Prof. Kirstin Hagelskjær Petersen
kirstin@cornell.edu

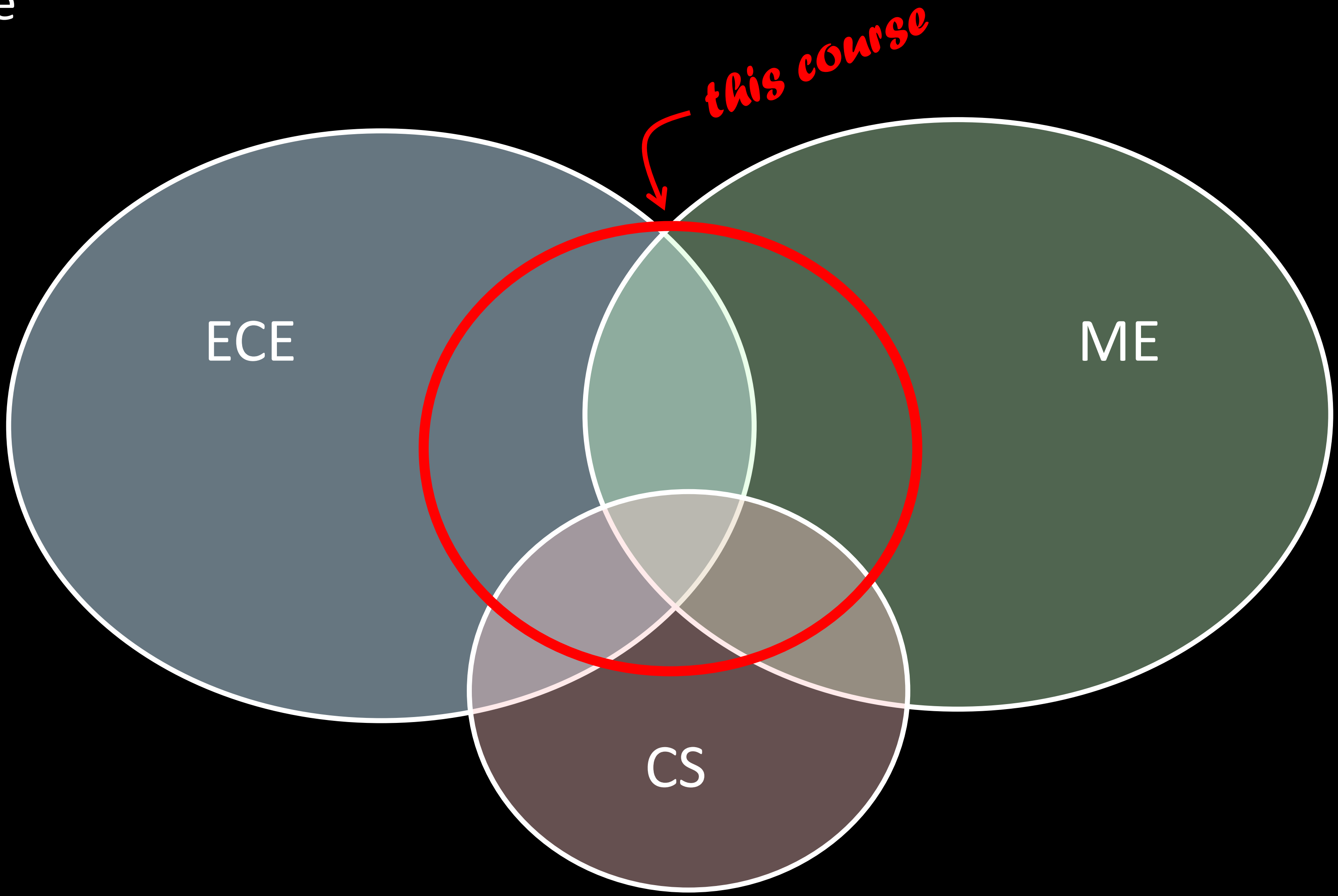
ECE 4160/5160
MAE 4910/5910

Fast Robots
Introduction

Why *this* class?

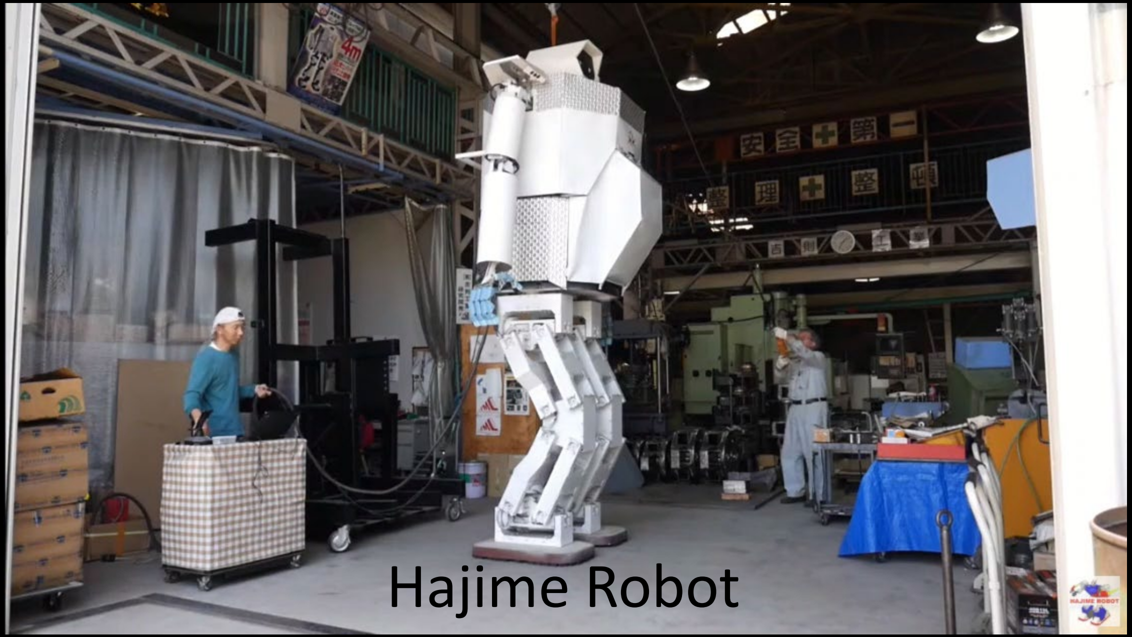
- Somewhere between a Culminating Design Experience (learn through implementation)
- ...and a foundations course

- Overlap with Autonomous Mobile Robots, Foundations of Robotics, and Feedback Control Systems



Why *this* class?

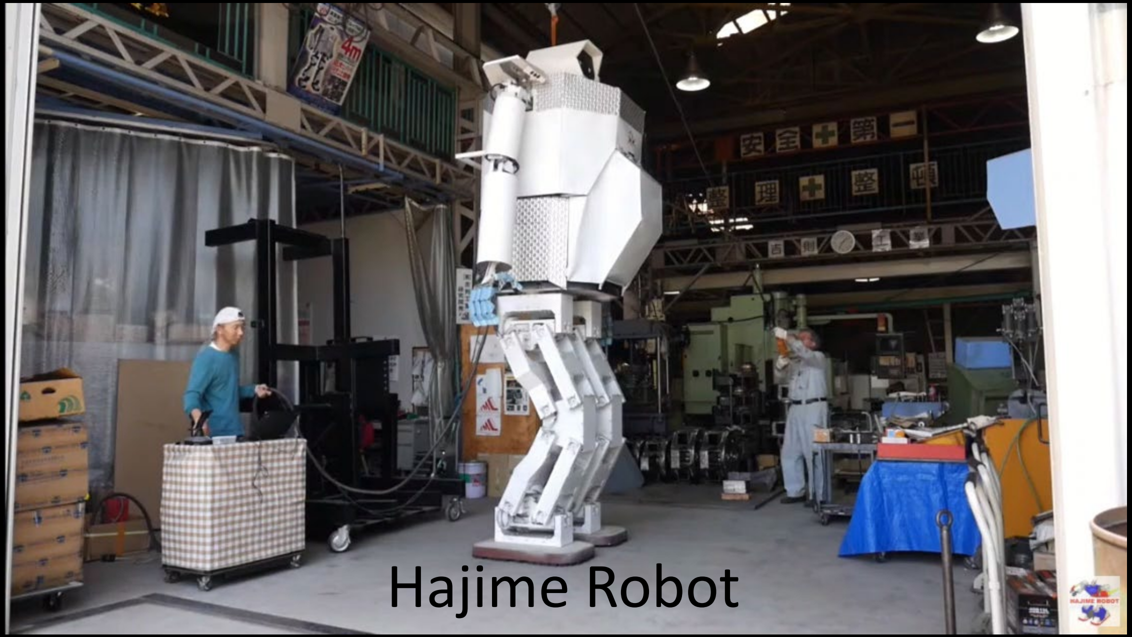
- "Fast"
  - Kinematics – Dynamics



Hajime Robot

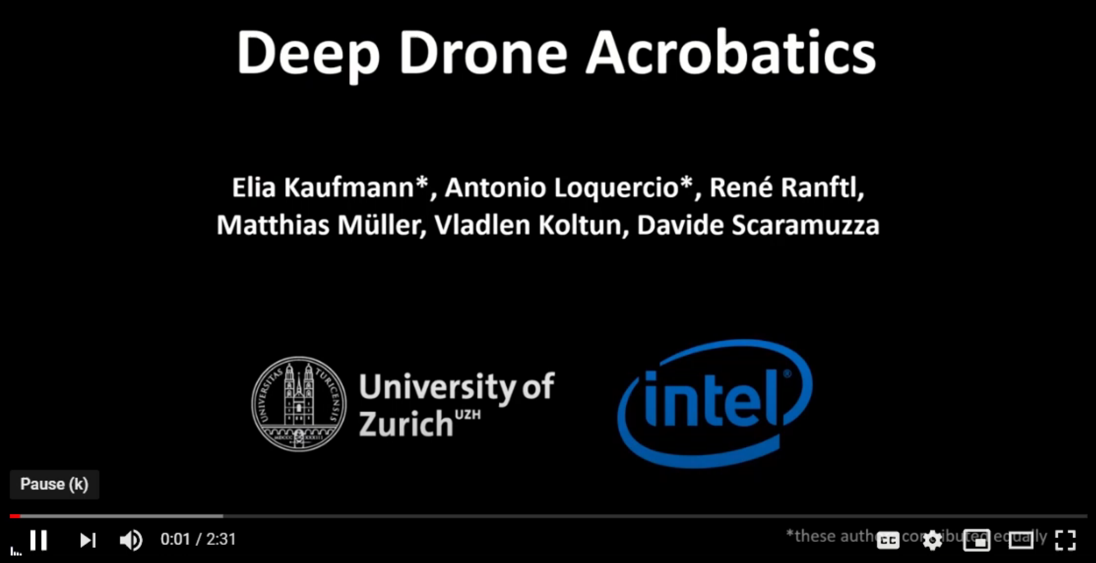
Why *this* class?

- "Fast"
  - Kinematics – Dynamics



Why *this* class?

