Foundations of Robotics

Lec 1: Overview

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Outline

1. Introduction
2. Course Outline
3. Course Logistics
4. Homework

Outline

Introduction

Robots around you – categorized according to application

Introduction

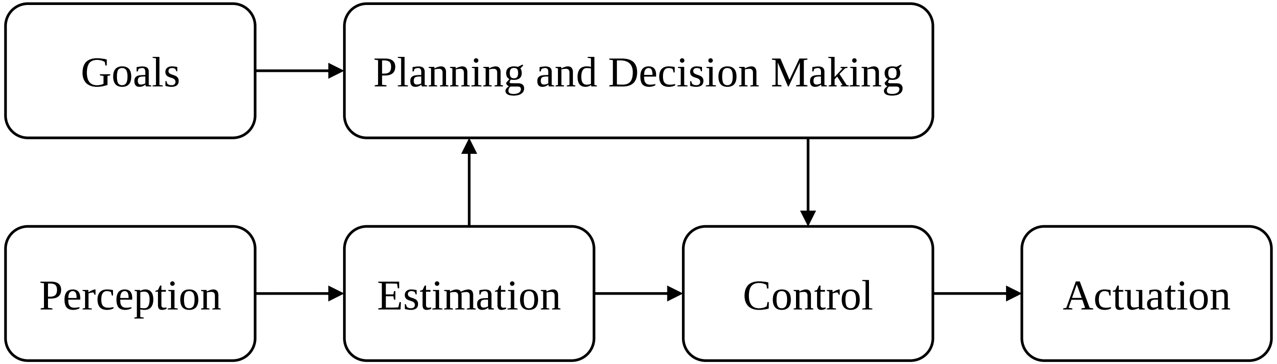
Robots around you – categorized according to mobility

Introduction

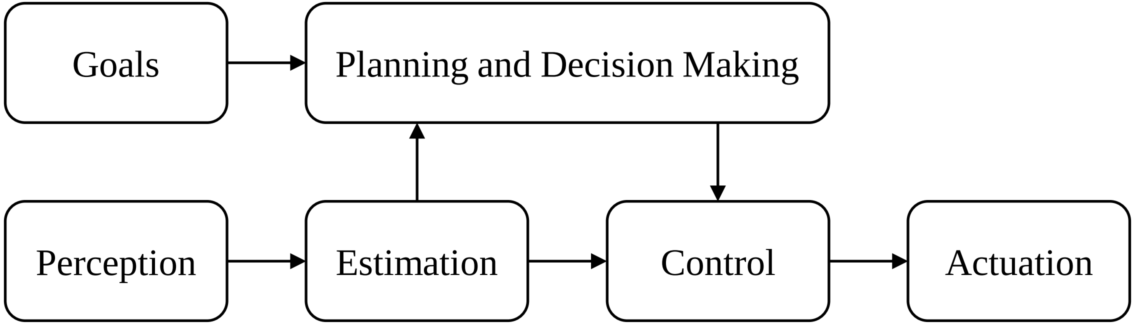
What is a robot?

Maja Matarić in her book “The Robotics Primer”:

- A robot is an **autonomous** system which exists in the **physical** world, can **sense** its environment, and can **act** on it to achieve some **goals**.



