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	Tuesday	Thursday	Optional Text Read
Modeling	1. Aug. 22, 24	Course Overview	Basics of Laplace Transfer and PID Control	MCE: 1.1 – 1.5
	2. Aug. 29, 31	Project: MATLAB	Project: Simulink Introduction	SD: 2.2 – 2.3
	3. Sep. 5, 7	Laplace Transform & Transfer Function	Mechanical System Modeling	MCE: 2.1, 2.2 & SD: 2.2 – 2.3
	4. Sep. 12, 14	Project: Simulink Introduction Part II	Electromechanical Systems Modelling	MCE: 3.1-3.2 & SD: 6.1-6.6-
	5. Sep. 19, 21	Wellness Day	Control Block Diagram Signal Flow Graph	MCE: 2.3 & SD: 8.1 – 8.3
	6. Sep. 26, 28	Time-Domain Analysis (1st order system)	Time-Domain Analysis (2nd order system)	SD: 8.1 – 8.3 & MCE: 5.1 – 5.8
Analysis	7. Oct. 3, 5	Midterm Review	Project: Robot Modeling	MCE: 5.1 – 5.8
	8. Oct. 10,12	No class (Fall break)	Frequency Domain Analysis Part I	MCE: 5.1 – 5.8
	9. Oct. 17, 19	Frequency Domain Analysis Part II	**Midterm**	MCE: 7.1 & MCE: 7.2 – 7.6
	10. Oct. 24, 26	Bode Diagram: Concept	Midterm Recap & Stability Analysis	MCE: 6.2 – 6.5 & MCE: 7.2 – 7.6
	11. Oct. 31, Nov 2	Bode Diagram: Gain and Phase Margin	Bode Diagram: Stability Criterion	MCE: 7.7 -7. 8
	12. Nov. 7, 9	Bode Diagram: Design and Control	Lead Compensation Control	MCE: 7.11 – 7.13
	13. Nov. 14, 16	Project: Robot System Simulation Implementation	Lag Compensation Control	MCE: 7.11 – 7.13
Control	14. Nov. 21, 23	Lead-Lag Compensation Control	No class (Thanksgiving Day)	
	15. Nov. 28, 30	Final Exam Review	Project: Control of Robot (Last Day of Class)	-
	16. Dec. 5	**Last day of classes**		-
	17. Dec. 7	**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.

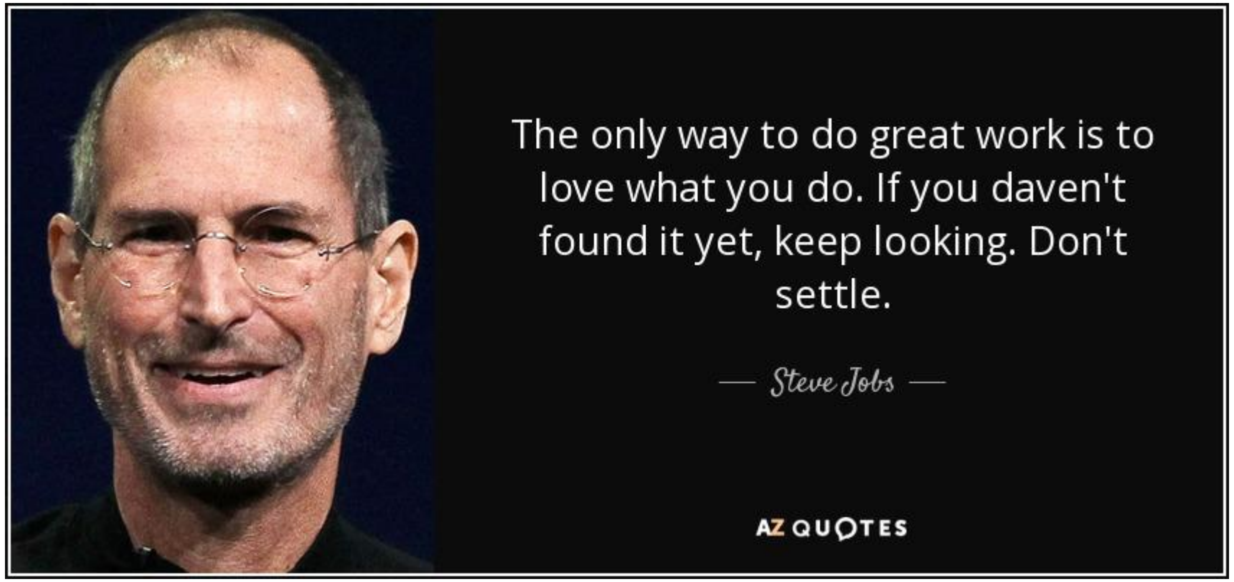
K. Ogata, ***System Dynamics***, 4th ed., Prentice Hall, Upper Saddle River, NJ, 2004.

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.

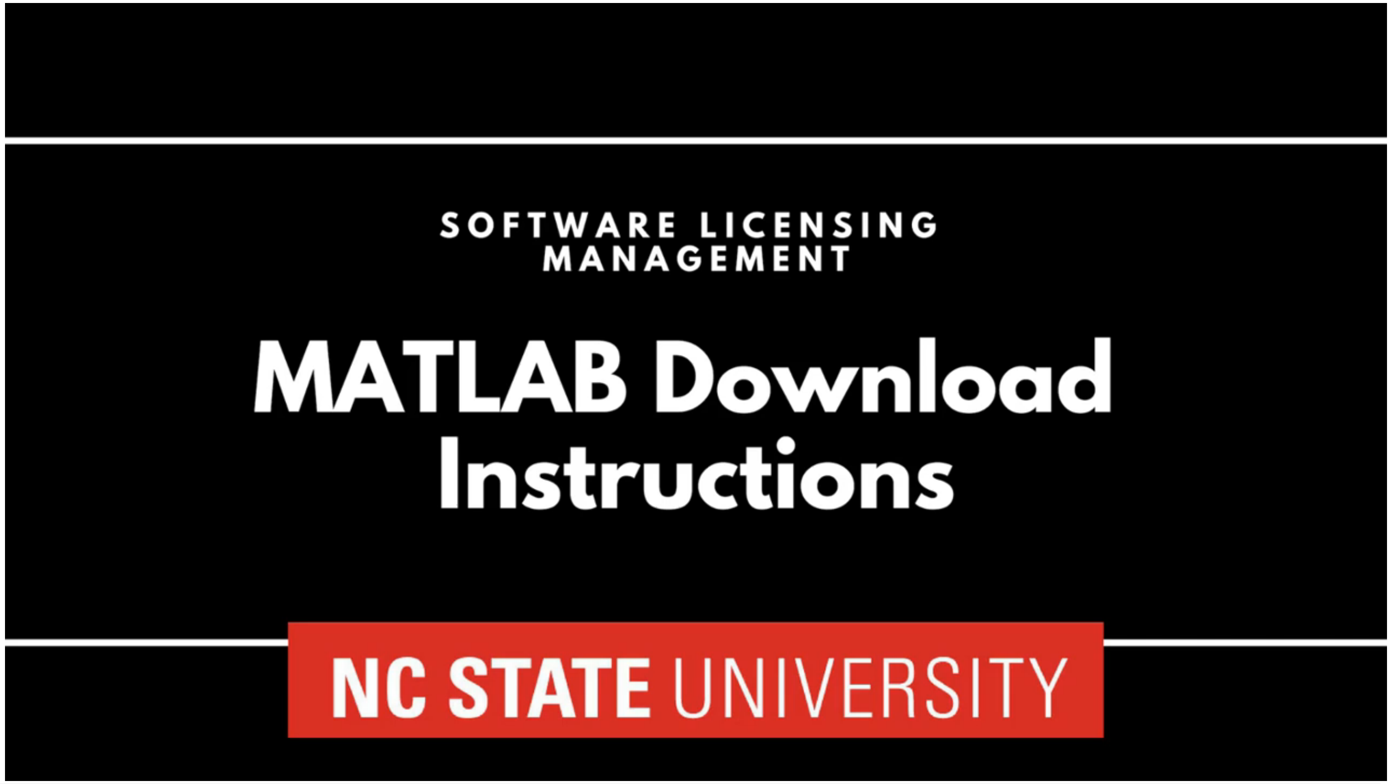


First principle is a physics way of looking at the world you boil things down to the most fundamental truth then reason up from there.

- 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 Automatic Control

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?