- "Fast"
  - Kinematics – Dynamics
  - Stable – Unstable
  - Computation

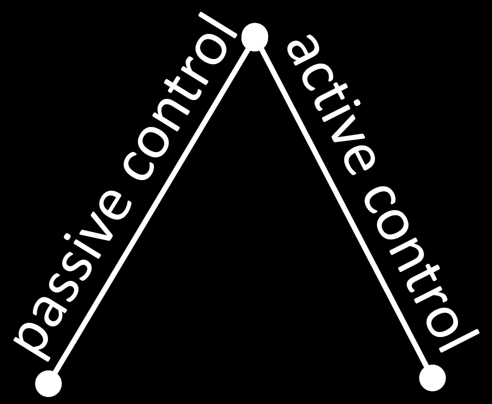


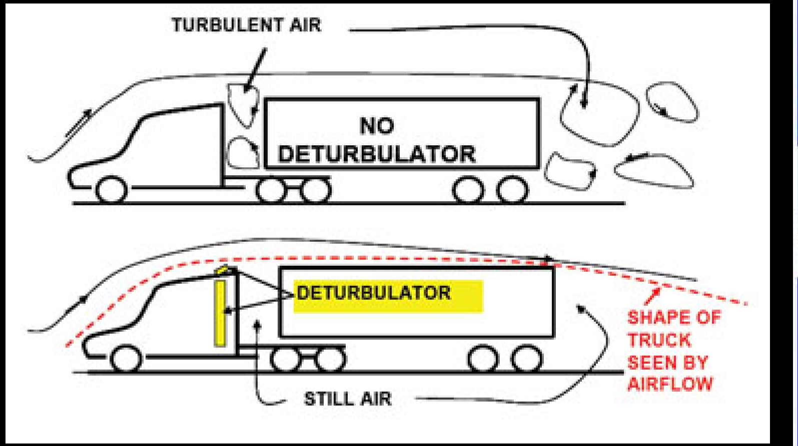

Cubli, ETH Zurich

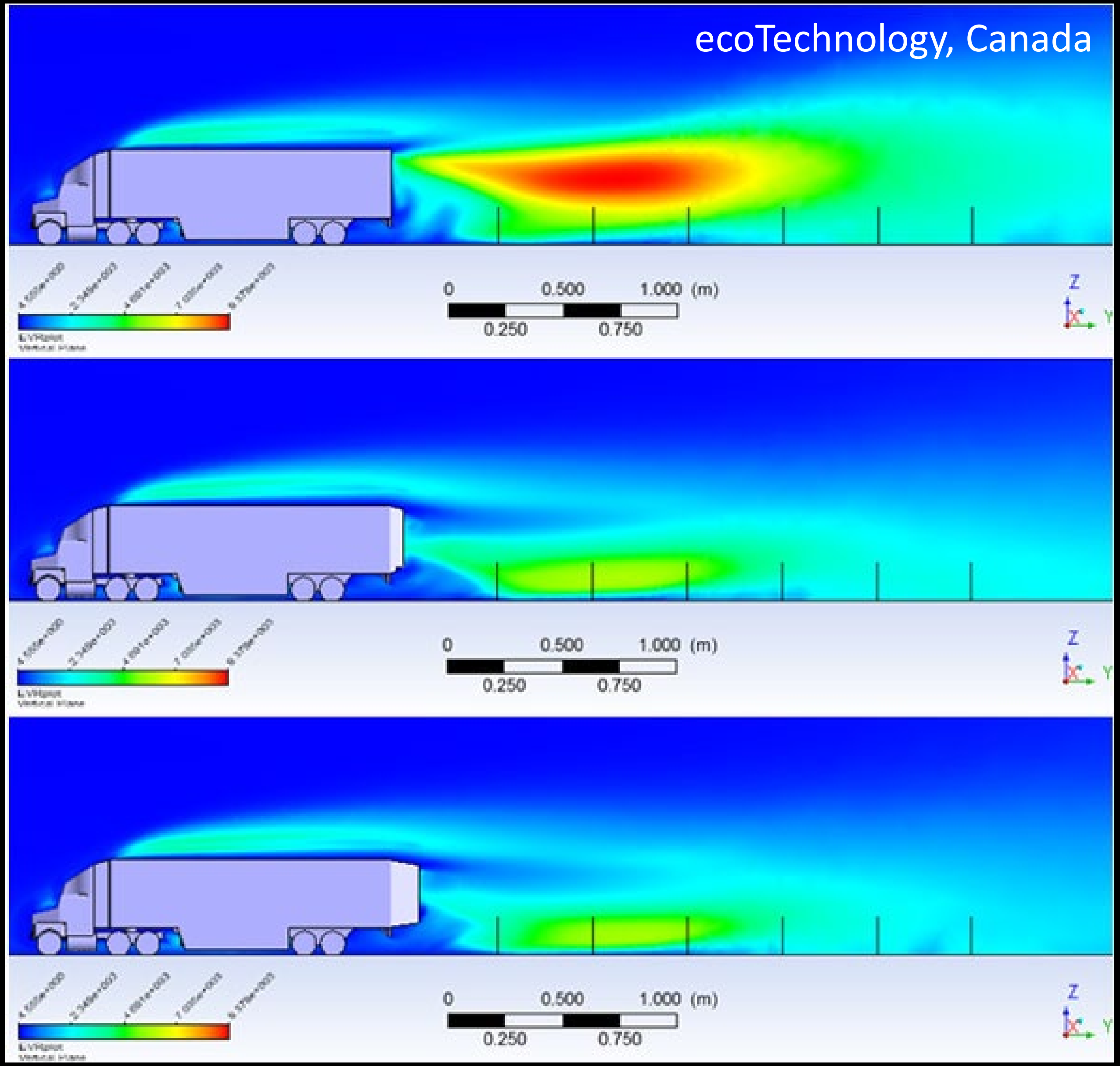
Why *this* class?

- “Fast”
  - Kinematics – Dynamics
  - Stable – Unstable
  - Computation
- Design for fast robots goes beyond just good control theory and dynamic models
  - Practical implementation, mechanics, sensors, processing, estimation, etc.

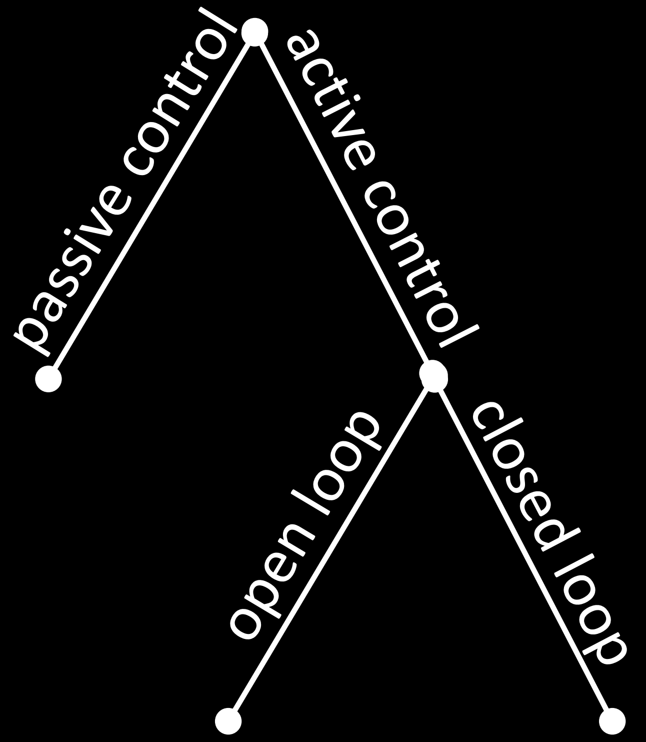
Control and its implications in fast robots

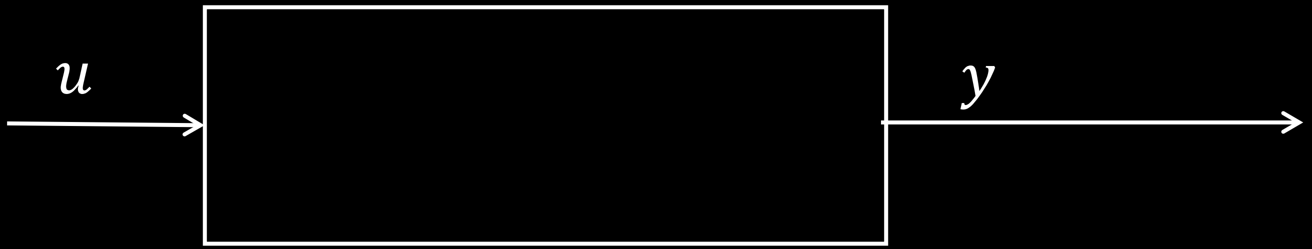






Control and its implications in fast robots

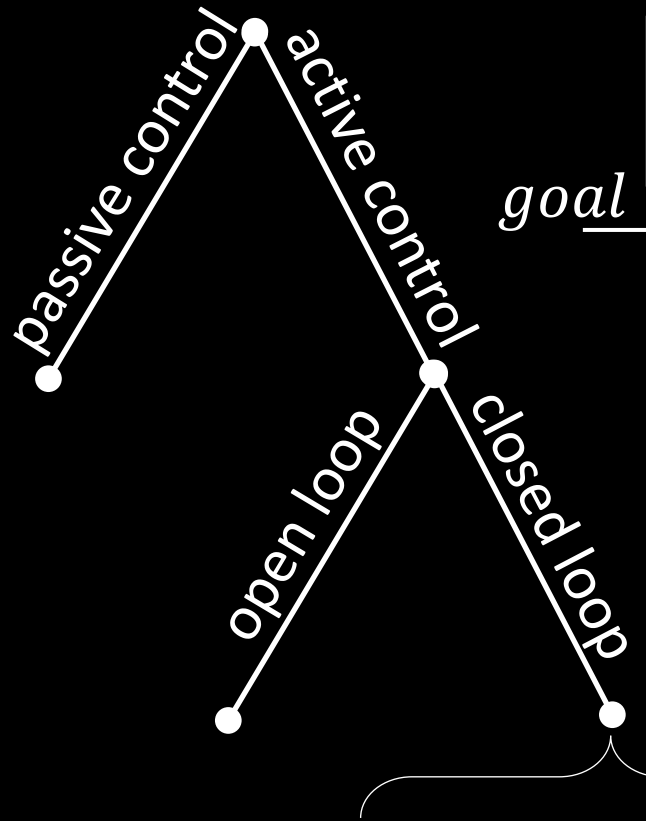




Why feedback?

