16-782 Fall’19
Planning & Decision-making in Robotics

Introduction;
What is Planning, Role of Planning in Robots

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Robotics Institute

Carnegie Mellon University

Class Logistics

- Instructor:

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- TA:

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- Website:

  http://www.cs.cmu.edu/~maxim/classes/robotplanning_grad

- Mailing List for Announcements and Questions:

  - 16782-pdr-fall19@lists.andrew.cmu.edu
  - TA will send a "welcome" email to everyone

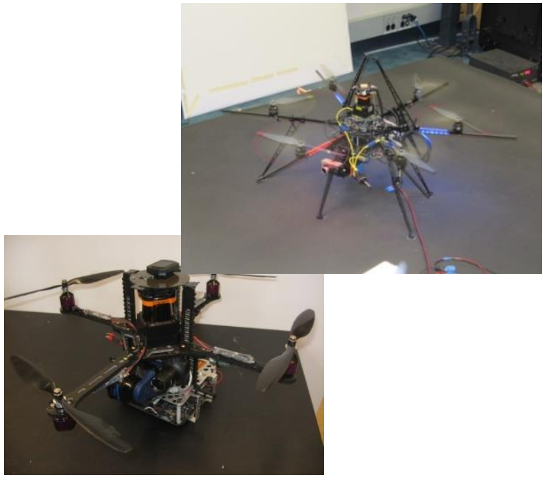
For those on the waitlist

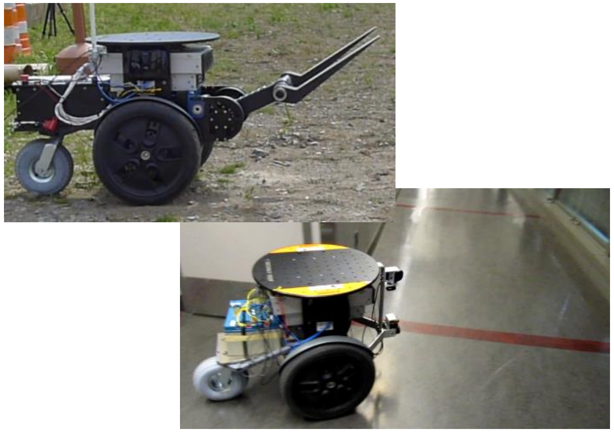
- **Consider** taking the undergraduate (basic) version:
  - 16-350 in Spring’20
  - basic version of this course (70% overlap, easier assignments)
  - <u>Master students should be able to register for it</u>
  - see syllabus from Spring’19:
    http://www.cs.cmu.edu/~maxim/classes/robotplanning

About Me

- My Research Interests:
  - Planning, Decision-making, Learning
  - Applications: planning for complex robotic systems including aerial and ground robots, manipulation platforms, small teams of heterogeneous robots

- More info: *http://www.cs.cmu.edu/~maxim*
- Search-based Planning Lab: *http://www.sbpl.net*





What is Planning?

- According to Wikipedia: *"Planning is the process of thinking about an organizing the activities required to achieve a desired goal."*

What is Planning **for Robotics**?

- According to Wikipedia: *"Planning is the process of thinking about an organizing the activities required to achieve a desired goal."*

- ***Given***
  - *model (states and actions) of the robot(s)* $M^R = \langle S^R, A^R \rangle$
  - *a model of the world* M^W
  - *current state of the robot* $s^R_{current}$
  - *current state of the world* $s^W_{current}$
  - *cost function C of robot actions*
  - *desired set of states for robot and world G*

- ***Compute a plan π that***
  - *prescribes a set of actions* $a_1,\ldots a_K$ *in* A^R *the robot should execute*
  - *reaches one of the desired states in G*
  - *(preferably) minimizes the cumulative cost of executing actions* $a_1,\ldots a_K$

