

MAE 435: Principles of Automatic Control

Lecture 1: Course Overview

Associate Professor: Hao Su, PhD

08/22/2023

MAE research experience for undergraduates (MAE-REU) program

Students will be awarded \$4,000 for the year (\$2,000 per semester).

Link: <https://forms.gle/HM6jB2ezQQ3PuqWQ9>



Google form QR code

Outline

- Course overview
- Introduction of Control Applications for Wearable Robots
- Introduction of Automatic Control

Outline

- Course overview
 - Syllabus
 - Course Details
 - Grading
 - Textbook
 - Preparation for MATLAB and Simulink
- Introduction of BIRO Lab and Students Projects
- Introduction of Automatic Control

Principles of Automatic Control Course Syllabus

	Week	Monday	Wednesday	Optional Text Read
Modeling	1. Aug. 19, 21	Course Overview	Basics of Laplace Transfer and PID Control	MCE: 1.1 – 1.5
	2. Aug. 26, 28	Project: MATLAB	Project: Simulink Introduction	SD: 2.2 – 2.3
	3. Sep. 2, 4	No Classes (Labor Day)	Laplace Transform & Transfer Function	MCE: 2.1, 2.2 & SD: 2.2 – 2.3
	4. Sep. 9, 11	Mechanical System Modeling	Project: Simulink Introduction Part II	MCE: 3.1-3.2 & SD: 6.1-6.6-
	5. Sep. 16, 18	Electromechanical Systems Modelling	Control Block Diagram Signal Flow Graph	MCE: 2.3 & SD: 8.1 – 8.3
Analysis	6. Sep. 23, 25	Time-Domain Analysis (1 st order system)	Time-Domain Analysis (2 nd order system)	SD: 8.1 – 8.3 & MCE: 5.1 – 5.8
	7. Sep. 30, Oct. 2	Midterm Review	Project: Robot Modeling	MCE: 5.1 – 5.8
	8. Oct. 7, 9	Frequency Domain Analysis Part I	Frequency Domain Analysis Part II	MCE: 5.1 – 5.8
	9. Oct. 14, 16	No Classes (Fall Break)	Midterm	MCE: 7.1 & MCE: 7.2 – 7.6
	10. Oct. 21, 23	Bode Diagram: Concept	Midterm Recap & Stability Analysis	MCE: 6.2 – 6.5 & MCE: 7.2 – 7.6
	11. Oct. 28, 30	Bode Diagram: Gain and Phase Margin	Bode Diagram: Stability Criterion	MCE: 7.7 -7. 8
Control	12. Nov. 4, 6	Bode Diagram: Design and Control	Lead Compensation Control	MCE: 7.11 – 7.13
	13. Nov. 11, 13	Project: Robot System Simulation Implementation	Lag Compensation Control	MCE: 7.11 – 7.13
	14. Nov. 18, 20	Lead-Lag Compensation Control	Final Exam Review	-
	15. Nov. 25, 27	Project: Control of Robot I	No Classes (Thanksgiving Day)	-
	16. Dec. 2	Project: Control of Robot II (Last Day of Class)		-
	17. Dec. 9	Final Exam		-

Teaching Philosophy

- Teaching Philosophy
 - Theory (lecture): modelling, analysis and control
 - Experiential learning (project): simulation of exoskeleton control
 - **Understand: What + Why**
- Key topics
 - Model development with applications to mechanical engineering systems
 - Laplace transform, transfer functions and block diagrams
 - PID control, tuning and compensation
 - Control analysis and design
 - Simulink for DC motor control

Instructors and Hours

- Instructor: Prof. Hao Su
- Email address: hsu4@ncsu.edu
- Lecture: Tue. & Thur. 3:00pm-4:15pm
- Office hours: 1:00pm-2:00pm

Course Materials

Slides: Will be available online.

Textbook:

K. Ogata, ***Modern Control Engineering***, 5th edition, Prentice Hall, 2010.

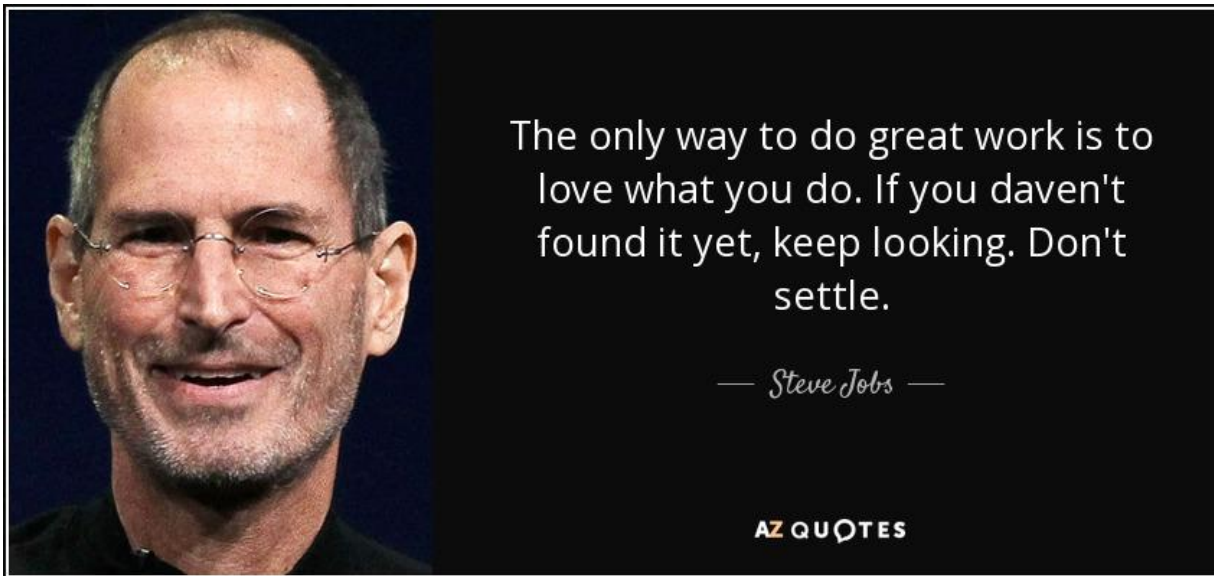
K. Ogata, ***System Dynamics***, 4th ed., Prentice Hall, Upper Saddle River, NJ, 2004.

References:

- Feedback Systems: An Introduction for Scientists and Engineers Karl J. Åström and Richard M. Murray

Grading

- 50% Midterm (1) and Final Exams (1)
- 30% Homework Assignments (6)
- 20% Project Reports (3)
- Your grade may also be affected by your attendance record and participation in class discussion and laboratory sessions.



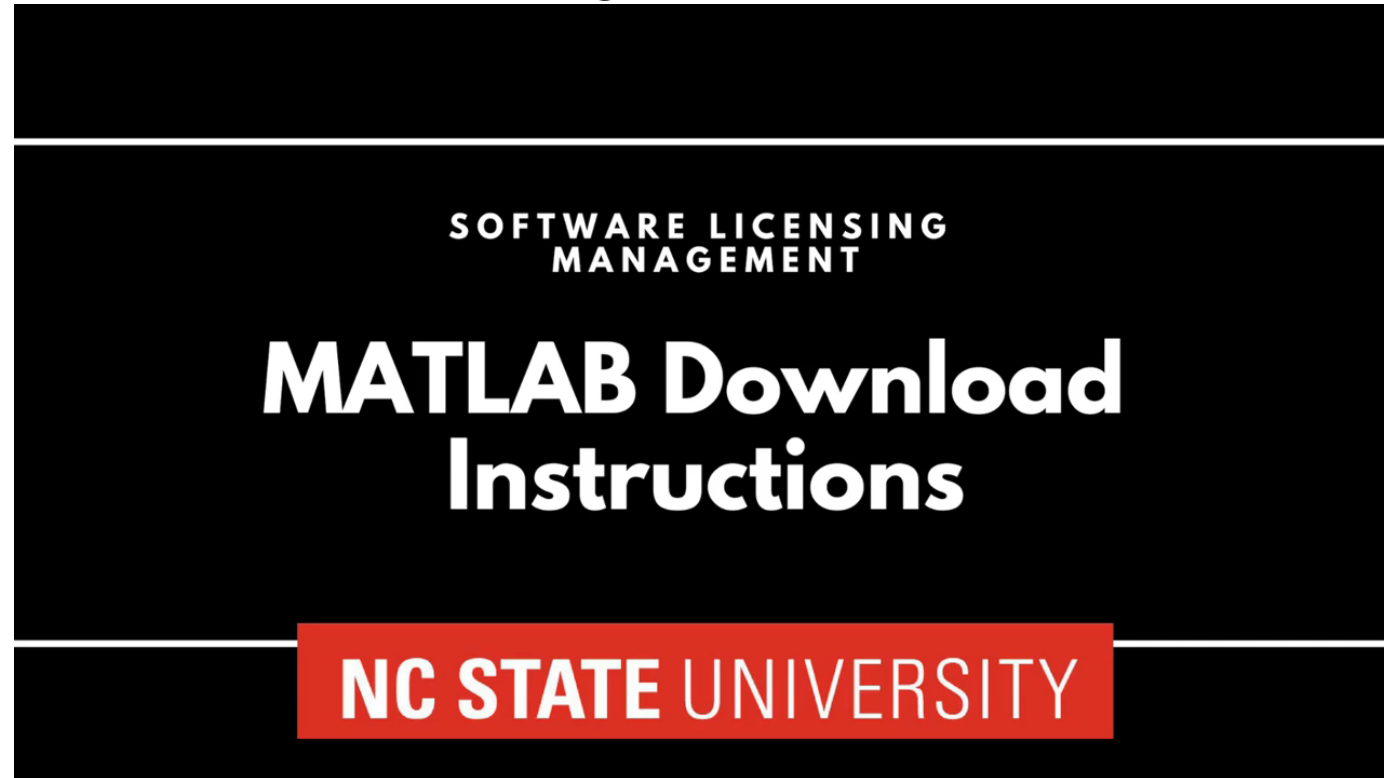
First principle is a physics way of looking at the world you boil things down to the most fundamental truth then reason up from there.

