

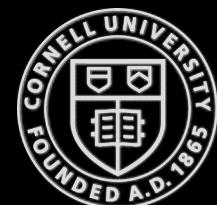
ECE 4160/5160

MAE 4910/5910

Prof. Kirstin Hagelskjær Petersen
kirstin@cornell.edu

Fast Robots

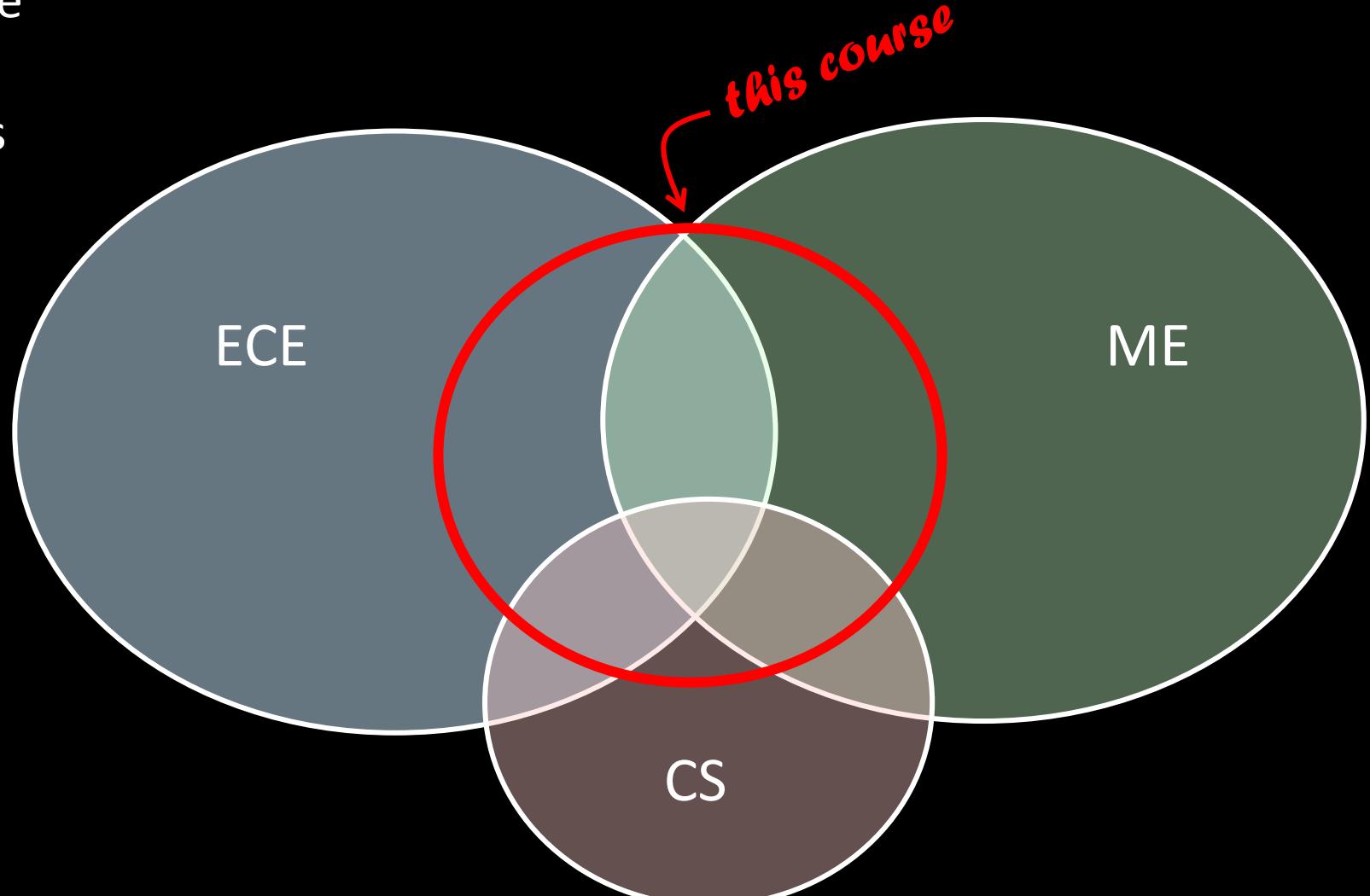
Introduction



Fast Robots

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 robots are fundamentally different from slow robots



Hajime Robot



Fast Robots

Why *this* class?

- Fast robots are fundamentally different from slow robots
 - Kinematics – Dynamics



Hajime Robot



Boston dynamics



Fast Robots

Why *this* class?

- Fast robots are fundamentally different from slow robots
 - Kinematics – Dynamics
 - Stable – Unstable

Deep Drone Acrobatics

Elia Kaufmann*, Antonio Loquercio*, René Ranftl,
Matthias Müller, Vladlen Koltun, Davide Scaramuzza



University of
Zurich
UZH



Pause (k)

II ▶ 🔍 0:01 / 2:31

*these auth. contribute equally



Cubli, ETH Zurich



Fast Robots

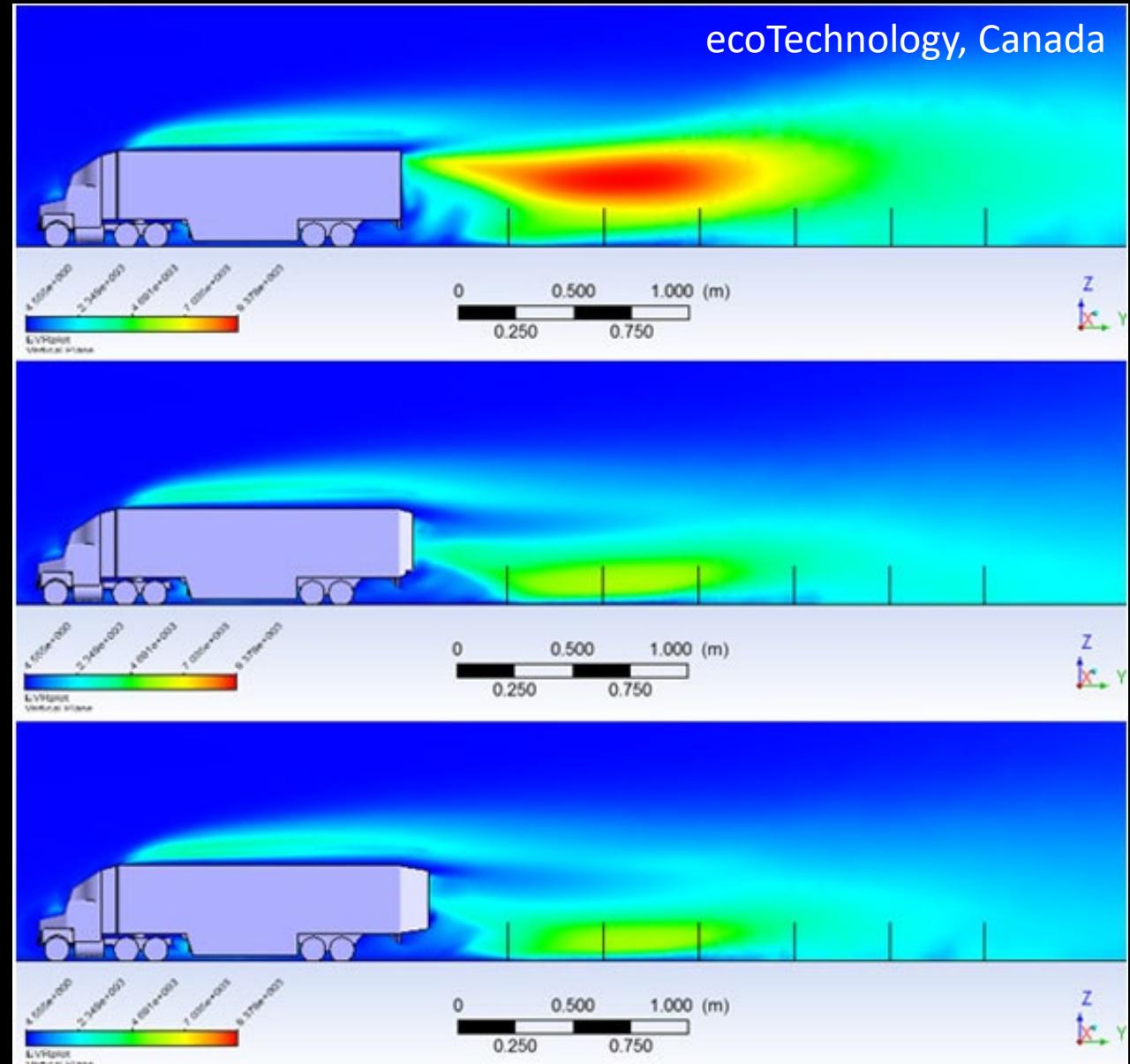
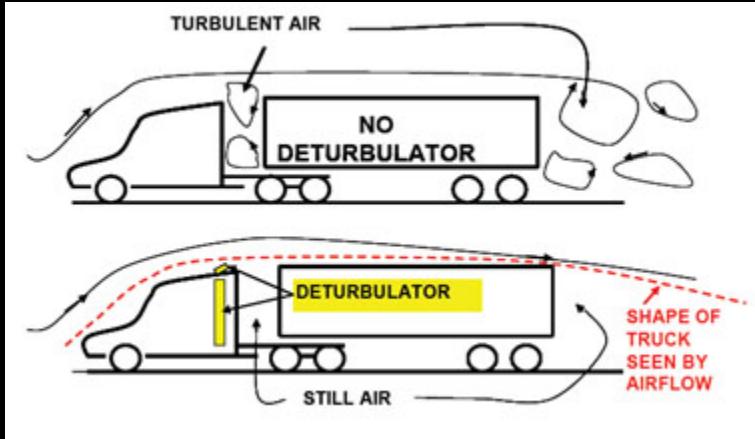
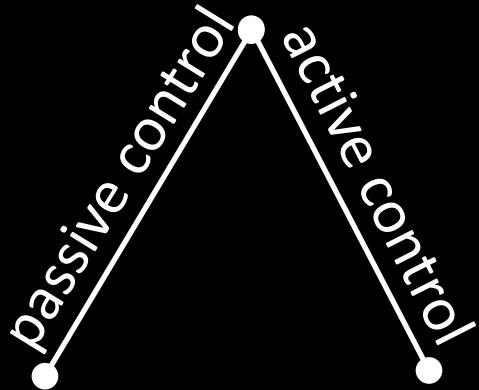
Why *this* class?

