16-782 Fall'21
Planning & Decision-making in Robotics

Introduction;
What is Planning, Role of Planning in Robots

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Carnegie Mellon University

Class Logistics

- Instructor:

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- Website:

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

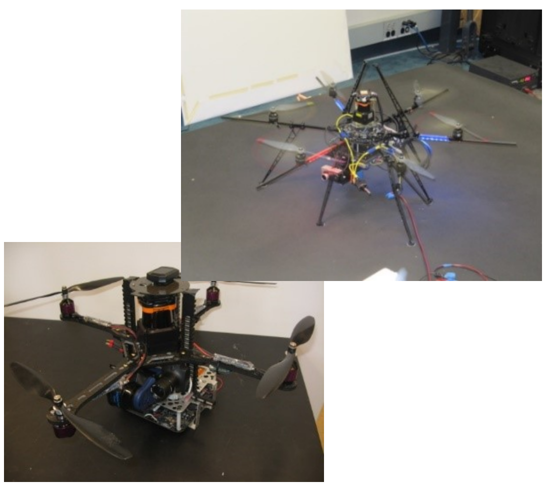
- Announcements, Questions, Recorded Lectures:

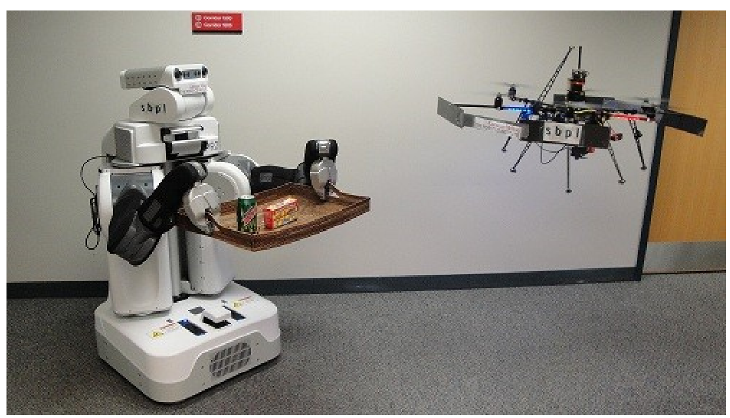
  - on Piazza
  - Should have received an email with access info

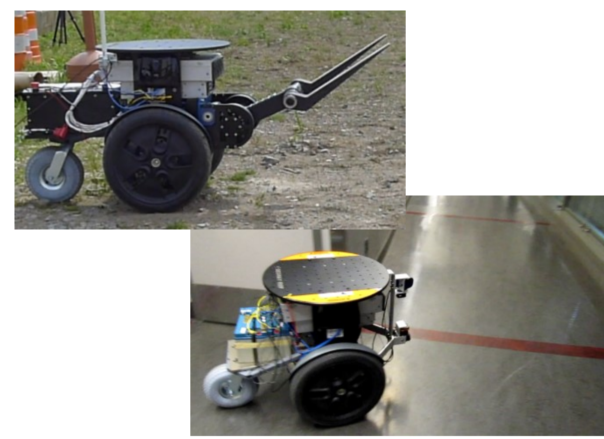
About Me

- 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







Class Objectives at High-level

- Understand and learn how to implement most popular planning and decision-making approaches in robotics
- Understand the challenges and basic approaches to interleaving planning and execution in robotic systems
- Learn common uses of planning/decision-making in robotics
- Get a sense for doing research in the area of planning/decision-making in robotics

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)* $M^R = <S^R, A^R>$
  - *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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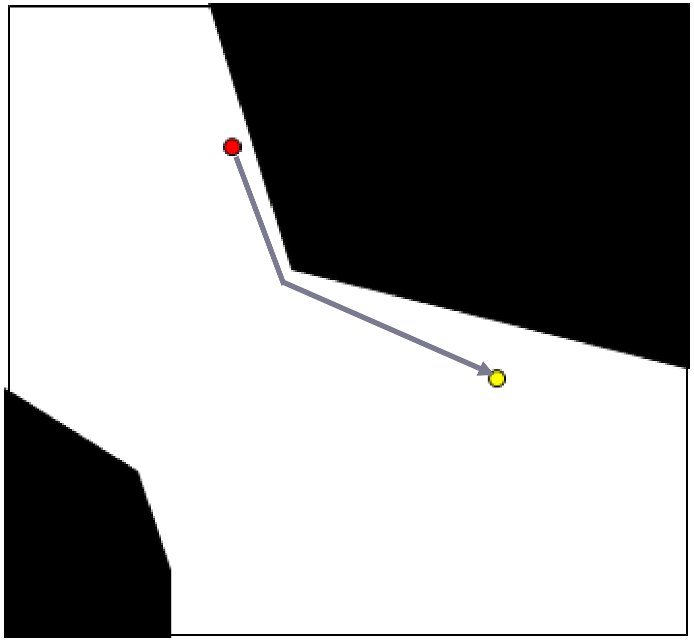
Planning for omnidirectional robot:

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*?*

What is M^W*?*

What is $s^R_{current}$*?*

What is $s^W_{current}$*?*

What is C?

What is G?

MacAllister et al., 2013

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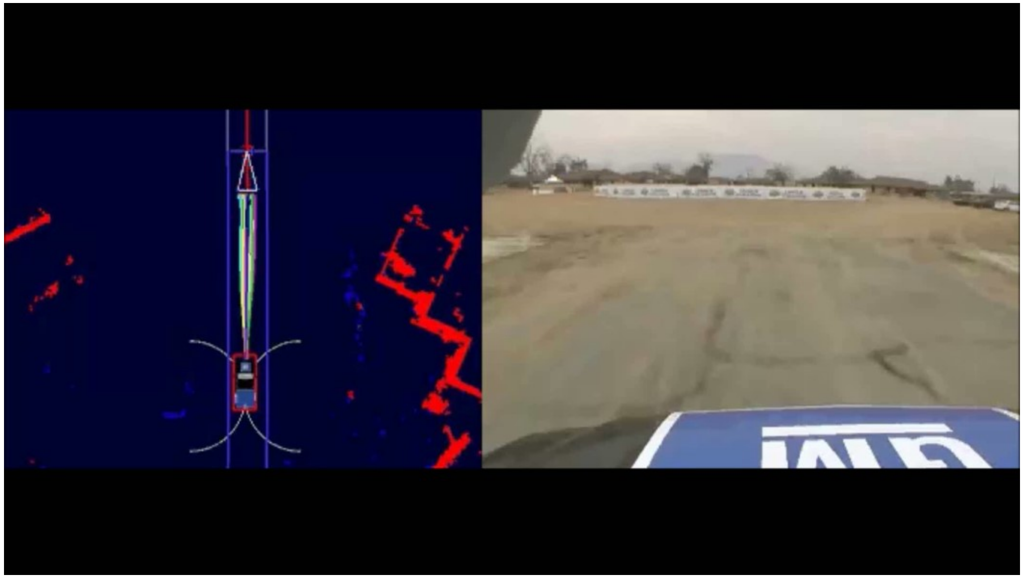
Planning for autonomous navigation:

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



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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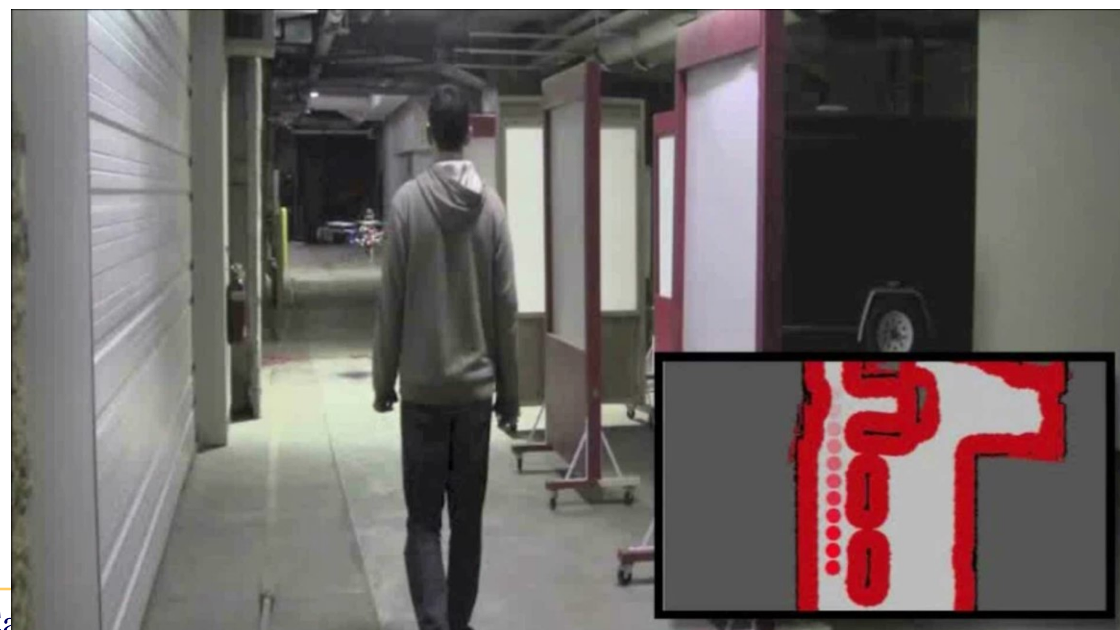