- Elon Musk



Preparation for Matlab and Simulink

- MATLAB version: MATLAB 2018b or later
- MATLAB download: <https://software.ncsu.edu/>
- Take your laptop for next week (Aug. 29, 31)



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- Introduction of Control Applications for Wearable Robots
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My Robotics Lab

- Looking for research assistants to work on wearable robots
 - Including but not limited to mechanical design, embedded system, controls, design of sensors and actuators
 - Students looking for internship are also welcome with stipend support by our lab
- Lab website: <https://haosu-robotics.github.io/>
- Contact information
 - Email: hsu4@ncsu.edu
 - Office: Engineering Building III (EB3) 3282

Powered Rigid Lower Limb Exoskeletons



2005
HAL-5



2010
Indego



2012
Ekso Bionics



2017
Keeogo



No metabolic cost reduction to able-bodied individuals

What are the key challenges?

*Significant mass
20-30Kg

*High friction
Resistive

*Joint misalignment
Discomfort

*Enforced movement
Needs assistive control

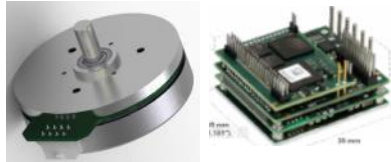
Disruptive Innovations for Wearable Robots

Rigid exoskeletons Challenges

- 10 Kg
- High friction
- Resistive



Low torque motors



Low torque,
high speed

Rigid Transmission



Heavy,
bulky

Wearable Structure



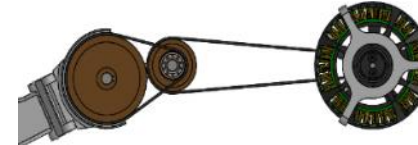
Time-consuming
to don/doff

Innovations

Ultra-lightweight actuator



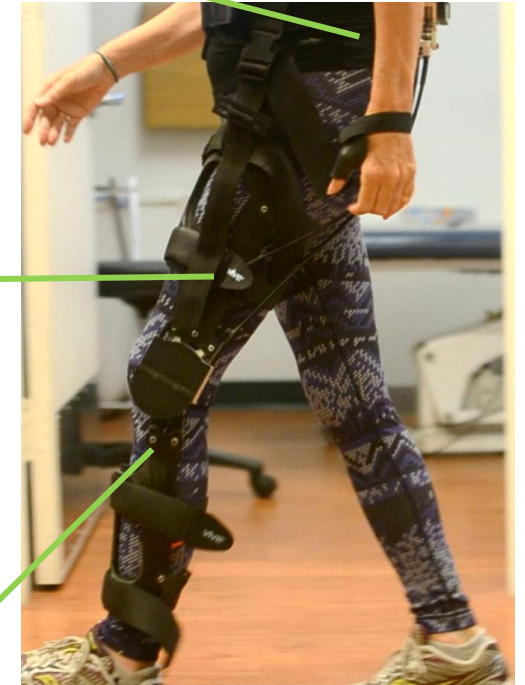
Soft transmission



3D printing Individualization

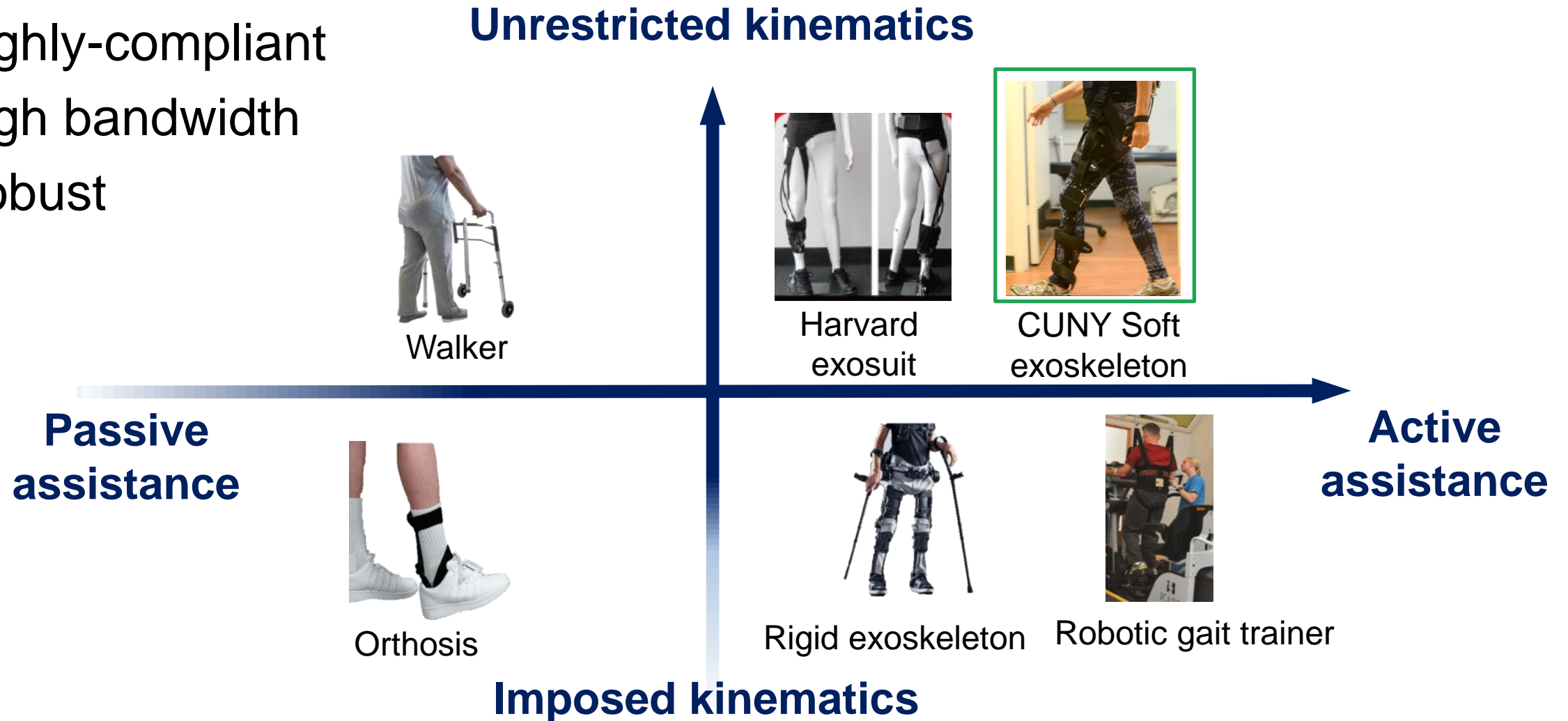


- 2.2 Kg (unilateral)
 - Compliant
 - Assistive
- ## Our Robot



Advantages of Our Soft Exoskeletons


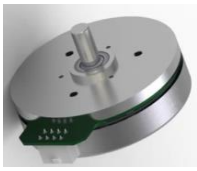
- Lightweight
- Highly-compliant
- High bandwidth
- Robust

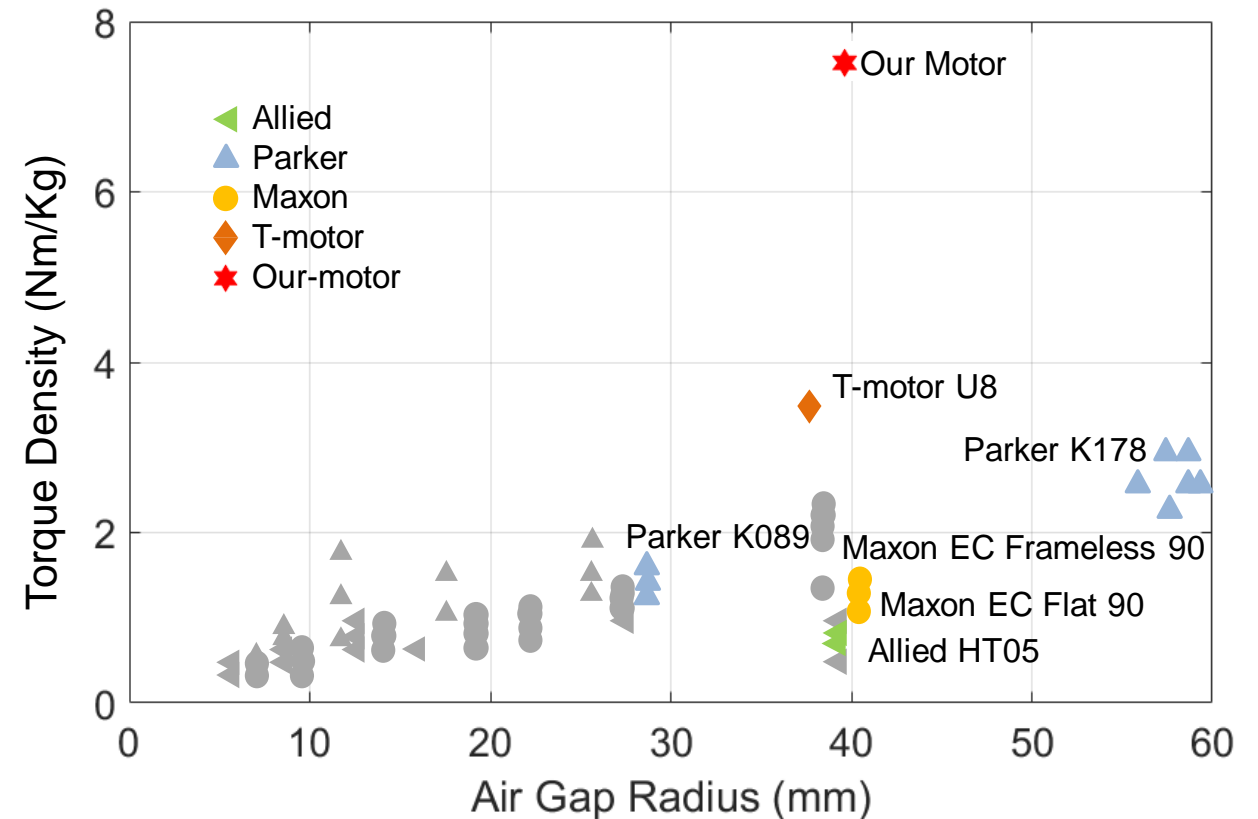


High-Torque Density Motors



National Robotics Initiative

Property	Our motor	EC-90 Flat
Motors		
Mass(g)	244	648
Nominal Power(W)	314	107
Nominal Voltage(V)	42	48
Nominal Current(A)	7.47	2.12
Nominal Torque(Nm)	2	0.5
Nominal Speed(RPM)	1500	2080
Nominal Speed(rad/s)	157	217
Power Density(W/Kg)	1145	165
Torque Density (Nm/Kg)	7.29	0.76