- Fast robots are fundamentally different from slow robots
 - Kinematics – Dynamics
 - Stable – Unstable
- Design for fast robots goes beyond just good control theory and dynamic models
 - Practical implementation, mechanics, sensors, processing, estimation, etc.

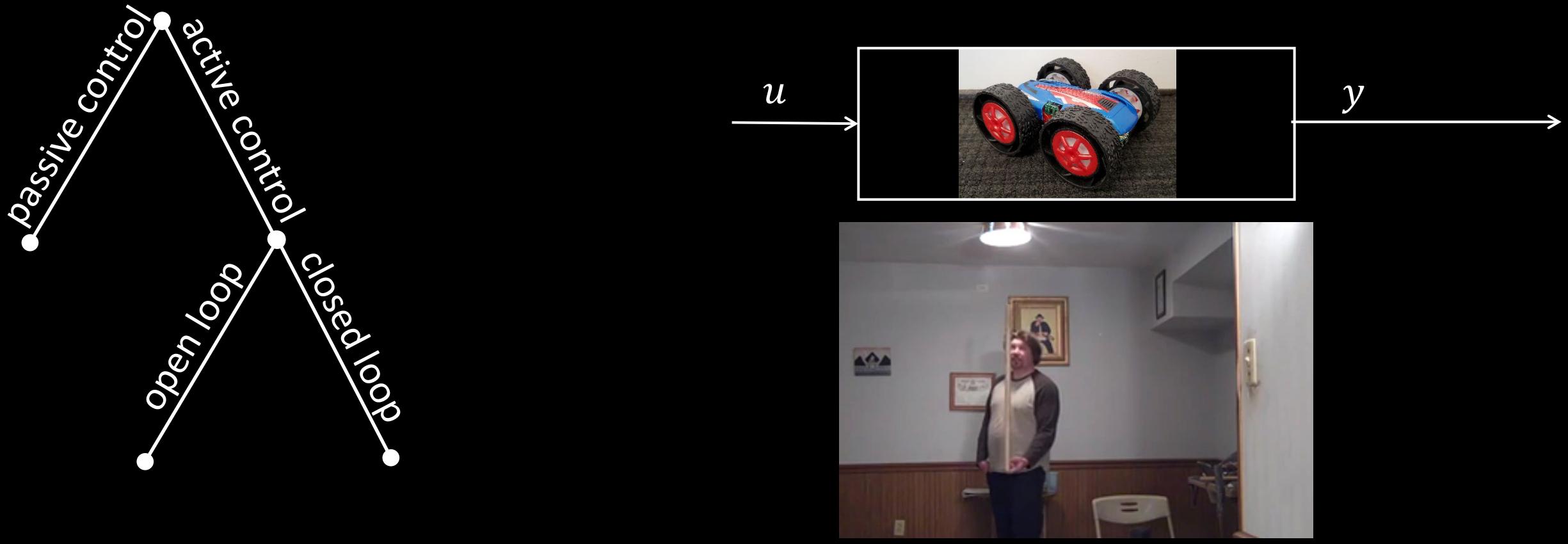


Fast Robots

Control and its implications in fast robots



Control and its implications in fast robots



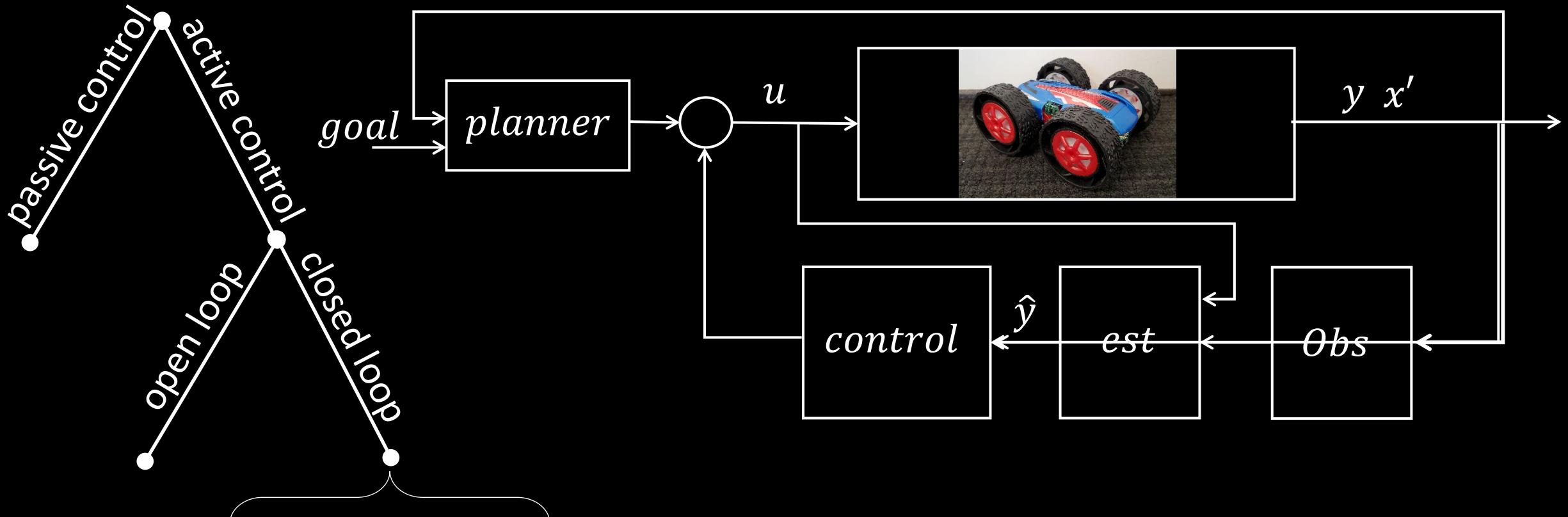
Why feedback?

- System uncertainty
- Instability
- Disturbances
- Efficiency



Fast Robots

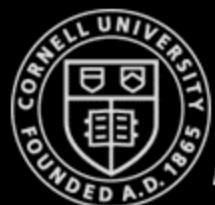
Control and its implications in fast robots



- processor
 - drivers
 - limits
- sensors
 - noise/bias

Why feedback?