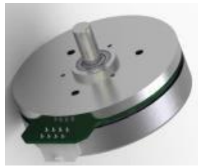
*Significant mass	*High friction	*Joint misalignment	*Enforced movement
20-30Kg	Resistive	Discomfort	Needs assistive control

Disruptive Innovations for Wearable Robots

Rigid exoskeletons

- 10 Kg
- High friction
- Resistive

Low torque motors



Rigid Transmission

Wearable Structure

Challenges

Low torque, high speed

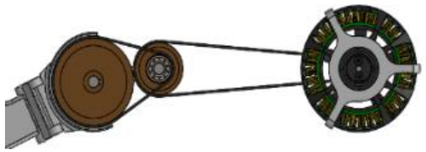
Heavy, bulky

Time-consuming to don/doff

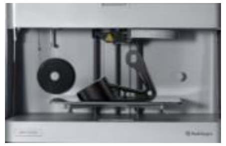
Innovations

Ultra-lightweight actuator

Soft transmission



3D printing Individualization

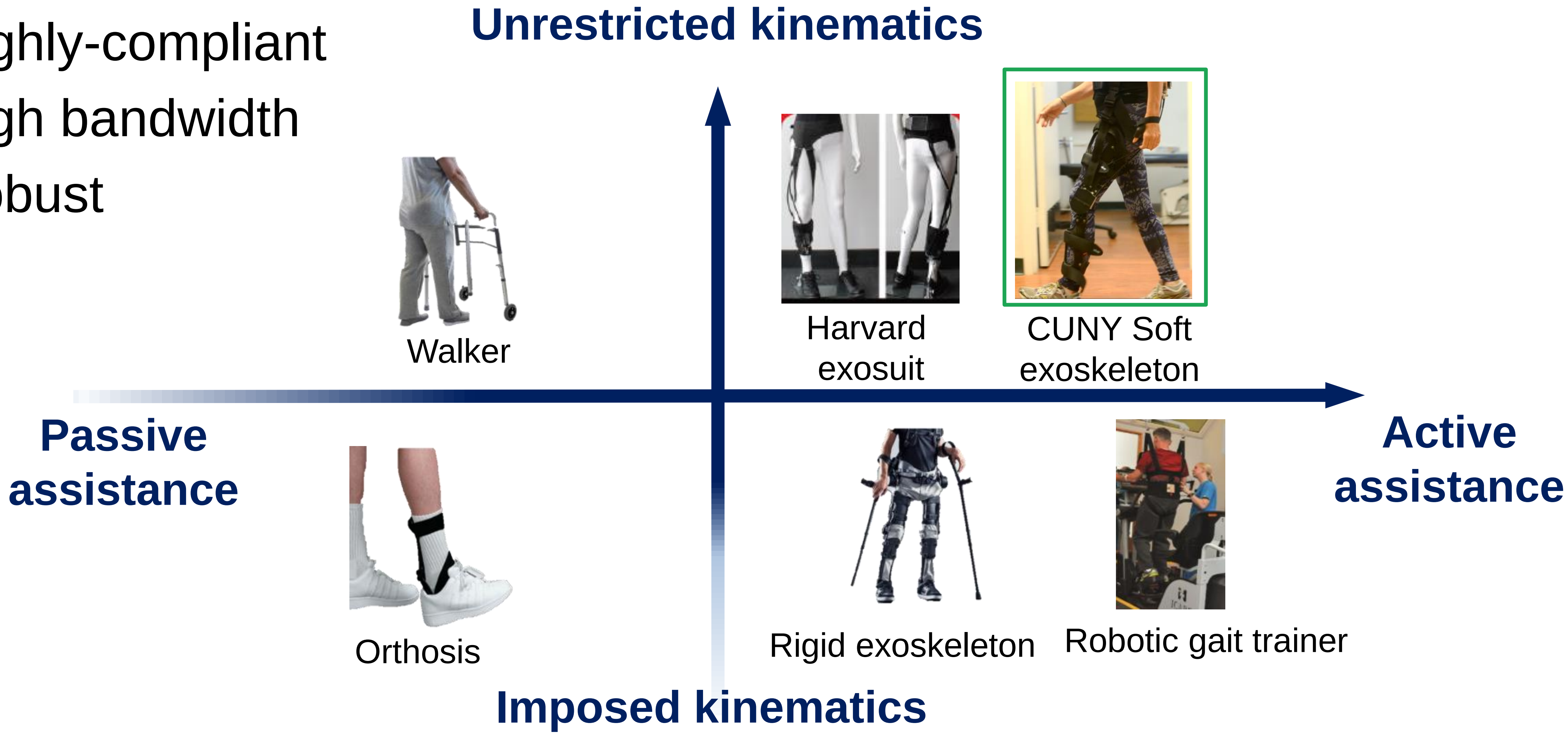


Our Robot

- 2.2 Kg (unilateral)
- Compliant
- Assistive

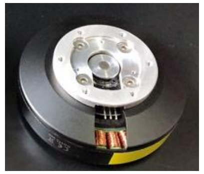
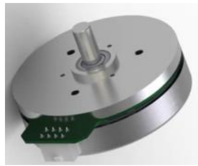
Advantages of Our Soft Exoskeletons

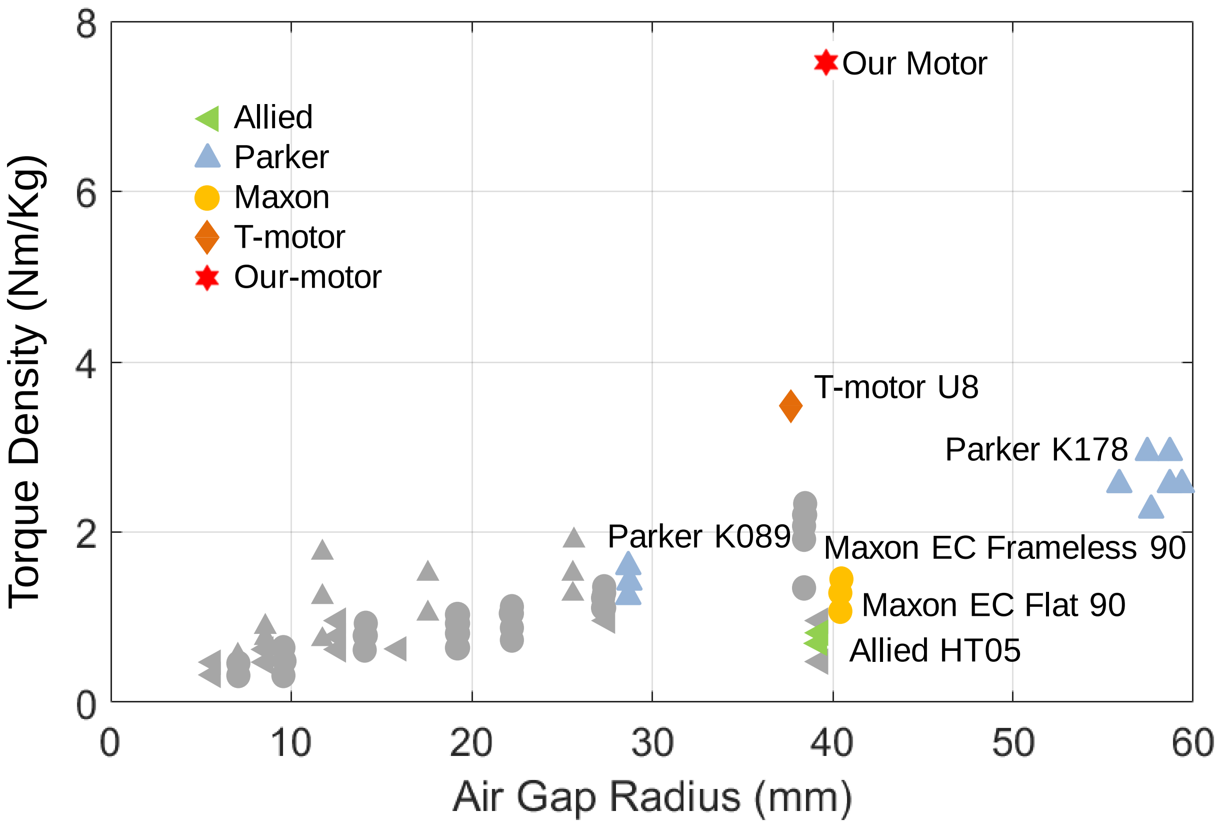
- Lightweight
- Highly-compliant
- High bandwidth
- Robust



