

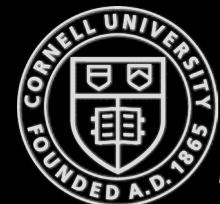
**ECE 4160/5160**

**MAE 4910/5910**

Prof. Kirstin Hagelskjær Petersen  
kirstin@cornell.edu

# Fast Robots

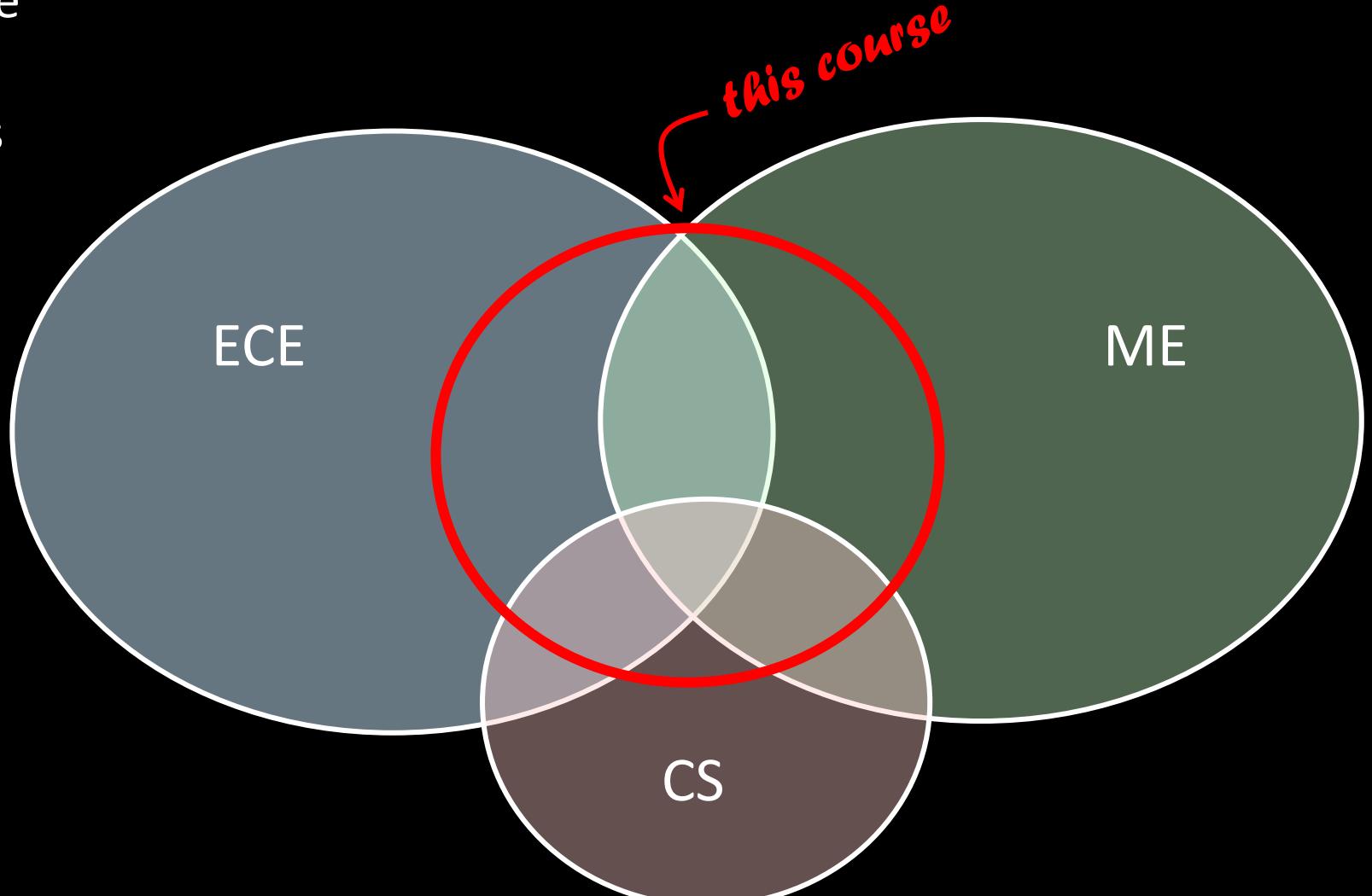
# Introduction



*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



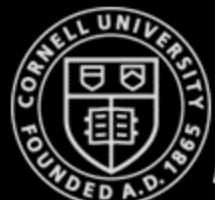
Pause (k)

II ▶ 🔍 0:01 / 2:31

\*these auth. contribute equally



Cubli, ETH Zurich



Fast Robots

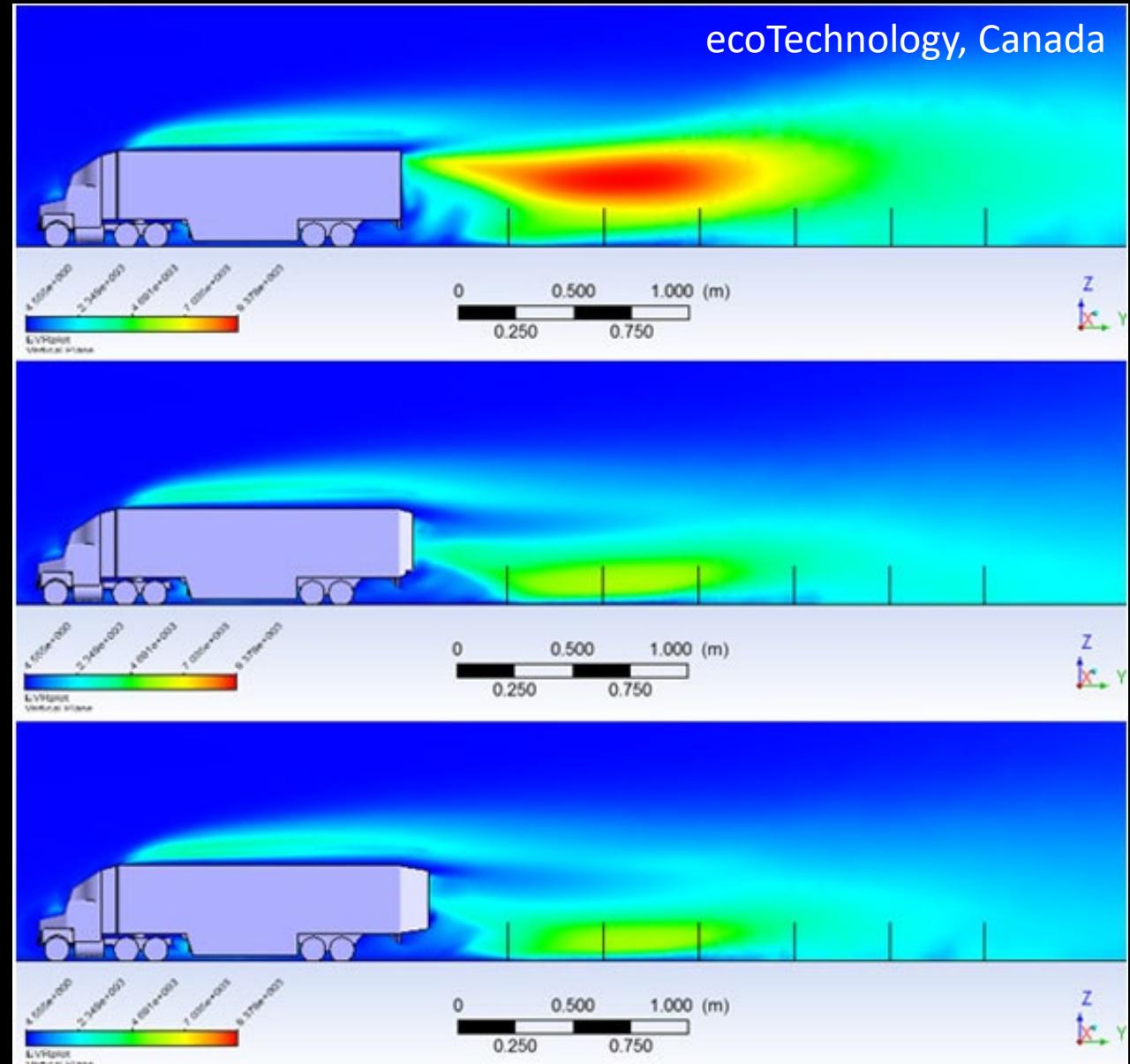
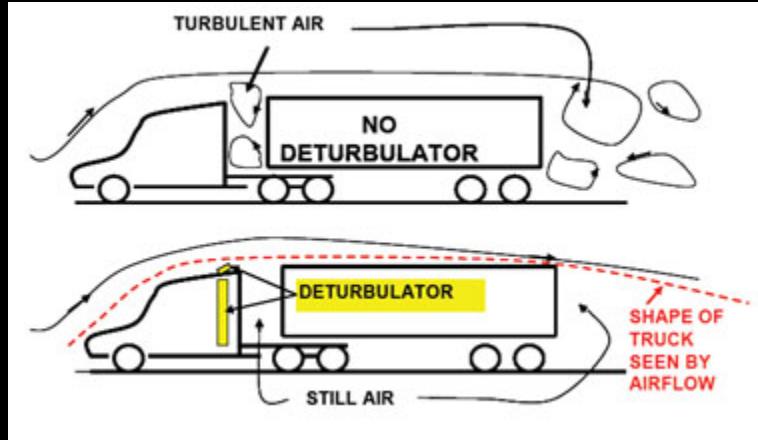
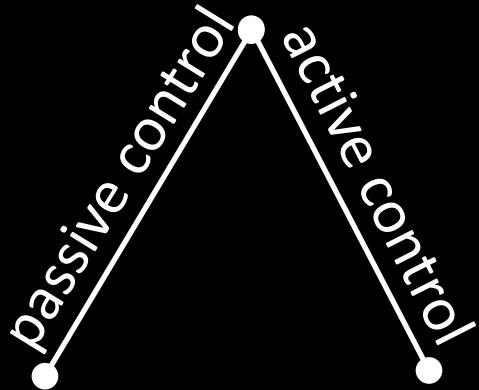
# Why *this* class?