- System uncertainty
- Instability
- Disturbances
- Efficiency



ECE 4160/5160

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Fast Robots

Class Layout



Fast Robots

Schedule

Lab 1-5 Hardware / Embedded SW

Lab 6-9 Feedback Control

**Lab 10-12 Localization and
Planning**



Fast Robots

Schedule

Lab 1-5 Hardware / Embedded SW

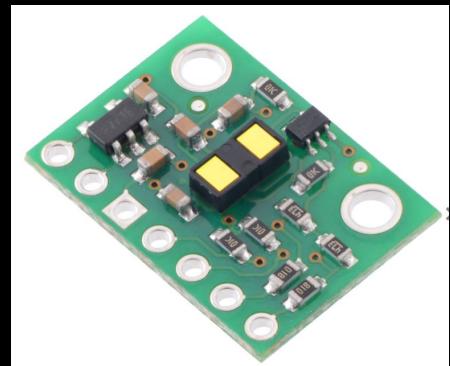
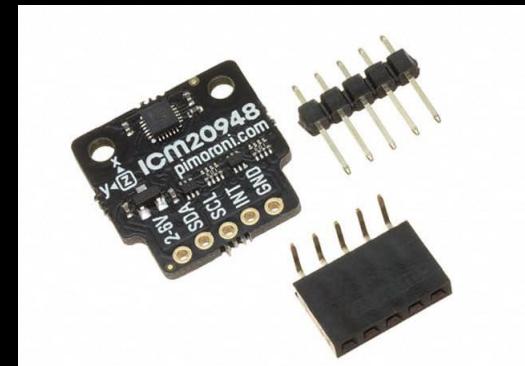
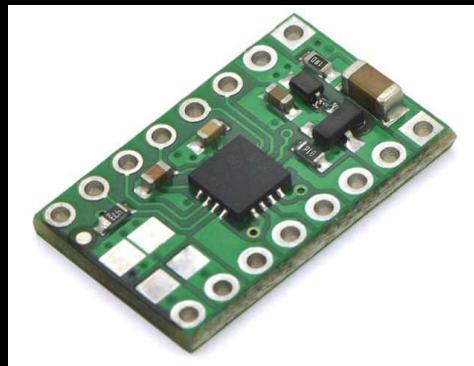
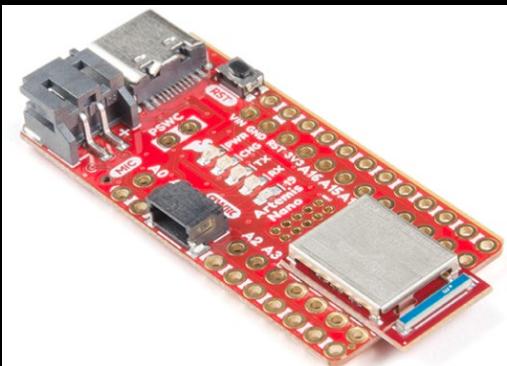
- Combine base with processor, drivers, and sensors
- Refresh on linear algebra and T-matrices
- Sensor modalities and types of sensors
- Actuators, drivers, circuits and routing, and EMI



Lab 6-9 Feedback Control

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

Lab 10-12 Localization and Planning



Fast Robots

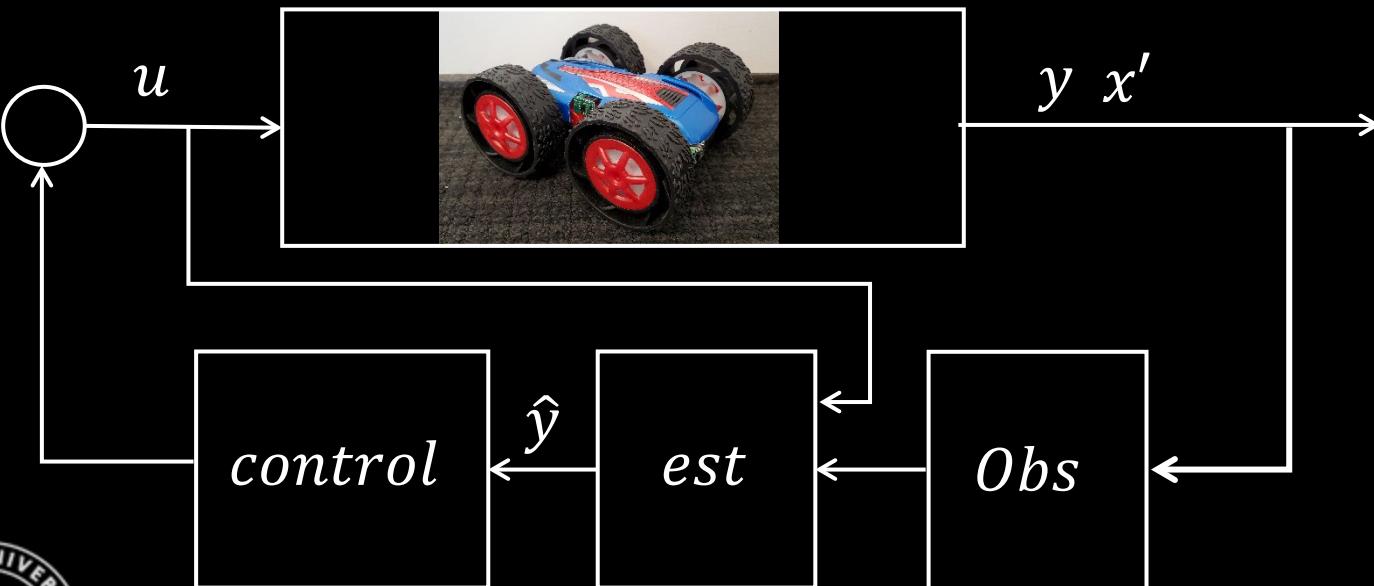
Schedule

Lab 1-5 Hardware / Embedded SW

Lab 6-9 Feedback Control

Lab 10-12 Localization and Planning

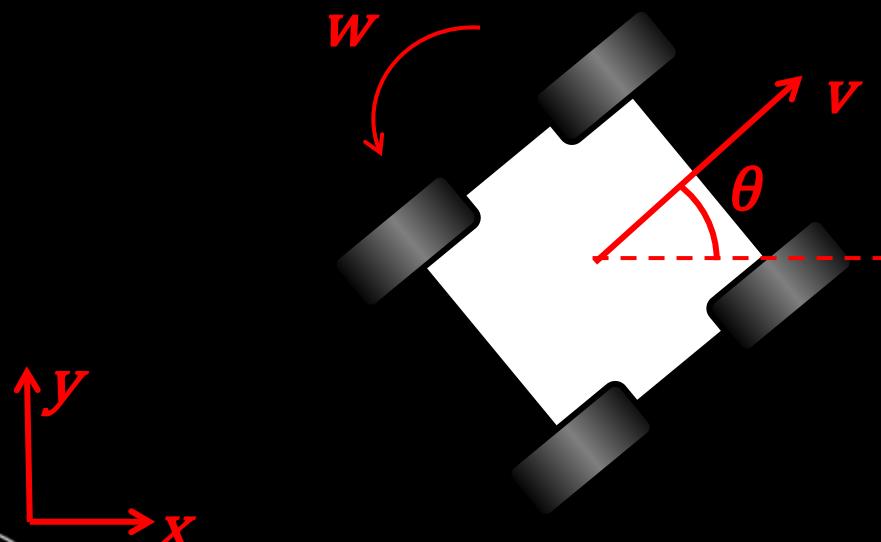
- Linear systems, model-free and model-based control



Schedule

Lab 1-5 Hardware / Embedded SW

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



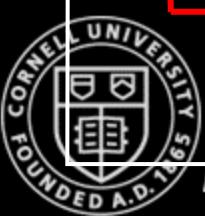
Lab 6-9 Feedback Control

Lab 10-12 Localization and Planning



$$\begin{aligned}\dot{x} &= \cos(\theta)v \\ \dot{y} &= \sin(\theta)v \\ \dot{\theta} &= w\end{aligned}$$

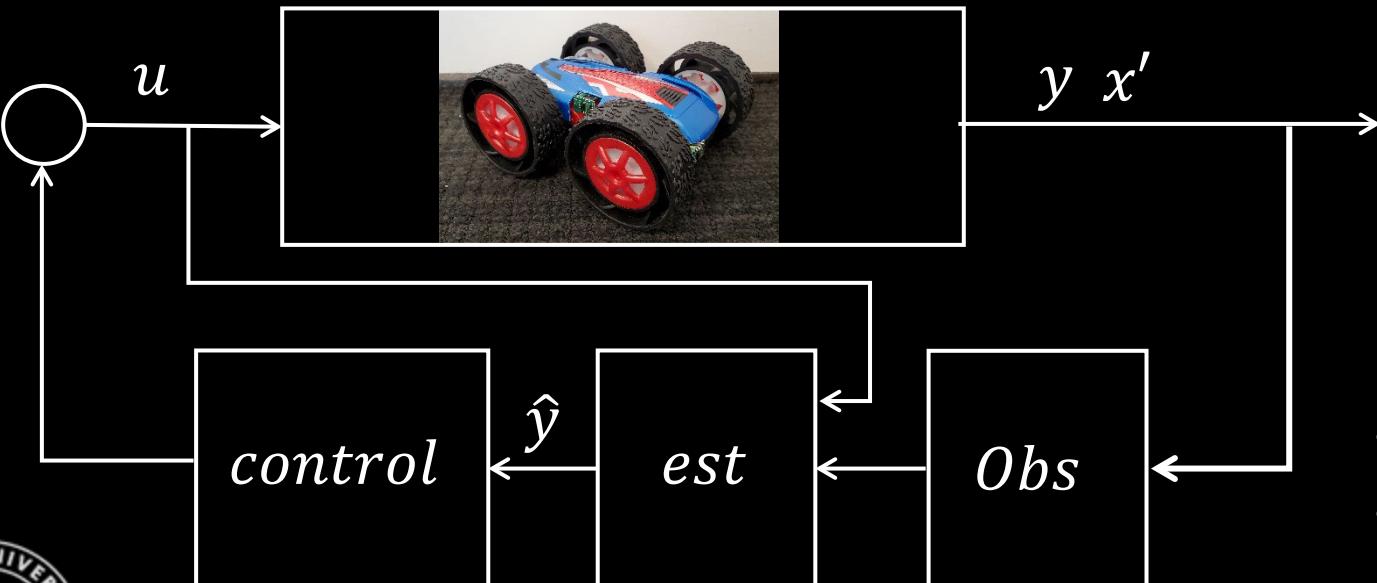
$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos(\theta)v & 0 \\ \sin(\theta)v & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix}$$



Schedule

Lab 1-5 Hardware / Embedded SW

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



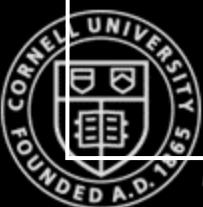
Lab 6-9 Feedback Control

Lab 10-12 Localization and Planning



Why do you think feedback control and observers are necessary?