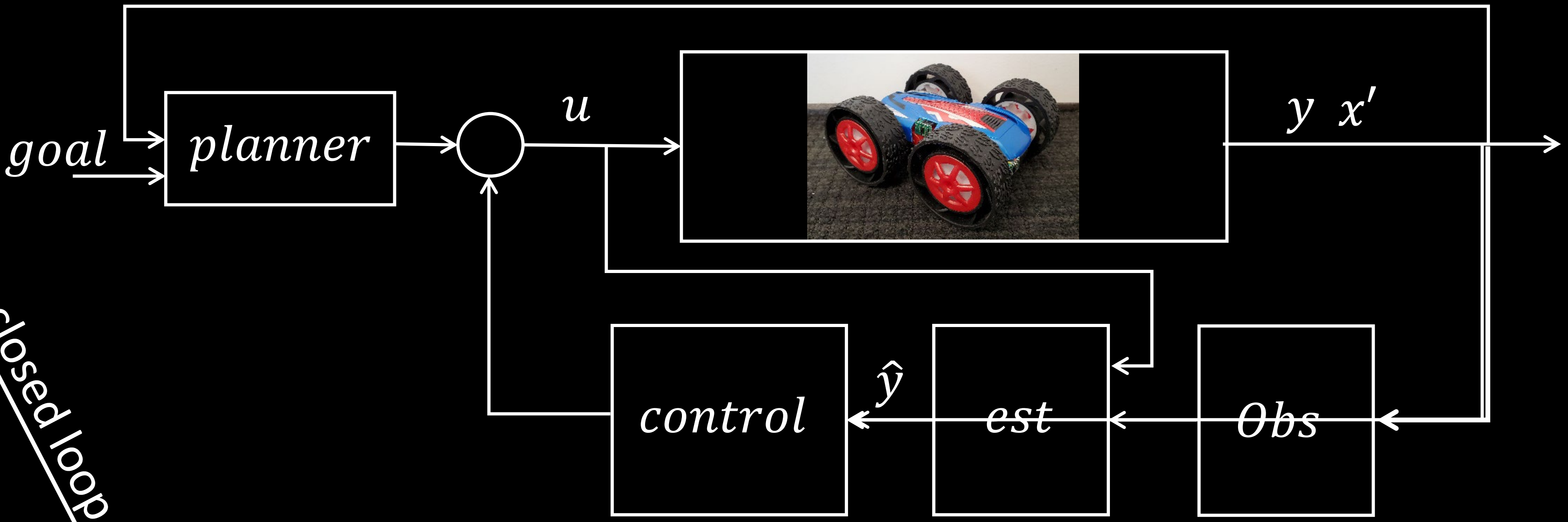
- System uncertainty
- Instability
- Disturbances
- Efficiency

Control and its implications in fast robots



- processor
- drivers
- limits

- sensors
- noise/bias



Why feedback?

- System uncertainty
- Instability
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- Efficiency

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Fast Robots
Class Layout

Schedule

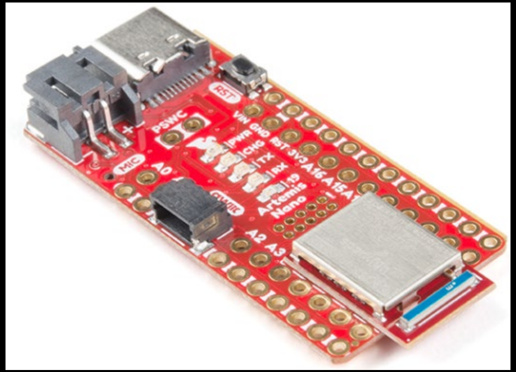
Lab 1-5 Hardware / Embedded SW	Lab 6-9 Feedback Control	Lab 10-12 Localization and Planning

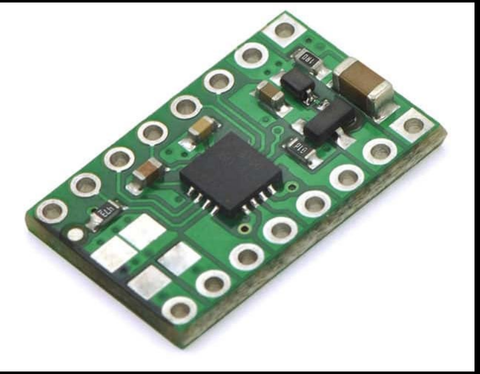
Schedule

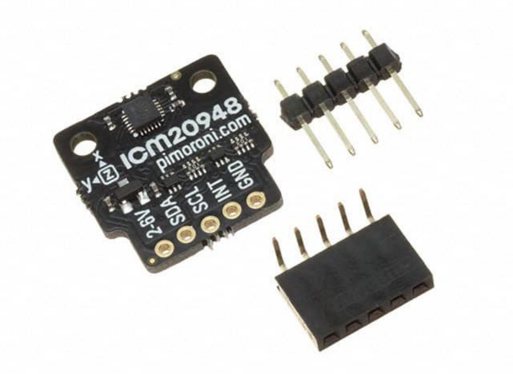
Lab 1-5 Hardware / Embedded SW	Lab 6-9 Feedback Control	Lab 10-12 Localization and Planning

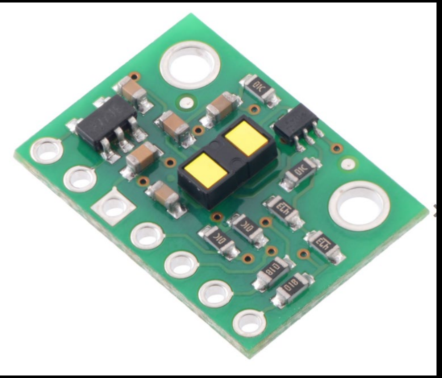
- Combine base with processor, drivers, and sensors
- Refresh on linear algebra and T-matrices
- Sensor modalities and types of sensors
- Actuators, drivers, circuits and routing, and EMI

- $142 lab kit
- Sponsored entirely by *ASML!*





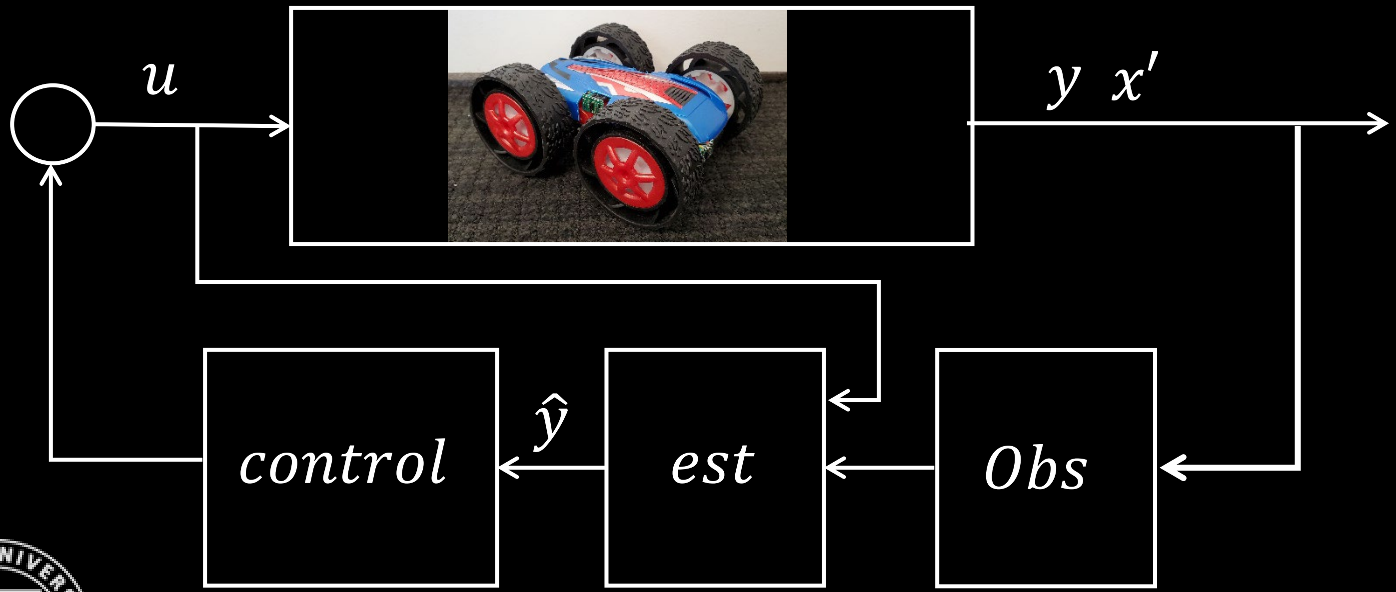




Schedule

Lab 1-5 Hardware / Embedded SW	Lab 6-9 Feedback Control	Lab 10-12 Localization and Planning

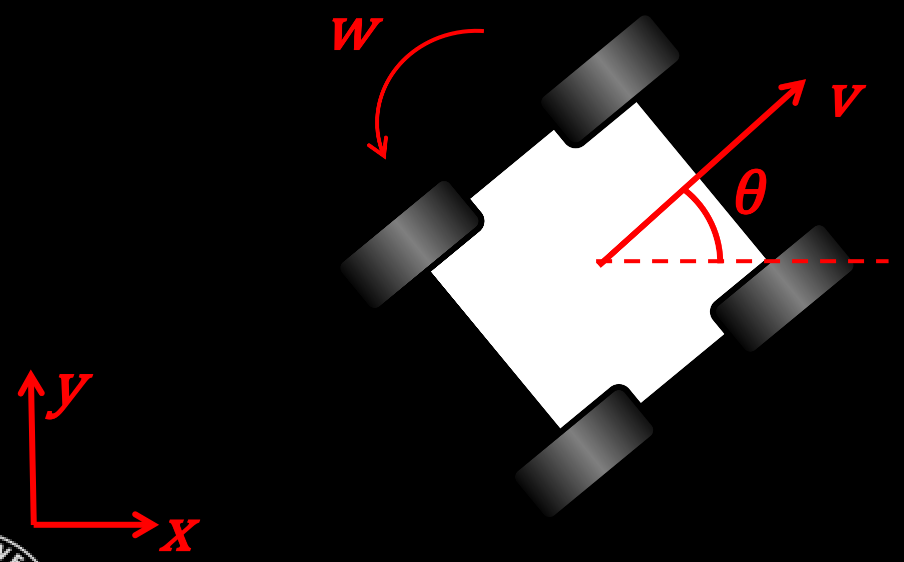
- Linear systems, model-free and model-based control



Schedule

Lab 1-5 Hardware / Embedded SW	Lab 6-9 Feedback Control	Lab 10-12 Localization and Planning

- Linear systems, model-free and model-based control
  - PID controllers, Control theory, LQG control, KF



$$\dot{x} = cos(\theta)v$$
$$\dot{y} = sin(\theta)v$$
$$\dot{\theta} = w$$

$$\Rightarrow \boxed{\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}cos(\theta)v & 0\\ sin(\theta)v & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}v\\ w\end{bmatrix}}$$

Schedule

Lab 1-5 Hardware / Embedded SW | **Lab 6-9 Feedback Control** | **Lab 10-12 Localization and Planning**