Few Examples

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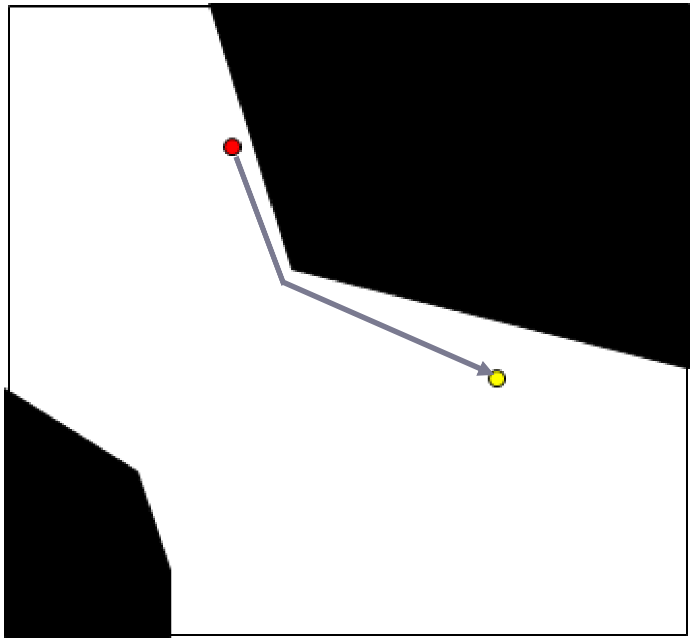
Planning for omnidirectional robot:

What is M^R*?*
What is M^W*?*
What is $s^R_{current}$*?*
What is $s^W_{current}$*?*
What is C?
What is G?



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Planning for omnidirectional drone:

What is M^R?
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MacAllister et al., 2013

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Planning for autonomous navigation:

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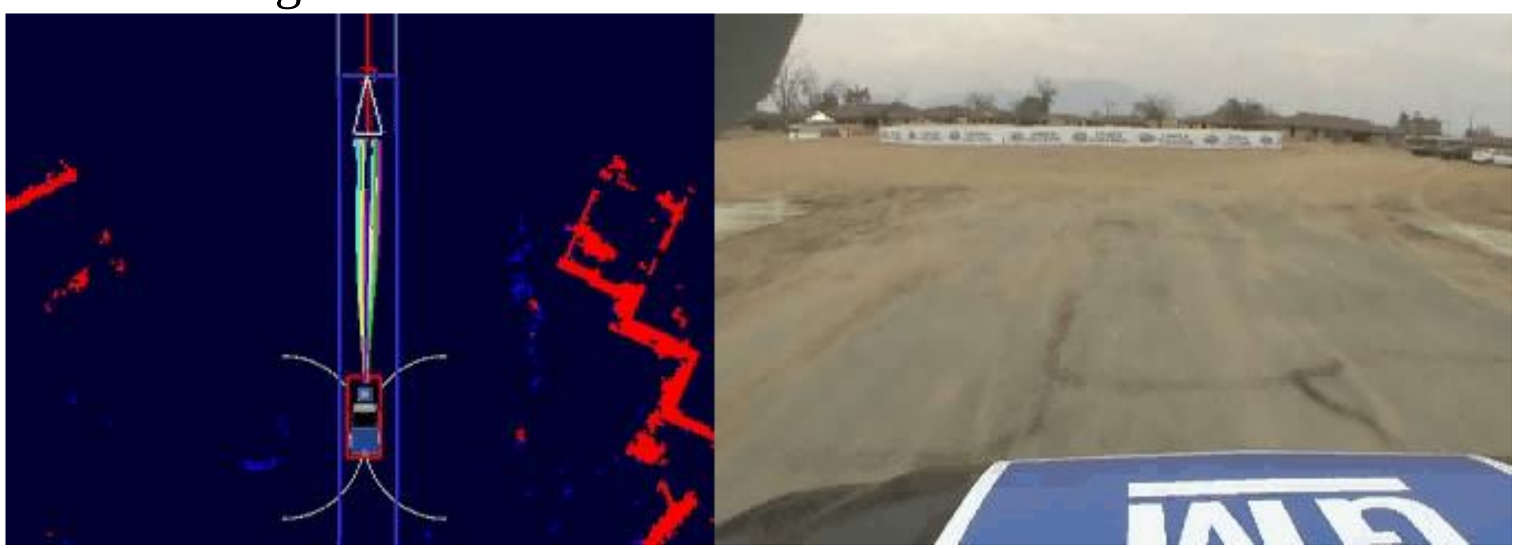