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

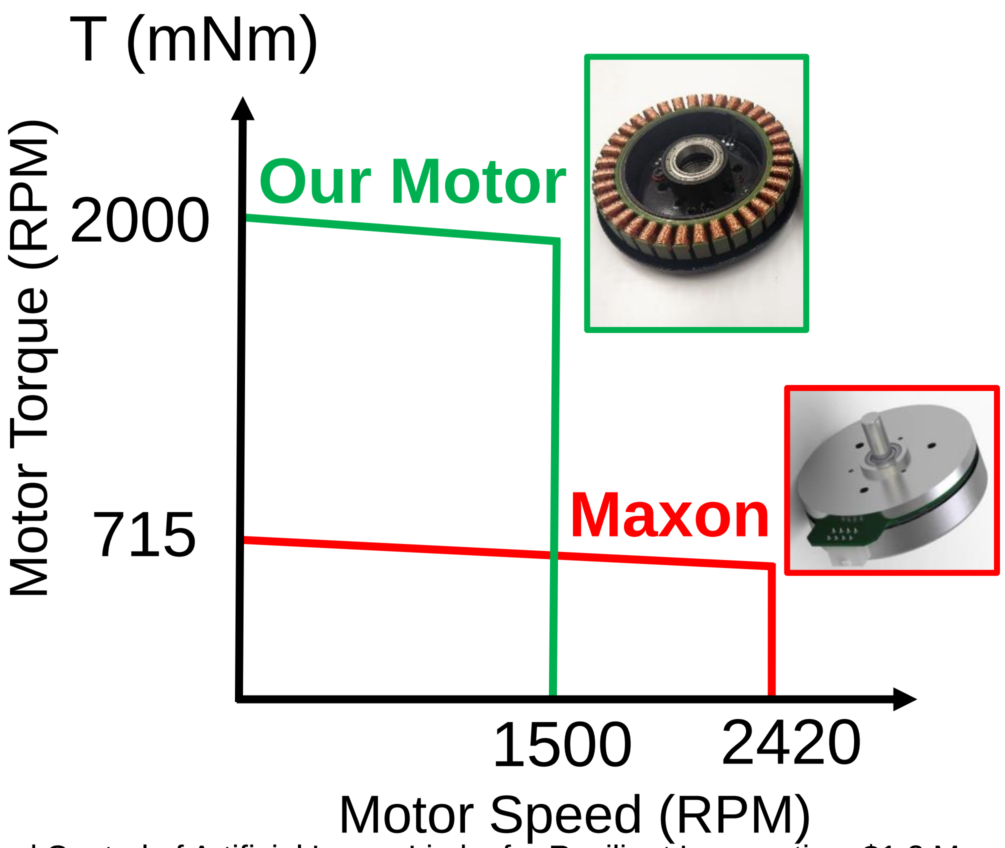
Wang, J., Li, X., Huang, T.H., Yu, S., Li, Y., Chen, T., Carriero, A., Oh-Park, M. and **Su, H.**, 2018. Comfort-Centered Design of a Lightweight and Backdrivable Knee Exoskeleton. IEEE Robotics and Automation Letters, 3(4), pp.4265-4272.

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

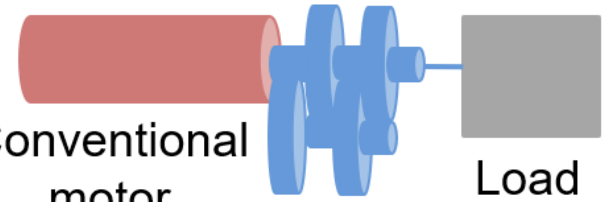
Reflected inertia is $J_m N^2$

J_m=Motor inertia

N: gear ratio

Position control

Geared Motor with Force/Torque Sensor

Compliance	Low ✗
Bandwidth	High ✓
Efficiency	Low ✗
Actuation Paradigm	

NSF CAREER, Versatile Wearable Robots for Pediatric Gait Rehabilitation

Yu S, Huang TH, Wang D, Lynn B, Sayd D, Silivanov V, Park YS, Tian Y, **Su H.** Design and Control of a High-Torque and Highly-Backdrivable Hybrid Soft Exoskeleton for Knee Injury Prevention during Squatting . IEEE Robotics and Automation Letters (RA-L), 2019