PI, NSF, National Robotics Initiative, Soft Wearable Robots for Injury Prevention and Performance Augmentation, 250K

Wang, J., Li, X., Huang, T.H., Yu, S., Li, Y., Chen, T., Carriero, A., Oh-Park, M. and **Su, H.**, 2018. Comfort-Centered Design of a Lightweight and Backdrivable Knee Exoskeleton. IEEE Robotics and Automation Letters, 3(4), pp.4265-4272.

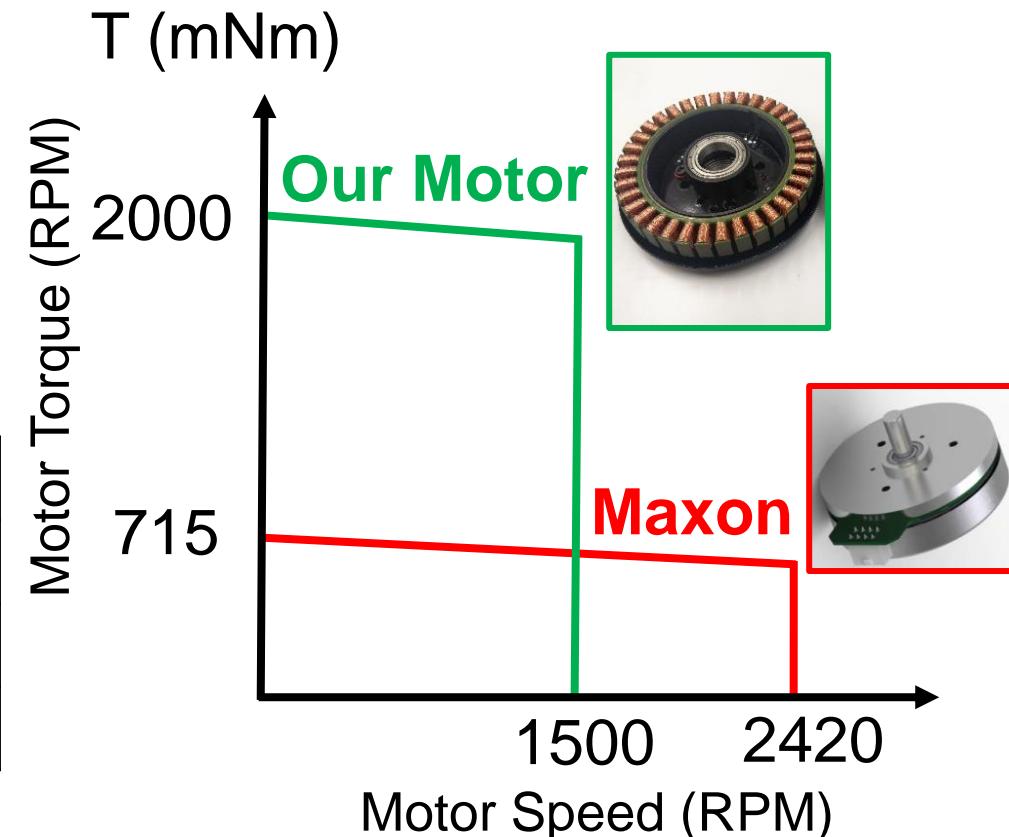
Biomimetic Actuators for Co-Robots



Cyber-Physical Systems

- Motion of human lower limbs
 - High torque: 40-125 Nm
 - Low speed: 60 RPM
- Conventional actuators
 - Low torque: 0.5 Nm (~100:1 ratio gear)
 - High friction: 20 Nm
 - High speed: 6000 RPM (unsafe)

Systems	Motion	Torque	Torque density
Human	Low	High	High
Conventional actuators	High	Low	Low
Our actuators	Low	High	High



CUNY PI, NIH R01, CPS: Medium: Collaborative Research: User and Environment Interactive Planning and Control of Artificial Lower Limbs for Resilient Locomotion, \$1.2 M




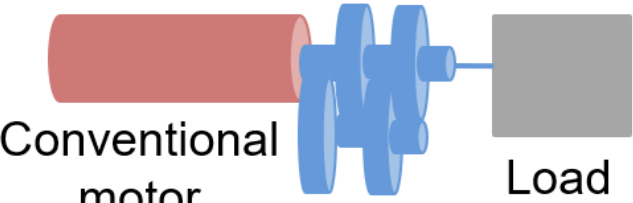
New Actuation Paradigm for Co-Robots

**Position
control**



Reflected inertia is $J_m N^2$
 J_m =Motor inertia
N: gear ratio

**Geared Motor with
Force/Torque Sensor**

Compliance	Low 
Bandwidth	High 
Efficiency	Low 
Actuation Paradigm	<div>High ratio gear</div> <div></div> <div>Conventional motor Load</div>

 NSF CAREER, Versatile Wearable Robots for Pediatric Gait Rehabilitation

Our Robot: Most Lightweight Exoskeleton

- Our Motor Results in 3 Times Torque Density of Harvard Exosuit
- Estimated Metabolics Reduction: 25%

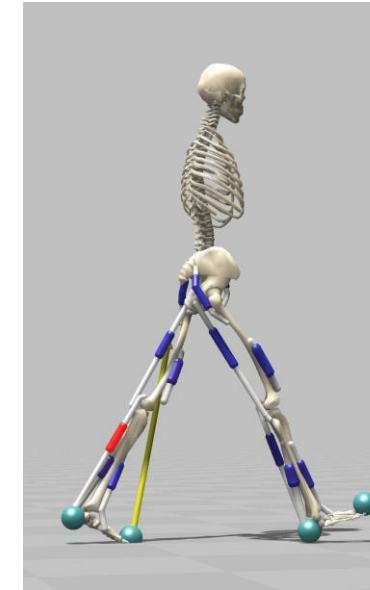
Harvard Exosuit
2019



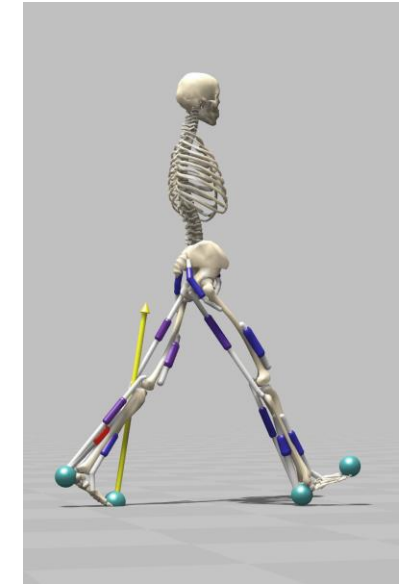
NCSU Exoskeleton



Without Exo



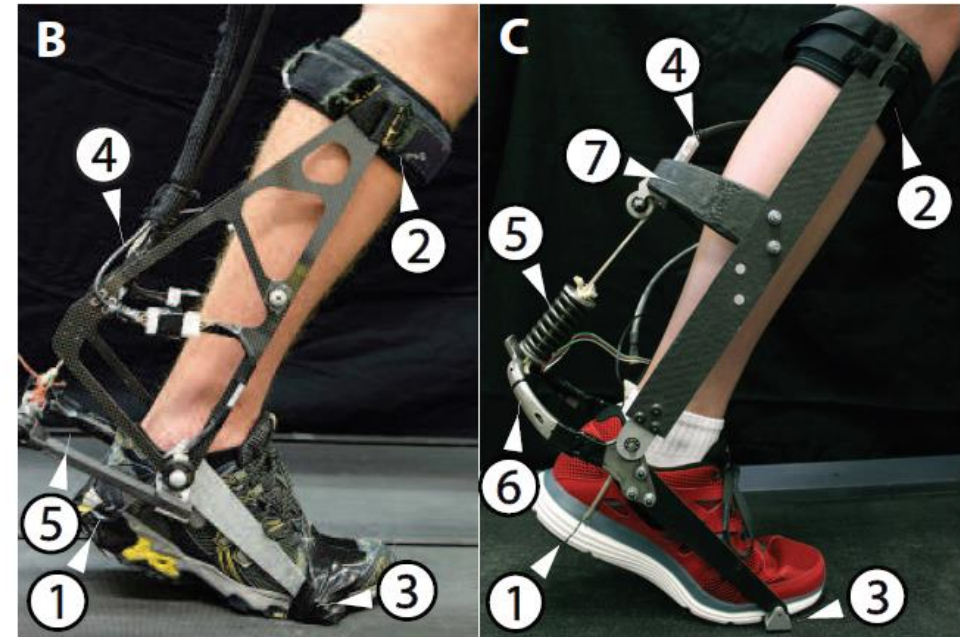
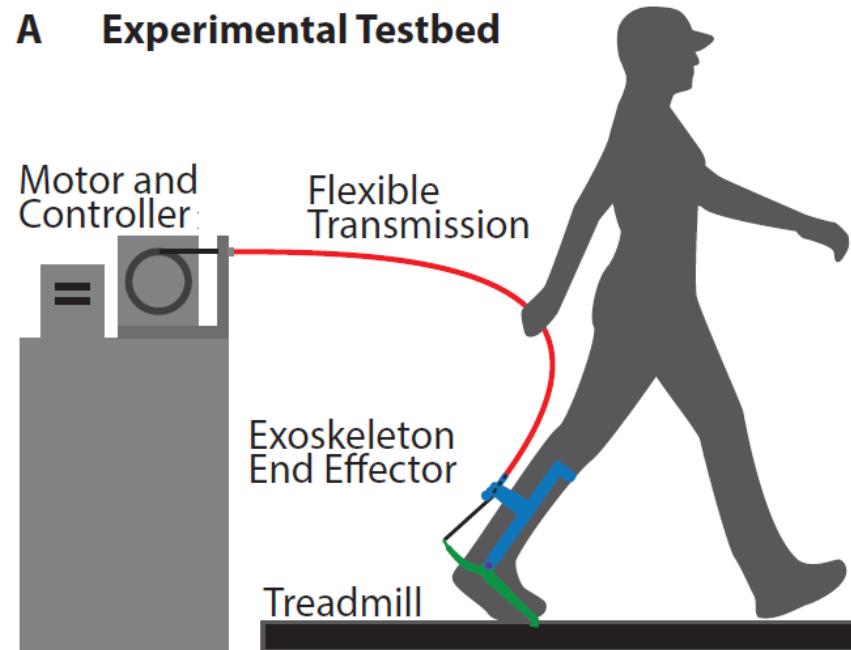
NCSU Exo Assistance