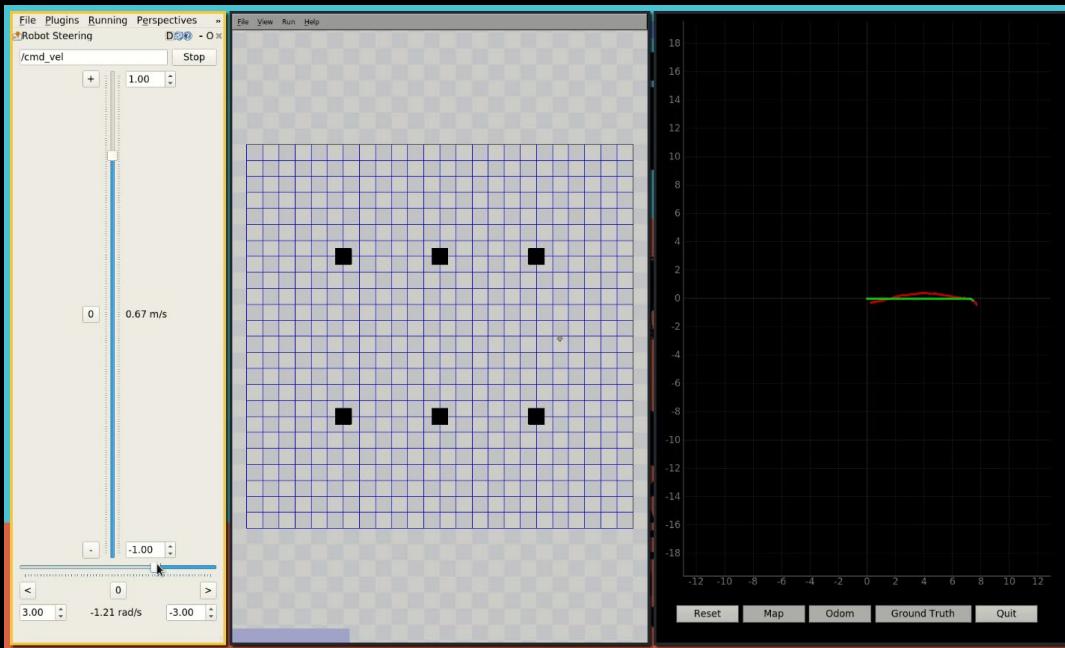
- Performance is battery dependent
- Our sensors are relatively slow
- Etc,



Schedule

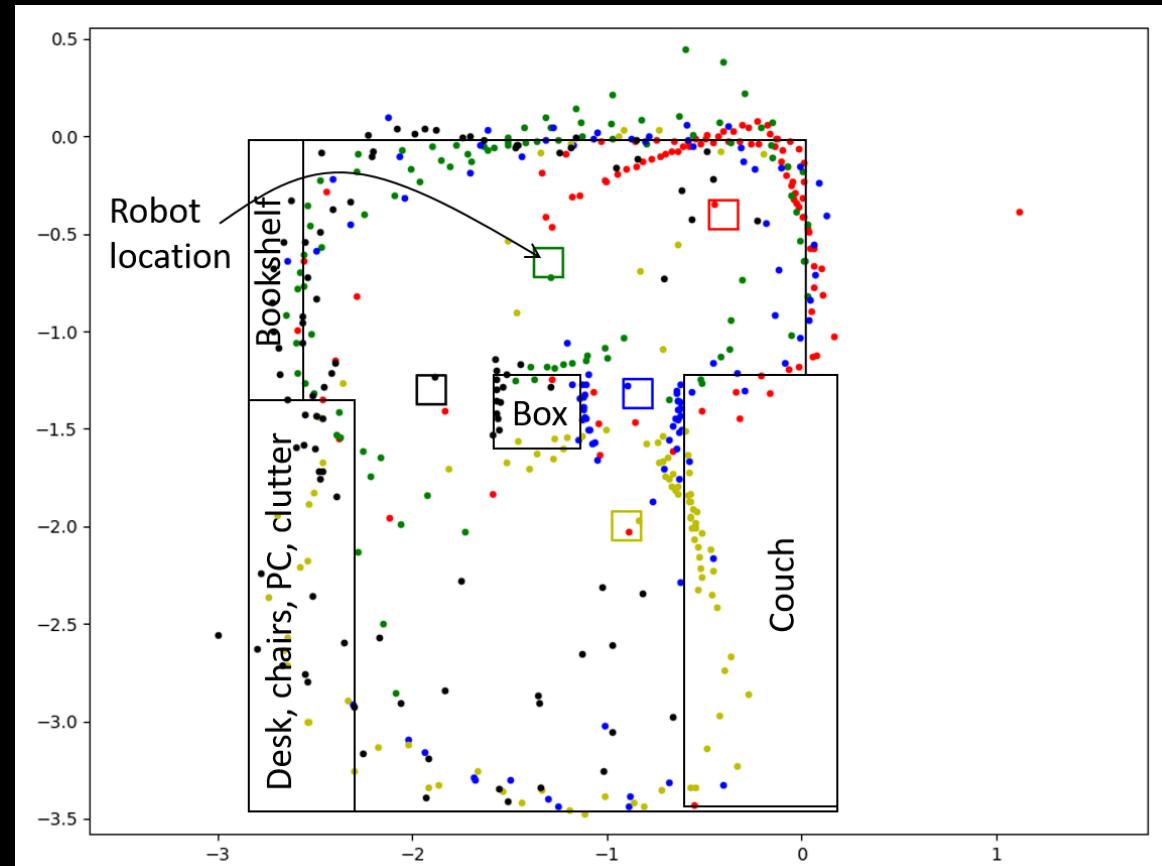
Lab 1-5 Hardware / Embedded SW

- Map representations
- Search and planning



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

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

What are sources of error?

- Skid steering



Schedule

Lab 1-5 Hardware / Embedded SW

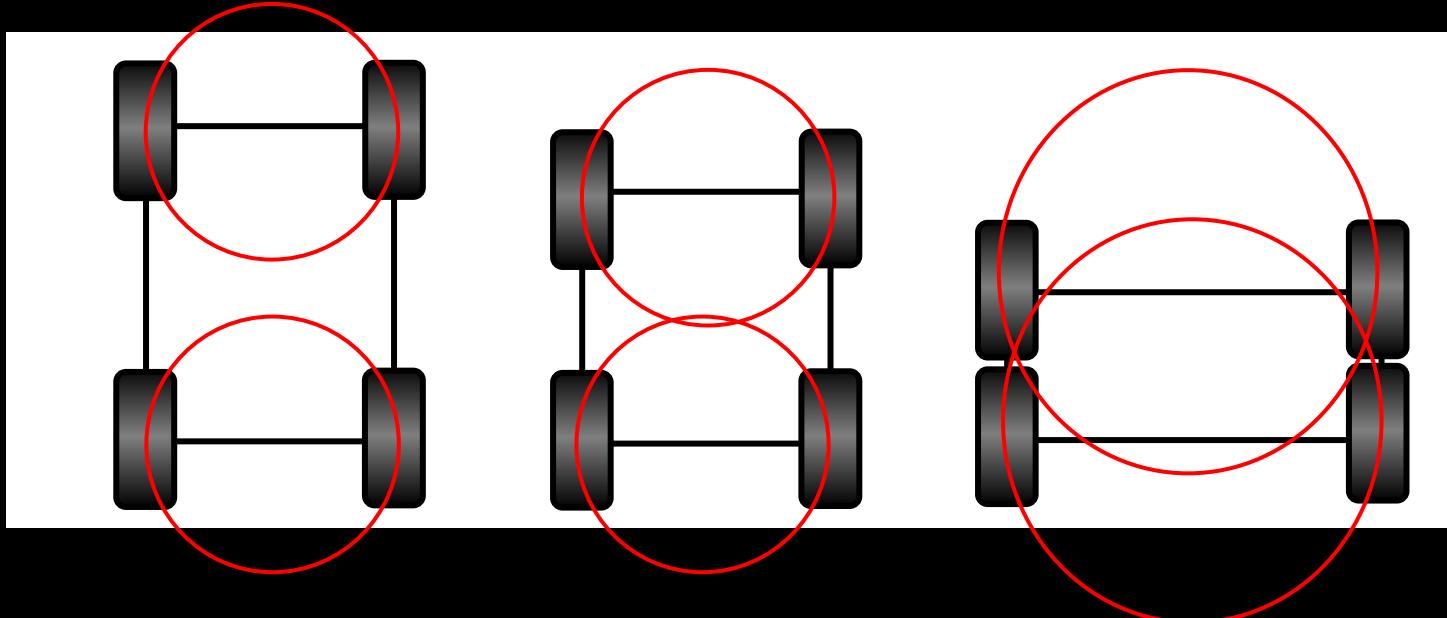
Lab 6-9 Feedback Control

Lab 10-12 Localization and Planning

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

What are sources of error?