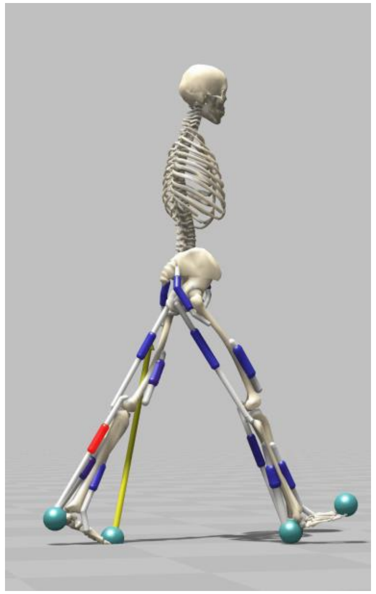
Our Robot: Most Lightweight Exoskeleton

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

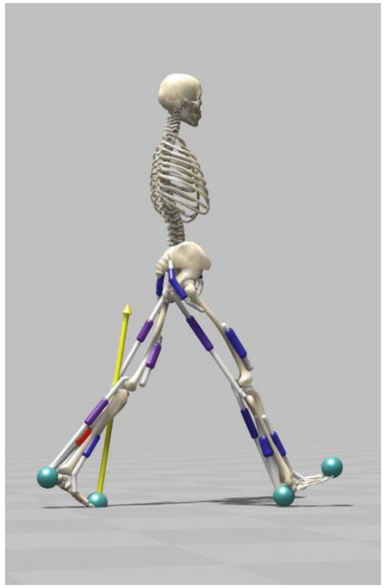
Harvard Exosuit 2019

NCSU Exoskeleton

Without Exo



NCSU Exo Assistance

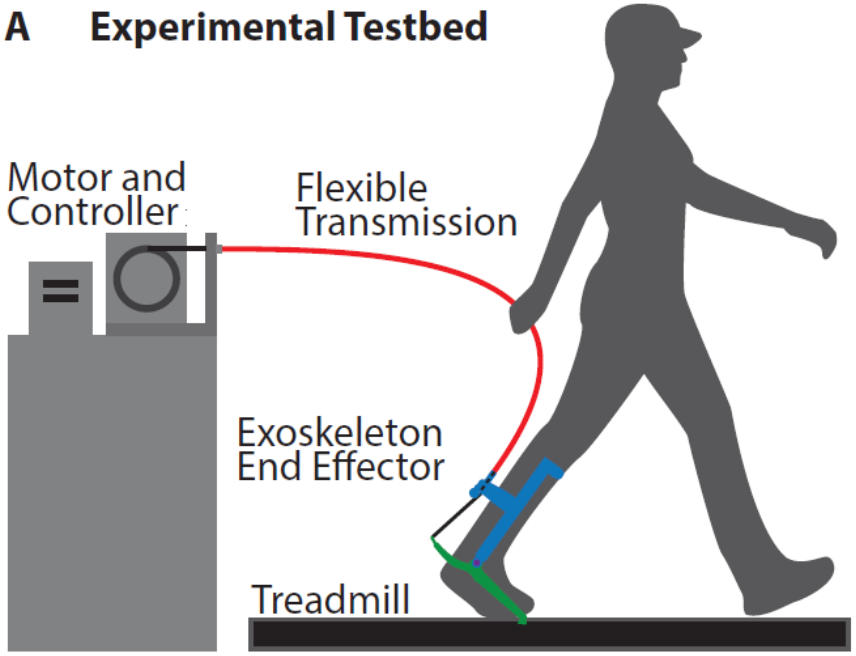


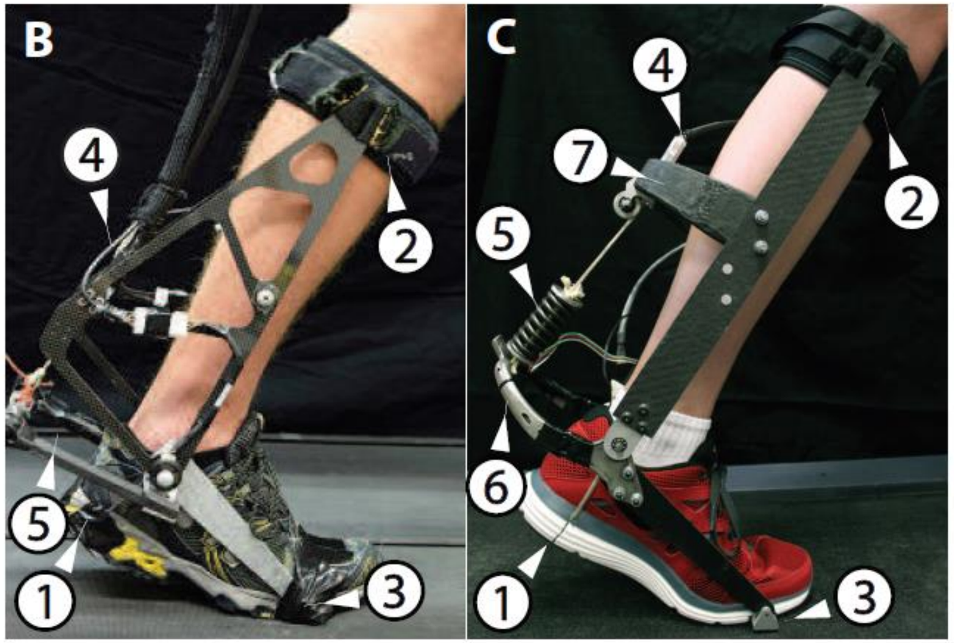
Parameters	Harvard [1]	Samsung [2]	Honda [3]	Our Exo
Peak Torque (Nm)	32	12	6	48
Mass (kg)	5.0	2.6	2.8	2.5
Torque Density (Nm/kg)	6.4	4.6	2.1	19.2
Metabolics Reduction	6%	19.8%	4%	25% (estimated)

[1] Kim. Reducing the metabolic rate of walking and running with a versatile, portable exosuit. Science. 2019 Aug 16;365(6454):668-72.
[2] Lee, Flexible sliding frame for gait enhancing mechatronic system (GEMS), EMBC, 2016
[3] Jayaraman, Stride management assist exoskeleton vs functional gait training in stroke. Neurology. 2019 Jan 15;92(3):e263-73.

Introduction of Control Metrics in Exoskeleton Robots

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

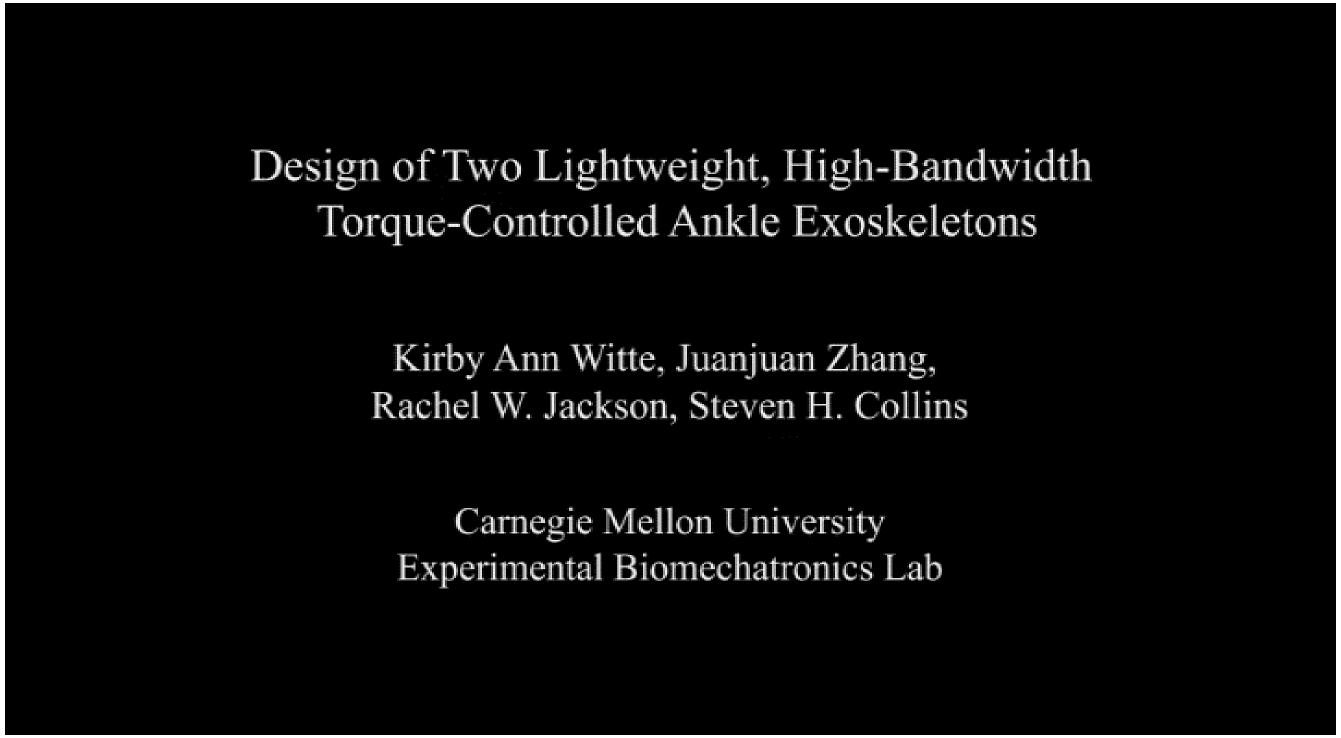


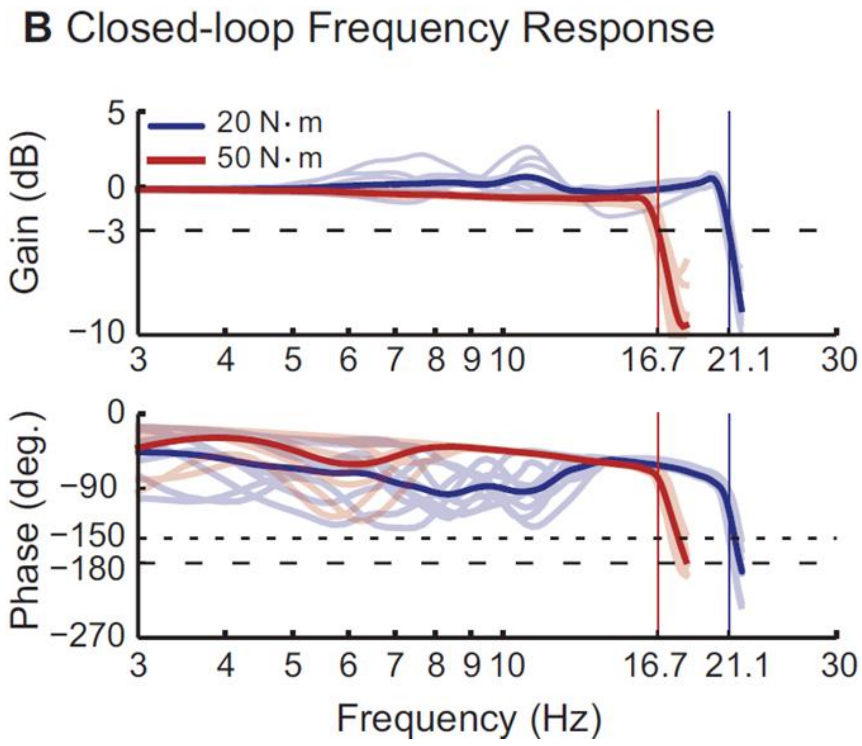


Witte, K. A., Zhang, J., Jackson, R. W., & Collins, S. H. (2015, May). Design of two lightweight, high-bandwidth torque-controlled ankle exoskeletons. In 2015 IEEE International Conference on Robotics and Automation (ICRA) (pp. 1223-1228). IEEE.

