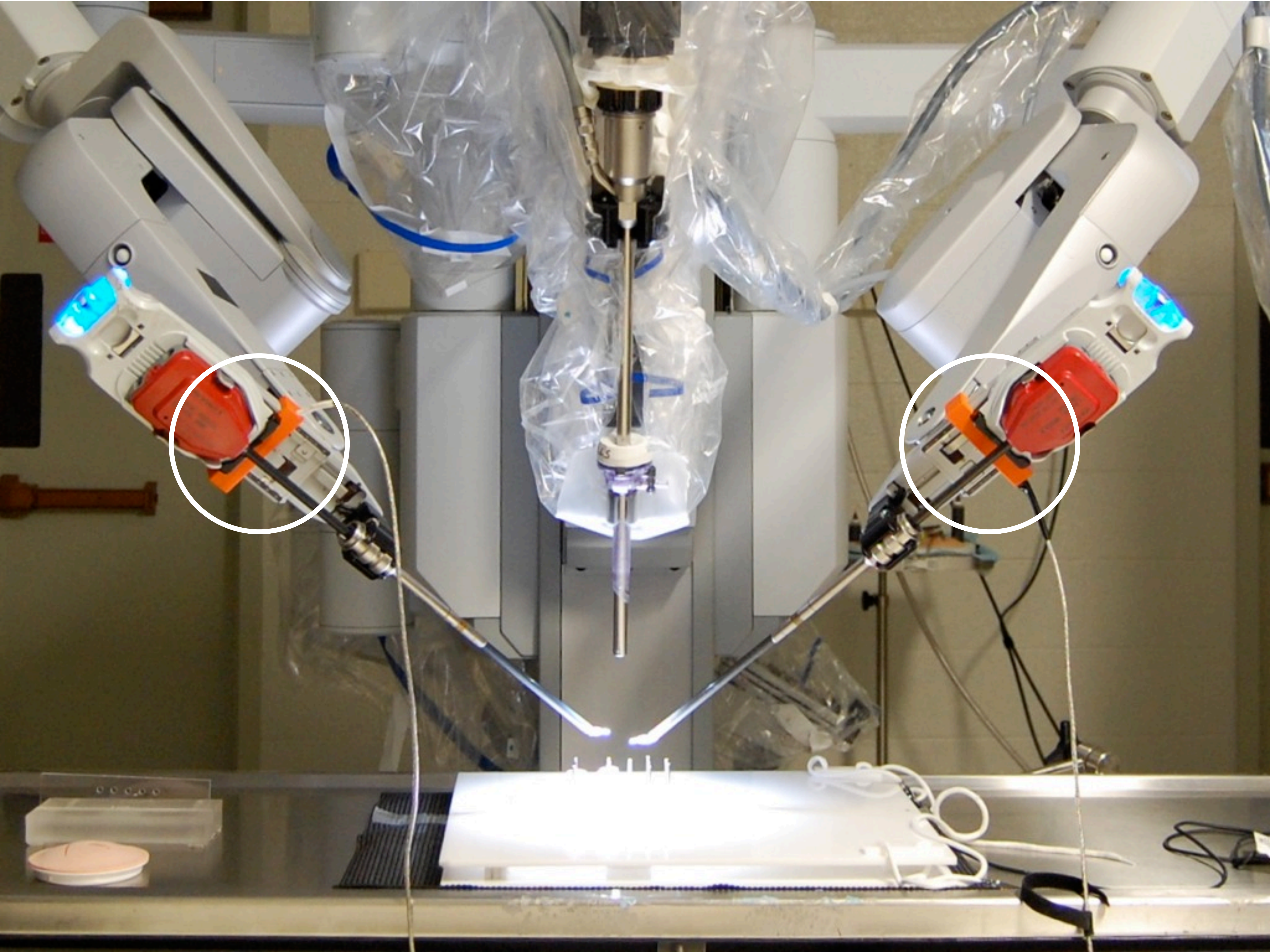
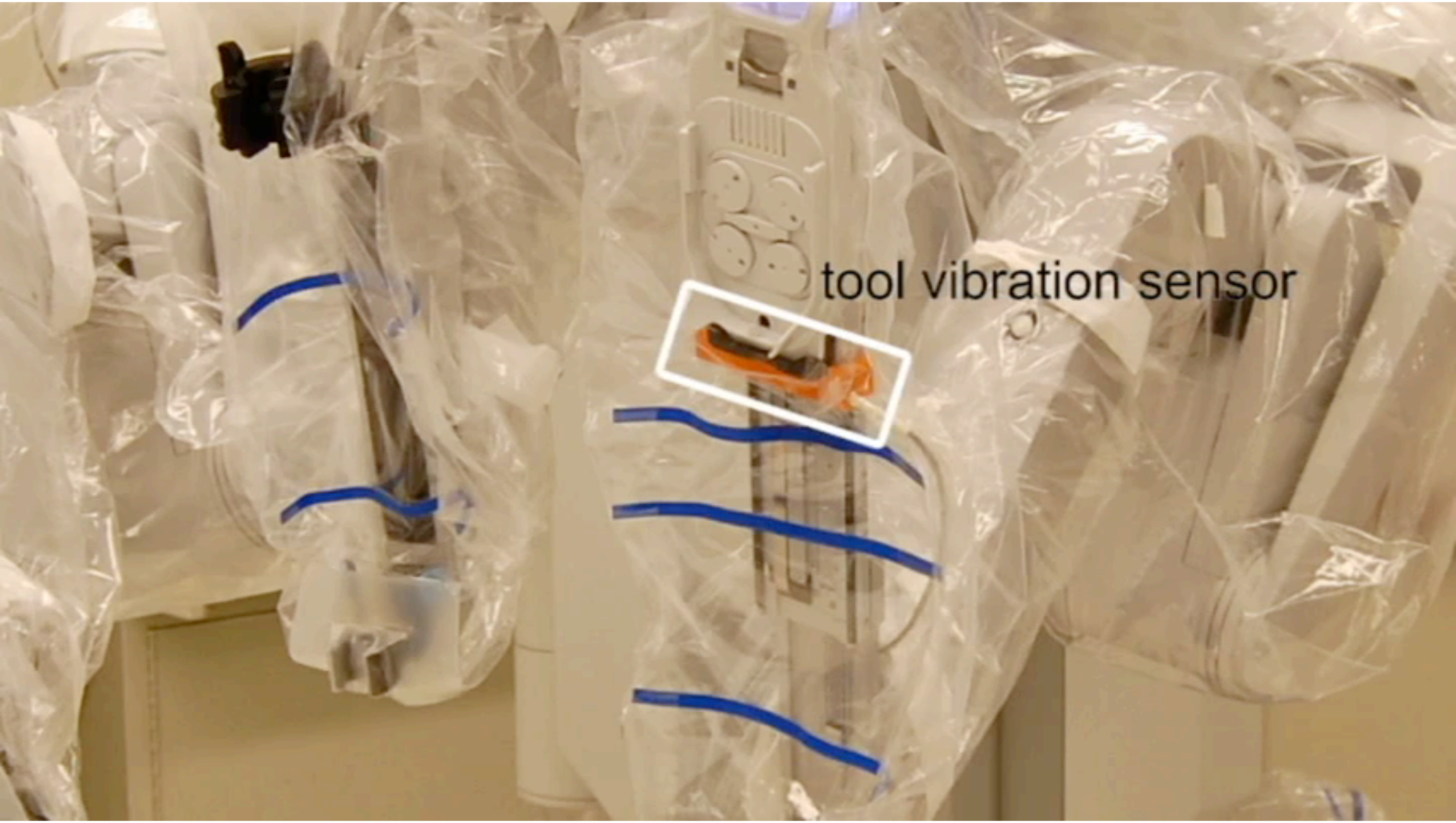
VerroTouch
Counterweight
Left
VerroTouch
Counterweight
Right