- 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.

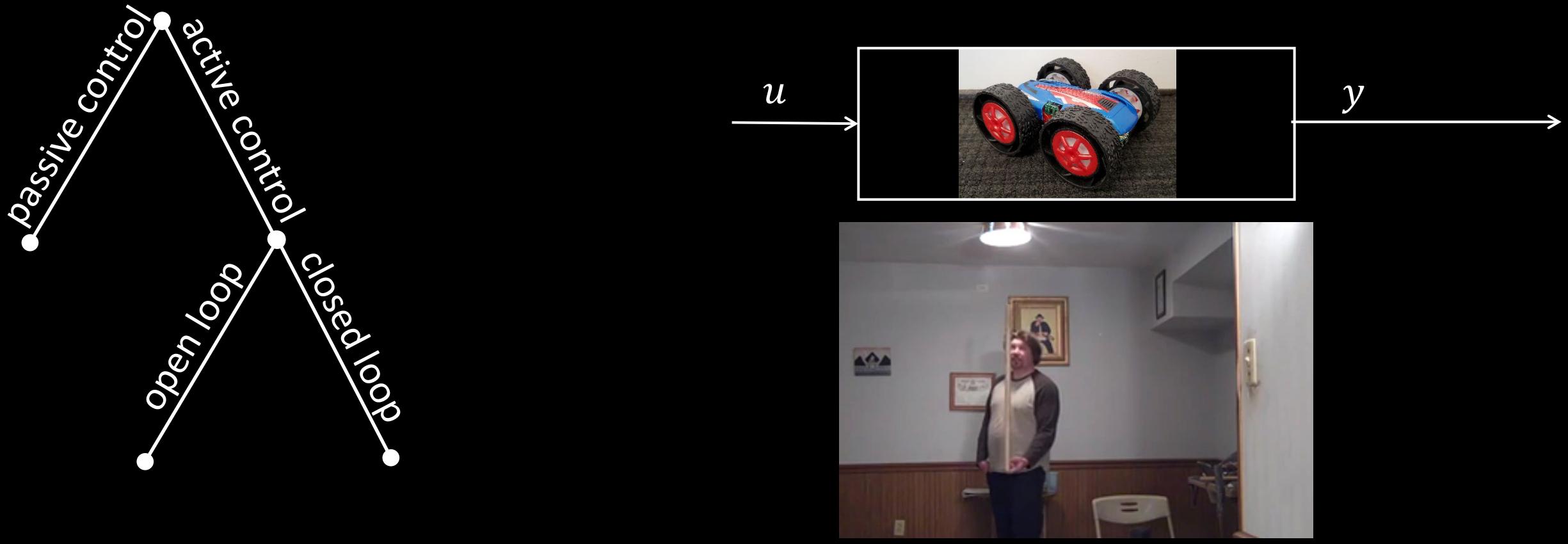


Fast Robots

# Control and its implications in fast robots



# Control and its implications in fast robots

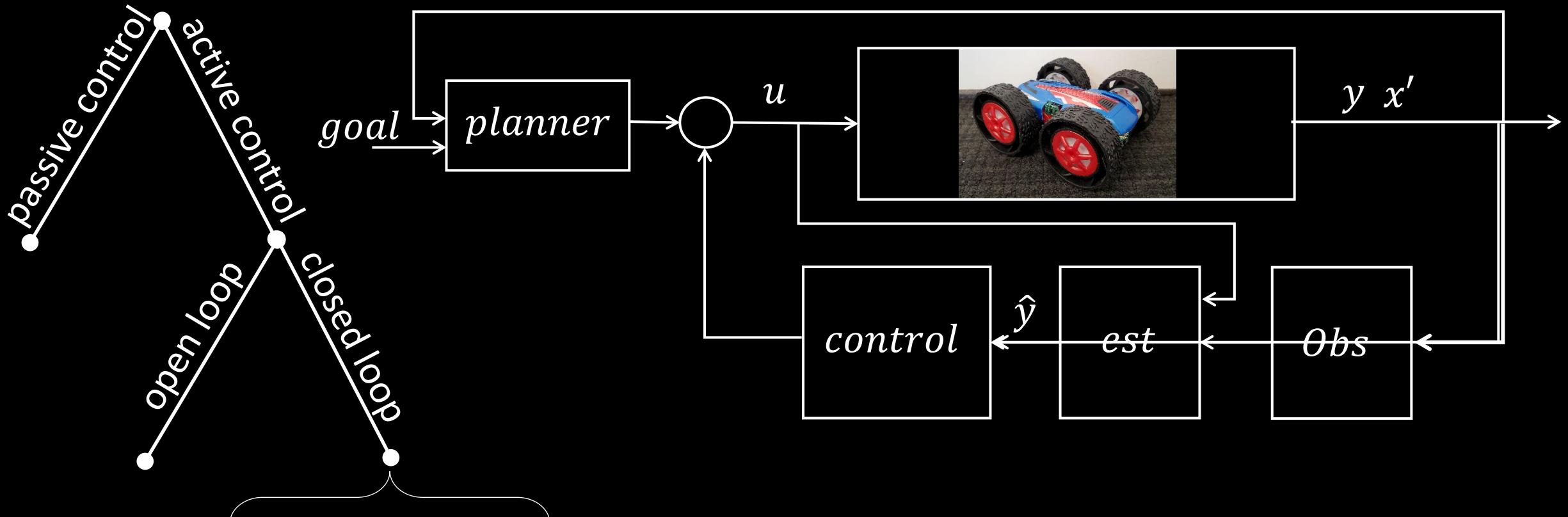


## Why feedback?

- System uncertainty
- Instability
- Disturbances
- Efficiency



# 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**



# Schedule

## Lab 1-5 Hardware / Embedded SW

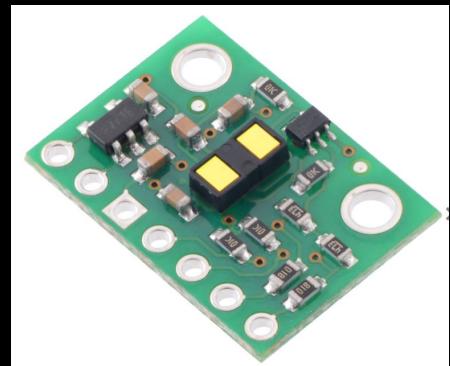
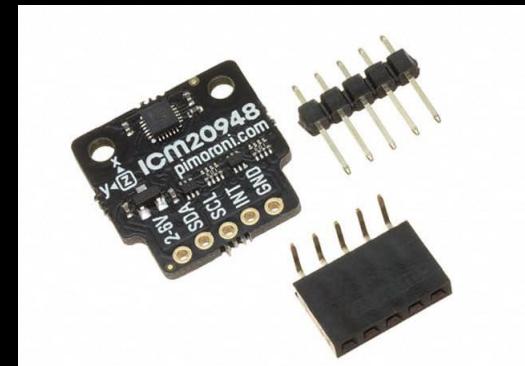
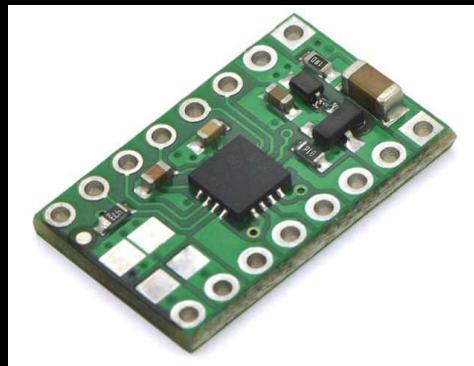
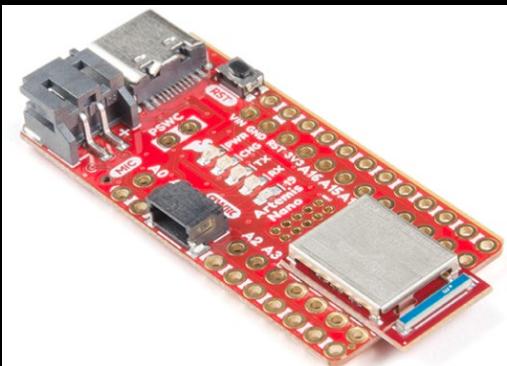
- Combine base with processor, drivers, and sensors
- Refresh on linear algebra and T-matrices
- Sensor modalities and types of sensors
- Actuators, drivers, circuits and routing, and EMI