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%)





From Compliant Robots to Soft-Material Robots

Compliant Robots

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

Battery — Motor — Transmission: Gear — Load

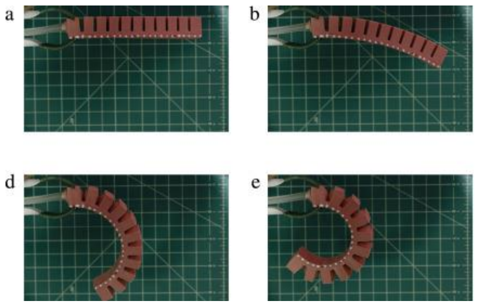
Soft-Material Robots

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

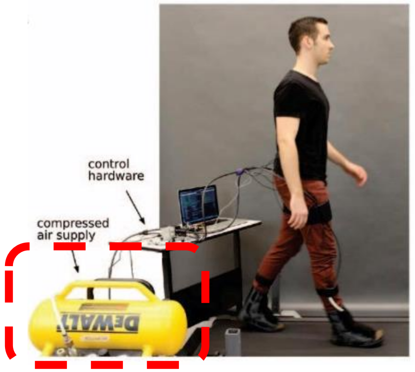
Wall — Tethered Pump — Transmission: Pneumatics — Load

Soft Wearable Robots

Vanderbilt, 2018



Polygerinos, IROS 2017



Walsh, Biorob, 2018

Mobility

Whiteside, Science, 2012

Toyota Mobility Challenge Discovery Award

TOYOTA mobility FOUNDATION

Videos – Bio-inspired Back Exo

Videos – Hydraulic Artificial Muscle

Outline

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

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

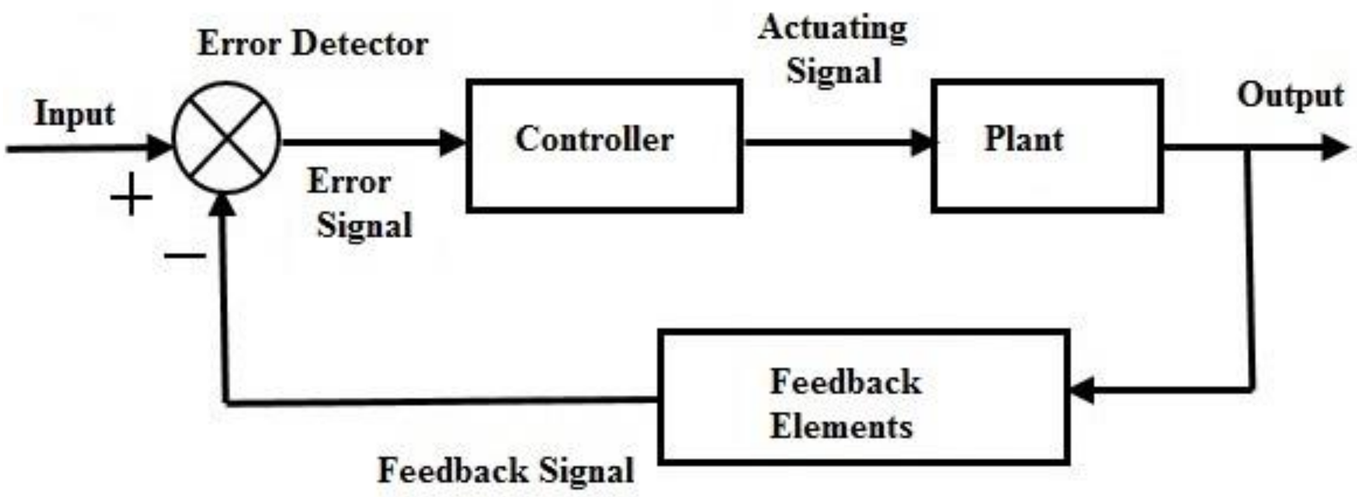
Example: Laundry Machine

- 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.