Likhachev & Ferguson, '09; part of Tartanracing team from CMU for the Urban Challenge 2007 race

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Planning for autonomous flight among people :

Narayanan et al., 2012

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Planning for a mobile manipulator robot opening a door:

Gray et al., 2013

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Planning for a mobile manipulator robot assembling a birdcage: *Cohen et al., 2015*

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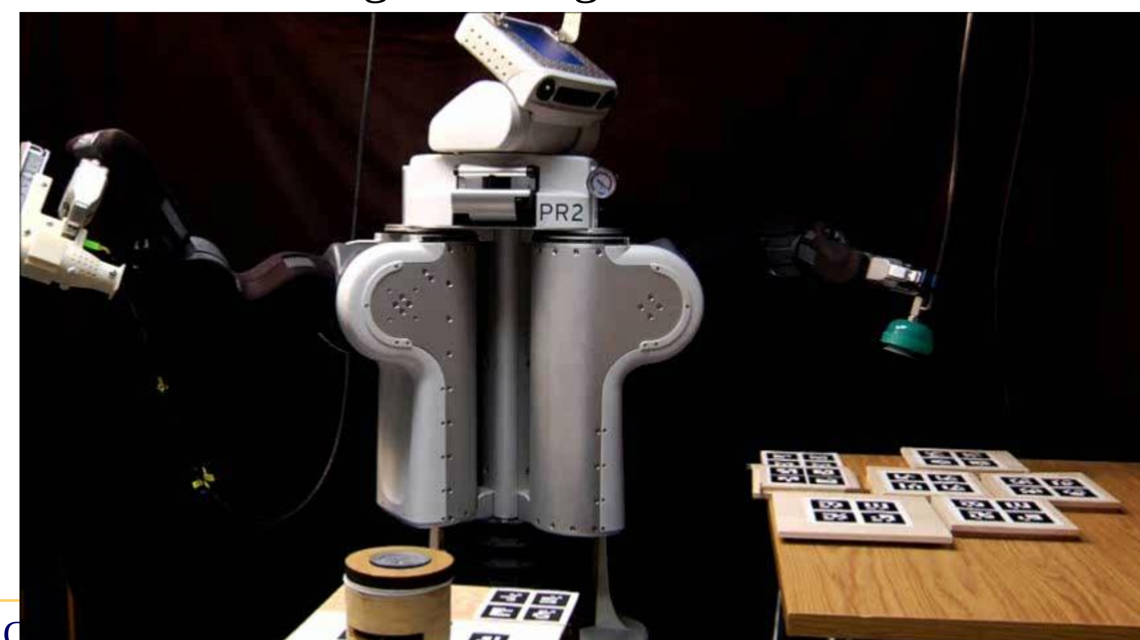

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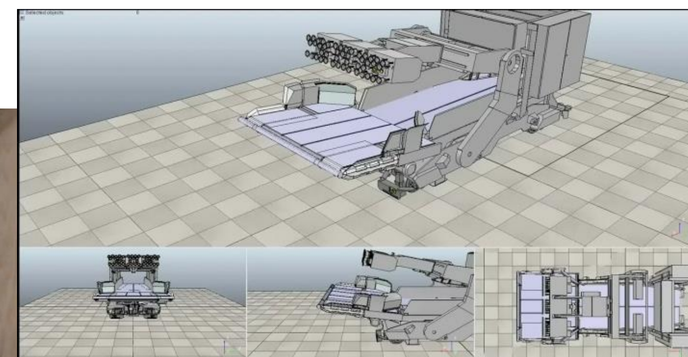
Planning for a mobile manipulator unloading a truck:



What is M^R?

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Assuming Infinite Computational Resources…

Where does Planning break?

Assuming Infinite Computational Resources…

Where does Planning break?

Reliance on the knowledge/accuracy of the model!

Role of Learning in Planning?