- Skid steering



Schedule

Lab 1-5 Hardware / Embedded SW

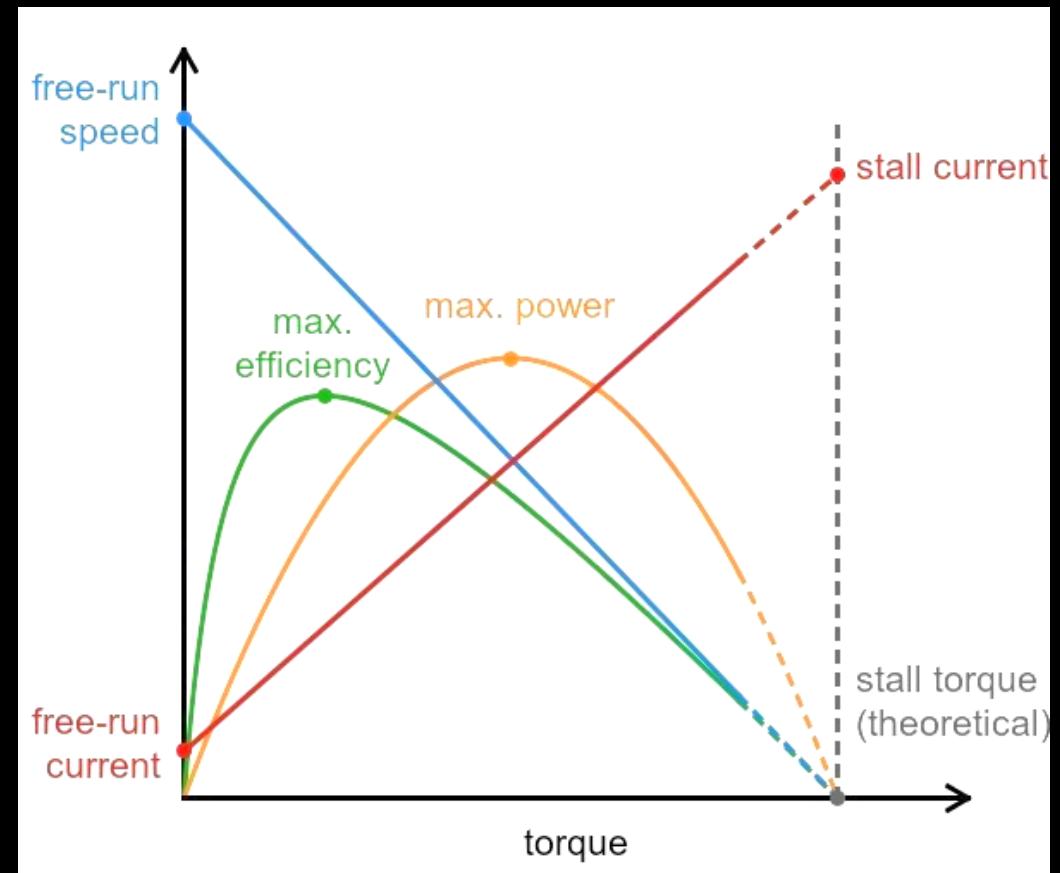
- Map representations
- Search and planning
- Noise, discrete probability
- Motion and sensor models

What are sources of error?

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

Lab 6-9 Feedback Control

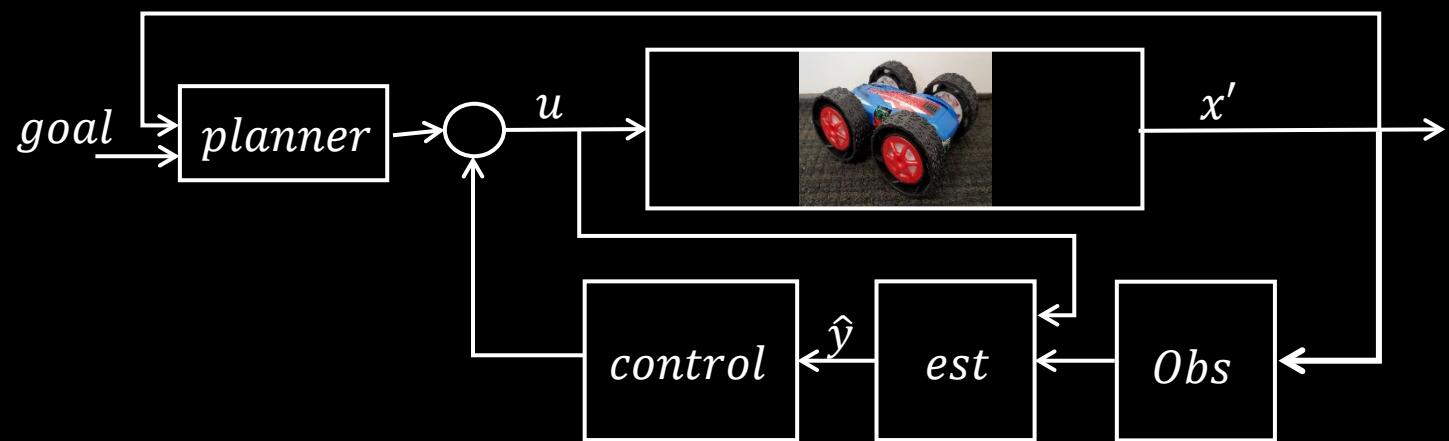
Lab 10-12 Localization and Planning



Schedule

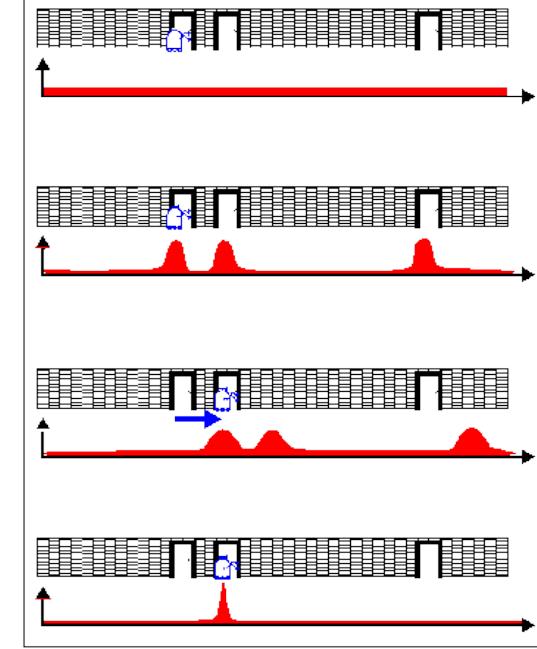
Lab 1-5 Hardware / Embedded SW

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



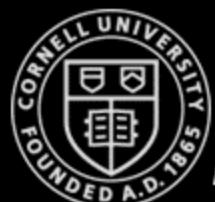
Lab 6-9 Feedback Control

Lab 10-12 Localization and 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



Fast Robots

ECE 4160/5160

MAE 4910/5910

Fast Robots Logistics



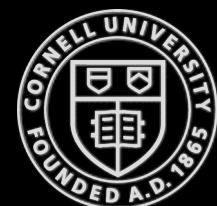
Fast Robots

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*

The image displays three side-by-side screenshots of web-based course management systems:

- GitHub:** A screenshot of the course website at <https://cei-lab.github.io/FastRobots-2023/>. It shows the course title "ECE4960/5960: Fast Robots", the semester "Cornell University, Spring 2022", and a brief description of the course focus on dynamic autonomous robots. It also features images of the robot hardware components: Artemis Nano, Inertial Measurement Unit, Proximity sensors, and Time of flight sensor.
- Canvas:** A screenshot of the Canvas LMS interface for the course ECE4960/ECE5960. The left sidebar shows navigation links for Account, Dashboard, Courses (highlighted), Groups, Calendar, Inbox, History, Commons, and Help. The main content area displays "Recent Announcements" with entries like "Lab Kit Hand out" and "Introduction".
- EdDiscussion:** A screenshot of the EdDiscussion forum for the course. It shows a list of threads: "Oscilloscope tutorial", "Soldering tutorial", and "Workload?". A large callout bubble points to the "Select a thread" button.