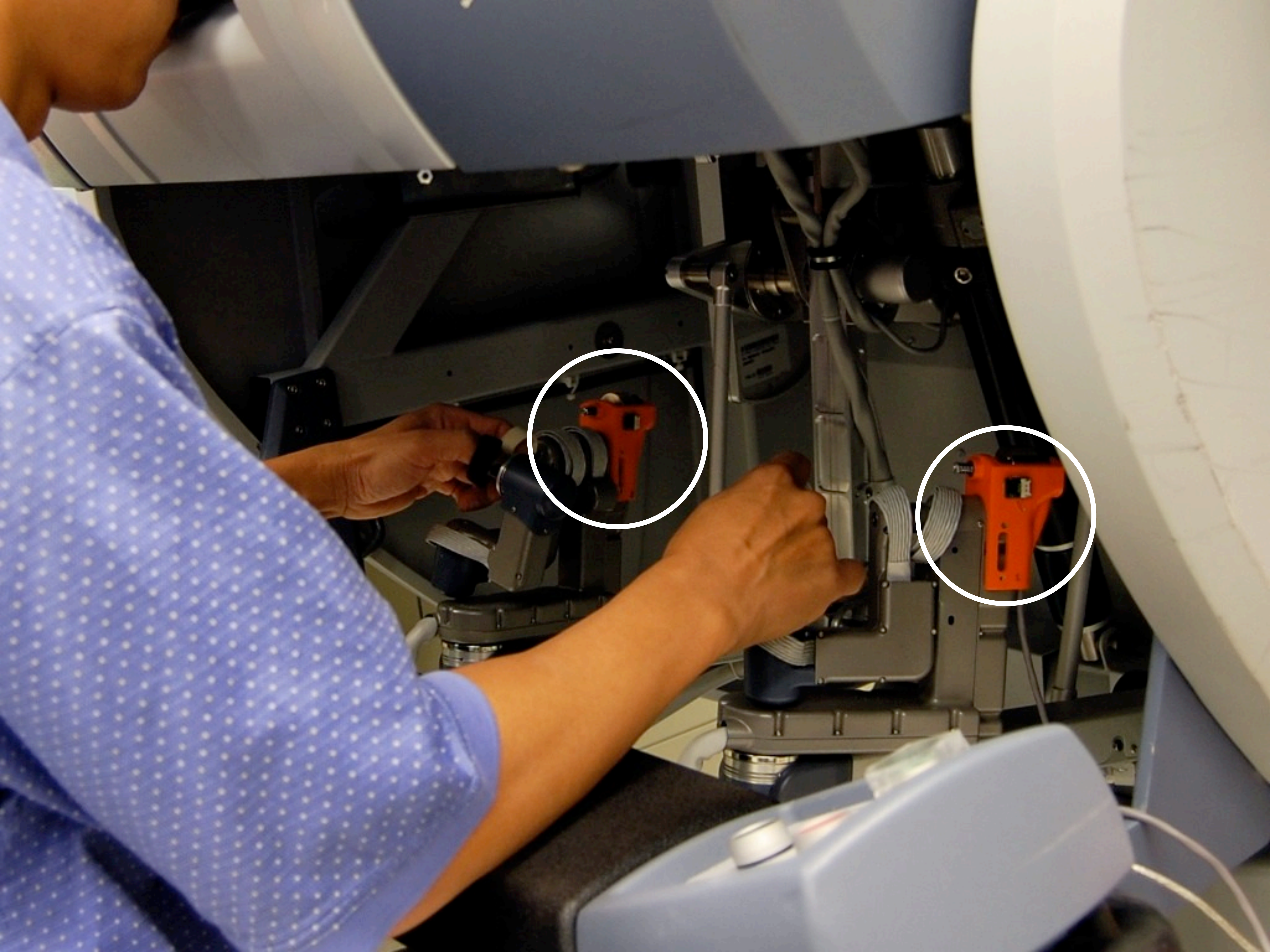

The Ben Franklin
Racing Team

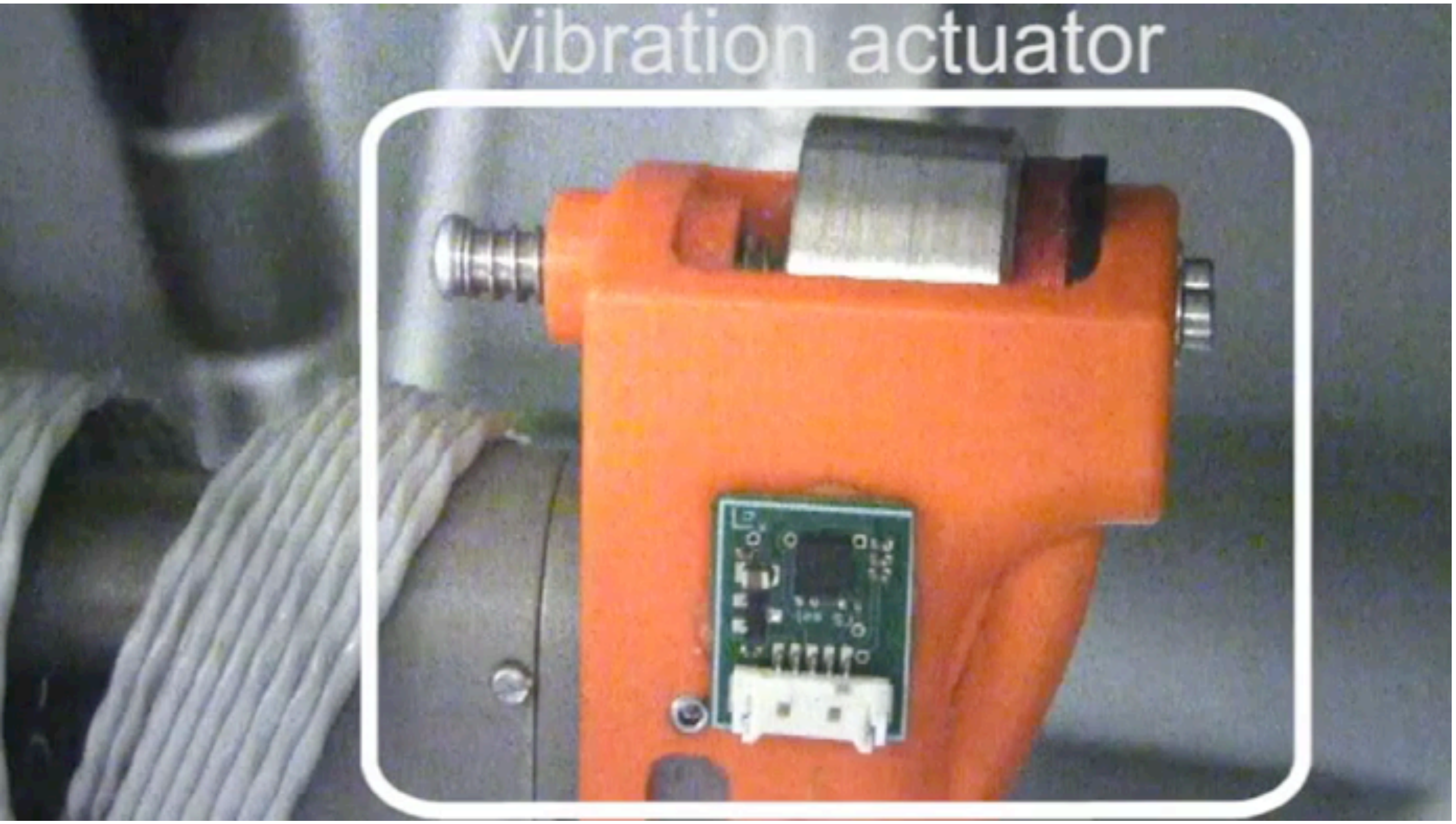






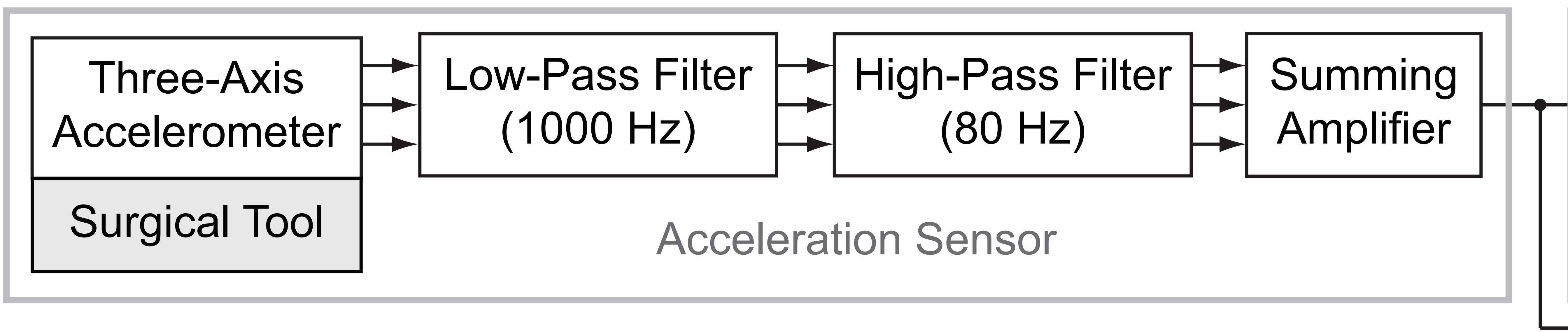
- Three-axis accelerometers are inexpensive and reusable
- Placement within the robot's sterile drapes avoids sterilization
- Sensor mounts can be modified to attach to any rigid instrument