Planning vs. Learning

Model-based approach

Learning models M^R, M^W and cost function C

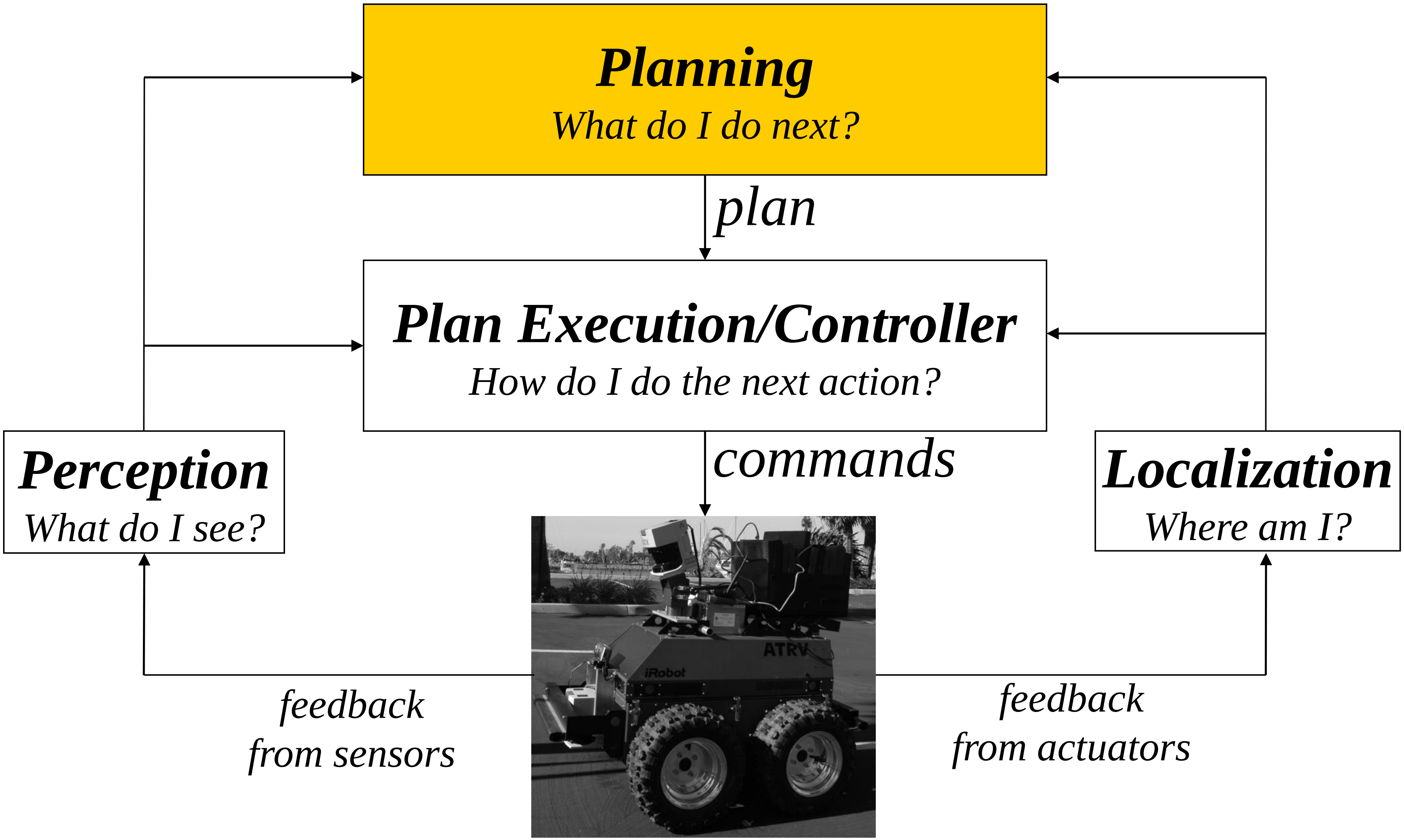
models M^R, M^W and cost function C

Planning using models M^R, M^W and cost function C

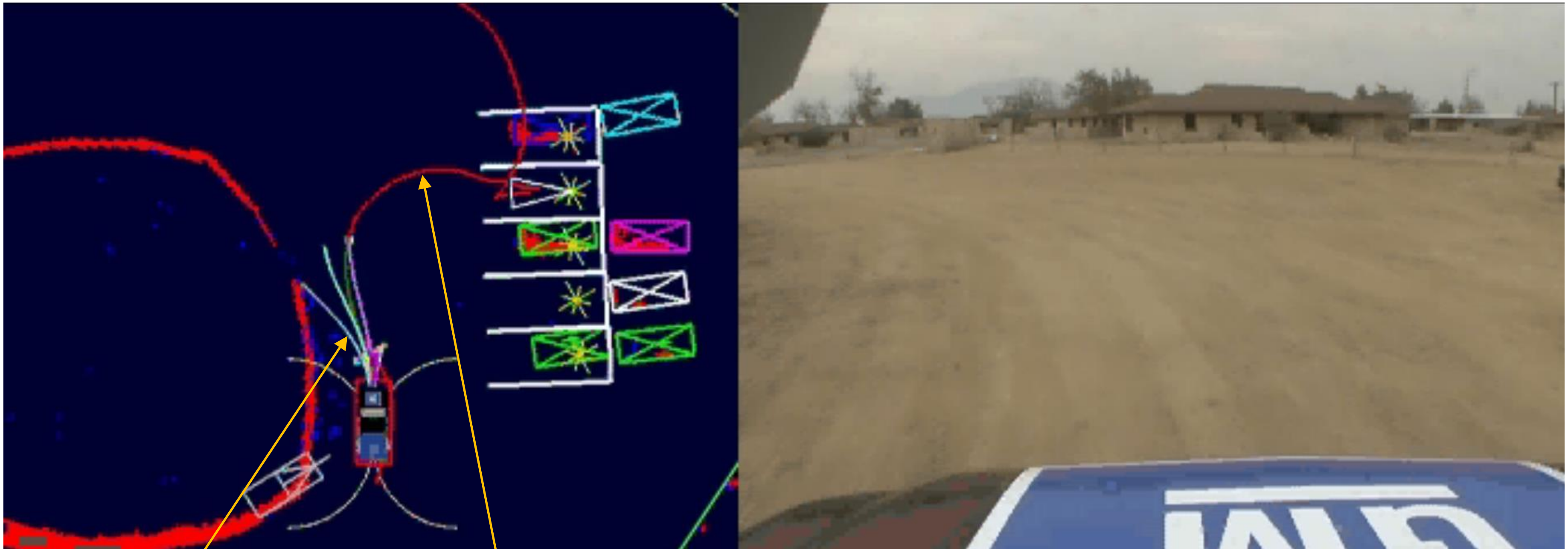
Model-free approach

Learning the mapping from "what robot sees" onto "what to do next" using rewards received by the robot (Reinforcement Learning)

Planning within a Typical Autonomy Architecture

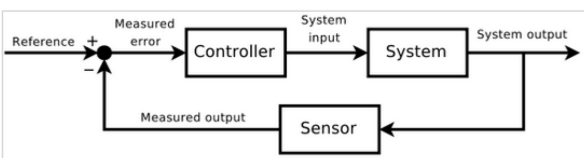


Planning vs. Trajectory Following vs. Control

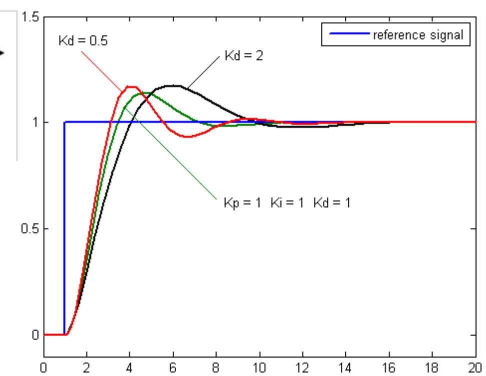


local planning
(trajectory following)

global planning



controller



Images from wikipedia

Class Logistics

- Books (optional):

- Planning Algorithms *by Steven M. LaValle*

- Heuristic Search, Theory and Applications *by Stefan Edelkamp and Stefan Schroedl*

- Principles of Robot Motion, Theory, Algorithms, and Implementations *by Howie Choset, Kevin M. Lynch, Seth Hutchinson, George A. Kantor, Wolfram Burgard, Lydia E. Kavraki and Sebastian Thrun*

- Artificial Intelligence: A Modern Approach *by Stuart Russell and Peter Norvig*

Class Prerequisites

- Knowledge of programming (e.g., C, C++)

- Working knowledge of data structures & basic Computer Science algorithms (e.g., graphs, linked lists, priority queues, BFS/DFS, etc.)