Introduction



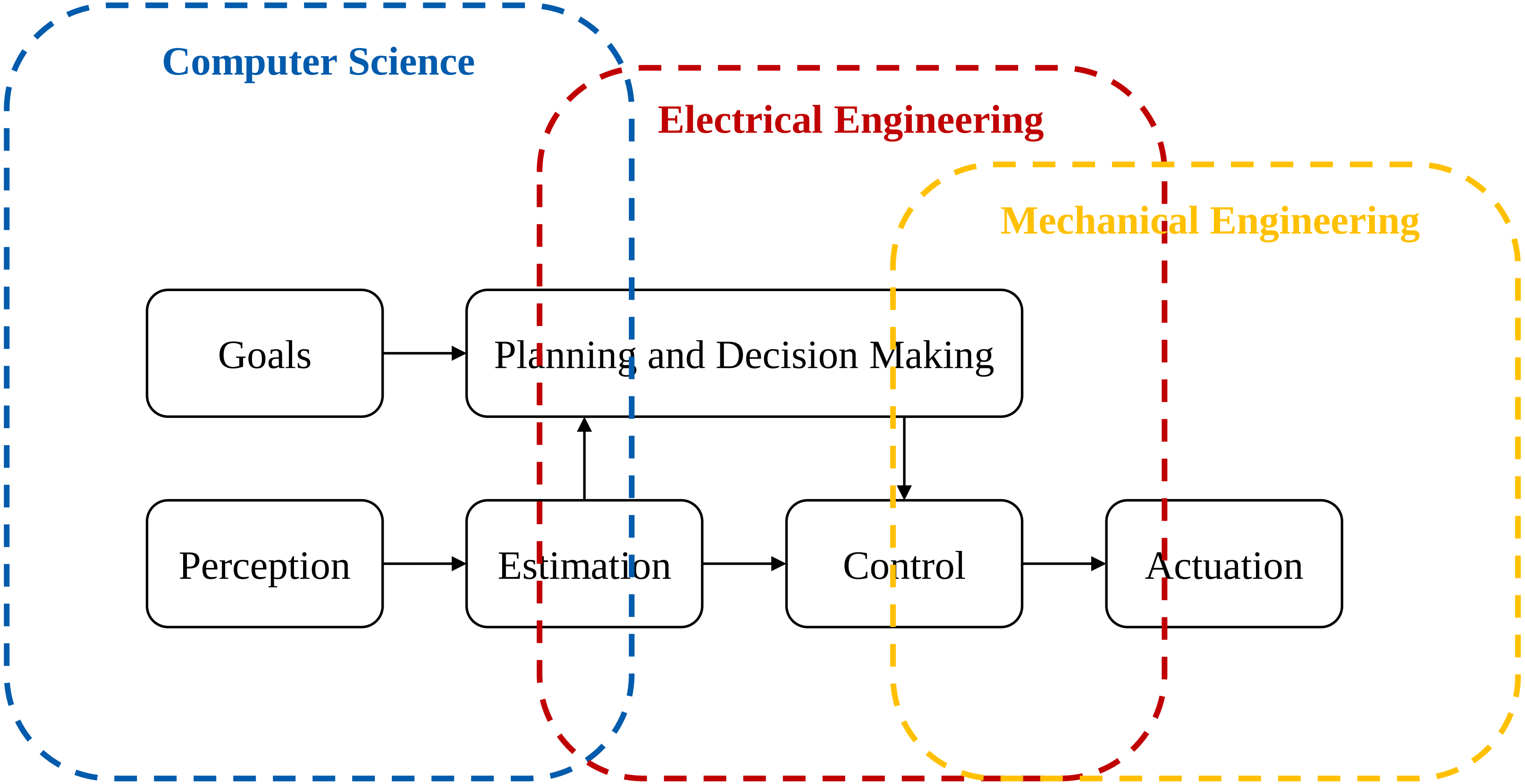
What are these components in the following examples?

a line-following robot

a robot vacuum cleaner

an autonomous driving car

Introduction



Introduction

Mechanical Engineering	frame design, force analysis, locknuts, belt friction, gear ratio, motor torque, infrared sensors	a beautiful appearance, brush pressure, docking system, wheel encoders, collision and lidar sensors	car frame, engine, fuel system, transmission, wheel encoders, perception sensors
Electrical Engineering	printed circuit board, analog/digital conversion, microcontroller, battery	power and circuits, tracking controller, non-holonomic robot model	energy system, circuits and chips, motion controller, adaptive cruise control, lane keeping
Computer Science	line-following strategy, transform goals to planning and decision-making algorithms	indoor localization, coverage path planning, trajectory generation with collision, trap recovery	motion estimation and planning, sensor fusion, scene understanding, object detection