- Linear systems, model-free and model-based control
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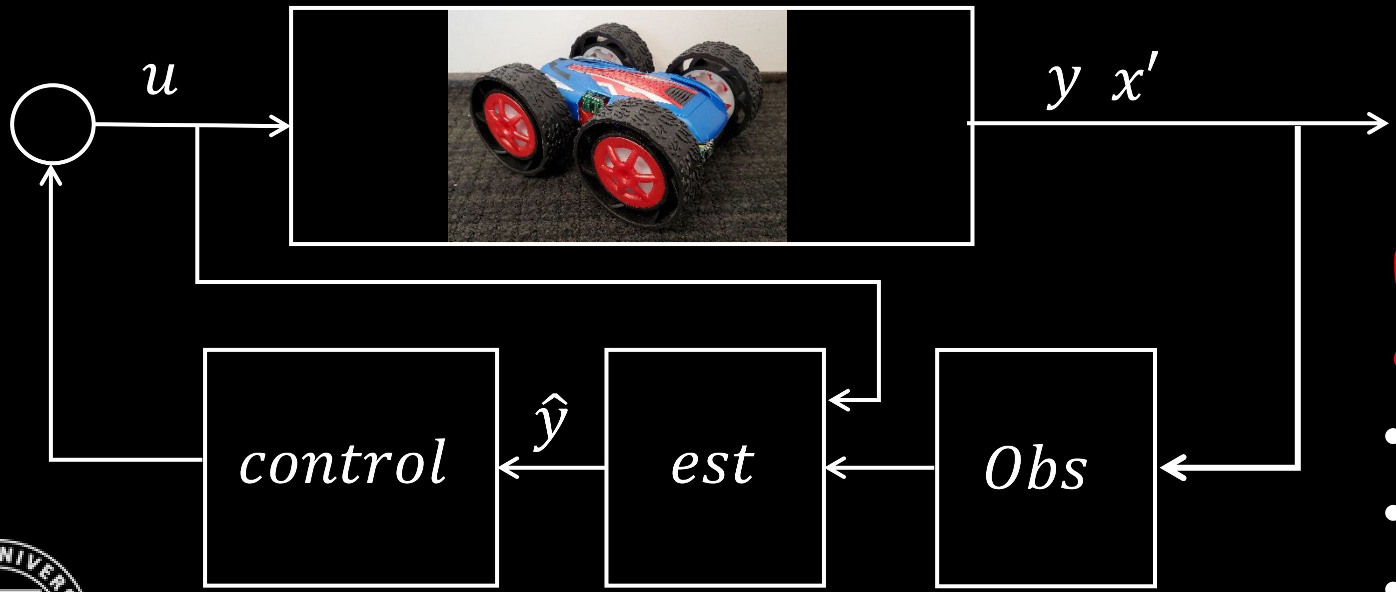


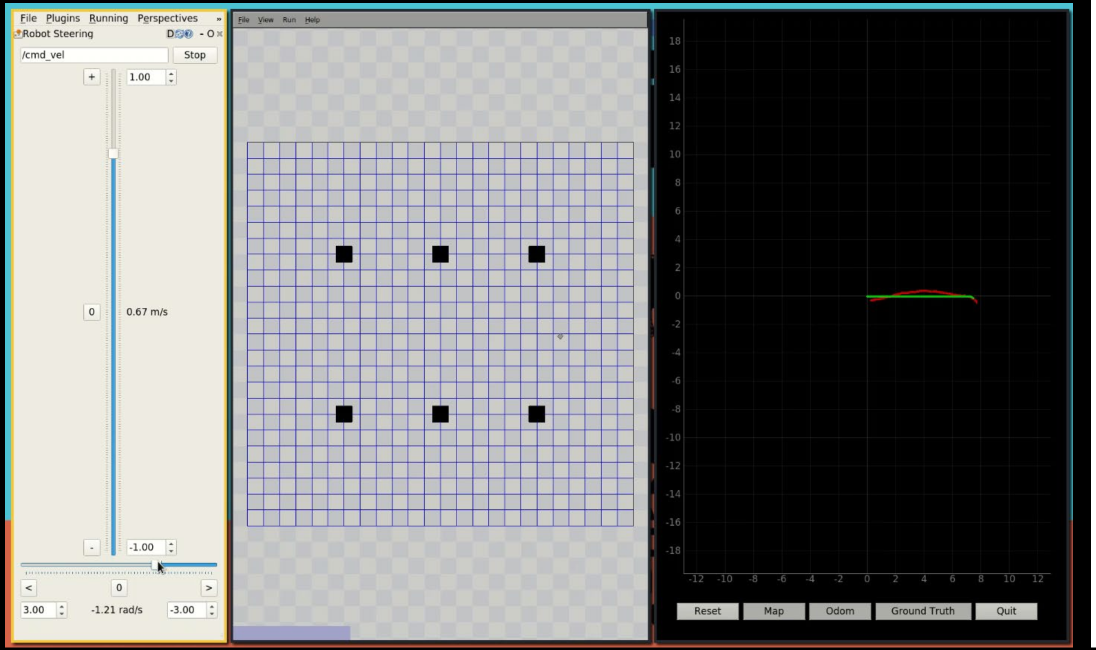
Why do you think feedback control and observers are necessary?

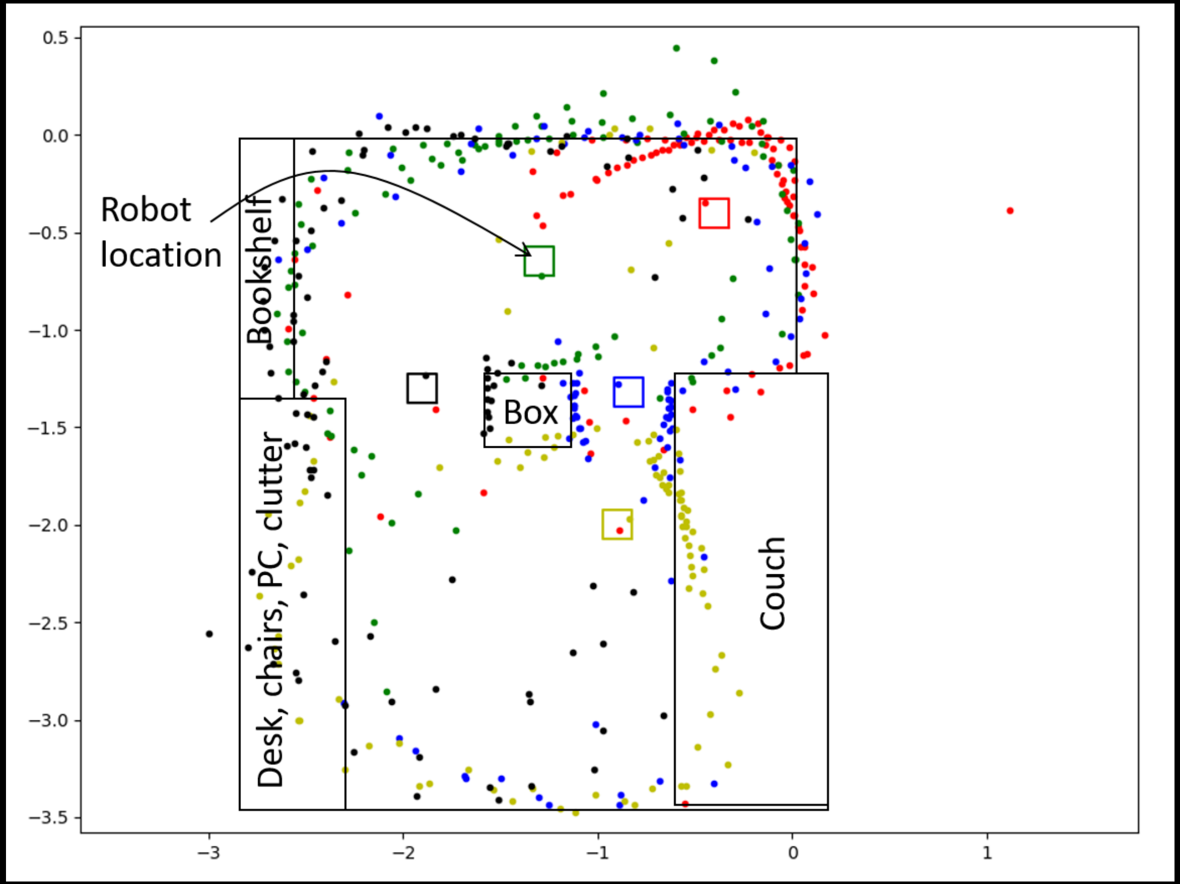
- Performance is battery dependent
- Our sensors are relatively slow
- Etc.

Schedule

Lab 1-5 Hardware / Embedded SW	Lab 6-9 Feedback Control	Lab 10-12 Localization and Planning

- Map representations
- Search and planning





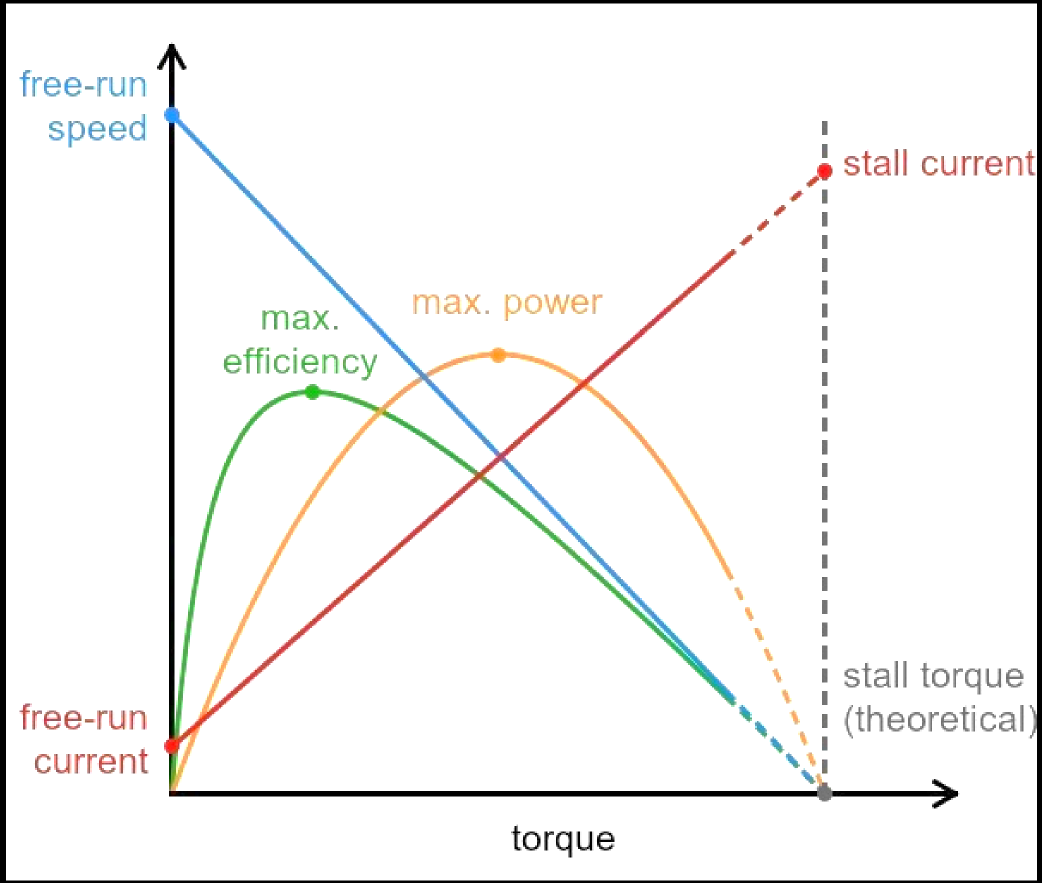
Schedule

Lab 1-5 Hardware / Embedded SW	Lab 6-9 Feedback Control	Lab 10-12 Localization and Planning

- Map representations
- Search and planning
- Noise, discrete probability
- Motion and sensor models

What are sources of error?