Parameters	Harvard [1]	Samsung [2]	Honda [3]	Our Exo
Peak Torque (Nm)	32	12	6	48
Mass (kg)	5.0	2.6	2.8	2.5
Torque Density (Nm/kg)	6.4	4.6	2.1	19.2
Metabolics Reduction	6%	19.8%	4%	25% (estimated)

Introduction of Control Metrics in Exoskeleton Robots

- Bandwidth
 - A measure of **how fast it responds** to the changing input command.



Introduction of Control Metrics in Exoskeleton Robots

■ Bandwidth

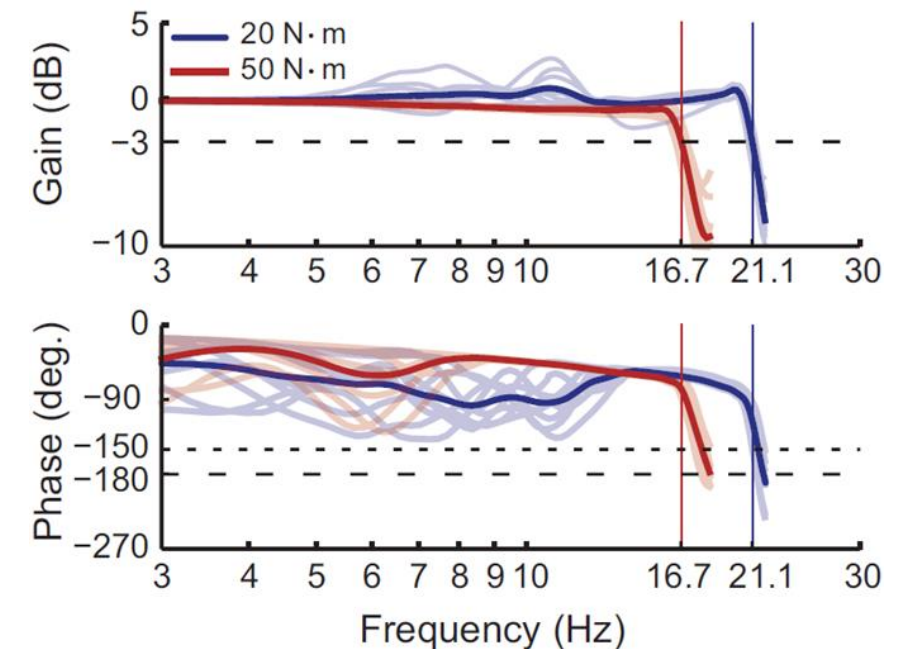
- In a control loop, bandwidth is defined as the frequency at which the closed-loop amplitude response reaches -3 dB
- At this point, the output gain (ratio of output to input) equals approximately 70.7 % of its maximum (the maximum is 100%)

Design of Two Lightweight, High-Bandwidth Torque-Controlled Ankle Exoskeletons

Kirby Ann Witte, Juanjuan Zhang,
Rachel W. Jackson, Steven H. Collins

Carnegie Mellon University
Experimental Biomechatronics Lab

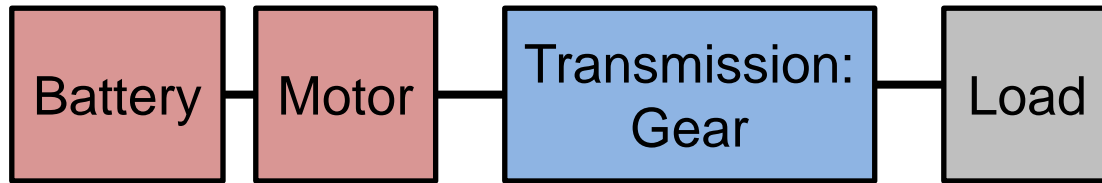
B Closed-loop Frequency Response



From Compliant Robots to Soft-Material Robots

Compliant Robots

- Structure-based compliance
- **Difficult to align human and robot joints**

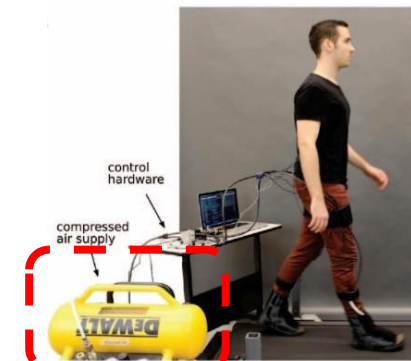
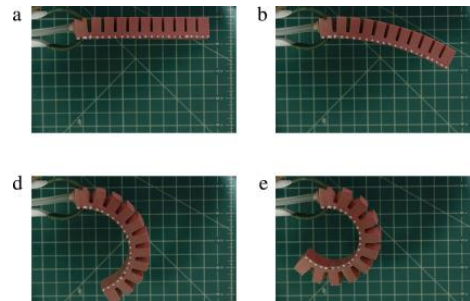


Vanderbilt, 2018



Polygerinos, IROS 2017

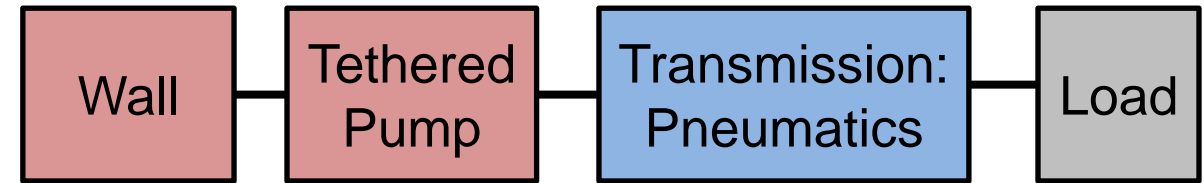
Soft Wearable Robots



Walsh, Biorob, 2018

Soft-Material Robots

- Material-based compliance: rubber, fabric
- Most are pneumatic-driven
- **Pneumatics is transmission not actuator**
- **Slow, Weak, Tethered (need a heavy pump)**



Mobility



Whiteside, Science, 2012

Toyota Mobility Challenge Discovery Award



Videos – Bio-inspired Back Exo



Videos – Hydraulic Artificial Muscle



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- Course overview
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Why to Study “Automatic Control”?

- The study of automatic control is essential for students pursuing degrees in many engineering disciplines (mechanical, electrical, structural, aerospace, biomedical, or chemical).
- Applications of automatic control include, but not limited to, aircraft, robots, civil engineering structures, process control,, etc.
- *Automatic control has played a vital role in the advance of engineering and science.*

What is “Control”?

- Make some object (called ***system, or plant***) behave as we desire.
- Imagine “control” around you!
 - Room temperature control
 - Car driving
 - Voice volume control
 - Balance of bank account
 - “Control” (move) the position of the pointer
 - etc.

Control System

- Basic control system concepts

- A control system consists of subsystems and processes (or plants) assembled for the purpose of obtaining a desired output with desired performance.



- Control

- Measuring the value of the controlled variable (output) of the system and applying accordingly the manipulated variable (input) to make the two as equal as necessary.

What is “Automatic Control”?