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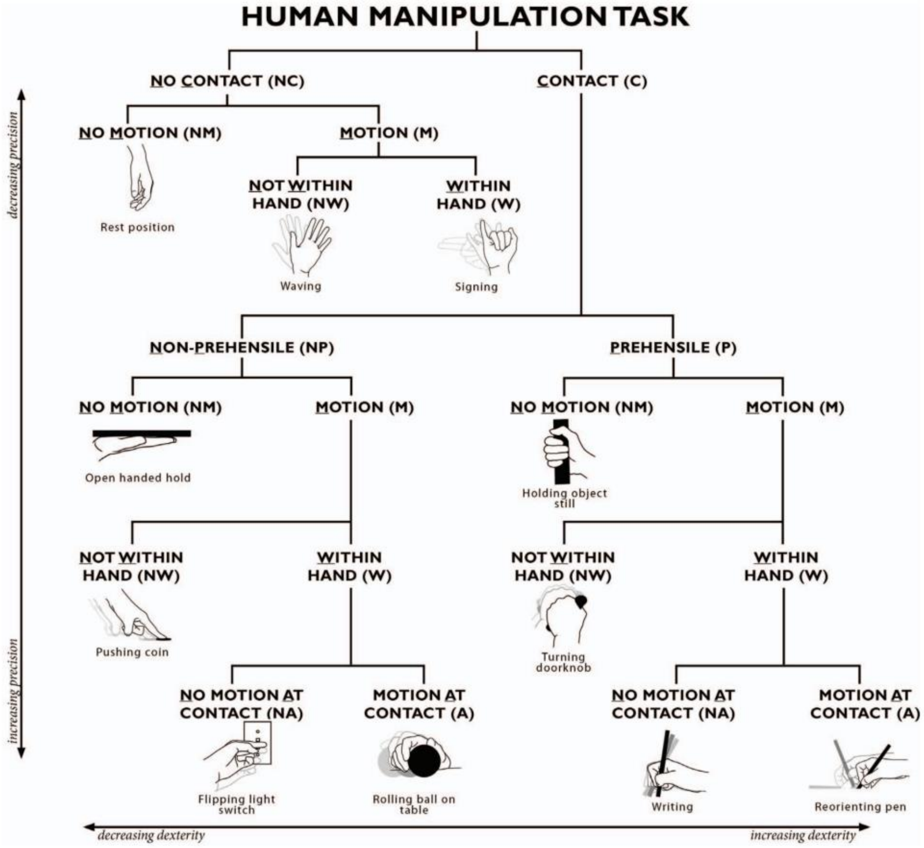
Course Outline

Example: how to control a manipulator to reach to any point you want?

- Lec 1: Overview
- Lec 2: Configuration Space
- Lec 3: Rigid-Body Motions: Rotation
- Lec 4: Rigid-Body Motions: Transformation
- Lec 5: Forward Kinematics
- Lec 6: Inverse Kinematics
- Lec 7: Trajectory Generation
- Lec 8: Motion Planning