## Lab 6-9 Feedback Control

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

## Lab 10-12 Localization and Planning



Fast Robots

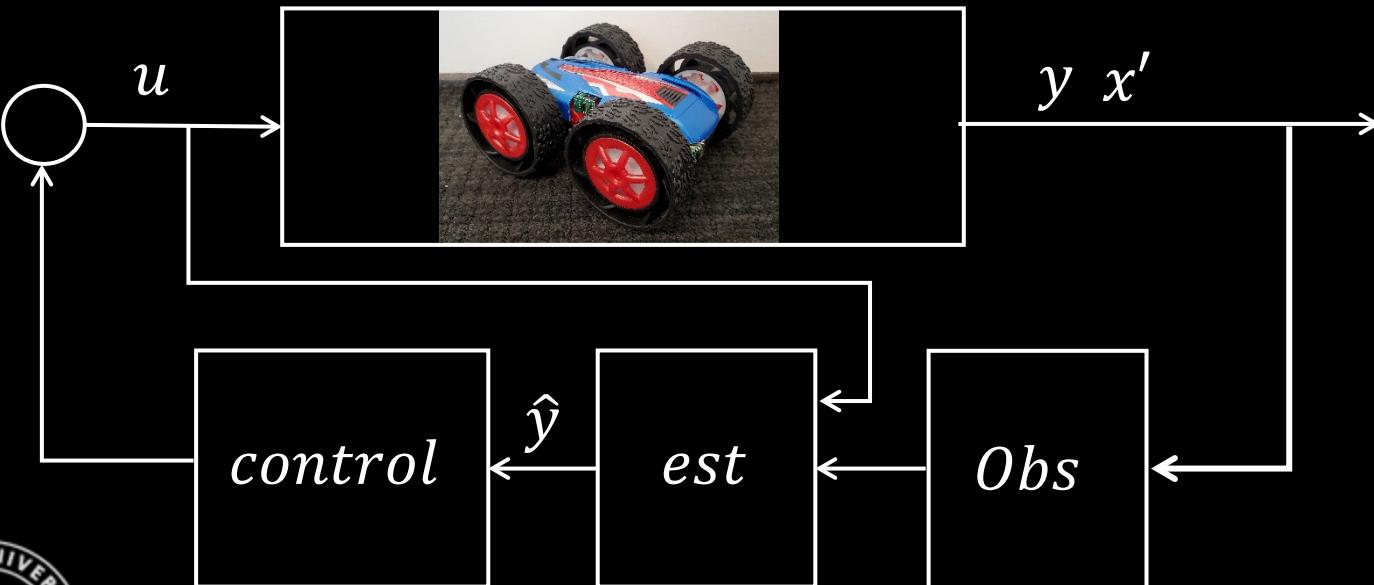
# Schedule

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



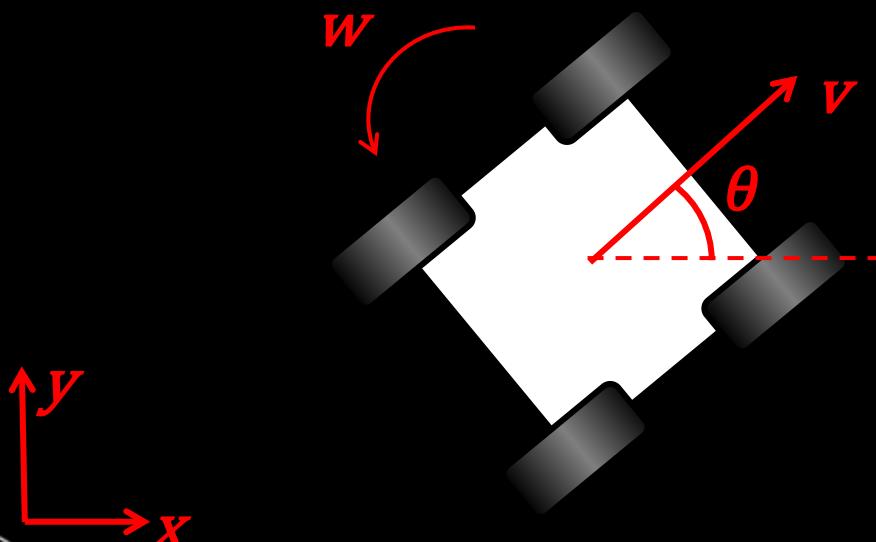
# Schedule

## Lab 1-5 Hardware / Embedded SW

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

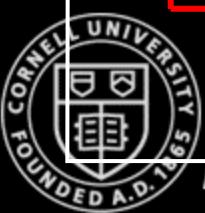
## Lab 6-9 Feedback Control

## Lab 10-12 Localization and Planning



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

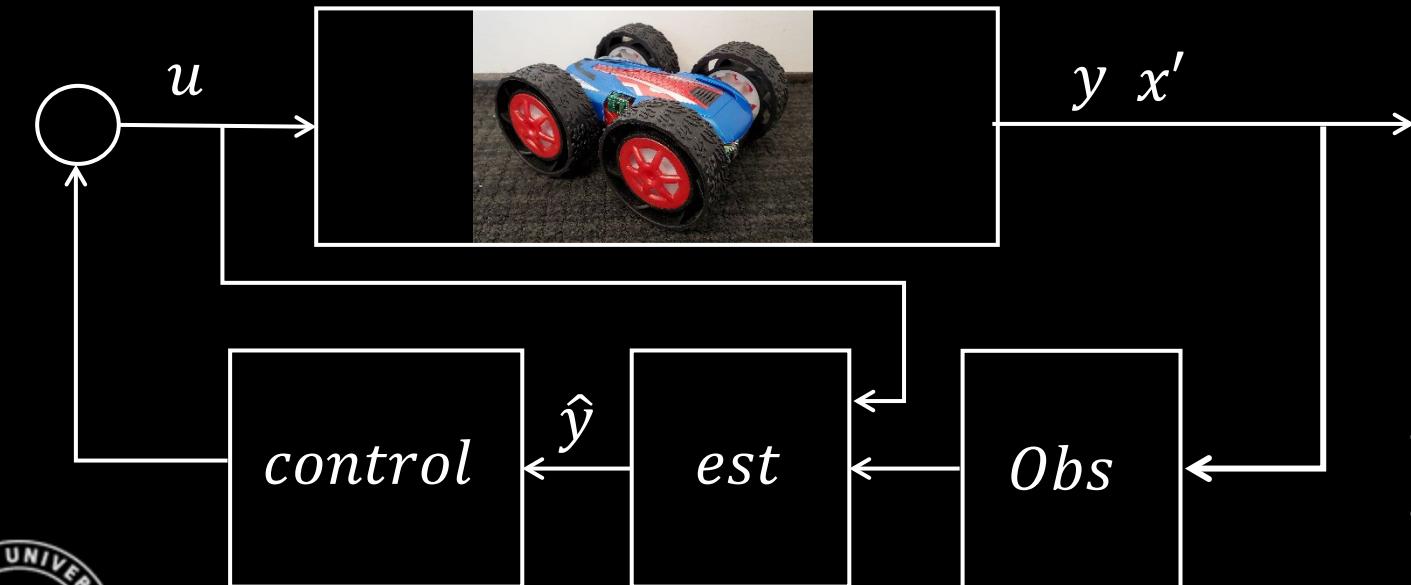
$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos(\theta)v & 0 \\ \sin(\theta)v & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ w \end{bmatrix}$$