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

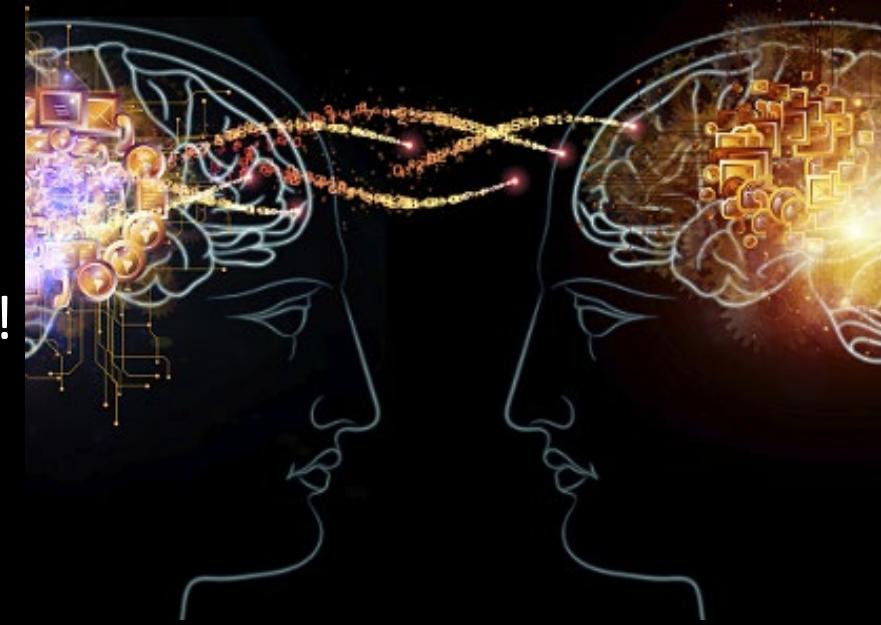
- Grading
 - 12 Labs (90 pts)
 - Points for solution (67)
 - Points for write-up (33)
 - Participation (10 pts)
 - Course evaluations (2 bonus pts)

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



ECE 4160/5160

MAE 4910/5910

Fast Robots Teaching Team



Fast Robots

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

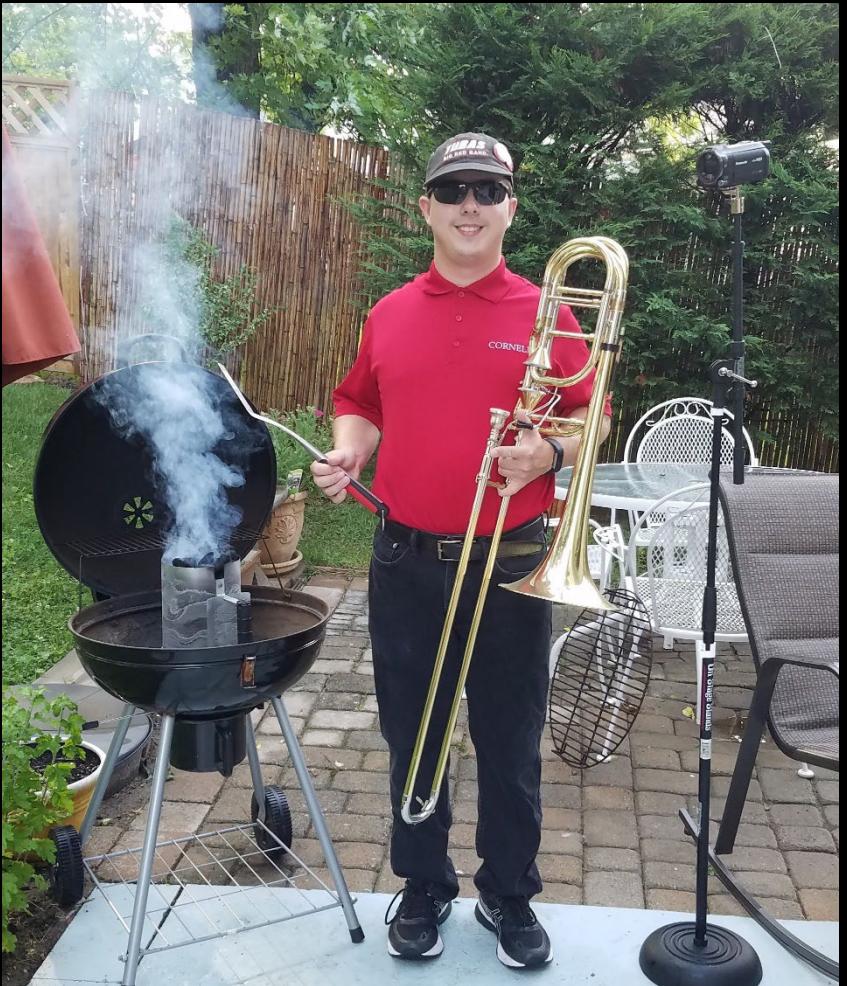
Mobile and Inflatable Interface for Human Robot Interaction

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



Fast Robots

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!



Fast Robots

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! ☺



Fast Robots

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



Fast Robots

Your Teaching Team: Joseph Horwitz (he/him)



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



Fast Robots

Your Teaching Team: Ryan Chan (he/him)

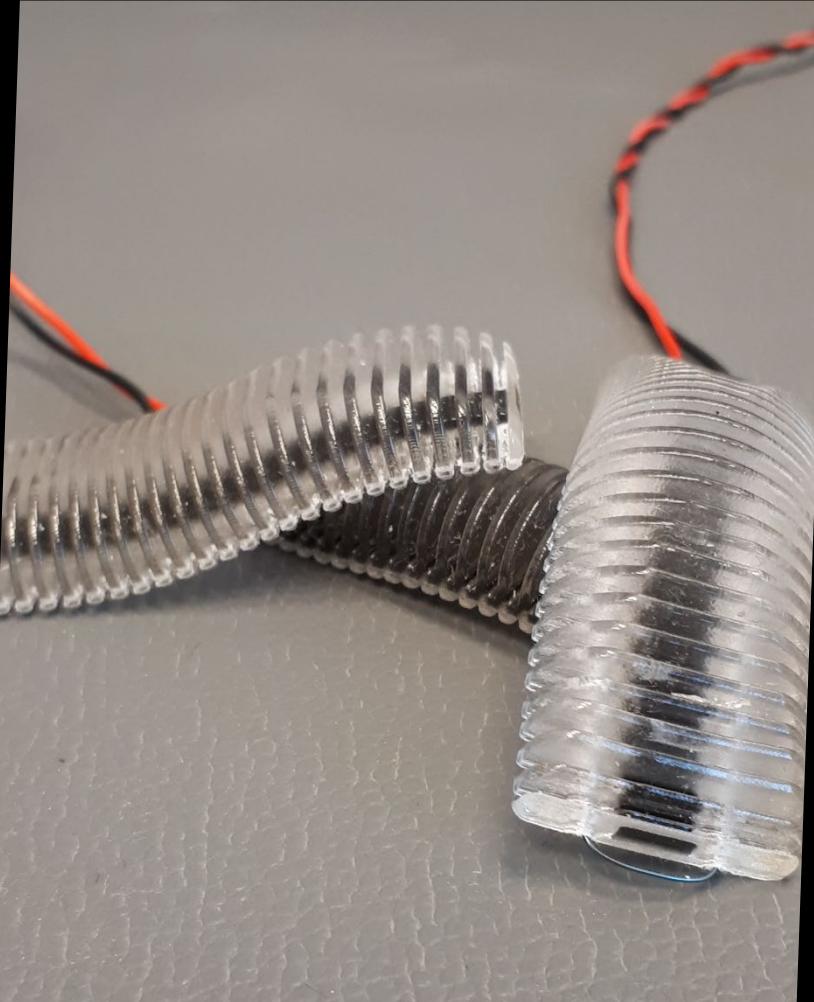
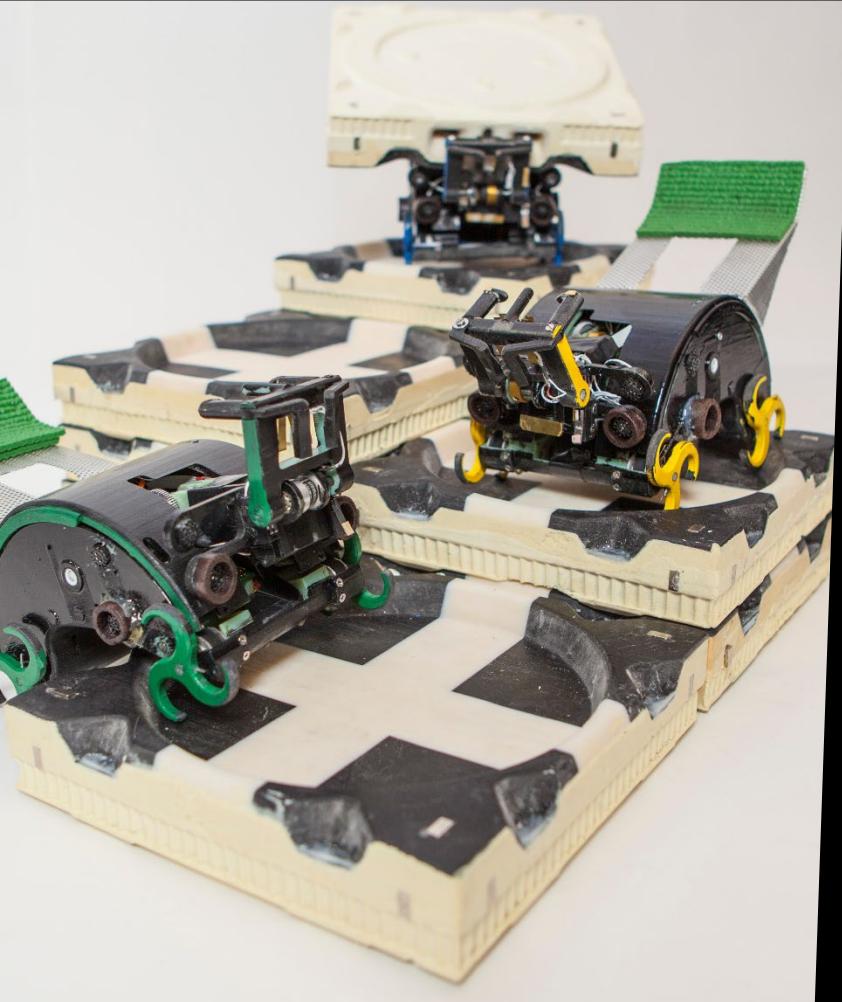


- Saturday Open labs
- Senior in ECE with a minor in CS
- Leads the electrical team at Cornell EWH
- Research in the Peck lab on Cubesats
- Research in the Shepherd lab on soft robots
- --likes turtles!