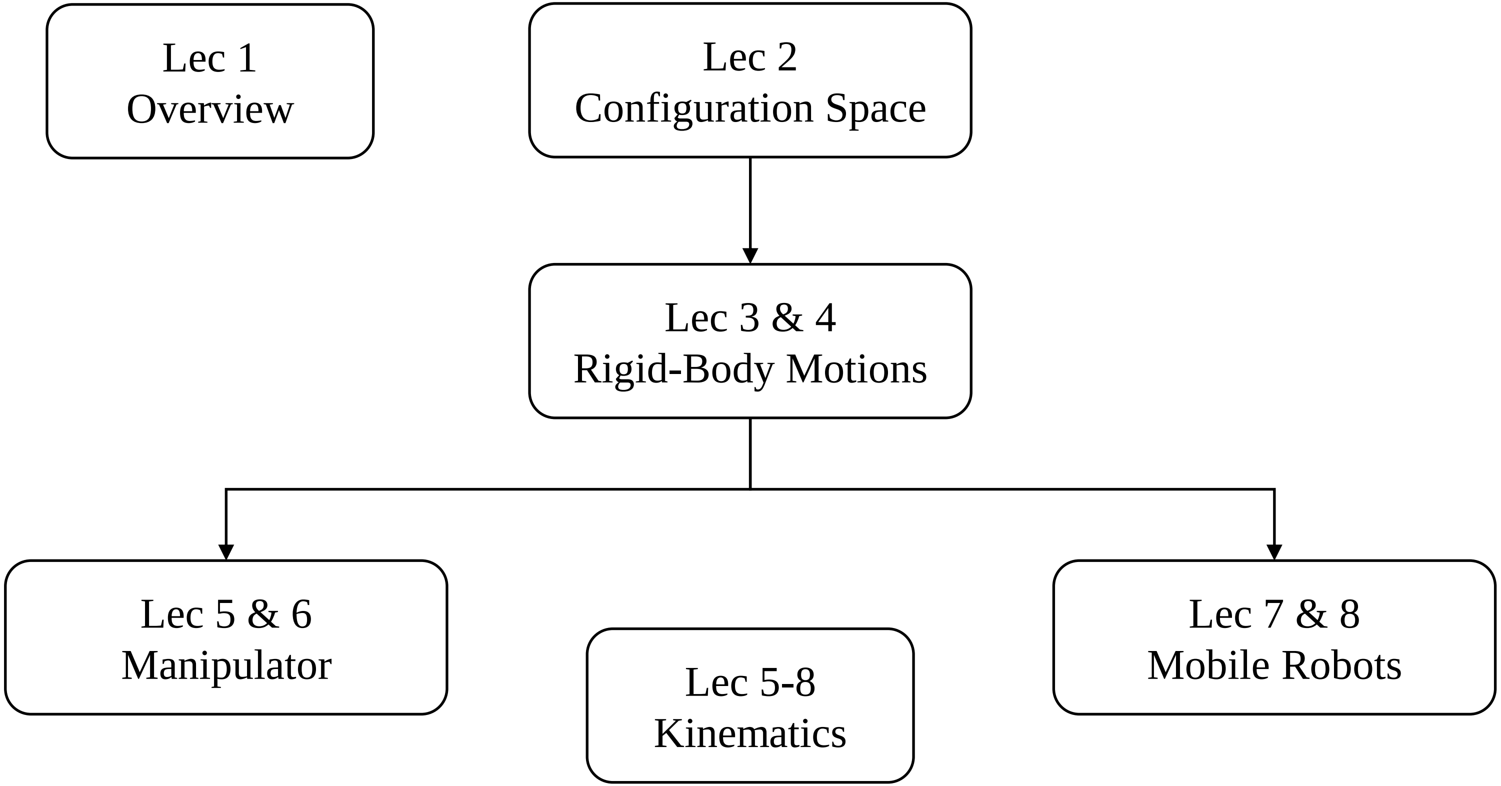
Course Outline

Future work? A long way to go!

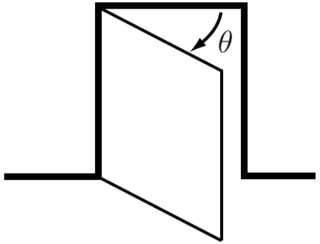


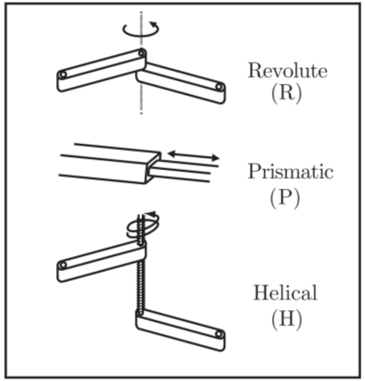
[1] I. Bullock and A. Dollar, “Classifying human manipulation behavior”