# Schedule

## Lab 1-5 Hardware / Embedded SW

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



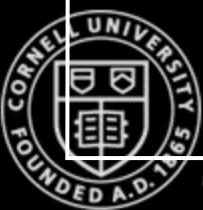
## Lab 6-9 Feedback Control

## Lab 10-12 Localization and Planning



*Why do you think feedback control and observers are necessary?*

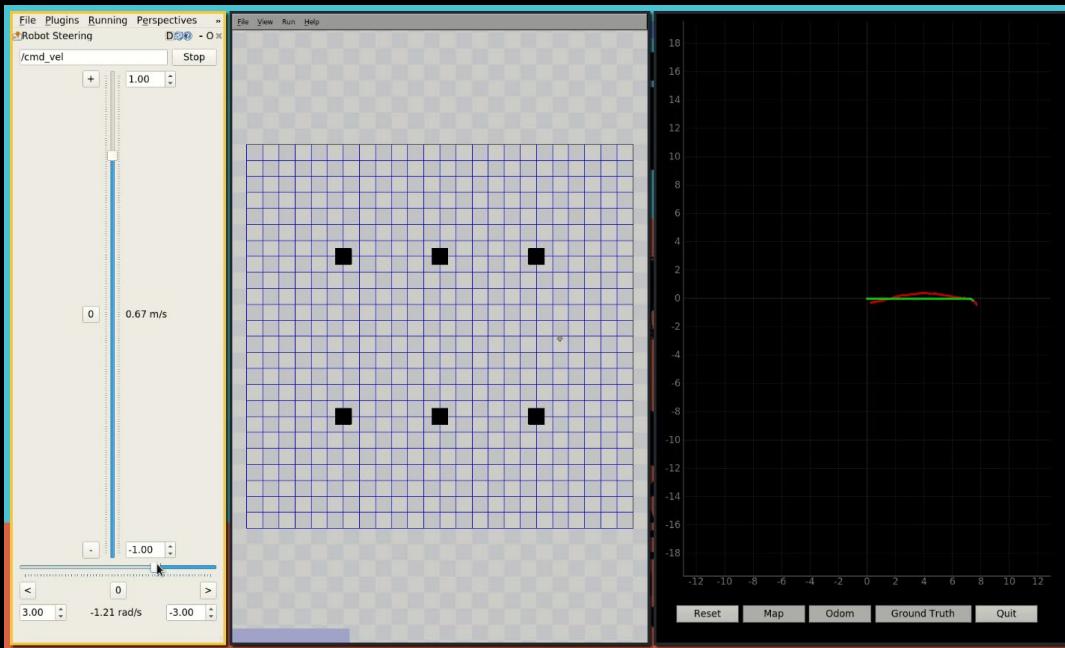
- Performance is battery dependent
- Our sensors are relatively slow
- Etc,