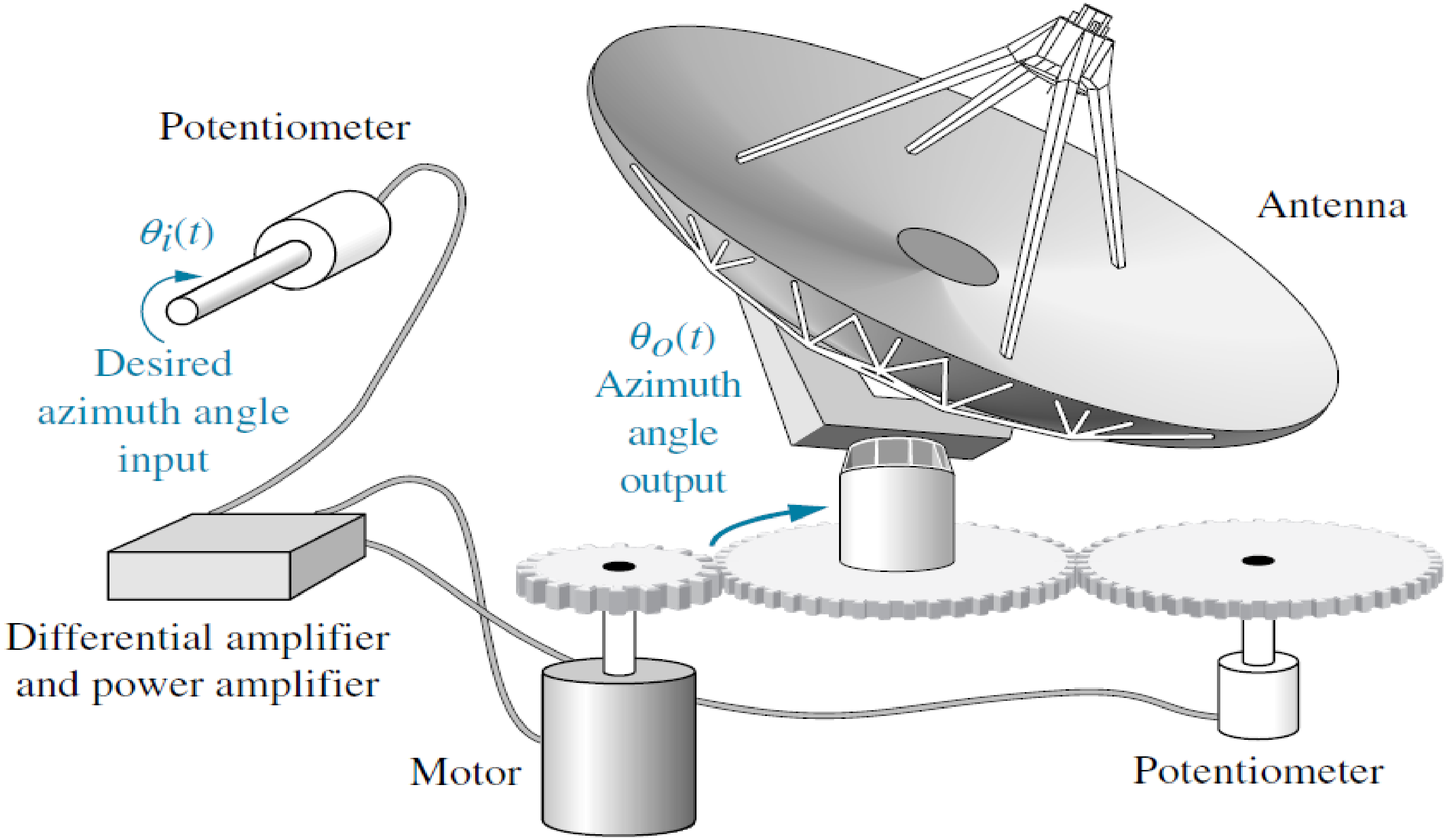


Example: Autopilot Mechanism

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

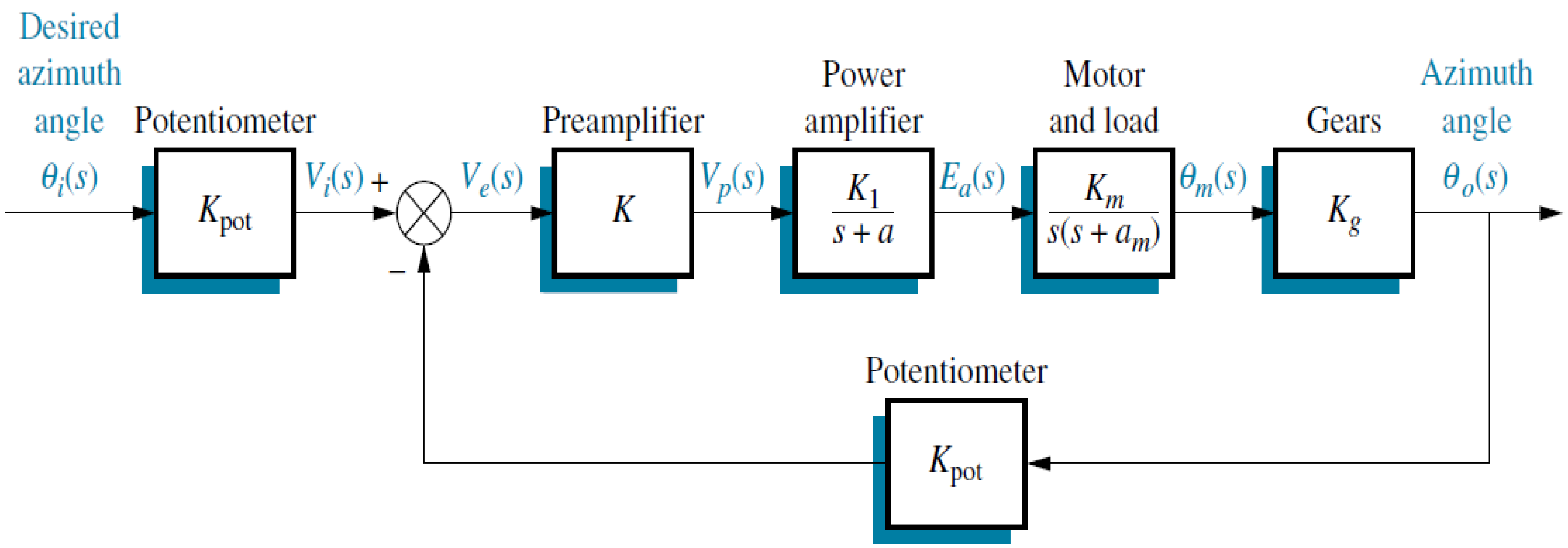
Example: Antenna Azimuth



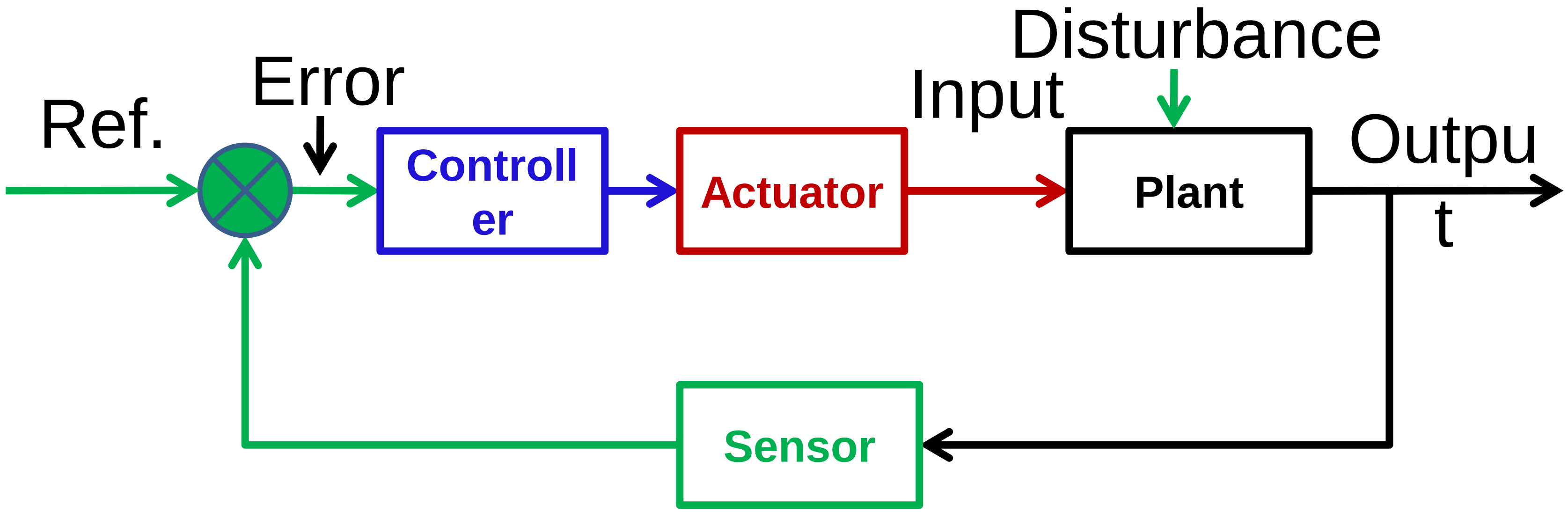
Closed-loop control

Example: Antenna Azimuth

Block Diagram



Basic Elements of Control Loop

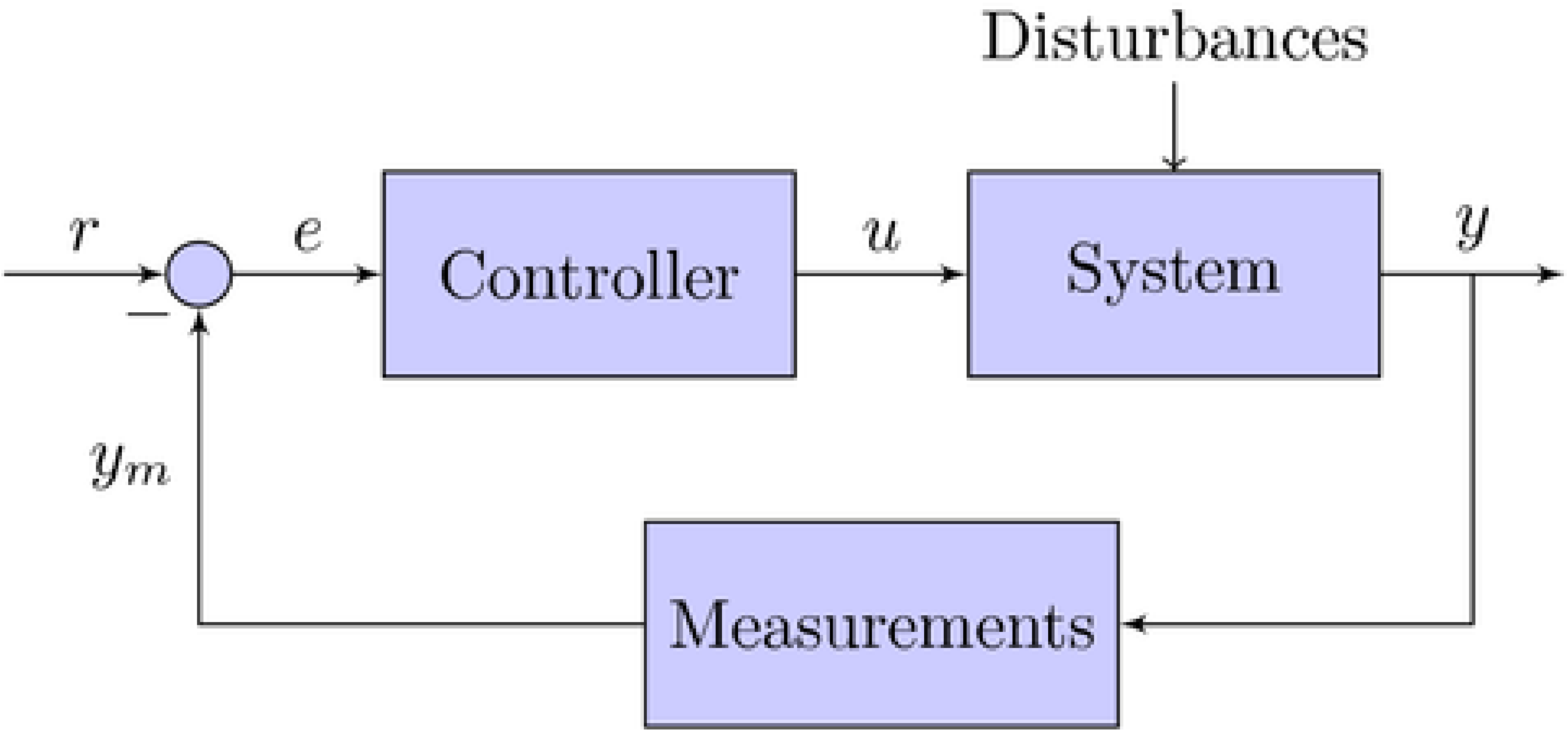


The role of the controller is to make the output following the reference in a “satisfactory” manner even under disturbances.