- Prior exposure to robotics

Class Objectives

- Understand and learn how to implement most popular planning algorithms in robotics including heuristic search-based planning algorithms, sampling-based planning algorithms, task planning, planning under uncertainty and multi-robot planning

- Learn basic principles behind the design of planning representations

- Understand core theoretical principles that many planning algorithms rely on and learn how to analyze theoretical properties of the algorithms

- Understand the challenges and basic approaches to interleaving planning and execution in robotic systems

- Learn common uses of planning in robotics

Tentative Class Schedule

TENTATIVE SCHEDULE FOR Planning and Decision-making in Robotics CLASS
Fall 2019

Date	Day	Topic	HW out	HW due
26-Aug	Mon	Introduction; What is Planning?		
28-Aug	Wed	planning representations: explicit vs. implicit graphs, skeletonization, cell decomposition & lattice-based graphs		
2-Sep	Mon	LABOR DAY - NO CLASS		
4-Sep	Wed	search algorithms: A*, Weighted A*, Backward A*		
9-Sep	Mon	search algorithms: Heuristic functions, Multi-Heuristic A*	HW1	
11-Sep	Wed	interleaving planning and execution: Anytime heuristic search, Incremental heuristic search		
16-Sep	Mon	interleaving planning and execution: Real-time heuristic Search		
18-Sep	Wed	case study: planning for autonomous driving		
23-Sep	Mon	planning representations: PRM for continuous spaces		HW1
25-Sep	Wed	planning representations/search algorithms: RRT, RRT-Connect	HW2	
30-Sep	Mon	planning representations/search algorithms: RRT*		
2-Oct	Wed	case study: planning for mobile manipulators and legged robots		
7-Oct	Mon	search algorithms: Multi-goal A*, Markov Property, dependent vs. independent variables, Dominance		
9-Oct	Wed	case study: planning for coverage, mapping and surveillance tasks		HW2
14-Oct	Mon	planning representations: state-space vs. symbolic representation for task planning	HW3	
16-Oct	Wed	search algorithms: planning on symbolic representations		
21-Oct	Mon	planning under uncertainty: Minimax formulation, Minimax Backward A*		
23-Oct	Wed	planning under uncertainty: Markov Decision Processes, Value Iteration, RTDP		
28-Oct	Mon	planning under uncertainty: Partially-Observable Markov Decision Processes		HW3
30-Oct	Wed	planning under uncertainty: Partially-Observable Markov Decision Processes (cont'd)		
4-Nov	Mon	final project proposal presentations		
6-Nov	Wed	learning in planning		
11-Nov	Mon	learning in planning (cont'd)		
13-Nov	Wed	multi-robot planning		
18-Nov	Mon	multi-robot planning (cont'd)		
20-Nov	Wed	exam review		
25-Nov	Mon	exam		
27-Nov	Wed	THANKSGIVING - NO CLASS		
2-Dec	Mon	TBD		
4-Dec	Wed	final project presentations		

Three Homeworks + Final Project

- <u>All homeworks are individual</u> (no groups)

- Final projects is a group project (3-5 people per group)

- Homeworks are programming assignments based on the material

- Final project is a research-like project
  - For example: to develop and implement a planner for a robot planning problem of your choice
  - Or: to extend a particular planning algorithm to improve its running time or to handle additional conditions

  - Two presentations (proposal and final) and meetings with groups

Class Structure

- Grading

Three homeworks	33%
Exam	20%
In-class pop quizzes	10%
Final project	32%
Participation	5%

- Exam is tentatively scheduled for Nov. 25 (<u>no final exam</u>)

- Late Policy
  - 3 free late days
  - No late days may be used for the final project!
  - Each additional late day will incur a 10% penalty

Questions about the class?