# Schedule

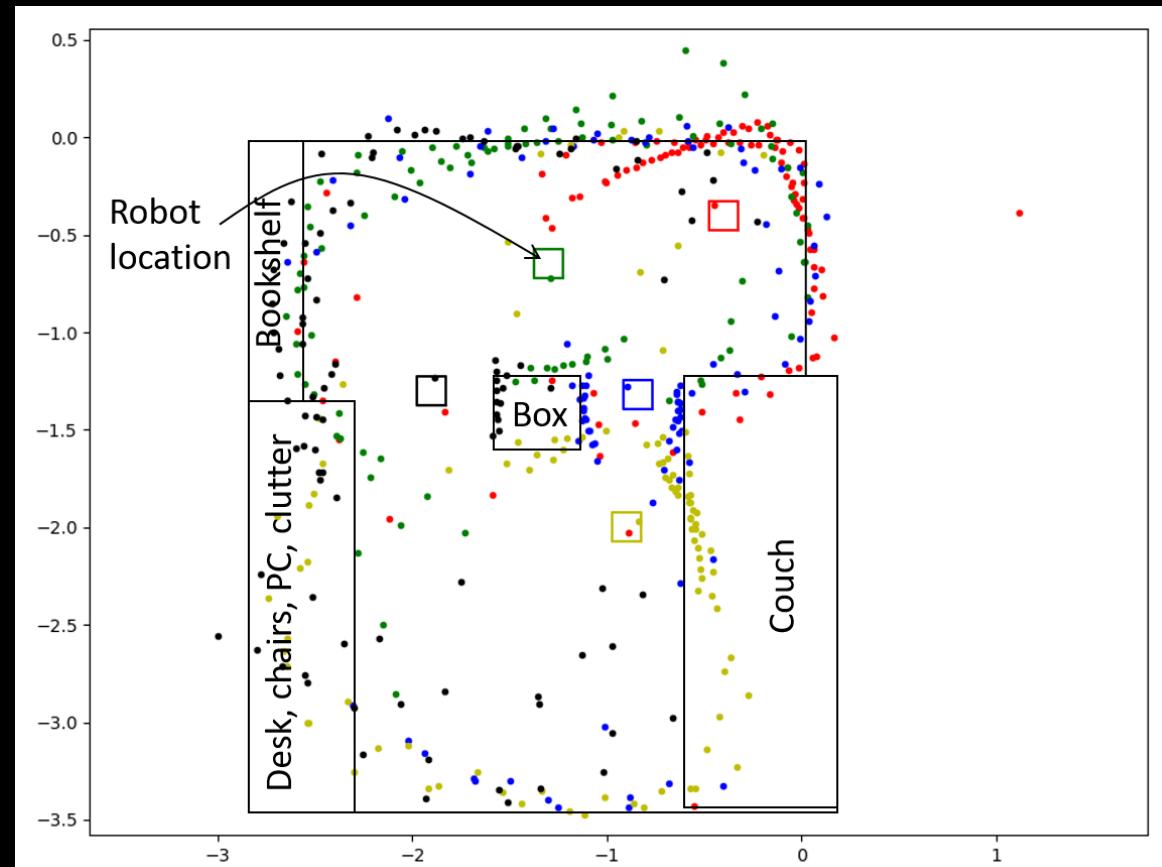
## Lab 1-5 Hardware / Embedded SW

- 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

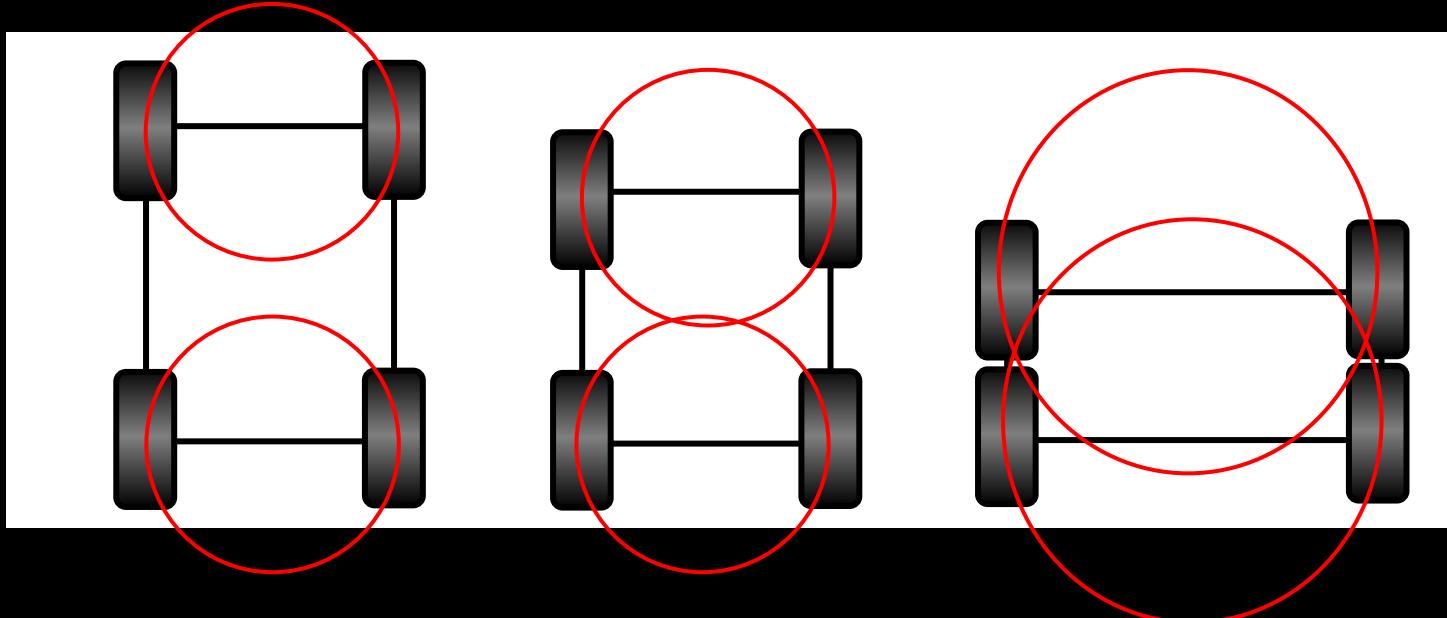
Lab 6-9 Feedback Control

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

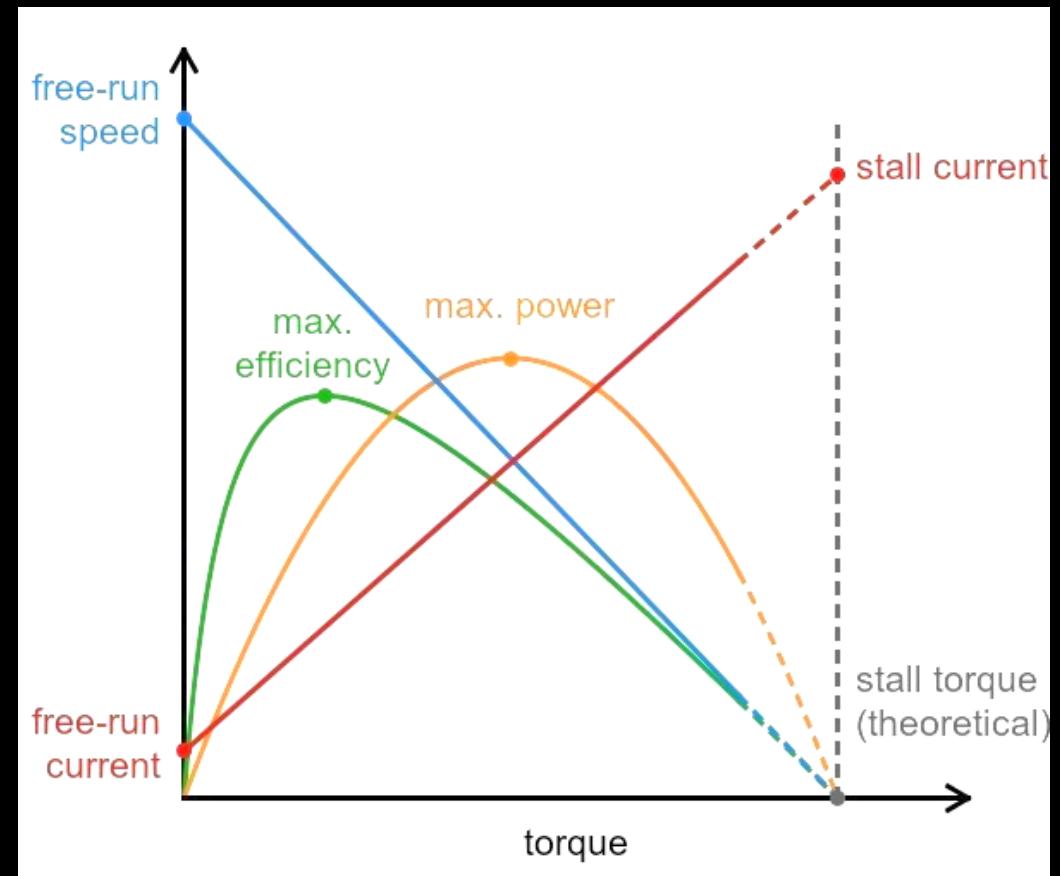
- Map representations
- Search and planning
- Noise, discrete probability
- Motion and sensor models

## *What are sources of error?*

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

## Lab 6-9 Feedback Control

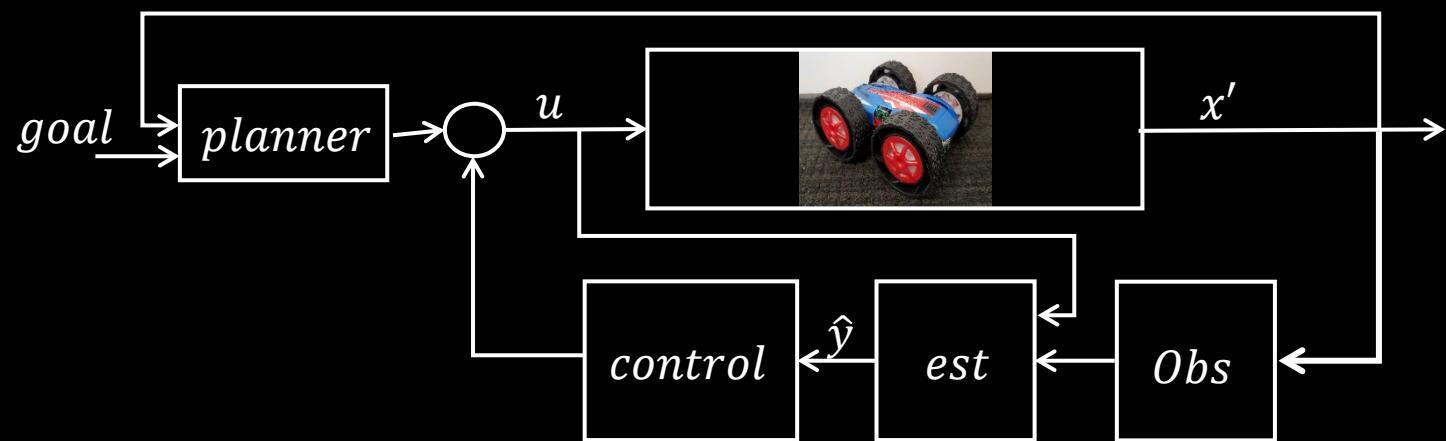
## Lab 10-12 Localization and Planning



# Schedule

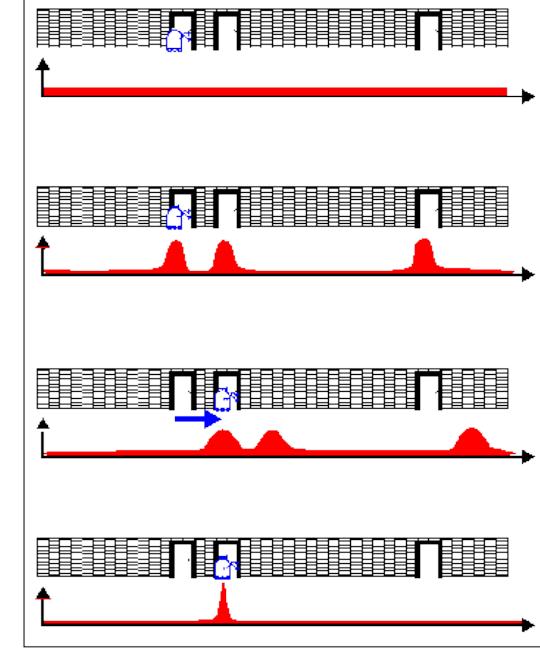
## Lab 1-5 Hardware / Embedded SW

- 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



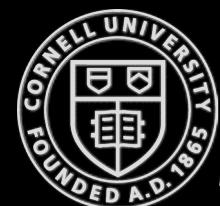
*Fast Robots*

# 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 "New Thread" button with the text "Select a thread".



# 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 1<sup>st</sup> half in lab 1
  - We will hand out the 2<sup>nd</sup> 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