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Planning for a mobile manipulator robot opening a door:

Gray et al., 2013

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

Few Examples

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

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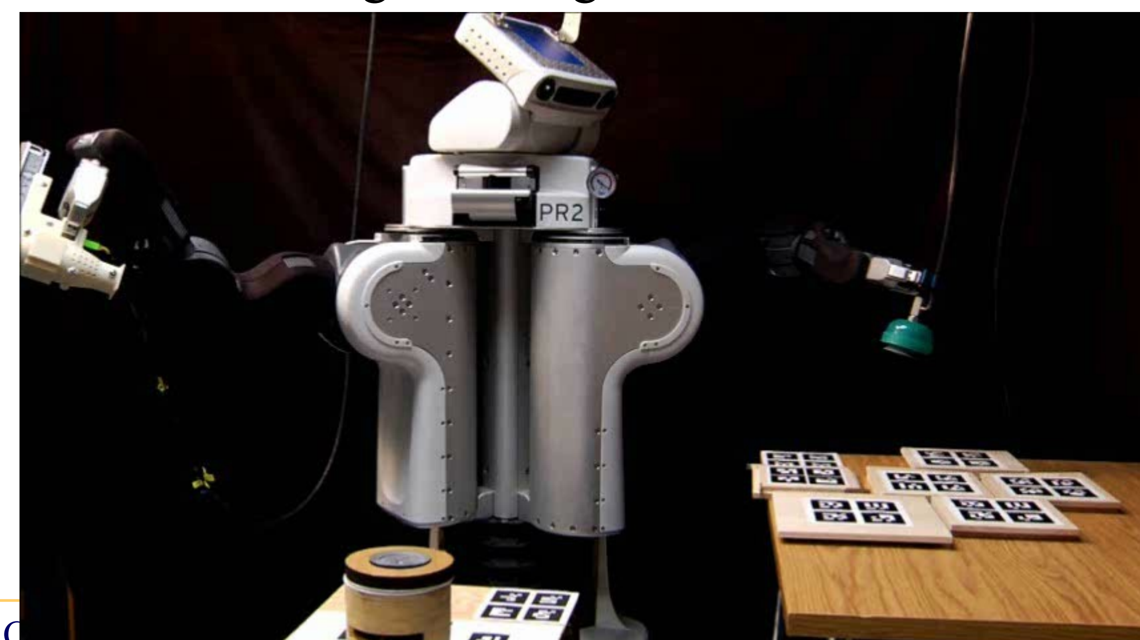

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Planning/decision-making for a mobile manipulator unloading a truck:

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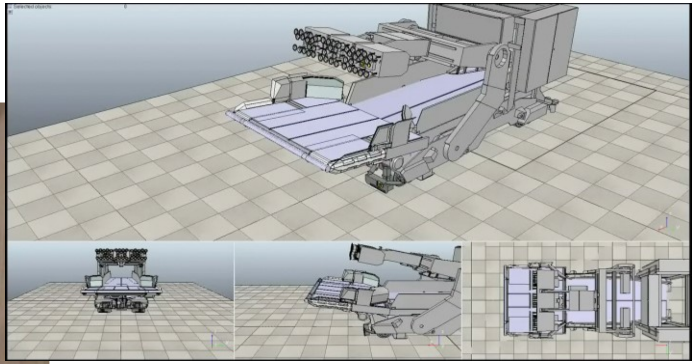
What is M^W*?*
What is $s^R_{current}$*?*
What is $s^W_{current}$*?*
What is C?
What is G?