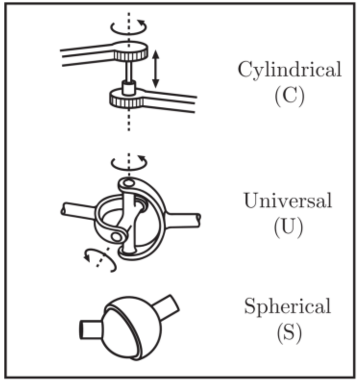
Course Outline

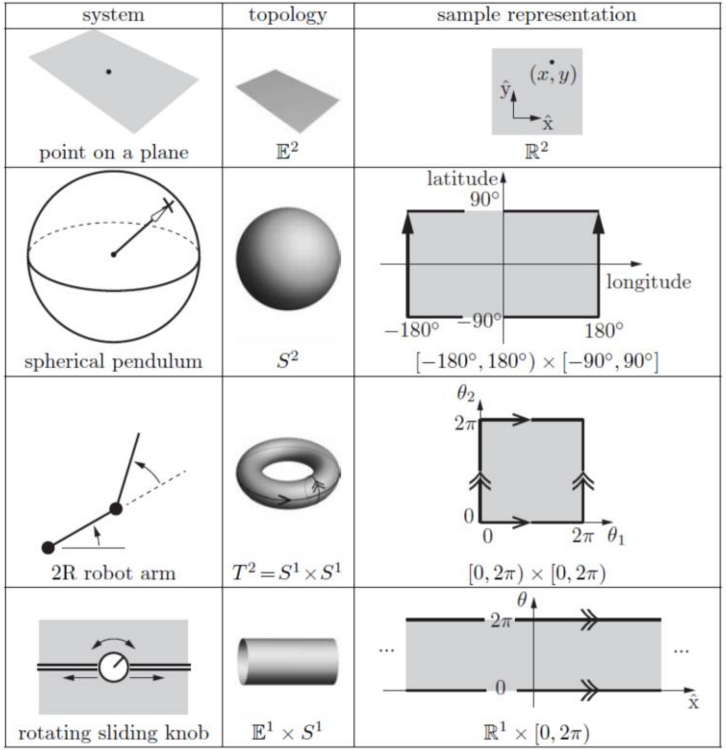


Lec 2: Configuration Space

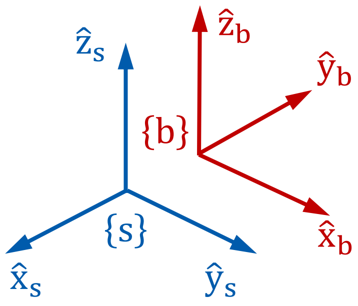








system	topology	sample representation
point on a plane	$\mathbb{E}^2$	$\mathbb{R}^2$
spherical pendulum	S^2	$[-180°, 180°) \times [-90°, 90°]$
2R robot arm	$T^2 = S^1 \times S^1$	$[0, 2\pi) \times [0, 2\pi)$
rotating sliding knob	$\mathbb{E}^1 \times S^1$	$\mathbb{R}^1 \times [0, 2\pi)$



$$R = [\hat{x}_b \;\; \hat{y}_b \;\; \hat{z}_b] = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Summary of the uses of rotation matrices

(1) represent an orientation
(2) change the reference frame (of a vector or a frame)
(3) rotate a vector or a frame (in its current frame)

Angular velocity

$$\omega = \hat{\omega}\dot{\theta}, \quad \dot{R} = [\omega]R$$

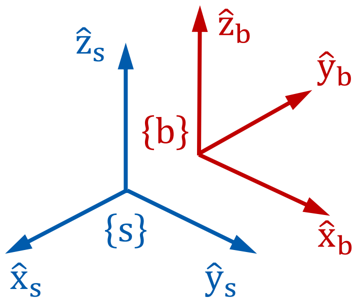
Exponential coordinate representation of rotation

$$e^{[\hat{\omega}]\theta} = I + \sin\theta\,[\hat{\omega}] + (1 - \cos\theta)[\hat{\omega}]^2 \in SO(3)$$