Fast Robots

Your Teaching Team: Kirstin Petersen (She/her)



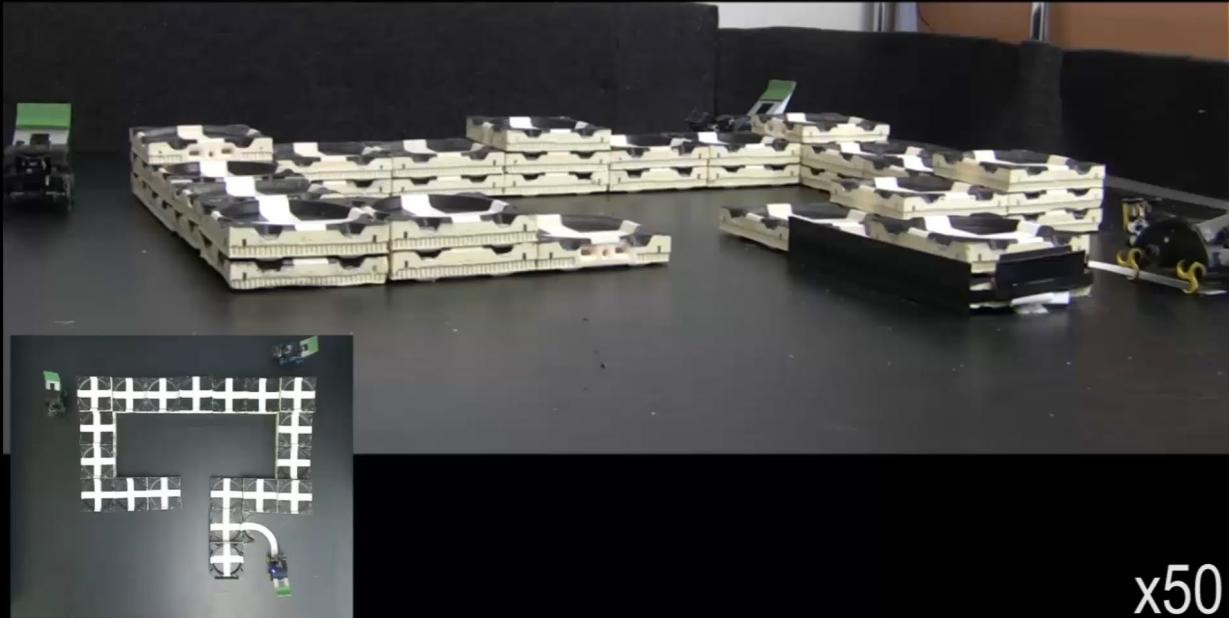
Collective Embodied Intelligence lab (www.cei.ece.cornell.edu)



Fast Robots

Your Teaching Team: Kirstin Petersen (She/her)

- Autonomous construction



x50



Fast Robots

Your Teaching Team: Kirstin Petersen (She/her)

- Autonomous construction
- Soft robots

Yoav Matia¹, Gregory Kaiser¹, Robert F. Shepherd¹, Amir Gat², Nathan Lazarus³, and Kirstin Petersen¹

¹College of Engineering, Cornell University, Ithaca, NY 14853, USA

²Technion - Israel Institute of Technology, Technion City, Haifa, Israel 3200003

³US Army Research Laboratory, Adelphi, MD 20783, USA

Contact: ym279@cornell.edu

Harnessing non-uniform pressure distributions in soft robotic actuators



Fast Robots

In submission with Advanced Intelligent Systems, Oct 2022

Your Teaching Team: Kirstin Petersen (She/her)

- Autonomous construction
- Soft robots
- Microrobots

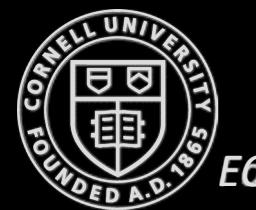
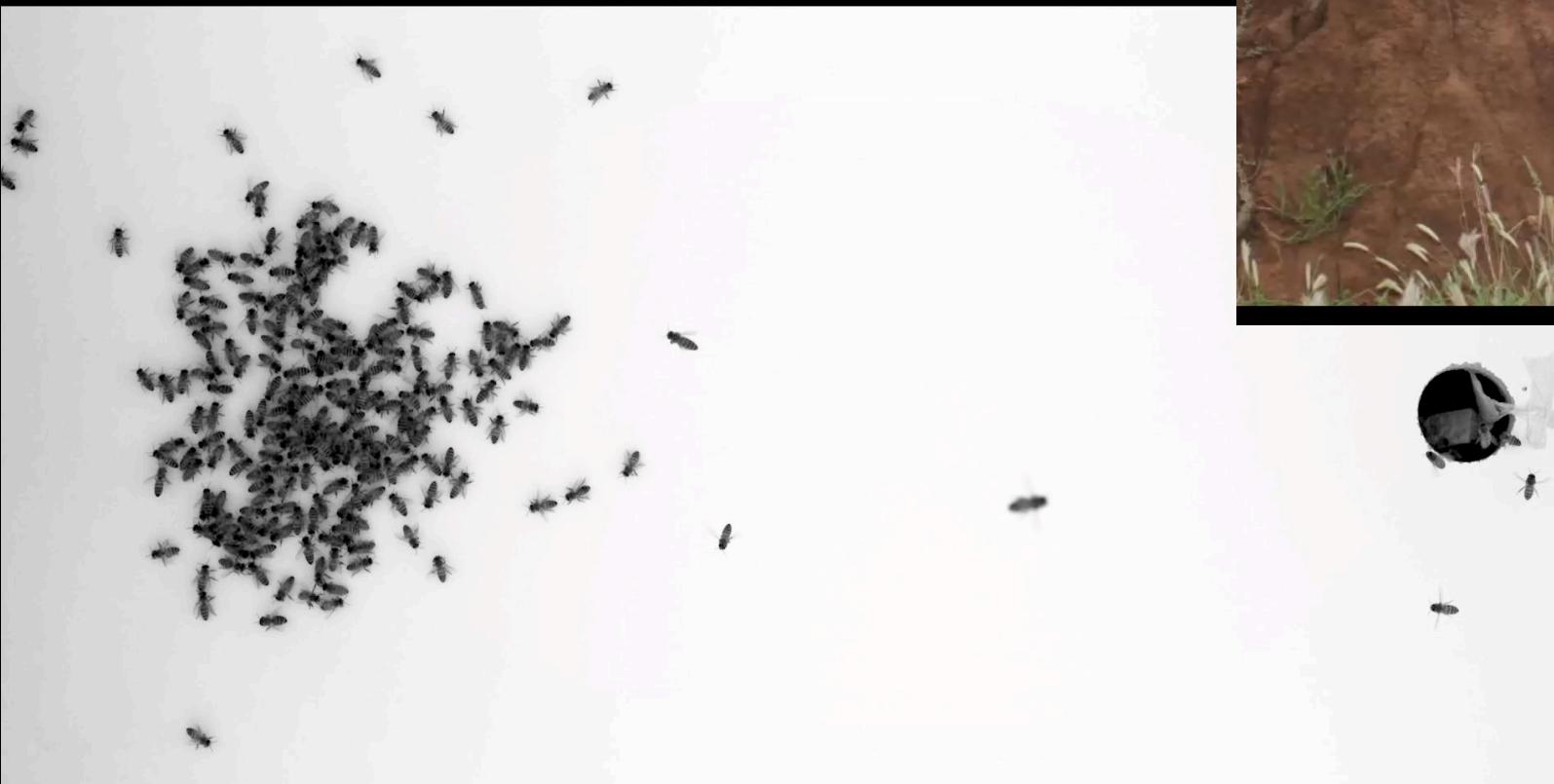
Movie S8: Navigation through an intricate environment



Fast Robots

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)