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



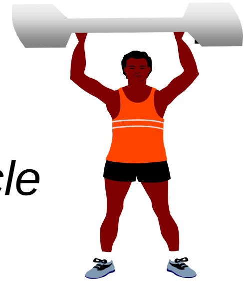
Example: Playing Sport

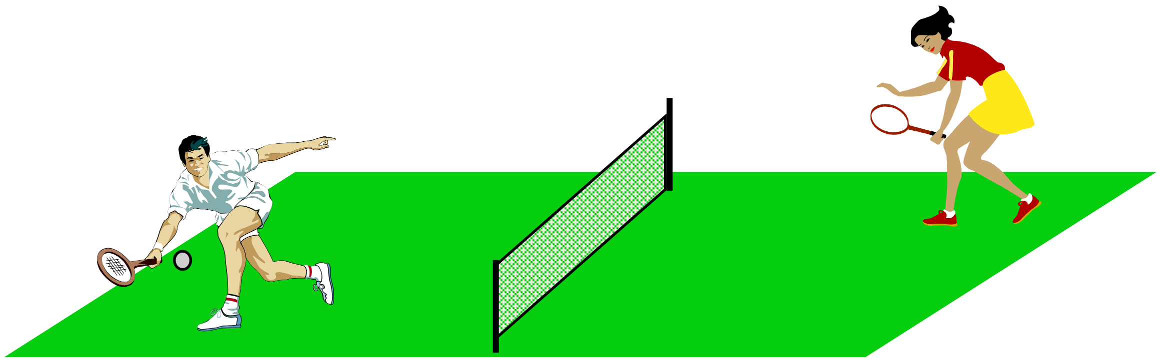
Better Sensors

Provide better *Vision*

Better Actuators

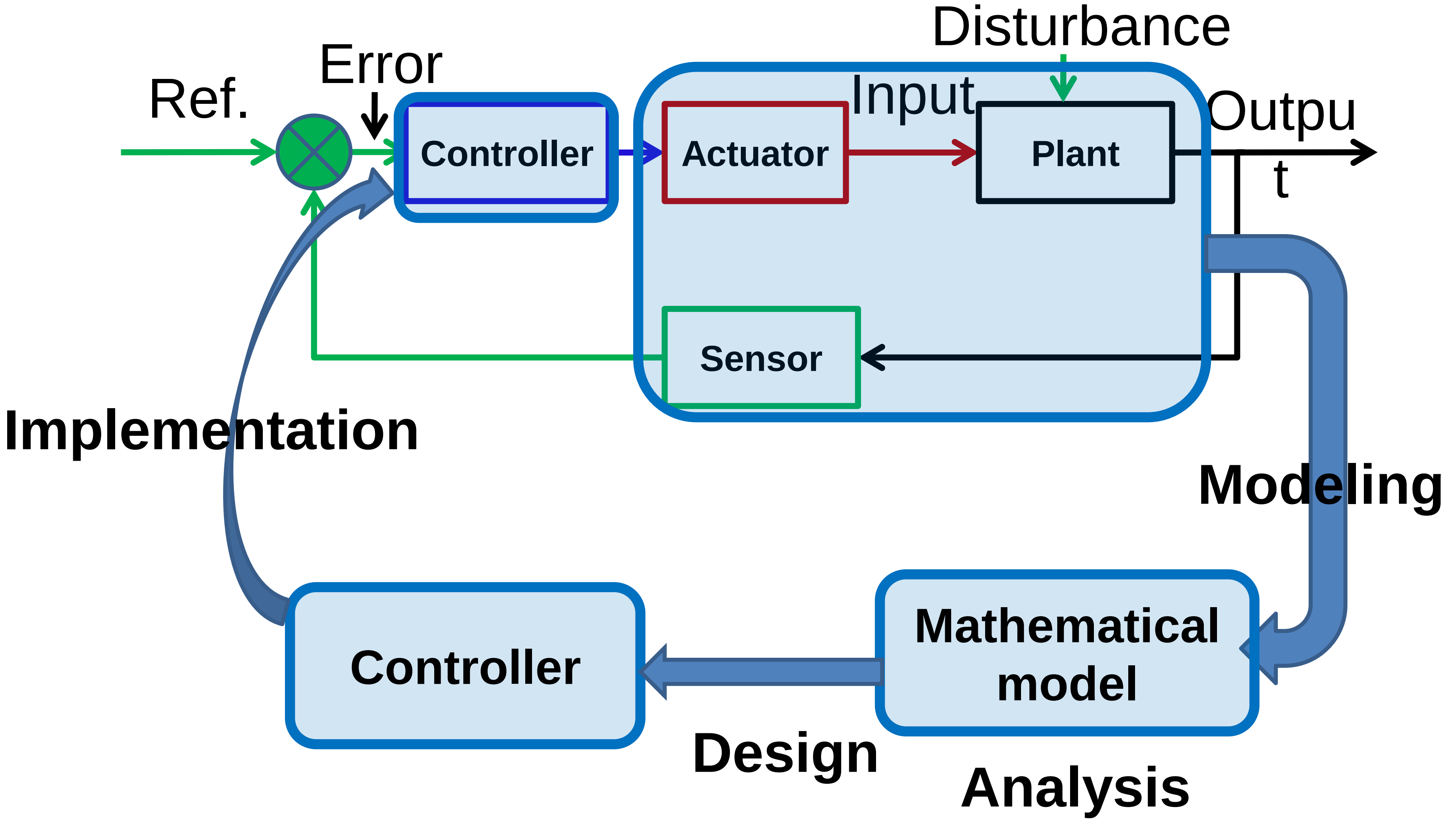
Provide more *Muscle*





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

Course Goals



Procedure of Design A Controller for System

Determine the requirements of a certain control system.

↓

Draw block diagram

↓

Transform physical systems into math. Eqs. (Math. Modeling).

↓

Block diagram simplification.

↓

Analyze, design, and test the control system to ascertain that the desired requirements are fulfilled.

Summary

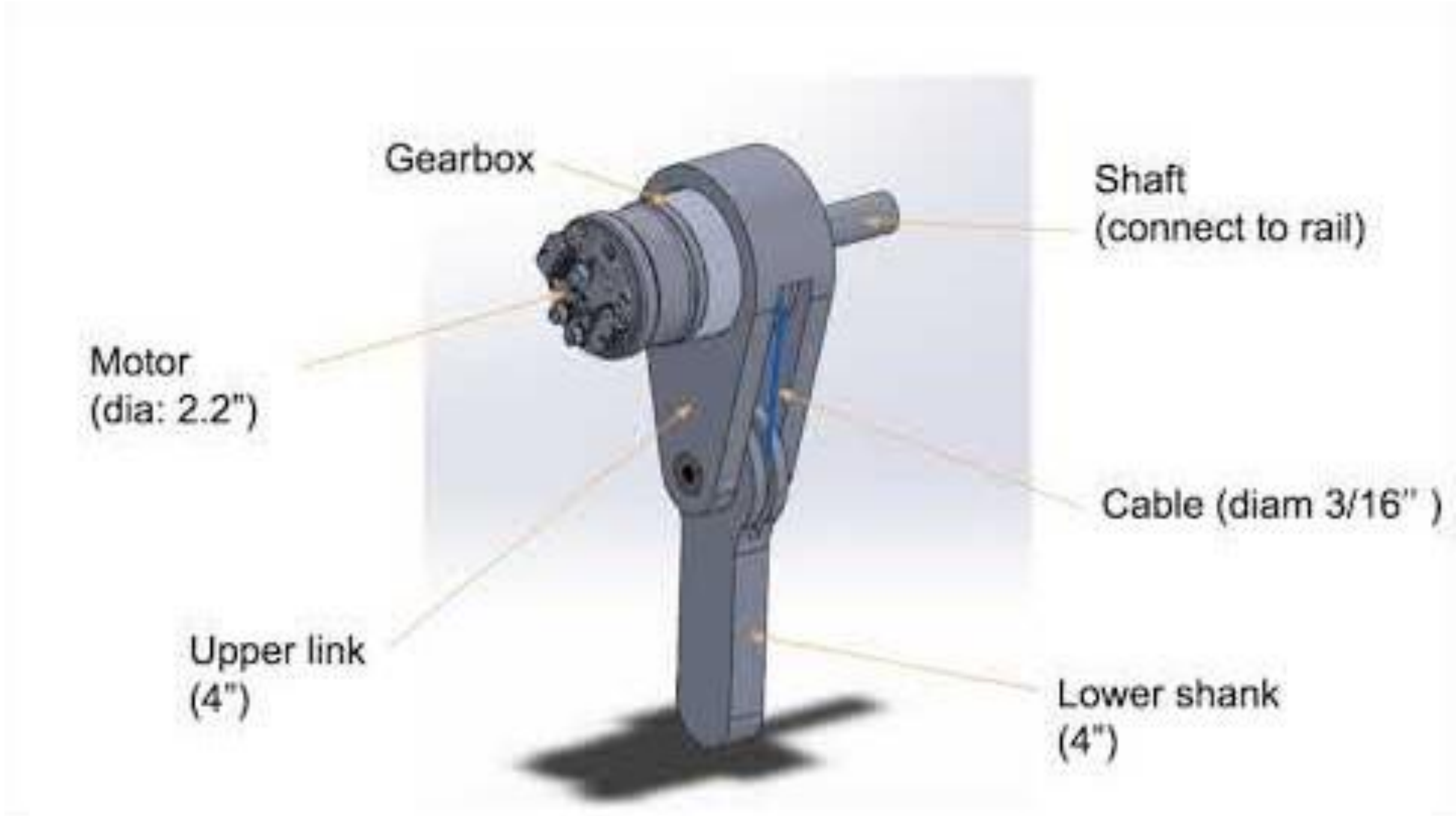
- Introduction
  - – Control essentiality
  - – Examples of control systems
  - – Open-loop vs. closed-loop control systems
- Next Week
  - – MATLAB and Simulink introduction