- Sensor noise, resolution
- Momentum and slippage
- Weak motors



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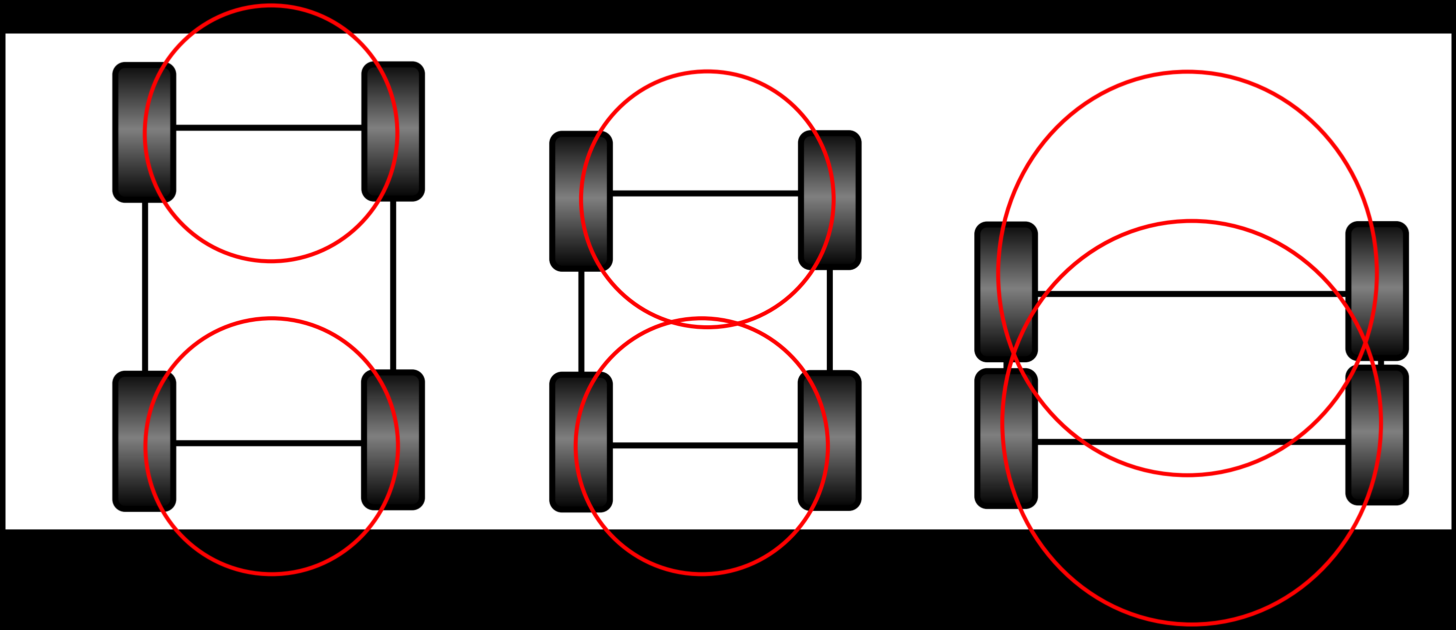

What are sources of error?

- Sensor noise, resolution
- Momentum and slippage
- Weak motors
- Skid steering

Schedule

Lab 1-5 Hardware / Embedded SW	Lab 6-9 Feedback Control	Lab 10-12 Localization and Planning

- Map representations
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What are sources of error?

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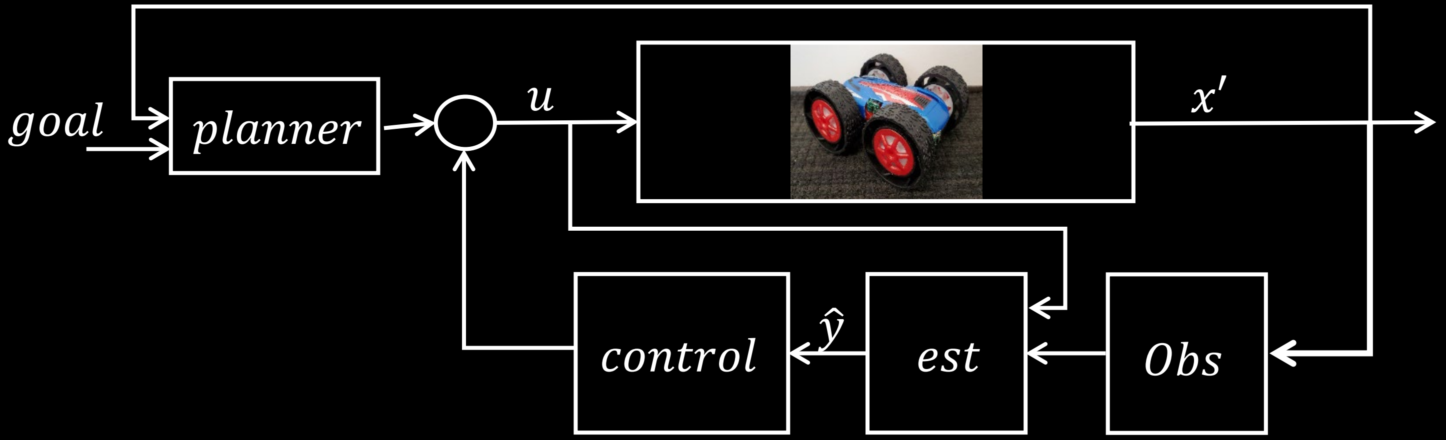
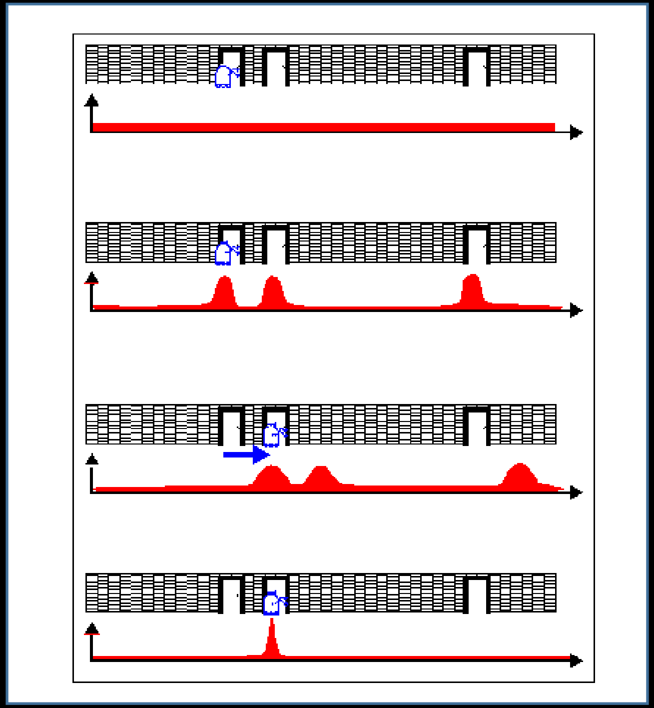
- Skid steering

Schedule

Lab 1-5 Hardware / Embedded SW	Lab 6-9 Feedback Control	Lab 10-12 Localization and Planning

- Map representations
- Search and planning
- Noise, discrete probability
- Motion and sensor models
- Bayes theorem/filters
- Localization, planning





Disclaimer!

- We work with real hardware
  - Everyone must build and operate a robot
  - And we *break* things!

- Take this course if you want a highly interactive teaching team, fun and advanced challenges, experience with real robots, and an opportunity to build up an online portfolio

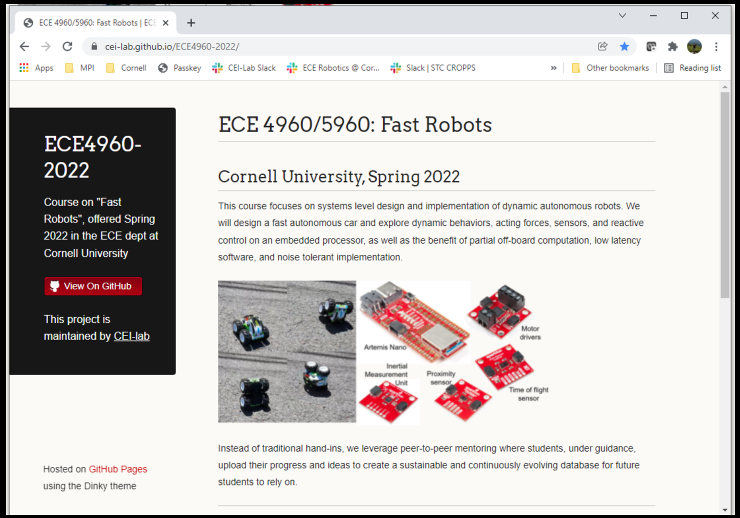
- Do *not* take this class, if you prefer a deep dive into fundamentals, mostly simulation, or if you have a busy schedule already

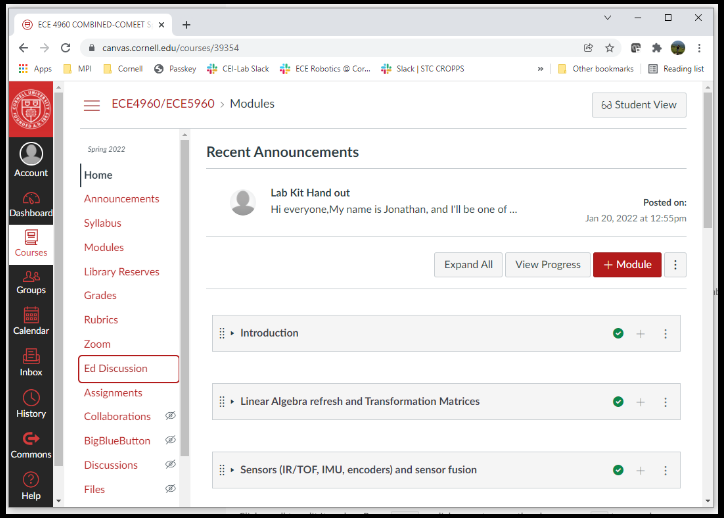
ECE 4160/5160
MAE 4910/5910

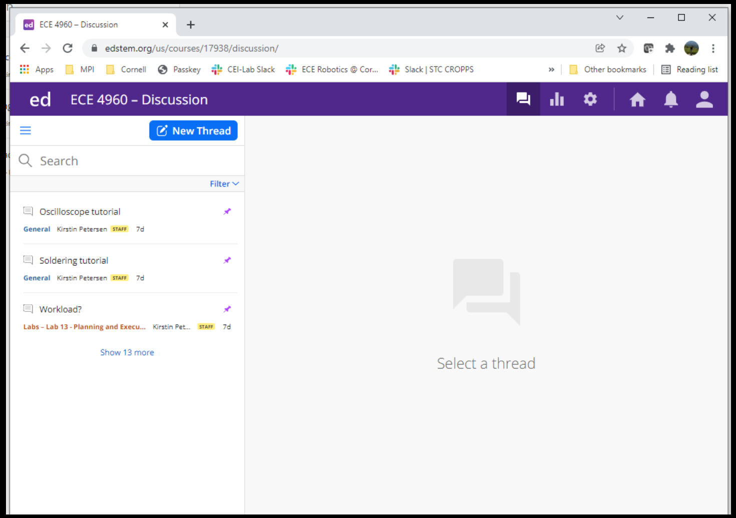
Fast Robots
Logistics

Logistics I

- *Github* (https://cei-lab.github.io/FastRobots-2023/)
  - Schedule, lab schedule, lecture slides, lab documents, tutorials, code examples, etc.
- *Canvas*
  - Lecture slides, deadlines, zoom-links, grades
- *EdDiscussion*