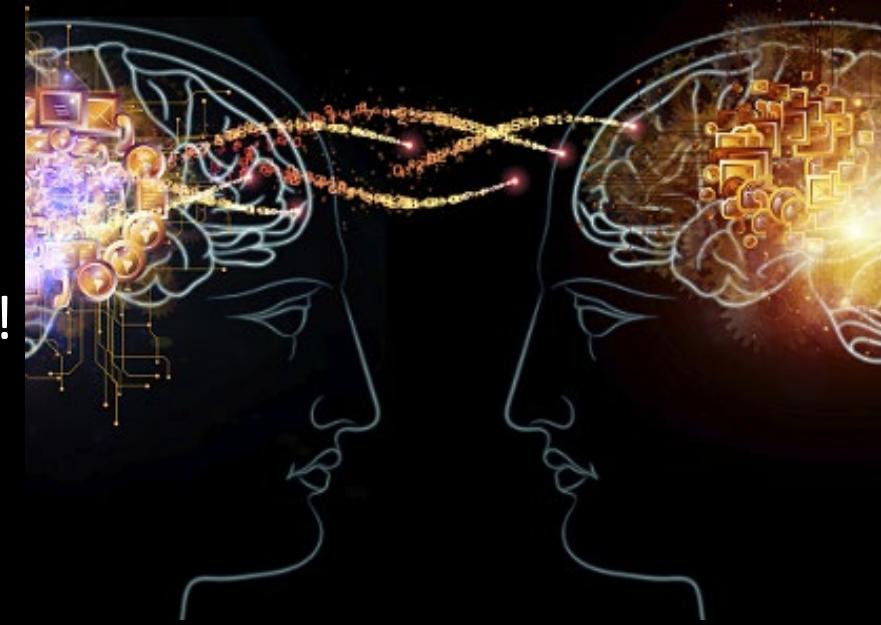
- Grading
  - 12 Labs (90 pts)
    - Points for solution (67)
    - Points for write-up (33)
  - Participation (10 pts)
  - Course evaluations (2 bonus pts)

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](http://www.cei.ece.cornell.edu)

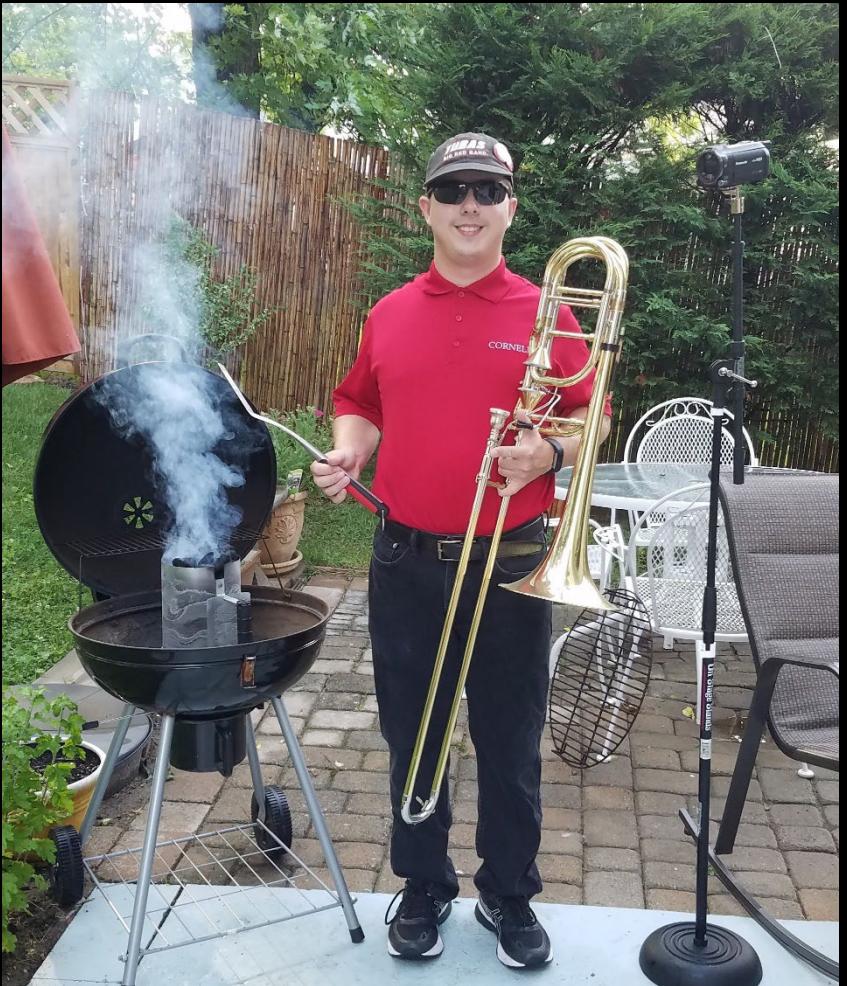
## Mobile and Inflatable Interface for Human Robot Interaction

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



*Fast Robots*

## 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



*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)