Bonus: other representations of rotation

- Euler angles vs. roll-pitch-yaw angles
- Unit quaternions

Lec 4: Rigid-Body Motions: Transformation



$$T = \begin{bmatrix} R & p \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Summary of the uses of transformation matrices

(1) represent a configuration (position and orientation)
(2) change the reference frame (of a vector or a frame)
(3) displace a vector or a frame (in its current frame)

Twist (angular and linear velocity)

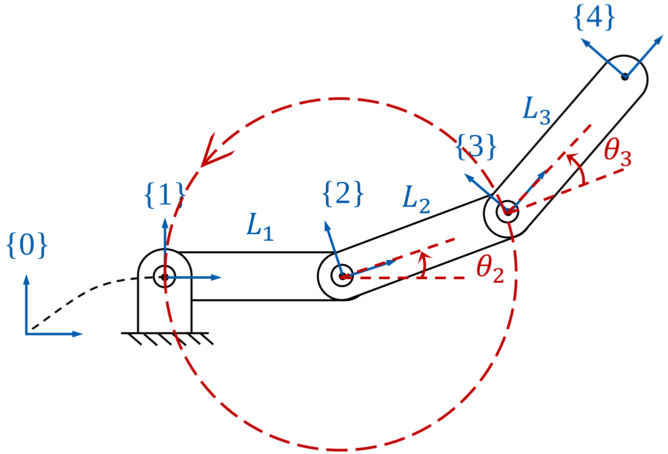
$$\mathcal{V} = \begin{bmatrix} \omega \\ v \end{bmatrix}, \quad \dot{T} = [\mathcal{V}]T$$

Exponential coordinate representation of rigid-body motions

$$e^{[\mathcal{S}]\theta} = \begin{bmatrix} e^{[\omega]\theta} & G(\theta)v \\ 0 & 1 \end{bmatrix} \in SE(3)$$

Forward Kinematics

- $\theta \in \mathbb{R}^n \quad \rightarrow \quad T(\theta) \in SE(3)$
- Given joint coordinates θ, calculate the configuration (position and orientation) $T(\theta)$ of the end-effector frame.



Two ways to solve forward kinematics

- Product of Exponentials
- D-H Parameters

Product of Exponentials

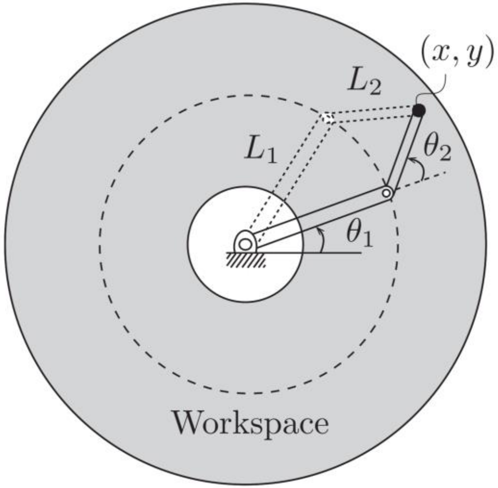
- No dependence on frame assignment
- Find exponentials of screw axes only
- $T(\theta) = e^{[\mathcal{S}_1]\theta_1} \ldots e^{[\mathcal{S}_{n-1}]\theta_{n-1}} e^{[\mathcal{S}_n]\theta_n} M$

D-H Parameters

- A minimal number of parameters associated with a convention for attaching frames
- $T(\theta) = T_{01}(\theta_1) T_{12}(\theta_2) \cdots T_{n-1,n}(\theta_n)$
- $T_{i-1,i} = \mathrm{Rot}(\hat{\mathrm{x}}, \alpha_{i-1})\ \mathrm{Trans}(\hat{\mathrm{x}}, a_{i-1})\ \mathrm{Trans}(\hat{\mathrm{z}}, d_i)\ \mathrm{Rot}(\hat{\mathrm{z}}, \phi_i)$

Lec 6: Inverse Kinematics

Inverse Kinematics
- $T(\theta) \in SE(3) \quad \rightarrow \quad \theta \in \mathbb{R}^n$
- Given a homogeneous transform $X \in SE(3)$ and forward kinematics $T(\theta)$, find solutions θ that satisfy $T(\theta) = X$.