- Not manual!
- Why do we need automatic control?
 - Convenient (room temperature, laundry machine)
 - Dangerous (hot/cold places, space, bomb removal)
 - Impossible for human (nanometer scale precision positioning, work inside the small space that human cannot enter, huge antennas control, elevator)
 - It exists in nature. (human body temperature control)
 - High efficiency (engine control)
- Many examples of automatic control around us

Open-loop Control Systems

- Advantages
 - Simple construction and ease of maintenance.
 - There is no stability concern.
 - Convenient when output is hard to measure or measuring the output precisely is economically not feasible. (For example, in the washer system, it would be quite expensive to provide a device to measure the quality of the washer's output, cleanliness of the clothes).
- Disadvantages
 - Disturbances and changes in calibration cause errors, and the output may be different from what is desired
 - Recalibration is necessary from time to time

Example: Laundry Machine

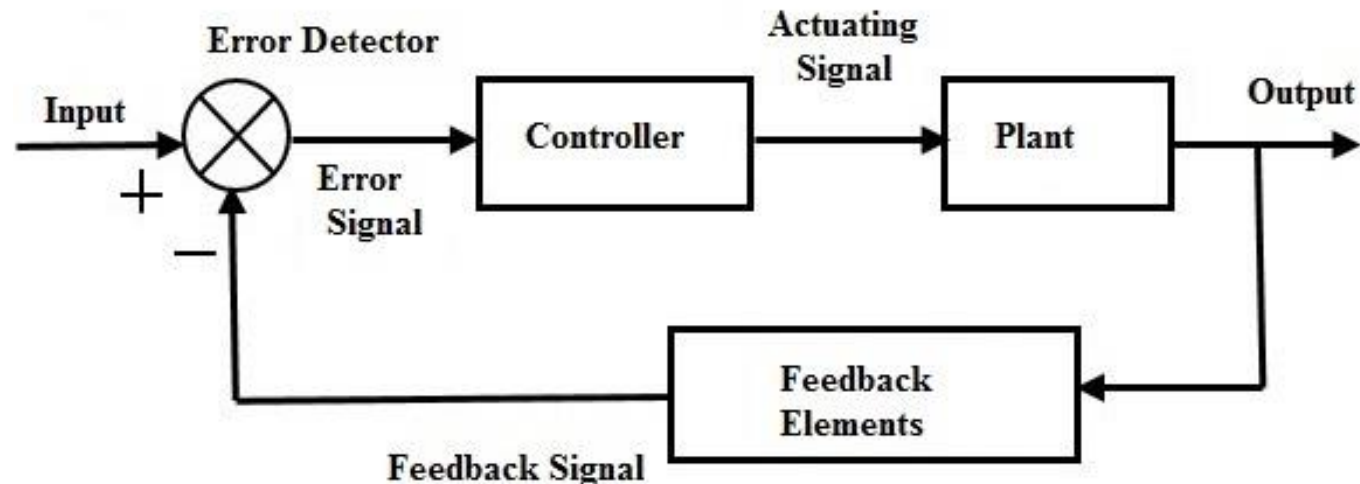
- A laundry machine washes clothes, by setting a program.



- A laundry machine does not measure how clean the clothes become.
- Control without using measuring devices (sensors) to derive control input is called ***open-loop control***

Closed-loop (Feedback) Control

- In this approach, the quantity to be controlled, say C , is measured, compared with the desired value, R , and the error between the two, $E = R - C$ used to adjust C . This means that the control action is somehow dependent on the output.



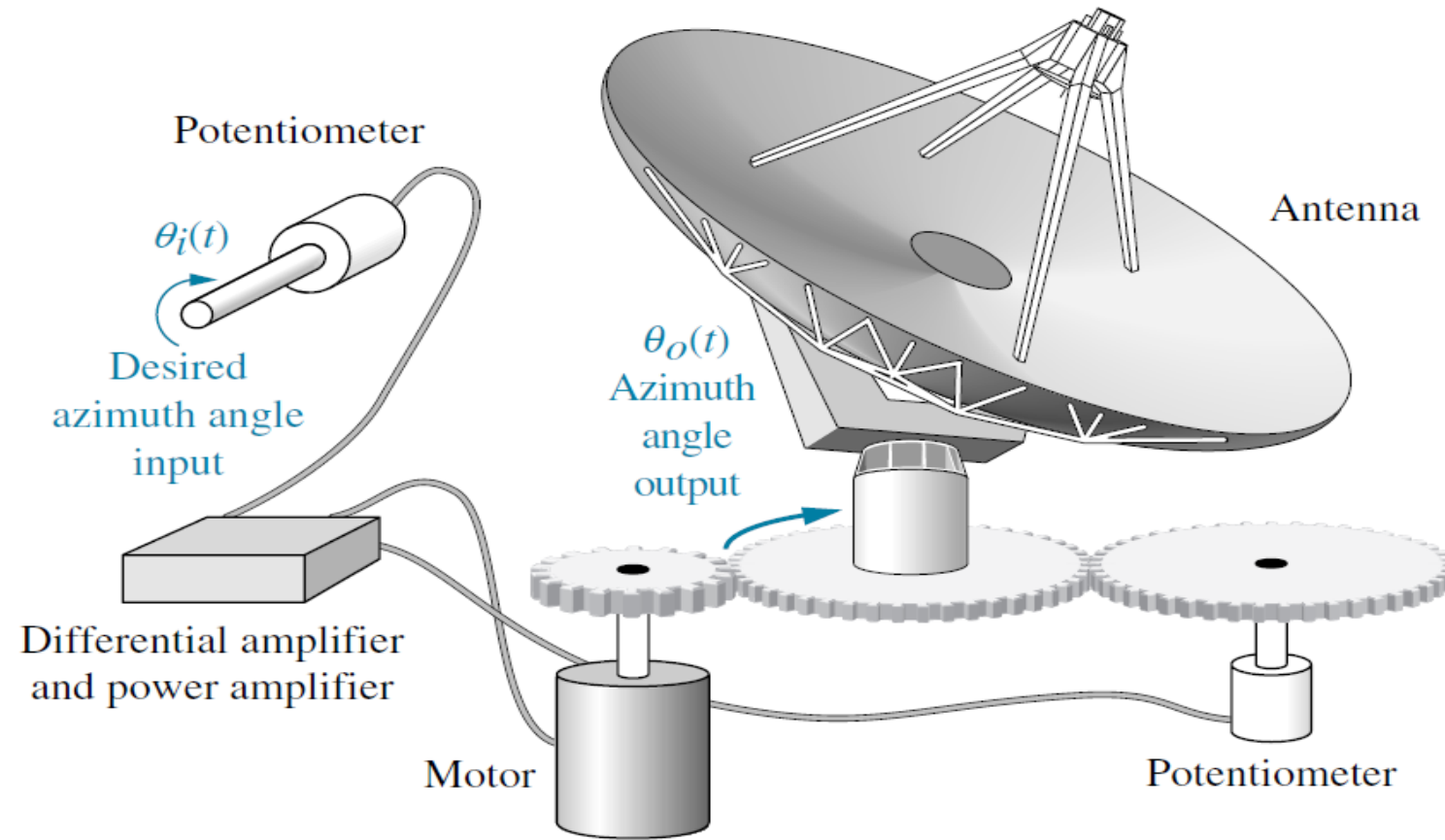
Example: Autopilot Mechanism

Its purpose is to maintain a specified airplane heading, despite atmospheric changes. It performs this task by continuously measuring the actual airplane heading, and automatically adjusting the airplane control surfaces (rudder, ailerons, etc.) so as to bring the actual airplane heading into correspondence with the specified heading.