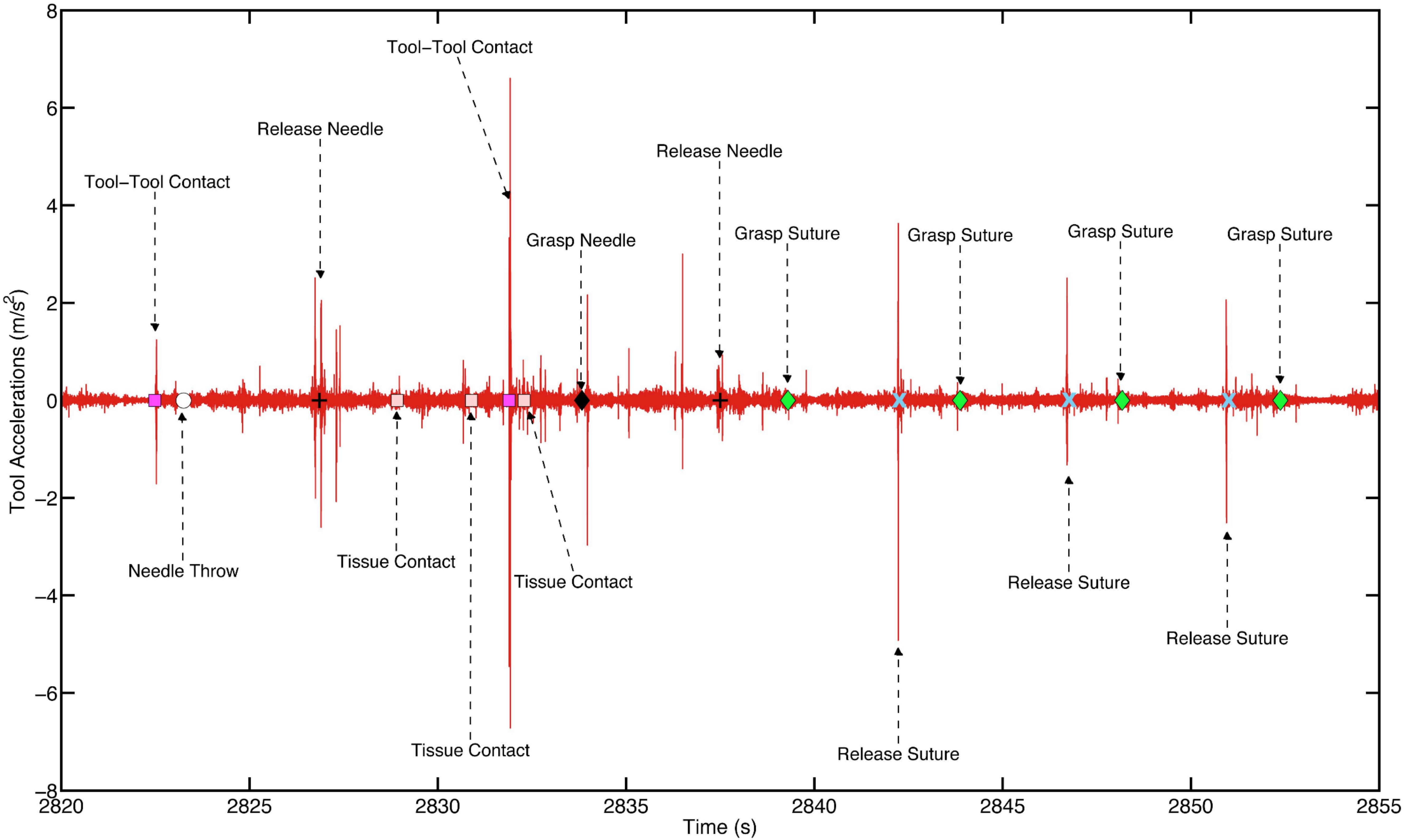


- Voice coil actuators are inexpensive and reusable
- Chosen placement on the control handles avoids interference
- Actuator mounts can be modified to attach to other hand controllers
- Auditory feedback through speakers is even simpler