Two ways to solve inverse kinematics
- Analytic Approach (Trigonometry)
- Numerical Approach (Newton's Method)

Analytic Approach (Trigonometry)
- Derive equations based on the geometric structure of the mechanism
- Provide zero, one or multiple solutions

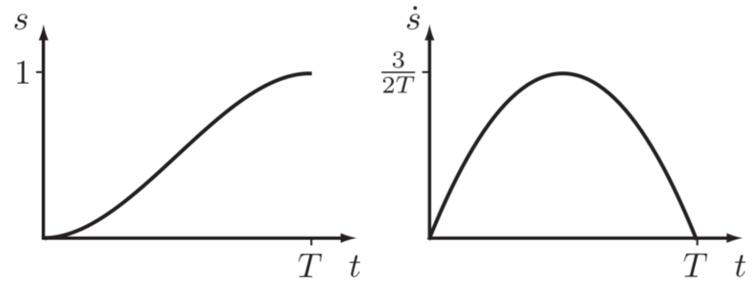
Numerical Approach (Newton's Method)
- Iteratively solve a non-linear optimization problem (require an initial guess)
- Always produce one solution (may not be optimal, best approximation)

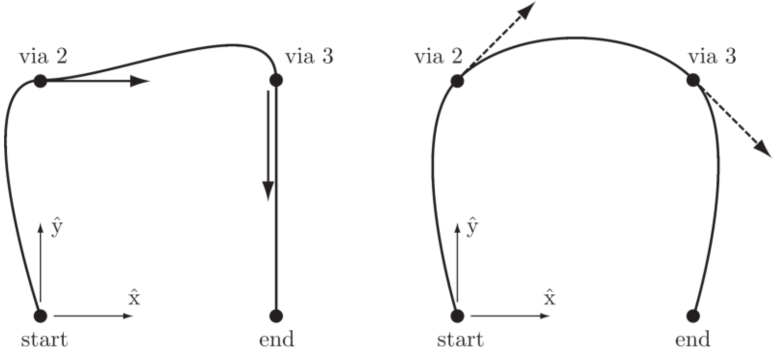
Lec 7: Trajectory Generation

Trajectory Generation
- Path: $\theta(s), s \in [0, 1]$
- Trajectory: $\theta(t), t \in [0, T]$

Polynomial Time Scaling
- Find constraints and solve for coefficients
- 3rd-order polynomials
  $s(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3, t \in [0, T]$
- 5th-order/7th-order polynomials
- Other time scaling methods