Closed-loop control

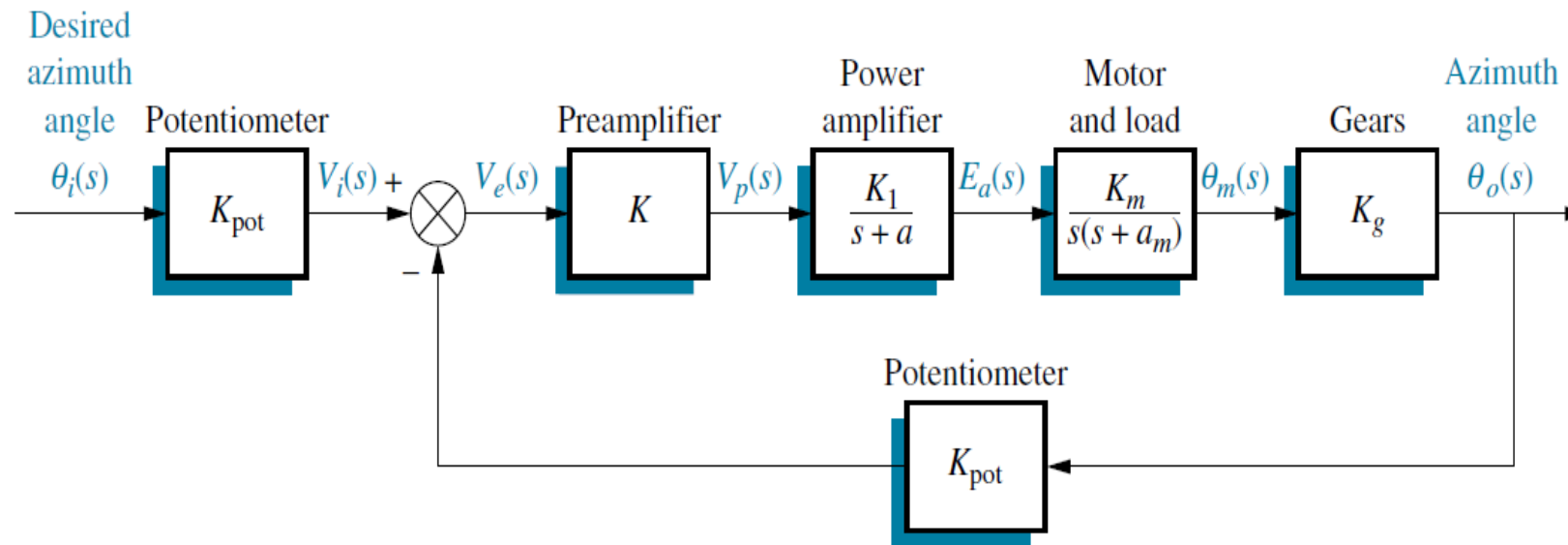
Example: Antenna Azimuth



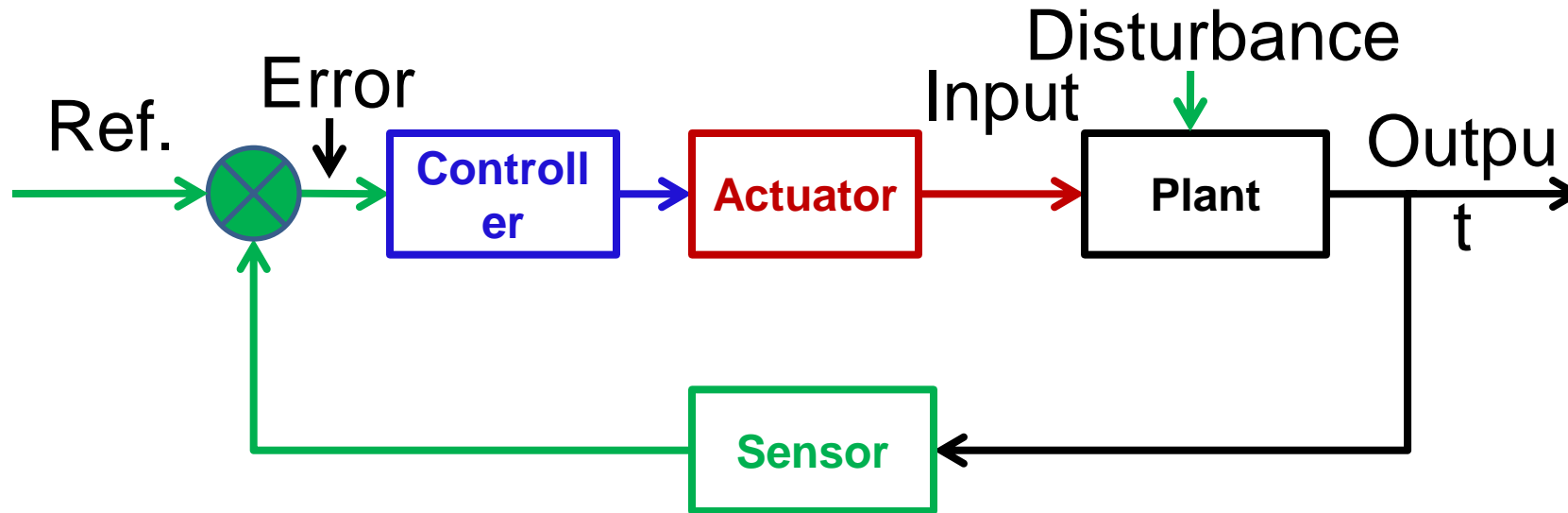
Closed-loop control

Example: Antenna Azimuth

Block Diagram



Basic Elements of Control Loop

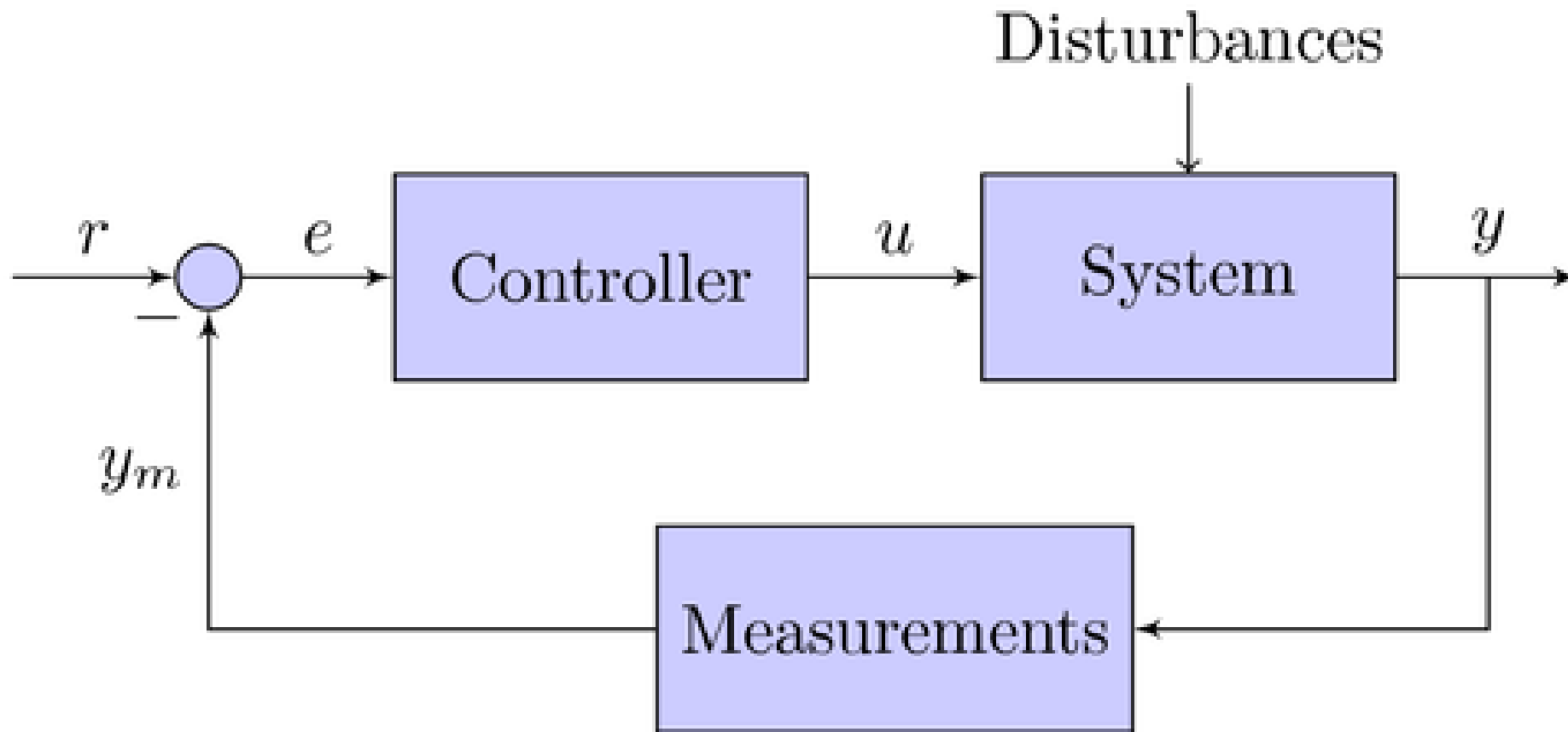


The role of the controller is to make the output following the reference in a “satisfactory” manner even under disturbances.

Understanding Control Systems

- Part 1: Open-Loop Control Systems
- Part 2: Feedback Control Systems
- Part 3: Components of a Feedback Control System