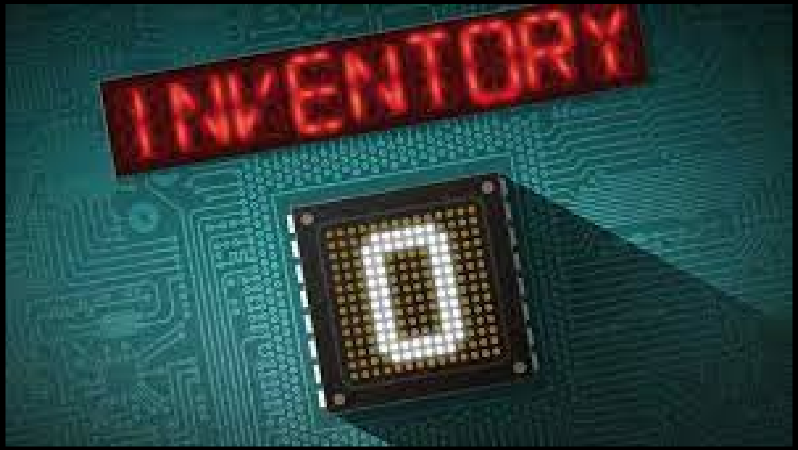






Logistics II

- Lab kit
  - ….Things will break, we have a small set of extra components, but please be careful
  - ….Supply crisis!
  - We will hand out the 1st half in lab 1
  - We will hand out the 2nd half in lab 5
  - If you drop the class, we want these items back!



Logistics III

- Lab software
  - *Guaranteed support on the 12 lab computers in PH427…*
  - But try to get things working at home if you have…
    - Windows 10, MacOS 12 and Linux (bluez>5.48, kernel=4.15)
    - Requirements:
      - Processor: Core i3-8100 3.6 Ghz/AMD Ryzen 5 1400 or equivalent
      - Memory: 4 GB RAM, Free Space: 8 GB (Windows)/1GB (else)

* We know there are issues with Windows 11 and the new Apple M1 Arm processors

Logistics IV

- Homework
  - Lab reports → Your own Github sites (check out examples from 2022 here)

- Labs
  - Tuesday – Wednesday – Thursdays in PH427, 2.40-5.10pm (max 20 students/TAs)
  - Regular open lab hours 2-6pm Saturdays
  - Kirstin's regular "office hours" 2:30-3.15pm Tu-We-Th in the lab
- Time commitment
  - Labs take an average of 8 hrs
    - Spread load over multiple days (batteries only last 10-15mins)
  - If you run low on time…
    - You have 15 slip days that can be partitioned over any 3 labs
      - You must submit these using the Canvas quiz *before* the lab deadline
      - (all except lab 12)

Logistics V - Grading

- Grading
  - 12 Labs (90 pts)
    - Points for solution (67)
    - Points for write-up (33)
  - Participation (10 pts)
  - Course evaluations (2 bonus pts)

- Final Showcase (May 9th 9-12)!!

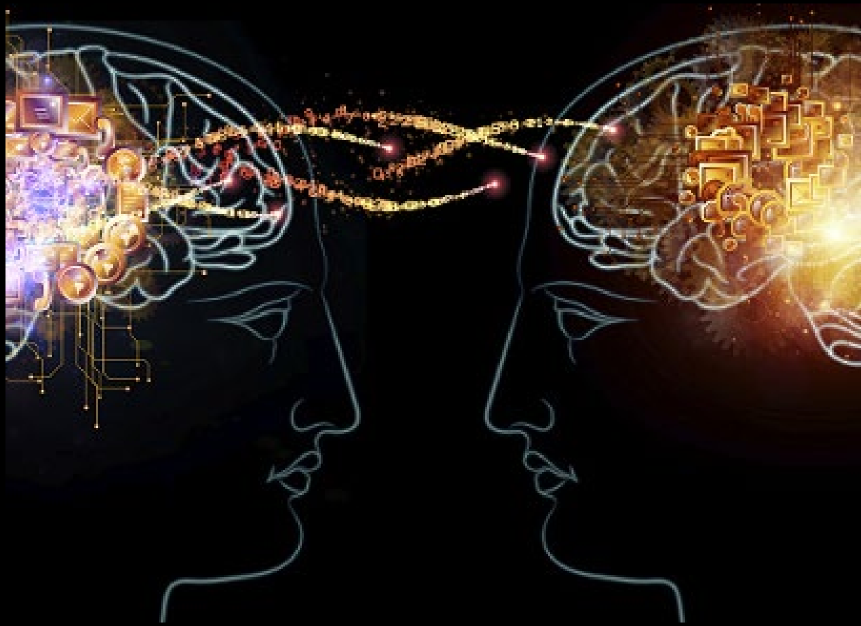
Task	pts
Lab 1 Artemis	5
Lab 2 Bluetooth	5
Lab 3 ToF Sensors	7.5
Lab 4 IMU Sensors	7.5
Lab 5 Motor driver, open loop control	7.5
Lab 6 PID	7.5
Lab 7 KF	7.5
Lab 8 Stunts	10
Lab 9 Mapping	7.5
Lab 10 Localization (sim)	U/S
Lab 11 Localization (real)	10
Lab 12 Planning and Execution	15
Participation	10
Bonus points for midway and final course evaluations!	2
Total:	**102**

Logistics VI - Collaborations

- Feel free to check lab write-ups from previous years

- Form teams of 2-3 people for Labs 3-12
  - Pick your own teammates / advertise for teammates on Ed Discussion

  - How to use your teammate(s)
    - Work/strategize together
    - Do the pre-lab together
    - Do electronics/mechanics/software *on your own*!
    - Debug jointly if things don't work
    - Compare results, but *write your own report*
    - If your robot fails, borrow your teammate's
    - *Always* credit collaborators and references



Fast Robots
Teaching Team

Your Teaching Team: Jonathan Jaramillo (he/him)

- Wednesday lab
- Graduate student in the CEI-lab
- Research focus is on low-cost systems to enable precision viticulture in small-scale vineyards
- Other projects: honeybee trackers and HRI

CornellEngineering

Collective Embodied Intelligence Lab
www.cei.ece.cornell.edu

Mobile and Inflatable Interface for Human Robot Interaction

Jonathan Jaramillo, Andrew Lin, Emma Sung, Isabel Jane Hunt Richter, and Kirstin Petersen

Ubiquitous Robots 2021

Your Teaching Team: Alex Coy (he/him)

- Tuesday lab
- Graduate student in the Molnar lab
- Research focus in on mmWave radio design
- Enjoys cooking, music, and A/V production

- Alex helped TA the first version of this class in 2020, and is this years Bluetooth guru!

Your Teaching Team: Cameron Urban (he/him)

- Thursday lab
- Graduate student in the Helbling lab
- Research focus on bio-inspired aerial robots
- Hobbies include open-source SW, scuba diving, and chess

Your Teaching Team: Anya Prabowo (she/her)

- Wednesday lab
- ECE M.Eng. Student
- Top student in 2022 – check out her website! ☺

Your Teaching Team: L.M. “Lemon” Nawrocki (they/them)

- Thursday lab
- Senior in MAE
- Research in the Napp lab on robotic grippers for rock assemblies
- Hobbies include skiing, snowboarding, sewing, and indoor rock climbing

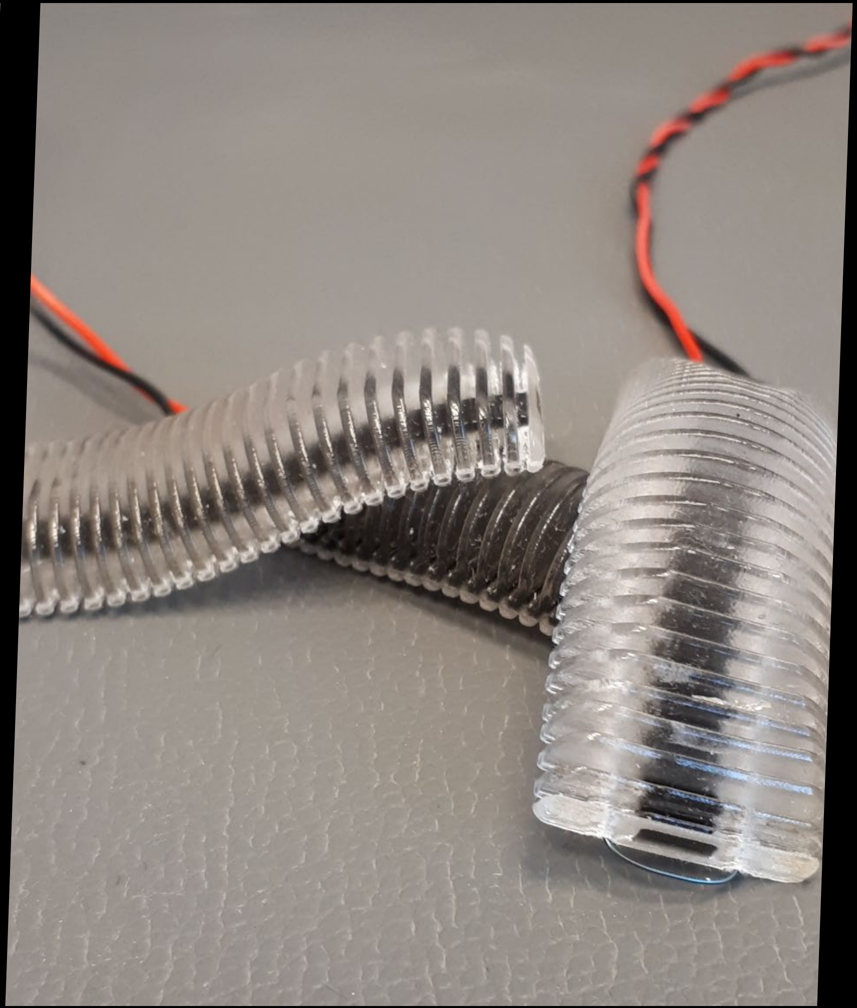
Your Teaching Team: Joseph Horwitz (he/him)

- Tuesday lab
- Senior in ECE with a minor in CS
- Hobbies include ice hockey and frisbee

Your Teaching Team: Ryan Chan (he/him)

- Saturday Open labs
- Senior in ECE with a minor in CS
- Leads the electrical team at Cornell EWH
- Research in the Peck lab on Cubesats
- Research in the Shepherd lab on soft robots
- --likes turtles!