Waypoint Navigation
- Add waypoint constraints to trajectory generation





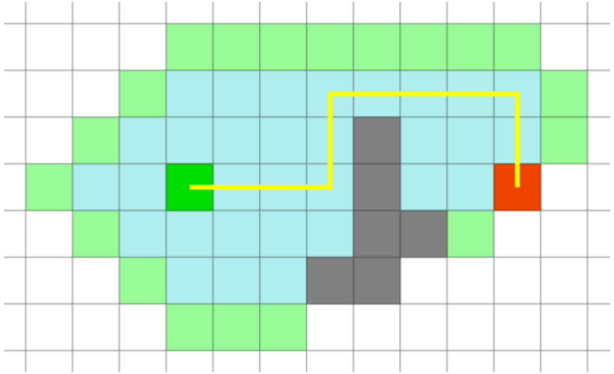
Lec 8: Motion Planning

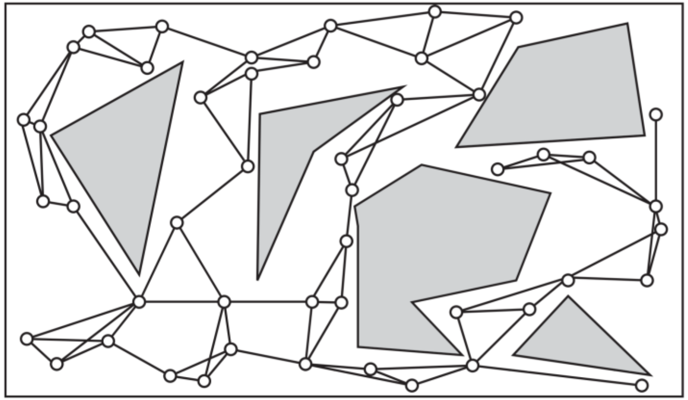
Motion Planning
- How to find a path or trajectory?
- C-space vs. C-obstacle space

Graph Search Algorithms
- A^* algorithm
- Dijkstra algorithm

Sampling-based Algorithms
- Probabilistic Roadmaps (PRM)
- Rapidly-exploring Random Trees (RRT)

Other Planning Algorithms
- Nonlinear optimization
- Virtual potential fields





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Course Logistics

About this course

- Theoretical and practical knowledge for modern Roboticists
  - Lectures and homework build up theoretical/analytical skills
  - Lab assignments build up practical/programming skills
- Equivalent to a graduate or senior undergrad level course in universities
  - The more time and efforts you spend, the more you gain

Expected background

- Engineering mathematics
  - Calculus (linear differential equations)
  - Linear algebra
- Development experience (may be optional)
  - Ubuntu 18 + ROS Melodic (or Ubuntu 20 + ROS Noetic)
  - Python or C++ programming

Course Logistics

Textbook

- “Modern Robotics: Mechanics, Planning, and Control,” by Kevin Lynch and Frank Park
- Website: http://modernrobotics.org
  - Preprint pdf available for free
  - Supplementary videos are also available
- Official Github repository: https://github.com/NxRLab/ModernRobotics
- Please respect the math convention used in the textbook and our lecture slides

Course load

- Lecture videos (1-2 hours/week)
- Homework exercises (2-8 hours/week)
- Lab assignments (2-8 hours/week)
- Capstone project

Course Logistics

Homework

- Mostly math exercises (taken from textbook + customized ones)
- Posted with lecture videos (in a separate PDF file) and due one week after posting
- Please cite any resources/ideas not originated from you

Lab Assignments

- Run simulation in Gazebo (Turtlebot2 mobile robot + ReactorX 150 manipulator)
- A detailed instruction will be posted every week (may include sample code)
- Due one week after posting; please submit in a zip file

Grading

- Will be posted one week after submission
- You have the chance to revise and resubmit until the deadline
- Please ask our course advisor and teaching assistants for more details

Course Logistics

Week	Lecture	Homework	Lab Assignment
1	Overview	/	Easy
2	Configuration Space	Medium	Easy
3	Rigid-Body Motions: Rotation	Hard	Medium
4	Rigid-Body Motions: Transformation	Hard	/
5	Forward Kinematics	Medium	Medium
6	Inverse Kinematics	/	Hard
7	Trajectory Generation	Easy	Medium
8	Motion Planning	Easy	Medium

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Homework

(1) Set up development environment
- A computer or virtual machine with Ubuntu 18/20 operating system
- Install ROS Melodic or Noetic accordingly
- Set up other development tools as needed (e.g., VS Code)

(2) Install Turtlebot2 packages
- https://github.com/UCR-Robotics/Turtlebot2-On-Melodic
- You may need to customize the installation script a bit if you are using Ubuntu 20
- Deliverable: be able to bring up a Turtlebot2 robot, and teleop it using keyboard

(3) Install manipulator packages
- https://github.com/UCR-Robotics/interbotix_ros_arms
- Deliverable: be able to bring up a ReactorX 150 robot arm and play with it

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Thanks for Listening！