Signal Processing

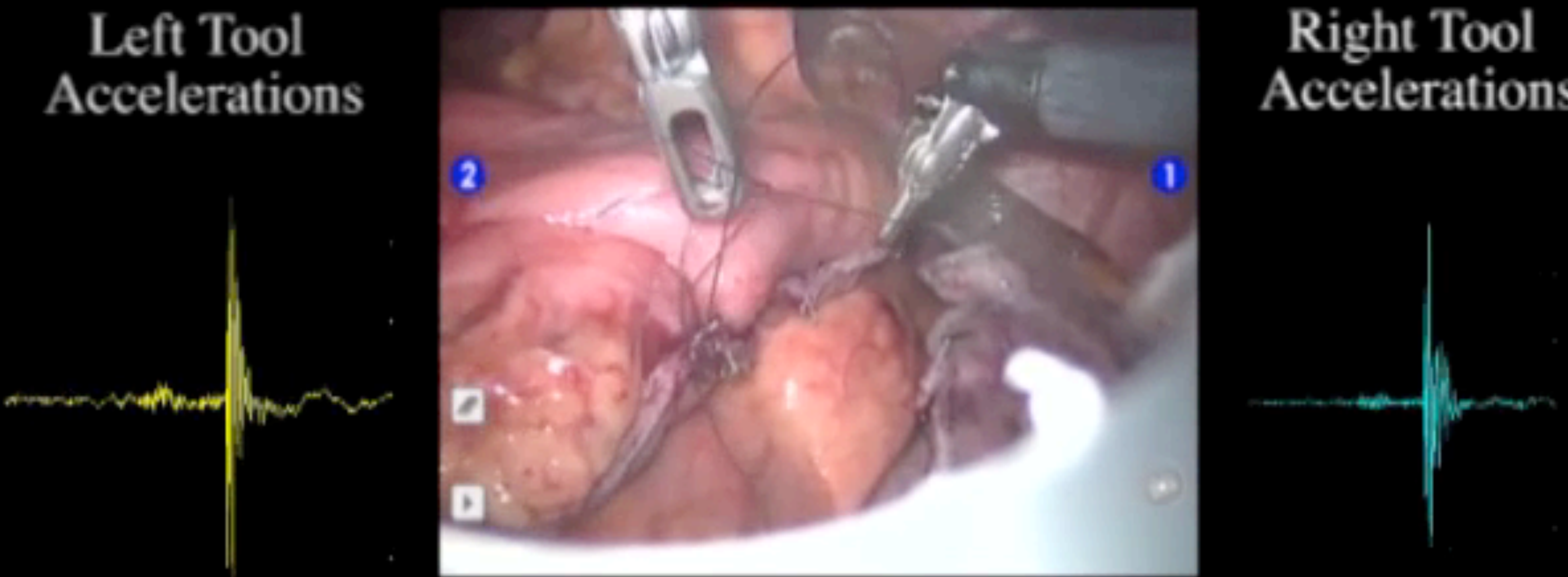


Sample Data - Right Tool



82% of actions cause measurable vibrations

Tying the Knot: Capturing multiple on/off screen tool and suture collisions



*Post-processed Acceleration Data