Control System Diagram



Example: Playing Sport

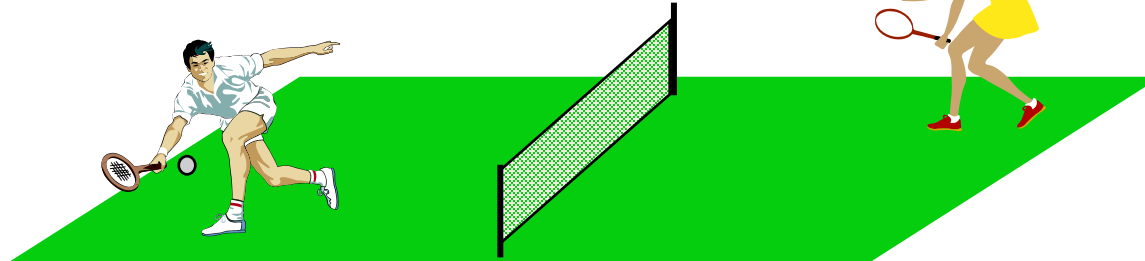
Better Sensors

Provide better *Vision*



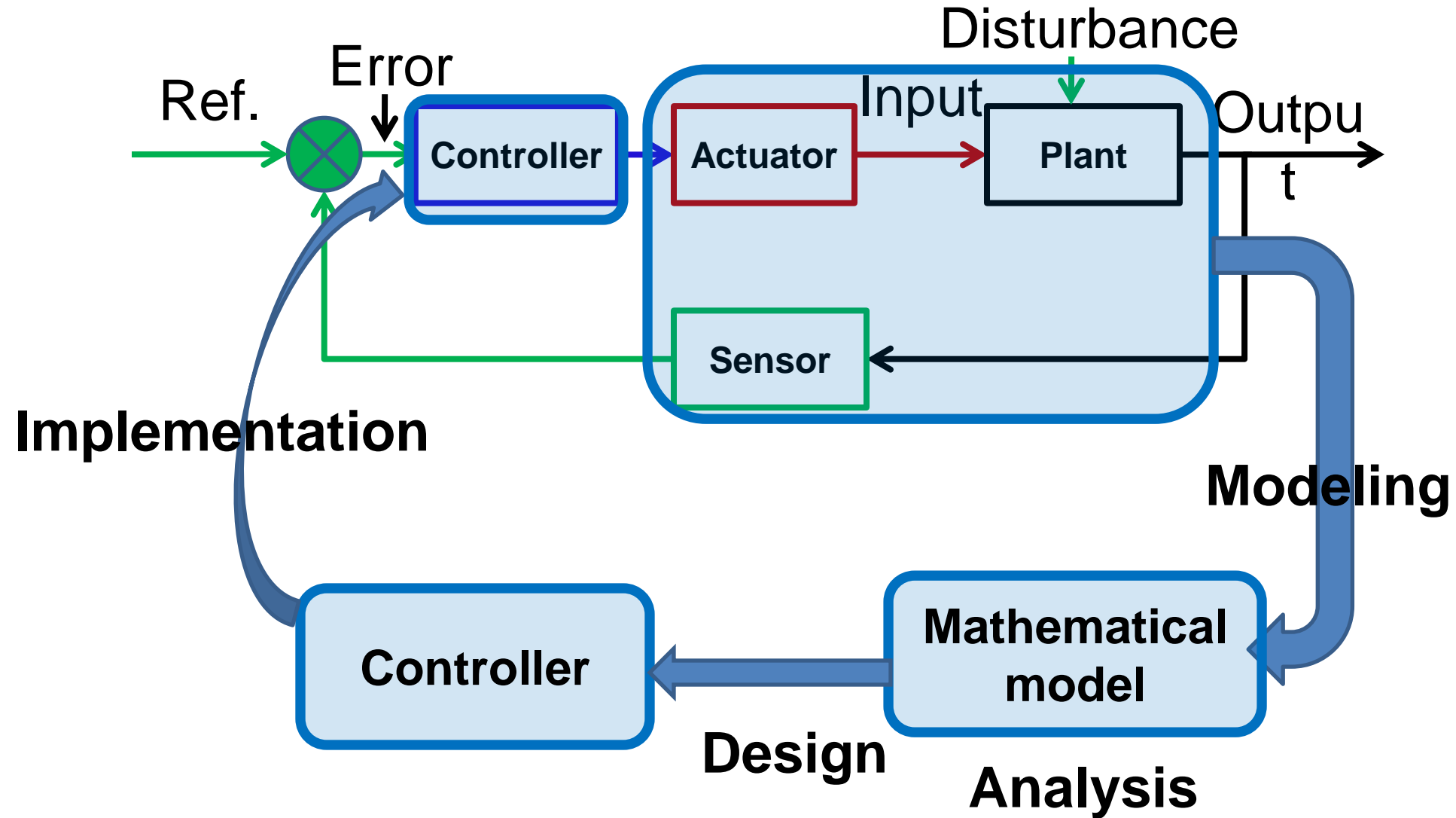
Better Actuators

Provide more *Muscle*

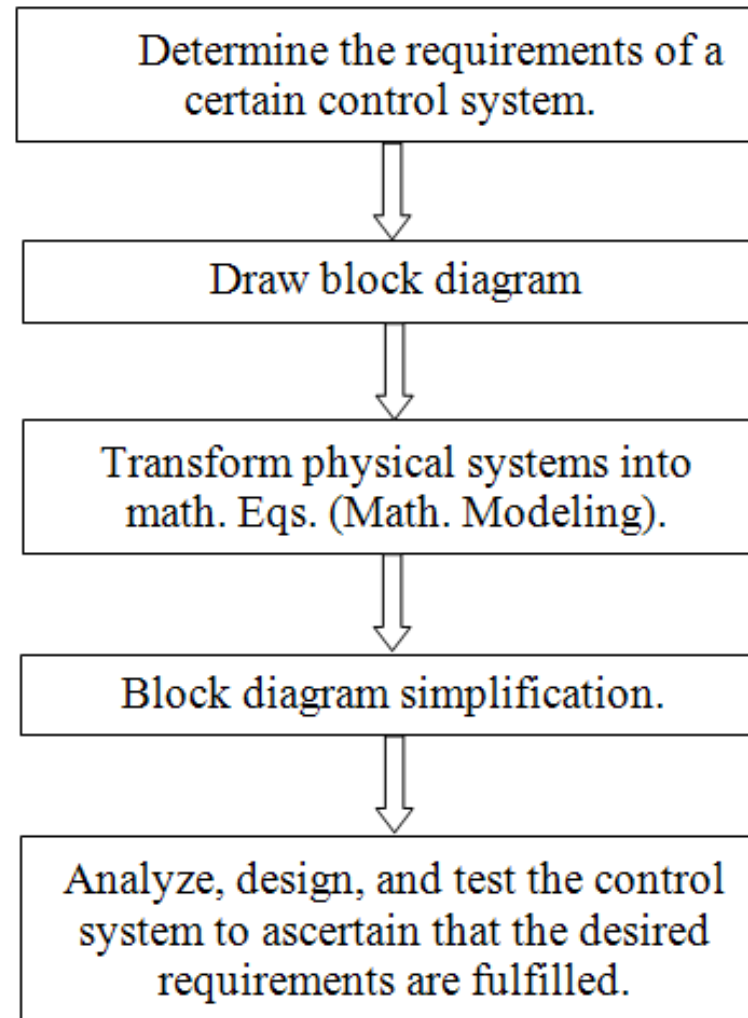


Better Control Provides more finesse by combining *sensors* and *actuators* in more intelligent ways

Course Goals



Procedure of Design A Controller for System



Summary

- Introduction
 - Control essentiality
 - Examples of control systems
 - Open-loop vs. closed-loop control systems
- Next Week
 - MATLAB and Simulink introduction
(Please install MATLAB and Simulink prior to the next class)
 - Take your laptop for next week (Aug. 29, 31)