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

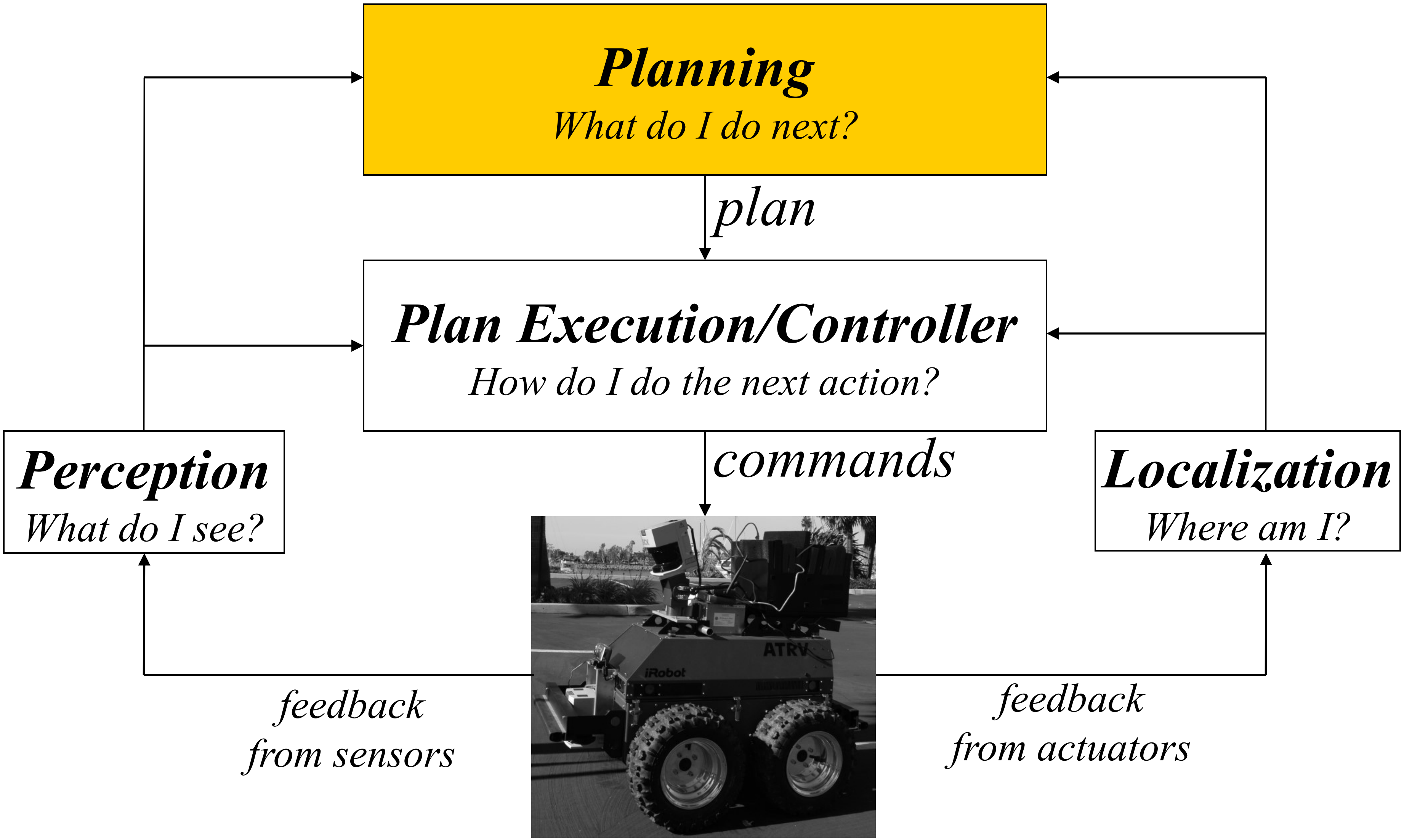
→ *models M^R, M^W and cost function C* →