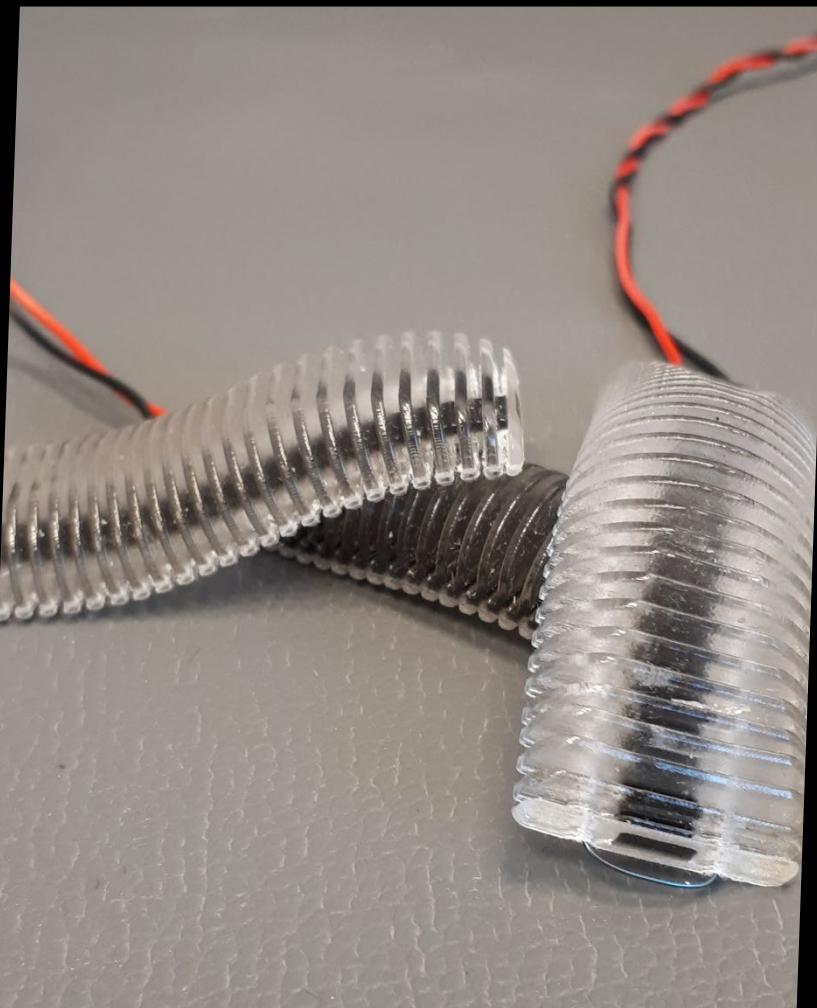
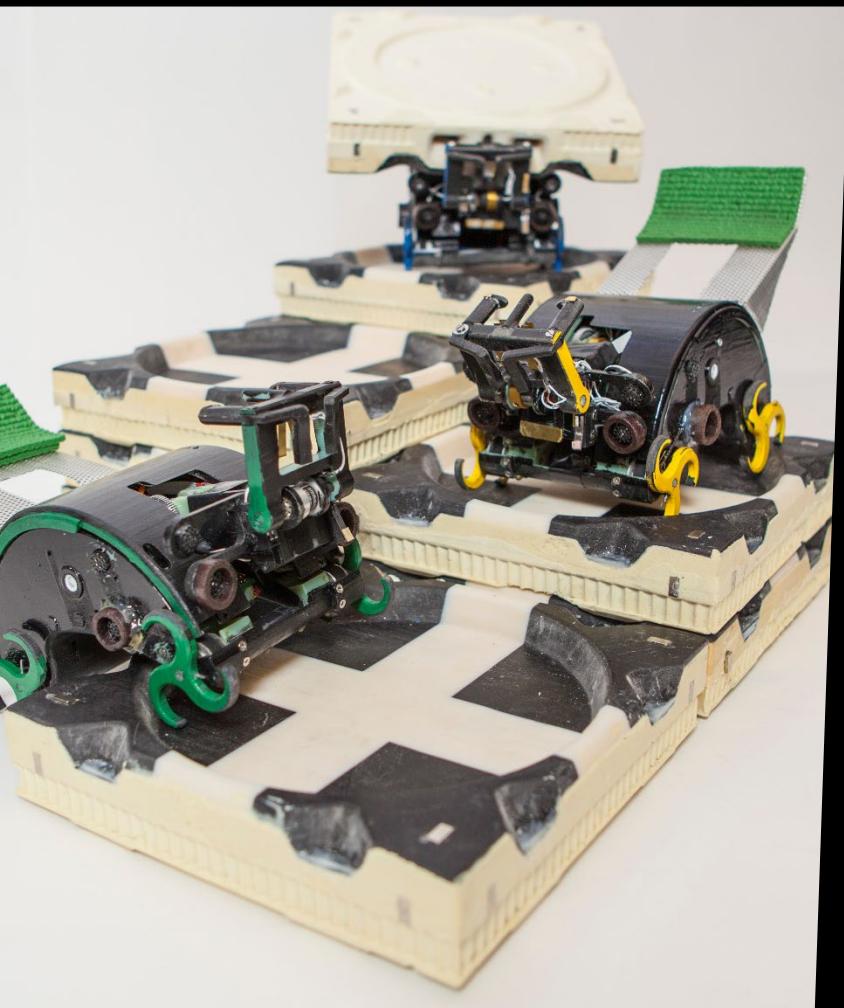


- Saturday Open labs
- Senior in ECE with a minor in CS
- Leads the electrical team at Cornell EWH
- Research in the Peck lab on Cubesats
- Research in the Shepherd lab on soft robots
- --likes turtles!



*Fast Robots*

# Your Teaching Team: Kirstin Petersen



*Collective Embodied Intelligence lab ([www.cei.ece.cornell.edu](http://www.cei.ece.cornell.edu))*



Fast Robots

# Your Teaching Team: Kirstin Petersen

- Autonomous construction



x50



*Fast Robots*

# Your Teaching Team: Kirstin Petersen

- Autonomous construction
- Soft robots

Yoav Matia<sup>1</sup>, Gregory Kaiser<sup>1</sup>, Robert F. Shepherd<sup>1</sup>, Amir Gat<sup>2</sup>, Nathan Lazarus<sup>3</sup>, and Kirstin Petersen<sup>1</sup>

<sup>1</sup>College of Engineering, Cornell University, Ithaca, NY 14853, USA

<sup>2</sup>Technion - Israel Institute of Technology, Technion City, Haifa, Israel 3200003

<sup>3</sup>US Army Research Laboratory, Adelphi, MD 20783, USA

Contact: [ym279@cornell.edu](mailto:ym279@cornell.edu)

## Harnessing non-uniform pressure distributions in soft robotic actuators

In submission with Advanced Intelligent Systems, Oct 2022



Fast Robots

# Your Teaching Team: Kirstin Petersen

- Autonomous construction
- Soft robots
- Microrobots

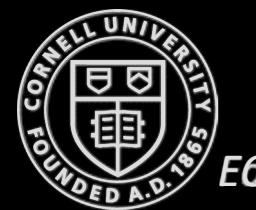
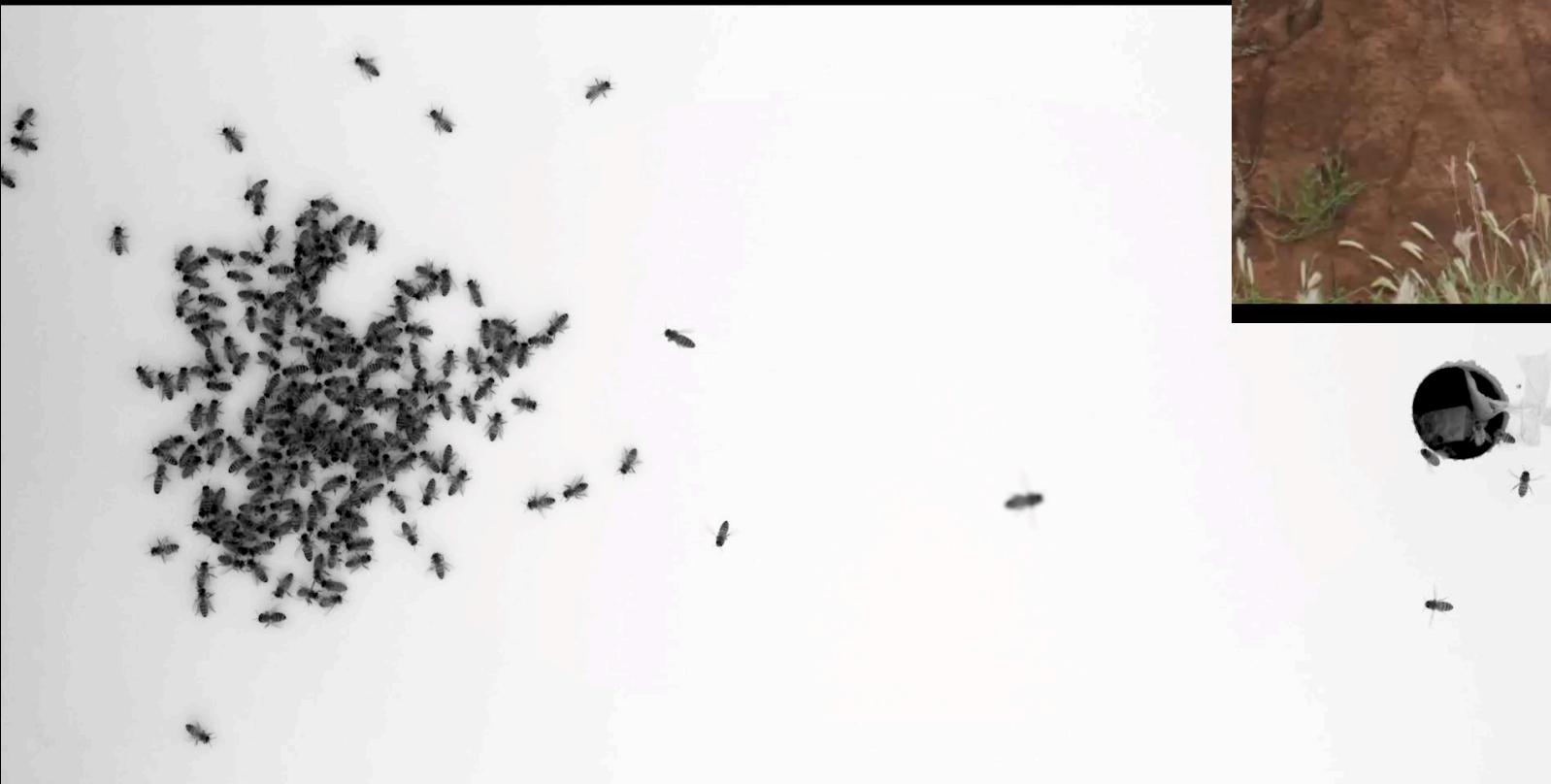
Movie S8: Navigation through an intricate environment