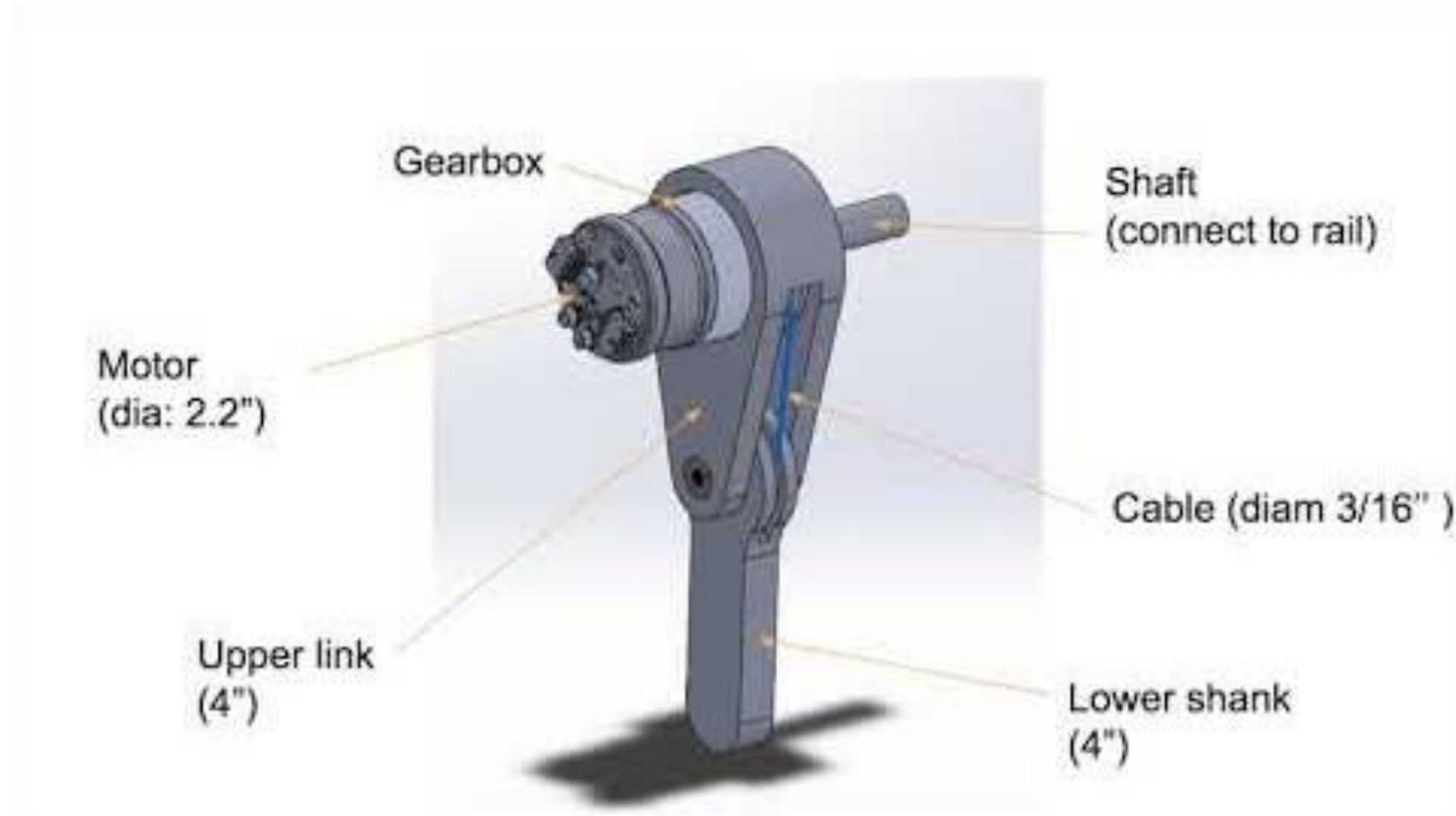
Videos – Cable-driven Knee Exo



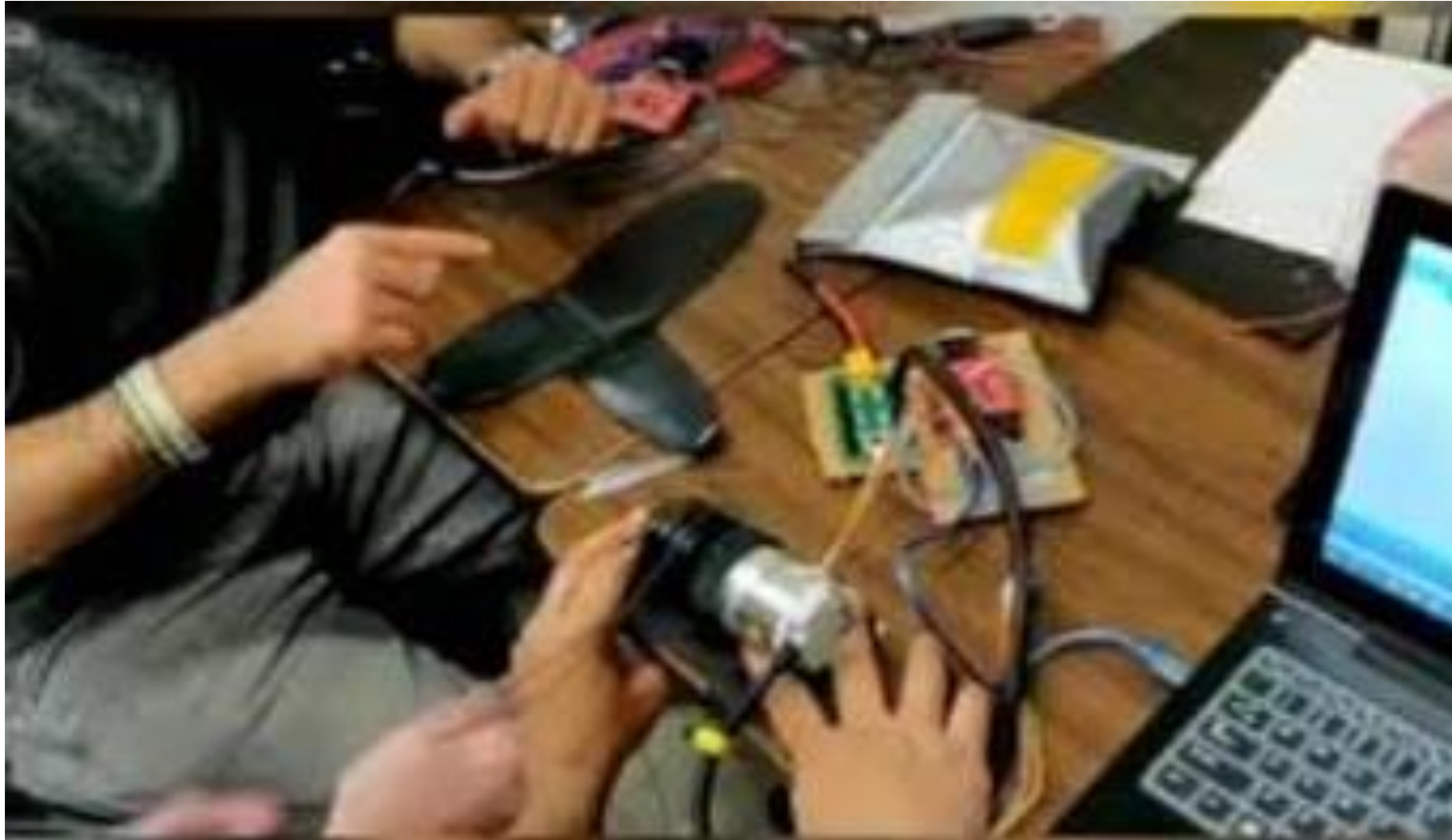
Videos – Cable-driven Hip Exo



Videos – Legged Jumping Robot



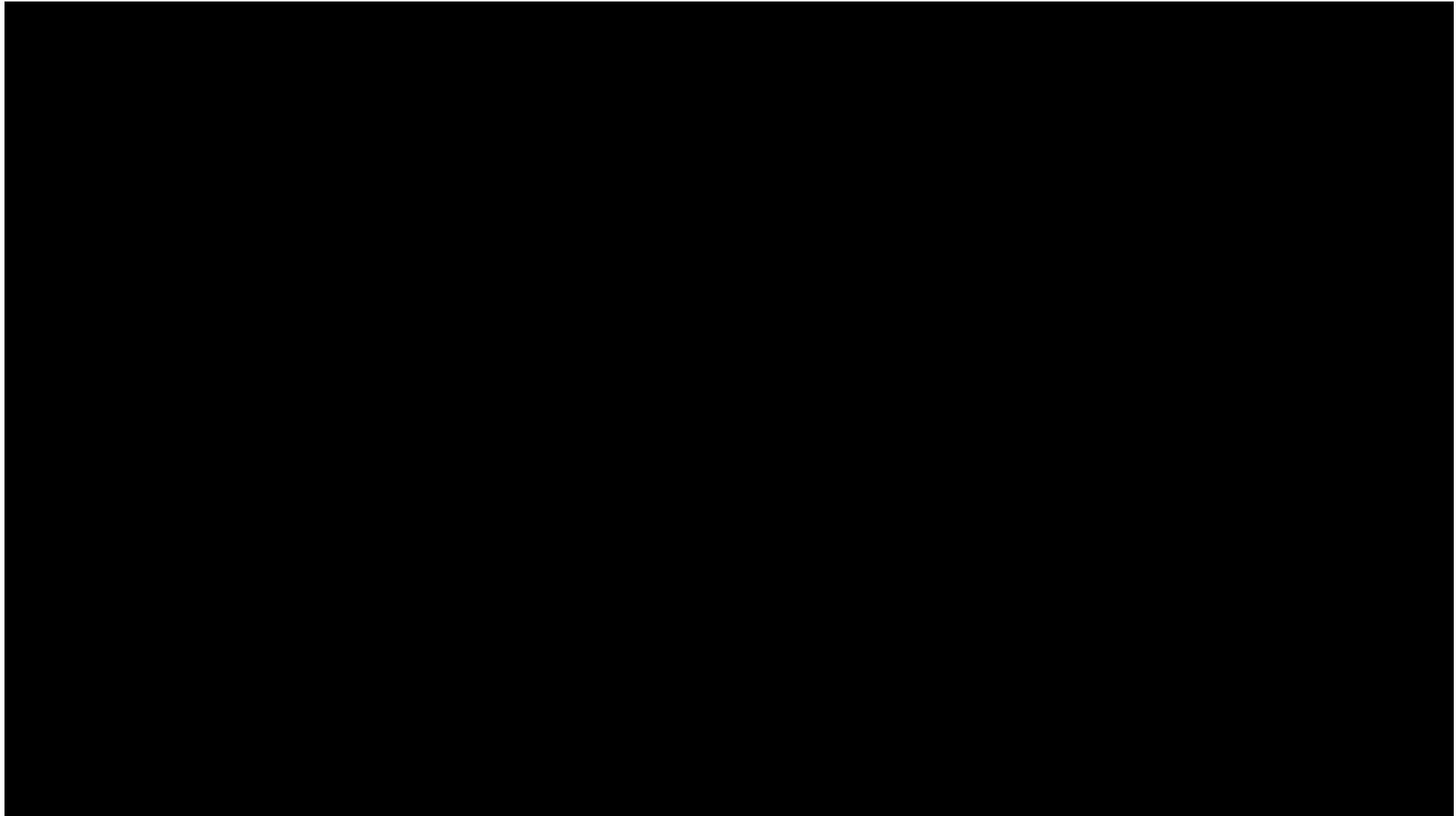
Videos – Cabled-driven Ankle Exo 2



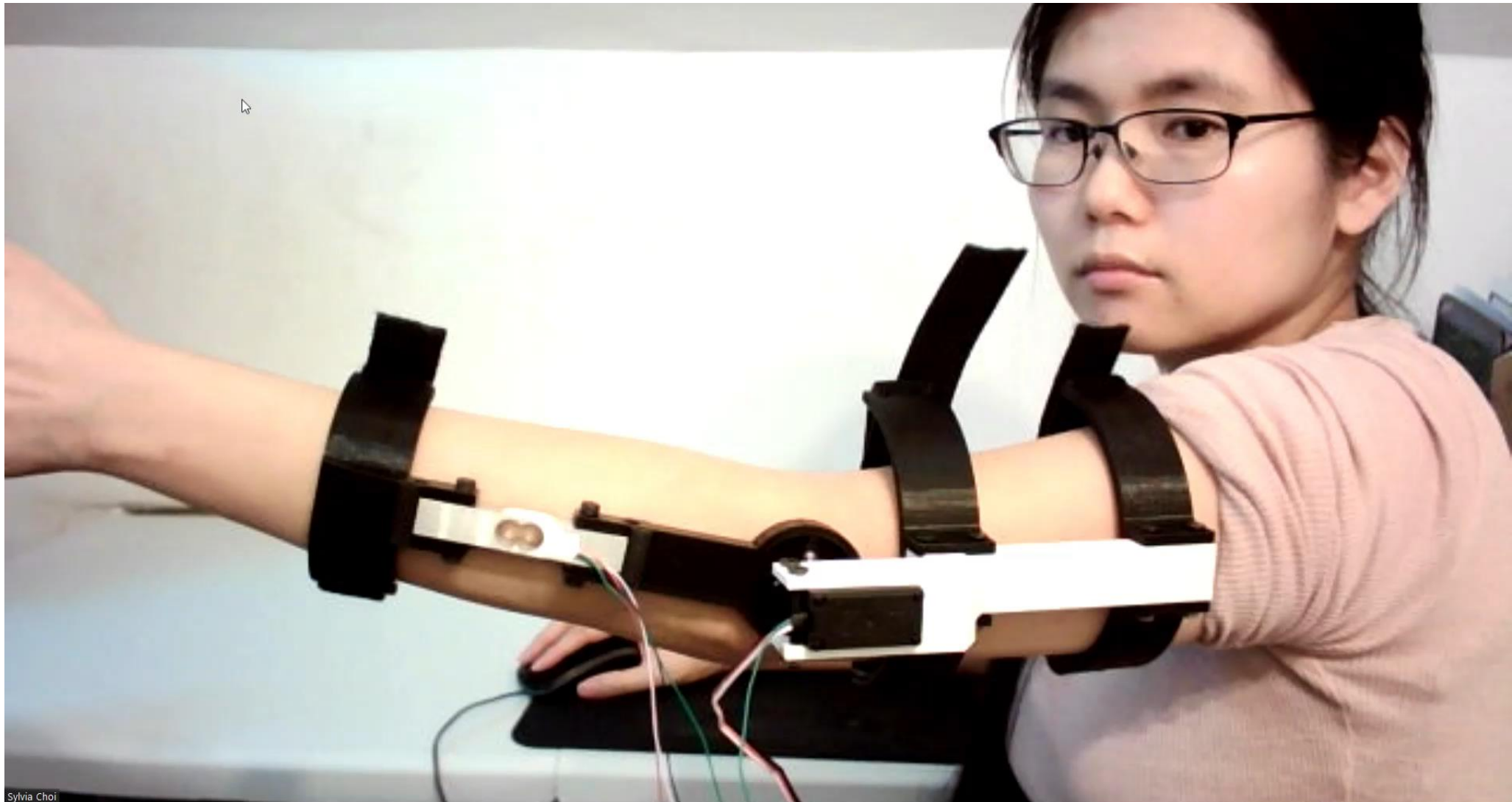
Videos – Rigid Knee Exo for Pediatric



Elbow Exo Student Presentation



Elbow Exo Student Presentation



Sylvia Choi