ECE 4160/5160

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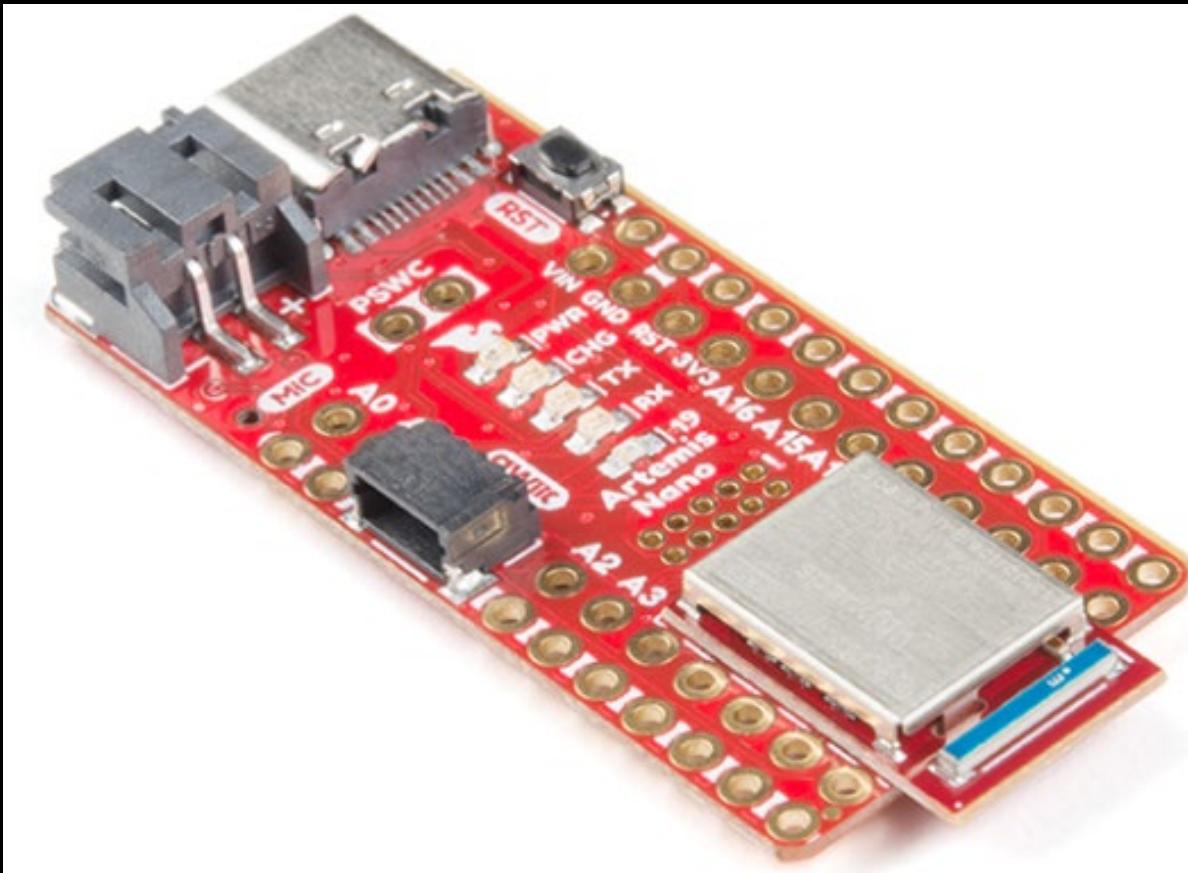
Fast Robots

Lab 1: Artemis

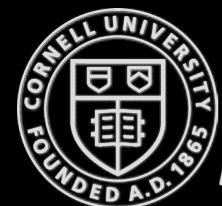


Fast Robots

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*
 - Apollo 3 MCU





Features

Ultra-low supply current:

- 6 μ A/MHz executing from FLASH or RAM at 3.3 V
- 1 μ A 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 Bluetooth¹ 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

Voice-on-SPOT™

Apollo3 Blue MCU Datasheet

Ultra-Low Power Apollo MCU Family

- 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 Sub-threshold 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

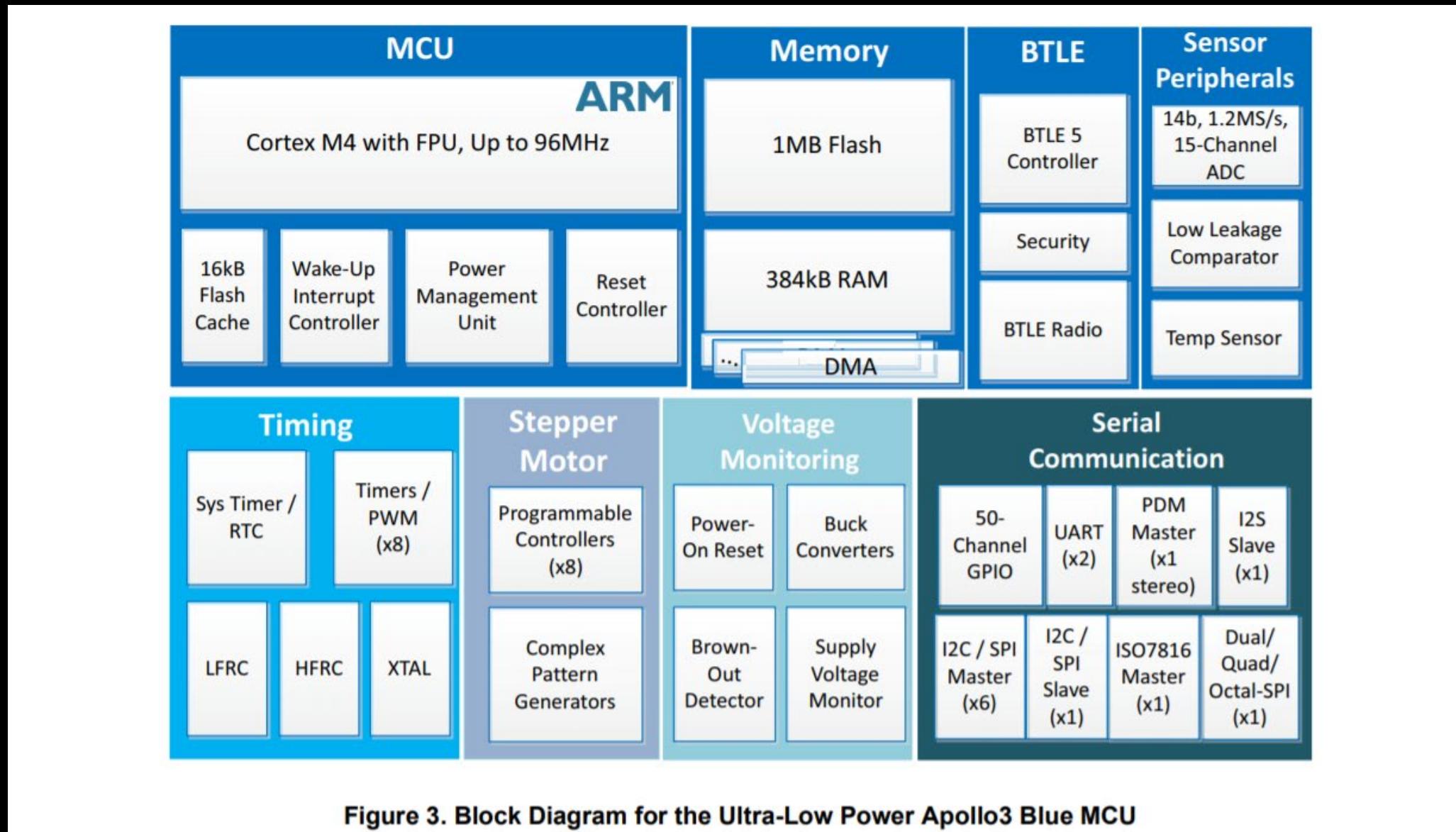


Figure 3. Block Diagram for the Ultra-Low Power Apollo3 Blue MCU



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...

The screenshot shows a web browser window with the title "ECE 4960 Website - Eli Zhang". The URL in the address bar is <https://pages.github.coecis.cornell.edu/ekz5/ECE-4960/#lab-1>. The page content is titled "LAB 1: THE ARTEMIS BOARD". It features a circular logo with a stick figure head and a list of 13 numbered topics: 1: INTRO TO ARTEMIS, 2: BLUETOOTH, 3: SENSORS, 4: CHARACTERIZATION, 5: OPEN LOOP CONTROL, 6: PID CONTROL, 7: KALMAN FILTER, 8: STUNTS, 9: MAPPING, 10: SIMULATOR, 11: LOCALIZATION (SIM), 12: LOCALIZATION (REAL), and 13: THE REAL DEAL. Below the title, a text block states: "This first lab was very straightforward. There was no code I wrote for it (all of the code was included in example Arduino sketches). The purpose of this lab was to test the Artemis board to make sure it's working and to get familiar with the Arduino IDE." To the right of the text is a photograph of an Arduino Nano connected to a breadboard via a USB cable. The breadboard has several wires connected to it, and the word "1: BLINK" is displayed on the breadboard. A portion of a computer keyboard is visible on the right side of the image. The page also includes sections for "PART 1 BLINK DEMO" and "PART 2 SERIAL TEST".

