Robotics
Spring 2023
Abhishek Gupta
TAs: Yi Li, Srivatsa GS
Course Logistics

- Where: MEB 242
- When: 11:30-1 Tu/Thu
- Who:
  - Abhishek Gupta (Instructor)
  - Yi Li (TA)
  - Srivatsa GS (TA)
- Office hours:
  - Abhishek: Gates 215, Friday 4-5pm
  - Yi: Gates 152, Thursday 3-4pm
  - Srivatsa: Gates 152, Monday 3-4pm
Course Logistics - Grading

- Grading:
  - 50% of grade is on Final Project
  - 15% of grade is on HW1
  - 15% of grade is on HW2
  - 15% of grade is on HW3
  - 5% participation

- Communications through EdStem/e-mail

- Every week: 2 lectures by Abhishek

- Final projects will be presented in a poster session.
  - Intermediate project proposals and milestone check ins.

- Please participate, otherwise it will be boring for all of us!
Course Logistics - Project

- Final project (50% of grade):
  - Project proposal (1 page)
  - Milestone report (3-4 pages)
  - Final report (6-8 pages)

- Project can be investigating any question related to robotics:
  - New algorithm
  - Performant/stable implementation
  - Empirical investigation
  - New robotic application
  - ...

- Can be done in groups of 1-2 students.
Course Logistics – Homeworks

- 3 homeworks covering 3 class modules:
  - Estimation: EKF/UKF/Particle filtering for localization
  - Control and Planning: RRT/RRT*/A*/D* for motion planning
  - End to end learning: Behavior cloning, Dagger, policy gradient, actor critic
- Homeworks are all in Python, using pybullet or pytorch
Course Logistics - Integrity

- Late policy

You are allowed to use **6 late days throughout the quarter**. After this, assignments turned in late will incur a penalty of 20%, for each day. Please plan ahead.

- Academic Honesty Policy

While we **encourage students to discuss homeworks, each student must write up their own solution.** It’s fine to use a source for generic algorithms (with attribution), but it is not allowed to copy solutions to the problems. Additionally, **students may not post their code online.** If we determine that a student posted their code online, they will get an automatic 50% reduction on the entire assignment (math + code) and if they copy code for the problems from another student or from online, they will get an automatic 0% for the entire assignment (and possibly reported to the college).

Please don’t cheat, make my life easier
Who am I?

- New assistant professor in CSE
- Grew up in Oregon/India, last 10 years in Berkeley
- Undergrad Berkeley, Ph.D. Berkeley, Postdoc MIT.
- Interests: RL/robotics/optimization and control/robustness and generalization
- Outside of work: Tennis/soccer/sketching/dog enthusiast
Who is Yi?

TA: Yi Li

- PhD student in RSElab
- Office hour: Thursday 3-4 pm
- Location: Gates 152
- Email: yili18@cs.washington.edu
- Research Experience:
  - Unseen Object Instance Segmentation and Tracking
  - Object 6D Pose Estimation
  - Instance Segmentation
  - Object Detection
2nd Year Masters Student in ME
- Working on Visual Odometry and SLAM on the RACER project.
- Previously worked on 6Dof Grasp generation and packing in UW-Amazon manipulation research and at Voaige Inc.
- Office hours: Gates 152, Monday 3-4pm
What is a robot?

- First definitions:
  - Karel Capek → robots were biological beings performing unpleasant labor.

Herbert Televox (1927)  Eric (1928)  Unimate (1961)
The first wave of robots

Shakey

Engelberger (Unimate ++)

Honda P series
The second wave of robots

DARPA Grand Challenge

PR1 Robot
Robots Today

Everyday Robotics - Google

Atlas – Boston Dynamics
Robotics Spans Applications and Industries

- Applicable in a variety of industries and spaces:
  
  - Industry:
    - Industrial manufacturing
    - Warehouse navigation
  
  - Outdoor navigation/locomotion:
    - Legged locomotion
    - Outdoor navigation
    - Last mile delivery
    - Self driving cars
  
  - Home and office manipulation
    - Mobile manipulation
    - Dexterous manipulation
Industrial Robotics
Industrial Robotics Today
Industrial Pick and Place
Navigation
Outdoor Off-Road Autonomy
Locomotion
Boston Dynamics BigDog (2008)
RoboCup
Boston Dynamics Spot
Humanoid Parkour
Drone Delivery
Indoor Manipulation
Dexterous Manipulation
Mobile Manipulation
Do you want me to solve that Rubik's Cube?
How should we start to formalize the robotics problem?

- **Agent**: Rational entity equipped with sensors and actuators
- **Environment**: accepts actuation commands and steps forward according to some dynamics
Graphical Model of Robotics

- **State**: Minimum sufficient statistic encapsulating the world, sufficient for prediction

- **Measurement/Observation**: Current sensor readings, potentially partially observed

- **Action**: Actuators that agent can use to affect the state
Graphical Model of Robotics

- **State**: sufficient statistic encapsulating the world, sufficient for prediction (this is a choice)

- **Measurement/Observation**: Current sensor readings, potentially partially observed (this is a choice)

- **Action**: Actuators that agent can use to affect the state (this is a choice)
Robotics has three primary subpieces:

1. **Sensing** → from measurements
2. **Planning** → from models
3. **Acting** → in the world
Sensing: Why is it nontrivial?

- Sensors have overwhelming amounts of information
- Partially observed
- Noisy and prone to drift
State is never perfectly known, only a belief over state can be estimated.
Probabilistic Robotics

A robot that carries a notion of its own uncertainty and that acts accordingly is superior to one that does not.