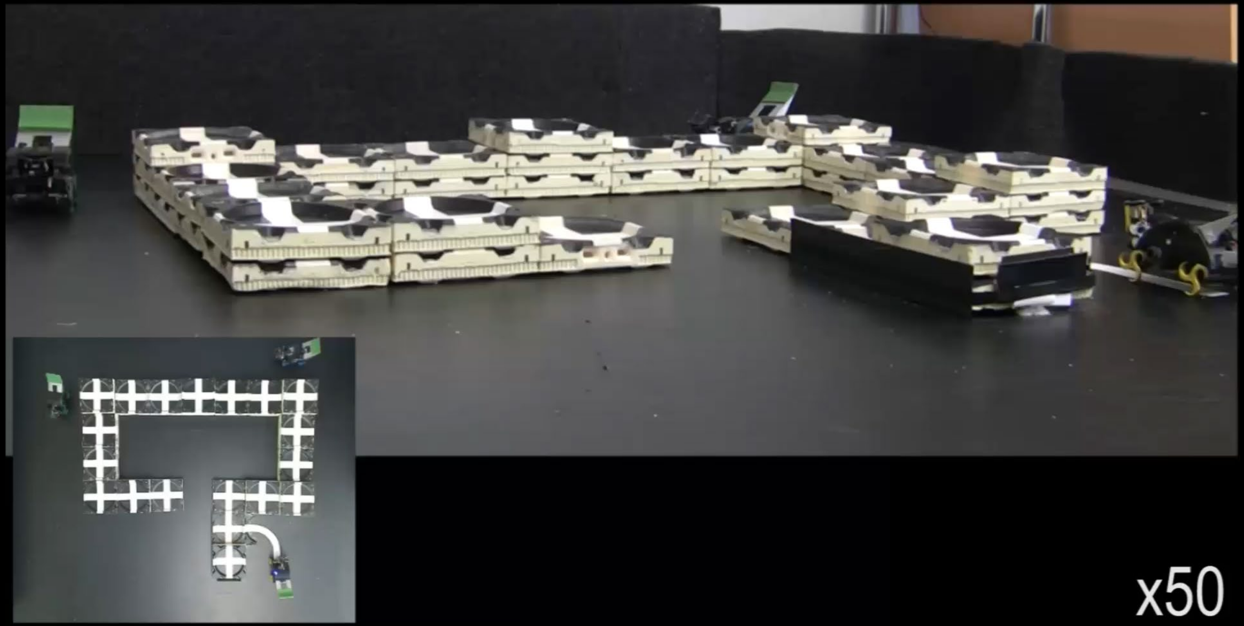
Your Teaching Team: Kirstin Petersen (She/her)



Collective Embodied Intelligence lab (www.cei.ece.cornell.edu)

Your Teaching Team: Kirstin Petersen (She/her)

- Autonomous construction



Your Teaching Team: Kirstin Petersen (She/her)

- Autonomous construction
- Soft robots

Yoav Matia[1], Gregory Kaiser[1], Robert F. Shepherd[1], Amir Gat[2], Nathan Lazarus[3], and Kirstin Petersen[1]
[1]College of Engineering, Cornell University, Ithaca, NY 14853, USA
[2]Technion - Israel Institute of Technology, Technion City, Haifa, Israel 3200003
[3]US Army Research Laboratory, Adelphi, MD 20783, USA
Contact: ym279@cornell.edu

Harnessing non-uniform pressure distributions in soft robotic actuators

In submission with Advanced Intelligent Systems, Oct 2022

Your Teaching Team: Kirstin Petersen (She/her)

- Autonomous construction
- Soft robots
- Microrobots

Movie S8: Navigation through an intricate environment

Your Teaching Team: Kirstin Petersen (She/her)

- Autonomous construction
- Soft robots
- Microrobots
- Insect swarms

Action items

- *If you decide not to take the course, let Kirstin/Sharif know ASAP (40+ on the waitlist)*

- Jan 27th, midnight: Make a Github repository and build a Github page
  - Your name, a small introduction, the class number, and a photo
  - Share the page link over Canvas

- Labs start this week
  - Upload your write-up of Lab 1 by 8am the following week
    - (E.g. Tuesday lab write-ups are due the following Tuesday 8am)

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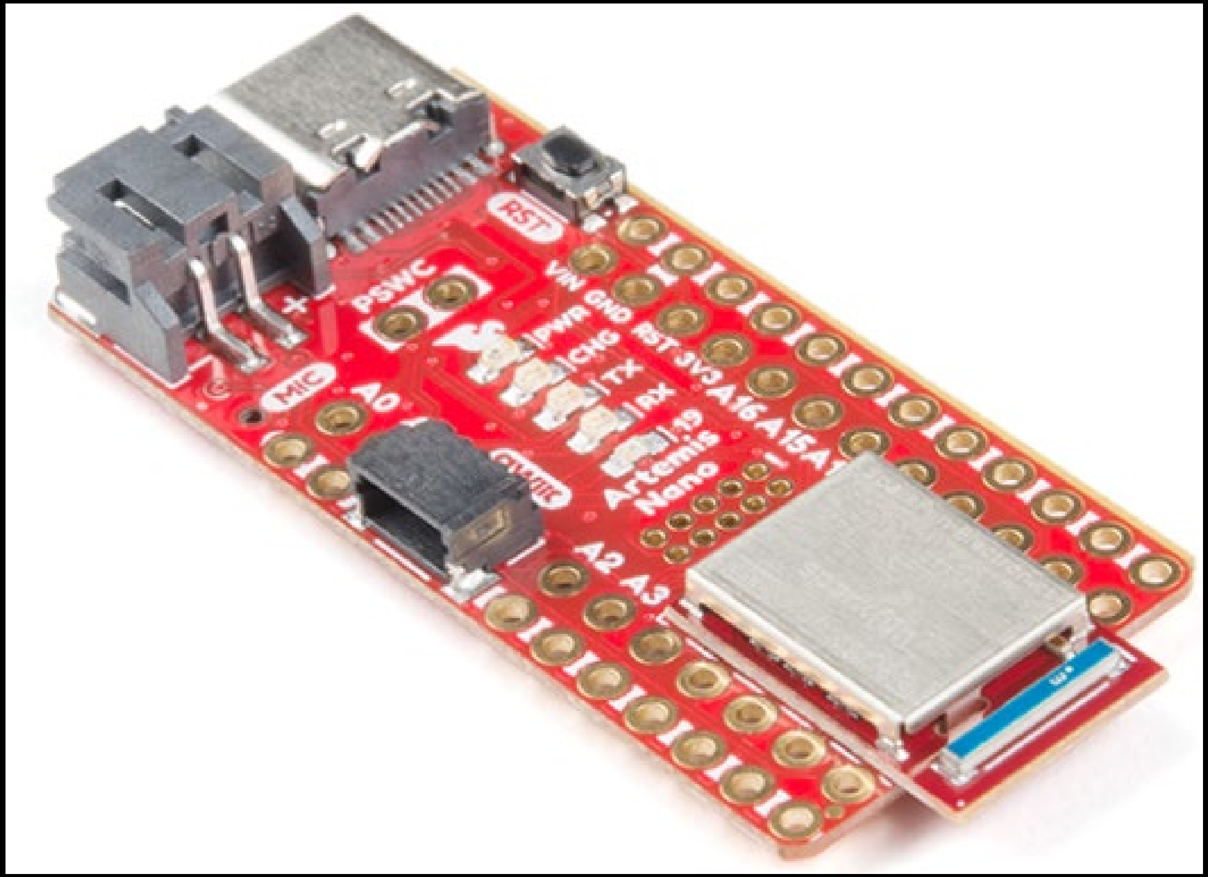
Fast Robots
Lab 1: Artemis

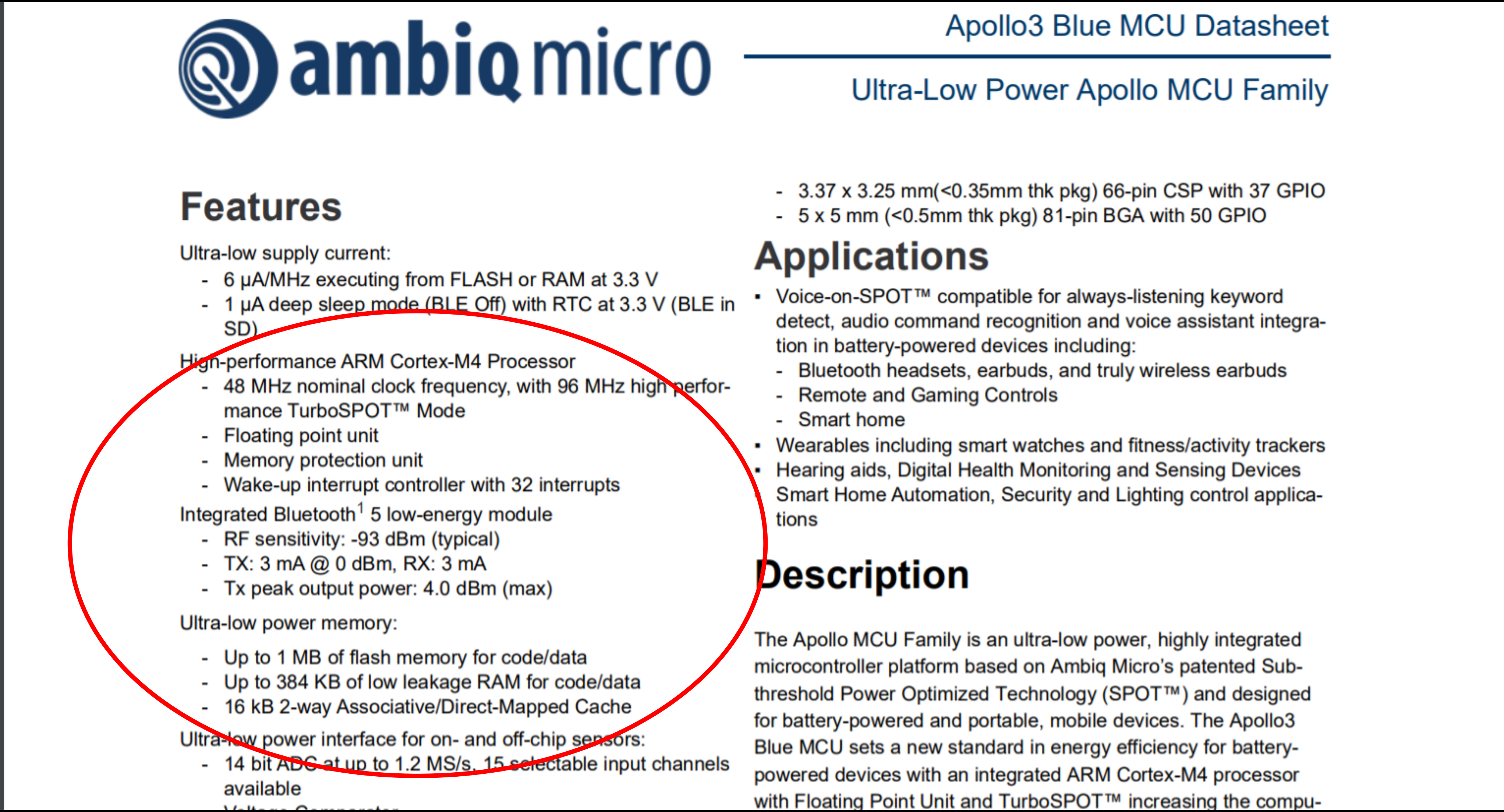
Lab 1: The Artemis Board



- The Board: https://www.sparkfun.com/products/15443
- Support forum: https://forum.sparkfun.com/viewforum.php?f=167&sid=903070e43f577f5afd5010828e1bf716
- Bluetooth
- PDM
- LiPo Charger
- I2C Qwiic connectors
- *3V board*
- ARM processor