*Fast Robots*

# Your Teaching Team: Kirstin Petersen

- 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 27<sup>th</sup>, 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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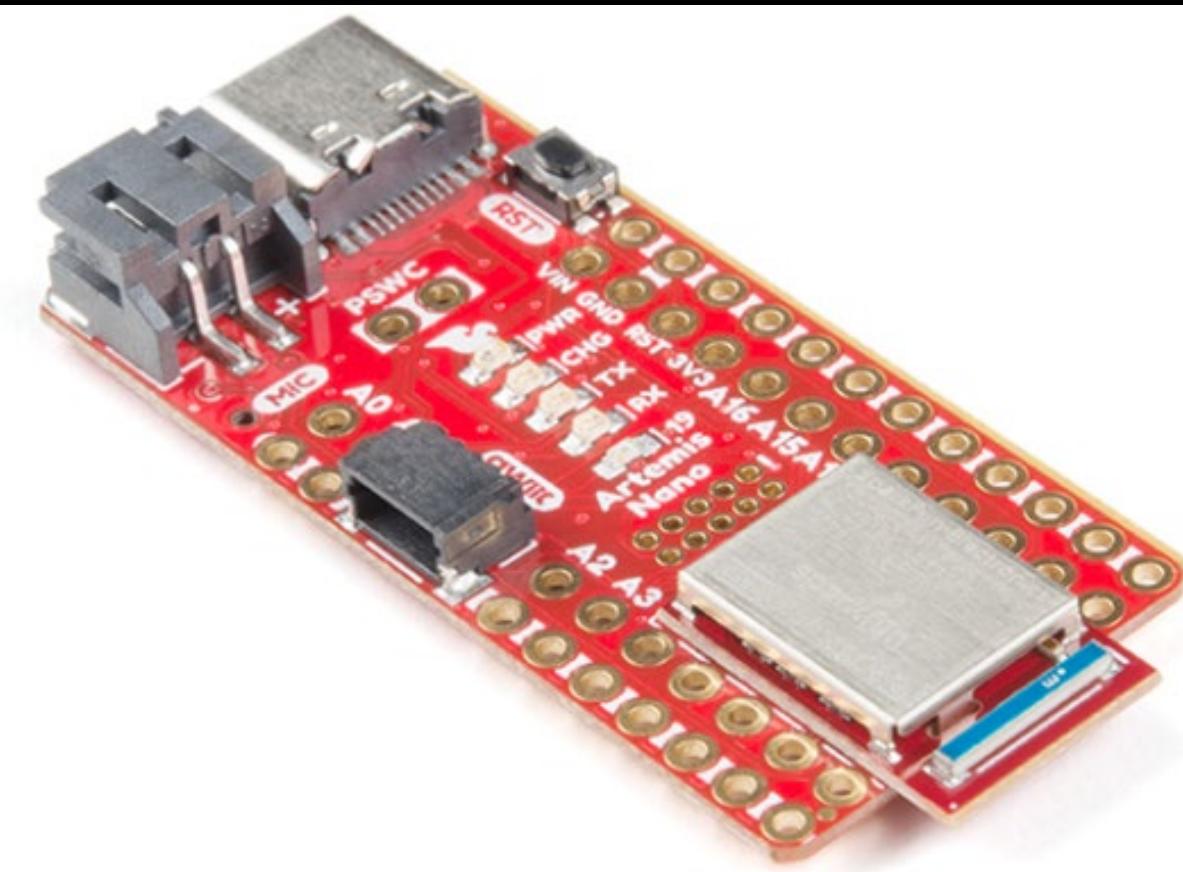
# Fast Robots

## Lab 1: Artemis



*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

# Lab 1: The Artemis Board

[https://cdn.sparkfun.com/assets/d/e/8/b/4/Apollo\\_03\\_Blue MCU Data Sheet v0 12 1 rZ9Akgo.pdf](https://cdn.sparkfun.com/assets/d/e/8/b/4/Apollo_03_Blue MCU Data Sheet v0 12 1 rZ9Akgo.pdf)



## 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<sup>1</sup> 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



Fast Robots

# 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](https://cdn.sparkfun.com/assets/d/e/8/b/4/Apollo3_Blue MCU Data Sheet v0_12_1_rZ9Akgo.pdf)

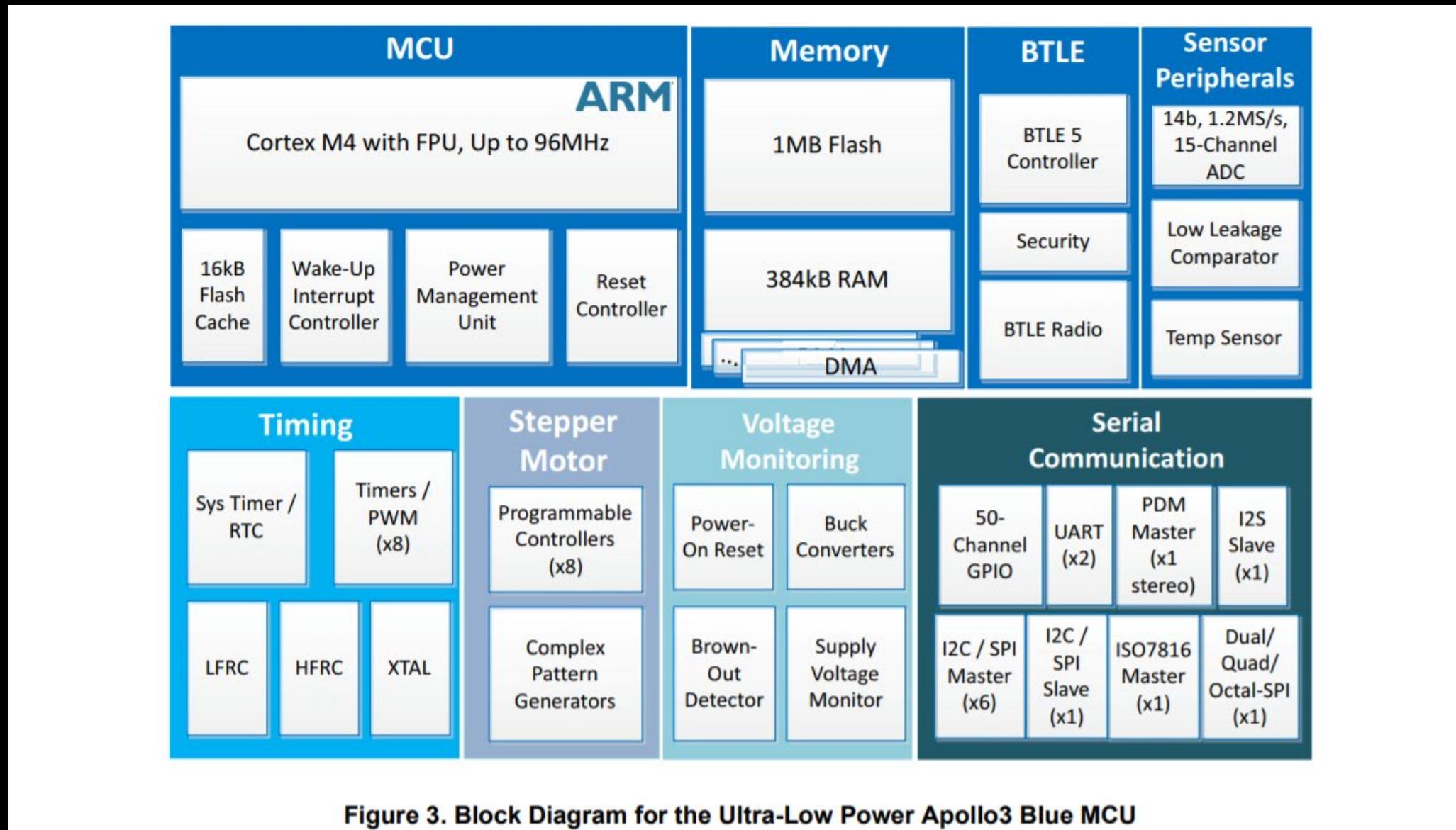


Figure 3. Block Diagram for the Ultra-Low Power Apollo3 Blue MCU



# 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".