- Maintaining uncertainty allows for
  - Information gathering
  - Robustness to imperfect sensing and actuation
  - Interpretability
  - Exploration
Planning: Why is it nontrivial?

- Searching/Optimization through a complex non-convex space
- Combination of discrete/continuous optimization
Rational Agents and Utility Maximization

- How do we even formulate planning?
  - Utility maximization: trajectory optimization
  - Search: shortest path finding

- Viewing planning through the lens of rationality allows us to use tools from optimization
Acting: Why is it nontrivial?

- Robot systems in the real world are subject to significant perturbations/noise → need to be stable in the face of these perturbations
Low-level control and Stabilization

- Unstable/suboptimal systems can be catastrophic
Focus on addressing all problems at once

\[ M(q)\ddot{q} + C(q, \dot{q})\dot{q} = \tau_g(q) + Bu, \]

State Estimation \rightarrow Modeling and Prediction \rightarrow High-level planning

Low-level planning \rightarrow Low-level control
What makes robotics hard?

Unique interplay of expectations and assumptions

- Expectations
- Assumptions
Expectations

- Significantly larger set of tasks being performed
- Failure can be catastrophic and unsafe
- Precision required may be much larger than other decision making problems
- Multi-step decision making problems
Assumptions

- Limited data due to the real world
- No perfect simulator
- Chicken and egg problem on deployment
- Evaluation is difficult
Why now?

Hardware is getting cheaper and more accessible

400K

30K

5K
Why now?

Algorithms/models have started maturing/stabilizing
Why now?

Data/compute is now available at a scale not possible before
Why now?

Adjacent fields are showing remarkable progress
Why now?

- Fast growing investment into automation/robotics
Is robotics useful to study beyond applications?

Arguably intelligence needs embodiment

- visually-guided paw placement:
- avoidance of a visual cliff
- blink to an approaching object:
- visual pursuit of a moving object:
- pupillary reflex to light:
- tactual placing response

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Robotics may be a way to study fundamental intelligence
Zooming out – why this matters for the study of intelligence?

Hypothesis: Intelligence with and without embodiment looks drastically different

Elephants don’t play chess!
Under certain assumptions, the optimal state estimation + optimal deterministic control yields an optimal system

\[ \dot{x} = Ax + Bu \]
\[ y = Cx \]

\[ u = -K\hat{x} \]
\[ u = -Kx \]

\[ \dot{\hat{x}} = A\hat{x} + Bu + L(y - C\hat{x}) \]
\[ \dot{e} = (A - LC)e \]

Control as if you had perfect state

Estimate as if you didn’t care about control

Not always true!
Why do we care?

\[ \hat{x} = A\hat{x} + Bu + L(y - C\hat{x}) \]
\[ \dot{e} = (A - LC)e \]

Module 1: Estimation

- Filtering/Smoothing
- Localization
- Mapping
- SLAM
Why do we care?

Module 2: Planning/Control

\[ u = -K \hat{x} \]
\[ u = -K x \]
When does this not hold?

\[ u = -K \hat{x} \]
\[ u = -Kx \]

Not always true!

\[ \hat{x} = A\hat{x} + Bu + L(y - C\hat{x}) \]
\[ \dot{e} = (A - LC)e \]

Imperfect and arbitrarily non-linear systems

MDPs and Reinforcement Learning

Imitation Learning

Solving POMDPs
How does a typical robotics pipeline look?

\[ M(q) \ddot{q} + C(q, \dot{q}) \dot{q} = \tau_g(q) + Bu, \]

State Estimation → Modeling and Prediction → High-level planning → Low-level planning → Low-level control
Deep reinforcement learning pipeline for robotics

State Estimation → Modeling and Prediction → High-level planning

State Estimation → Modeling and Prediction → Low-level planning

End to end policy – perception + control

Not quite so simple, agent environment interface must be chosen!
Why might we not want to do this?

Lack of Interpretability
Lack of Reusability
Often data inefficient

Modules compensate for each other
Avoids hand-designing and supervising interfaces
Often more performant/less biased
Course Outline

Filtering/Smoothing  Localization
Mapping  SLAM

Search  Motion Planning
TrajOpt  Stability/Certification

MDPs and RL
Imitation Learning  Solving POMDPs
Goal of this course

- Understand what makes robotics so challenging
- Cover fundamental techniques and provide historical context on methods in robotics estimation and planning
- Provide exposure to state of the art and modern techniques in robotics and control
What broader tools will we learn?

**Estimation:**
- Bayesian Inference
- Maximum likelihood inference

**Control:**
- Discrete search
- Convex optimization
- Dynamic Programming

**End to end:**
- Statistical inference
- Deep neural networks
- Reinforcement Learning

Useful beyond robotics across decision making problems
What we will not cover?

Kinematics or Dynamics Modeling

\[ M(q)\ddot{q} + C(q, \dot{q})\dot{q} = \tau_g(q) + Bu, \]
What we will not cover?

Advances in Computer Vision
What we will not cover?

Task and Motion Planning

Humanoid Manipulation Planning using Backward-Forward Search

by
Michael X. Grey and Caelan R. Garrett
advised by
C. Karen Liu, Aaron D. Ames, and
Andrea L. Thomaz

Goal: all objects are on different-color regions
\( \forall o_1. \exists o_2. \text{Region}(o_2) \land \neg \text{Region}(o_1) \rightarrow \text{Color}(o_1) \neq \text{Color}(o_2) \land \text{On}(o_1, o_2) \)