Lab 1: The Artemis Board

https://cdn.sparkfun.com/assets/d/e/8/b/4/Apollo3_Blue_MCU_Data_Sheet_v0_12_1_rZ9Akgo.pdf



ambiq micro

Apollo3 Blue MCU Datasheet

Ultra-Low Power Apollo MCU Family

Features

Ultra-low supply current:
- 6 μA/MHz executing from FLASH or RAM at 3.3 V
- 1 μA deep sleep mode (BLE Off) with RTC at 3.3 V (BLE in SD)

High-performance ARM Cortex-M4 Processor
- 48 MHz nominal clock frequency, with 96 MHz high performance TurboSPOT™ Mode
- Floating point unit
- Memory protection unit
- Wake-up interrupt controller with 32 interrupts

Integrated Bluetooth[1] 5 low-energy module
- RF sensitivity: -93 dBm (typical)
- TX: 3 mA @ 0 dBm, RX: 3 mA
- Tx peak output power: 4.0 dBm (max)

Ultra-low power memory:
- Up to 1 MB of flash memory for code/data
- Up to 384 KB of low leakage RAM for code/data
- 16 kB 2-way Associative/Direct-Mapped Cache

Ultra-low power interface for on- and off-chip sensors:
- 14 bit ADC at up to 1.2 MS/s, 15 selectable input channels available

- 3.37 x 3.25 mm(<0.35mm thk pkg) 66-pin CSP with 37 GPIO
- 5 x 5 mm (<0.5mm thk pkg) 81-pin BGA with 50 GPIO

Applications

- Voice-on-SPOT™ compatible for always-listening keyword detect, audio command recognition and voice assistant integration in battery-powered devices including:
  - Bluetooth headsets, earbuds, and truly wireless earbuds
  - Remote and Gaming Controls
  - Smart home
- Wearables including smart watches and fitness/activity trackers
- Hearing aids, Digital Health Monitoring and Sensing Devices
- Smart Home Automation, Security and Lighting control applications

Description

The Apollo MCU Family is an ultra-low power, highly integrated microcontroller platform based on Ambiq Micro's patented Subthreshold Power Optimized Technology (SPOT™) and designed for battery-powered and portable, mobile devices. The Apollo3 Blue MCU sets a new standard in energy efficiency for battery-powered devices with an integrated ARM Cortex-M4 processor with Floating Point Unit and TurboSPOT™ increasing the compu-

*Single-Instruction Multiple-Data ops, floating point unit
-> Audio, Fast-control loop closure

Lab 1: The Artemis Board

https://cdn.sparkfun.com/assets/d/e/8/b/4/Apollo3_Blue_MCU_Data_Sheet_v0_12_1_rZ9Akgo.pdf

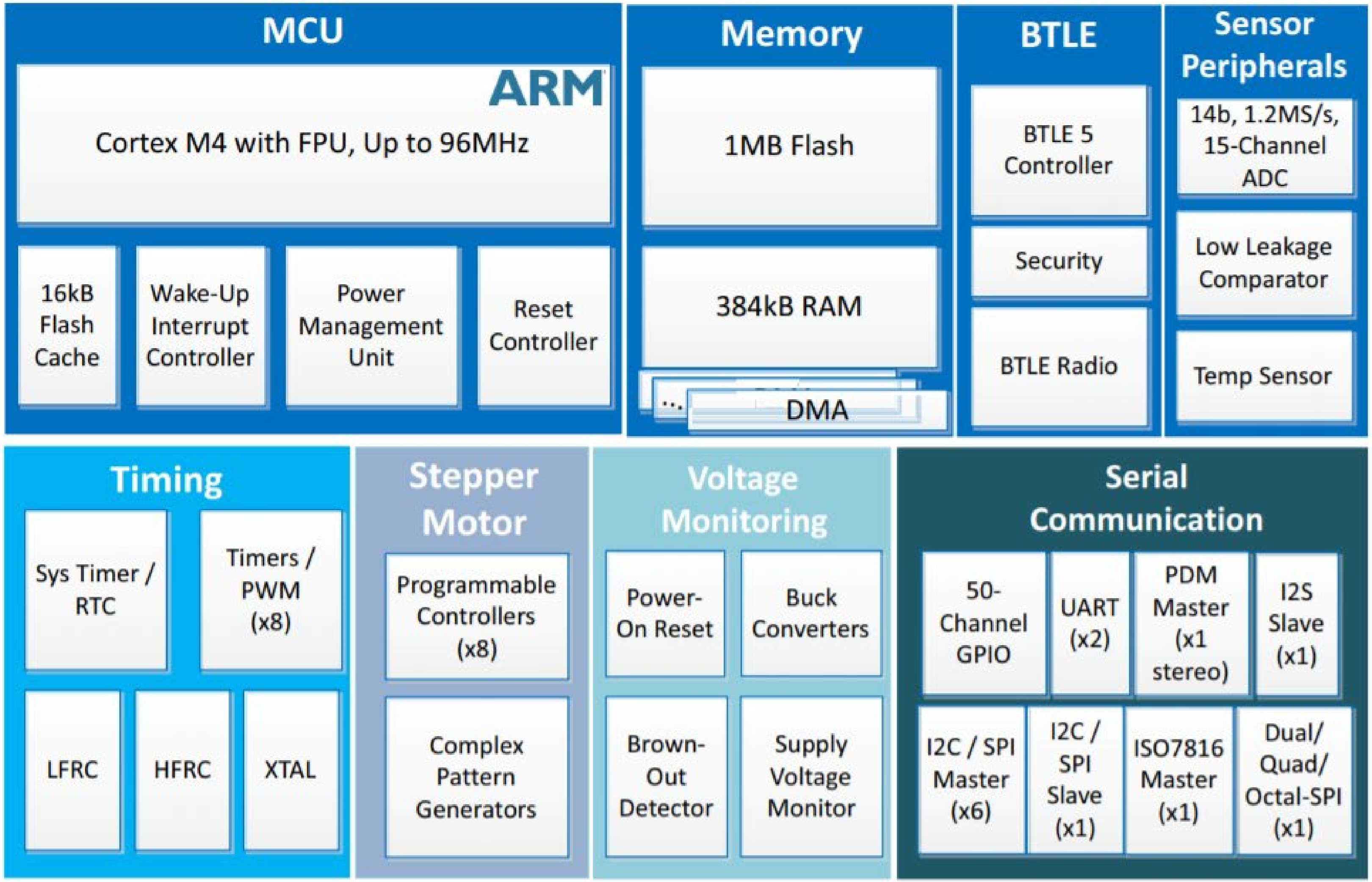
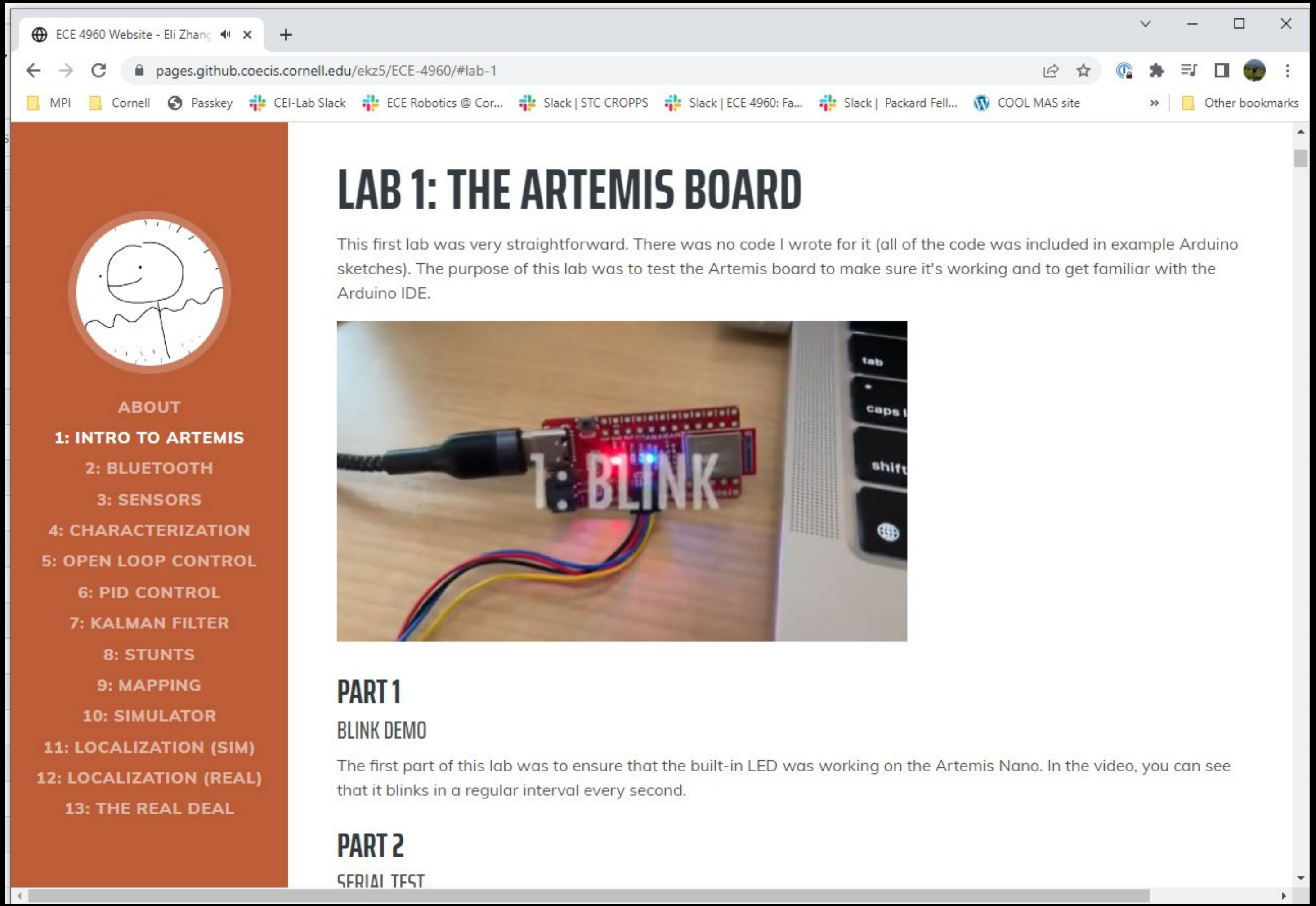


Figure 3. Block Diagram for the Ultra-Low Power Apollo3 Blue MCU

Lab 1: The Artemis Board

- Example write-up from last semester…
  - Comprehensive
  - Concise
  - Visually appealing



- *Note*
  - Lab 1 is super easy
  - Lab 2 is *much more* time consuming
    - Start the prelab early…

https://pages.github.coecis.cornell.edu/ekz5/ECE-4960/#lab-1