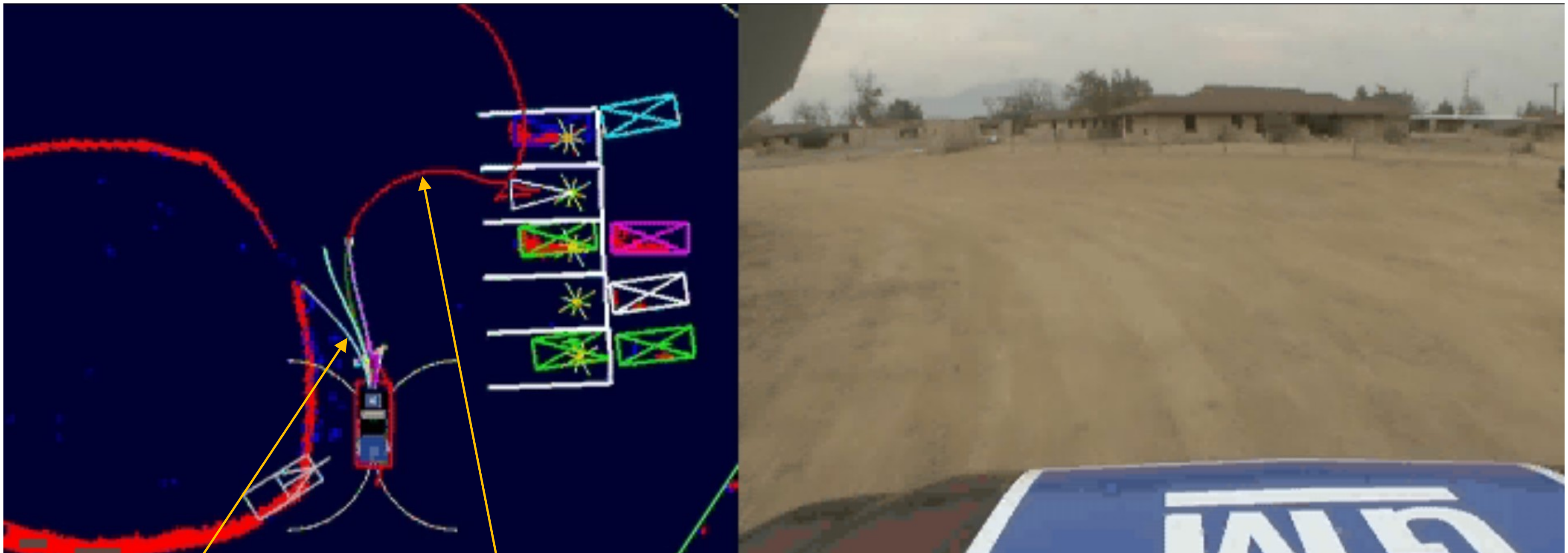
Planning using models M^R, M^W and cost function C

Model-free approach

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

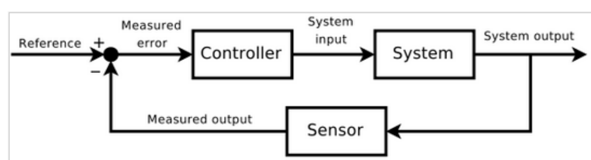
Planning within a Typical Autonomy Architecture



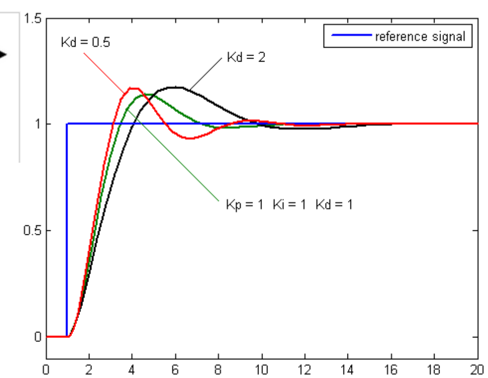


local planning
(trajectory following)

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
- Get a sense for doing research in the area of planning/decision-making in robotics

Tentative Class Schedule

TENTATIVE SCHEDULE FOR Planning and Decision-making in Robotics CLASS
Fall 2021

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

Three Homeworks + Final Project

- All homeworks are individual (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. 17

- 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?