    (Please install MATLAB and Simulink prior to the next class)
  - – Take your laptop for next week (Aug. 29, 31)

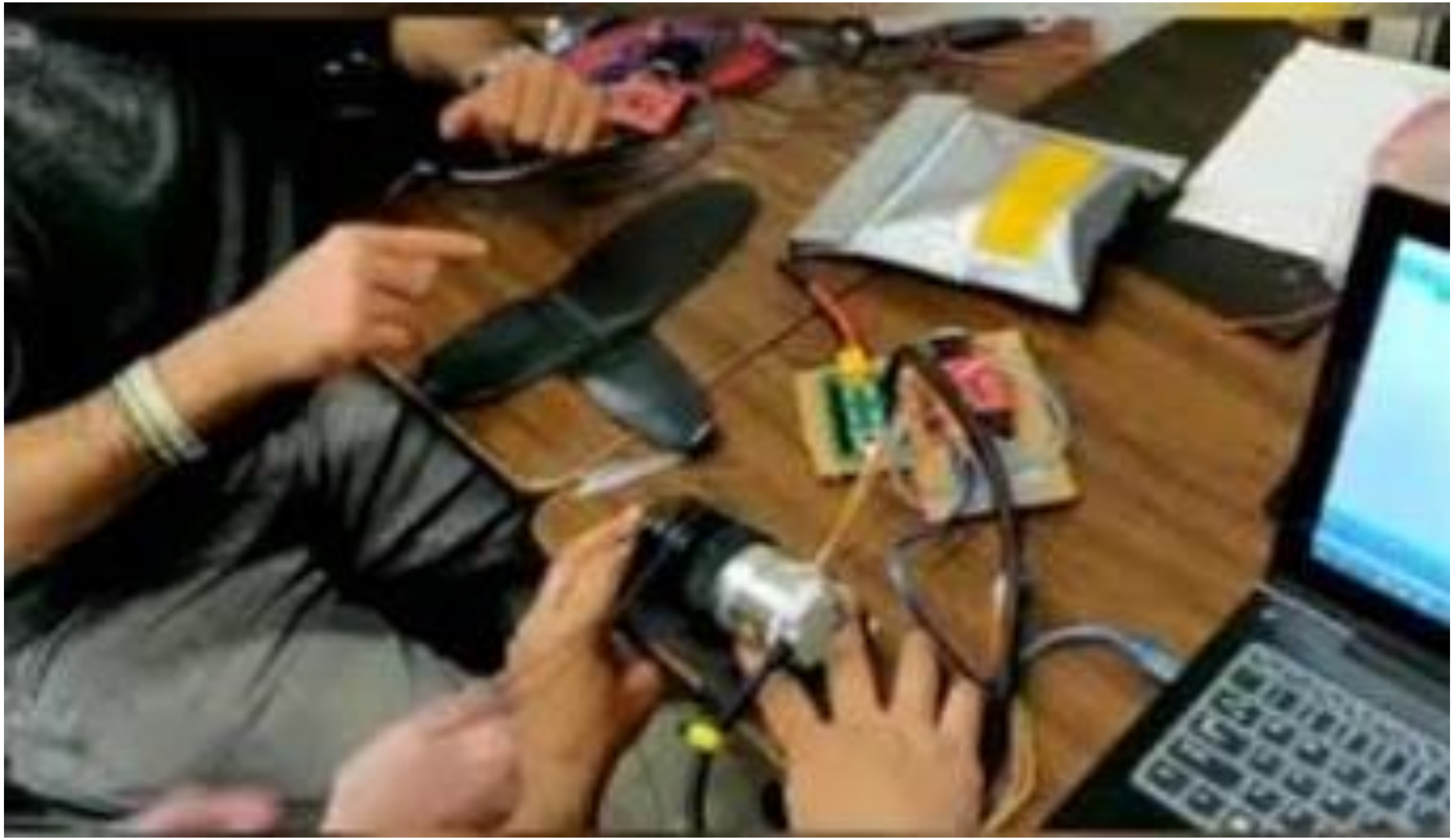
Videos – Cable-driven Knee Exo

Videos – Cable-driven Hip Exo

Videos – Legged Jumping Robot

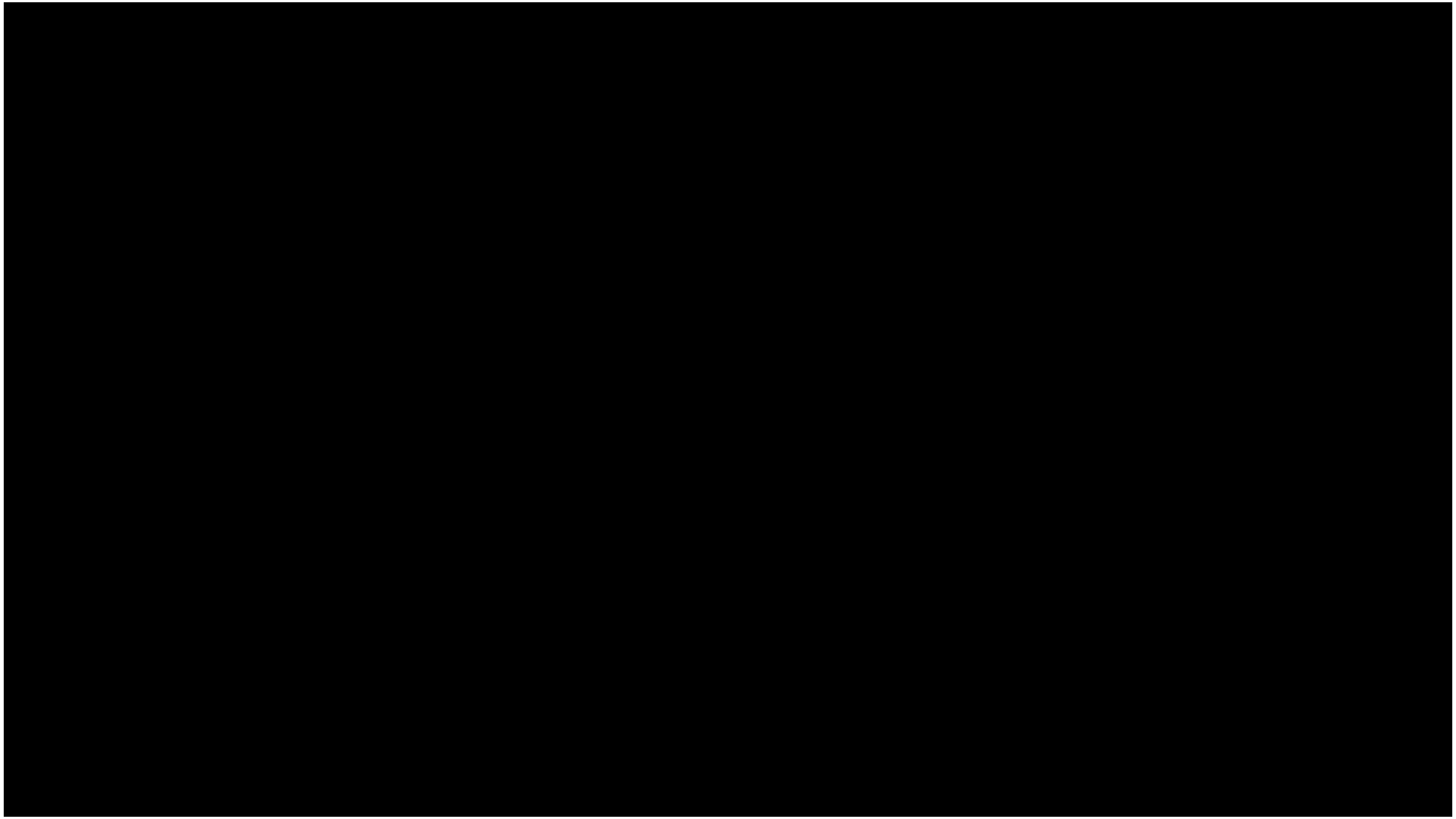


Videos – Cabled-driven Ankle Exo 2



Videos – Rigid Knee Exo for Pediatric

Elbow Exo Student Presentation



Elbow Exo Student Presentation