Principles of Robot Autonomy I

Course overview, mobile robot kinematics
Team

Instructor

Prof. Jeannette Bohg

Course Assistants

Zhengguan (Gary) Dai
Brian Dobkowski
Mason Murray-Cooper

Collaborators

Daniel Watzenig
Hao Li
Stephanie Newdick
Alvin Sun

Labs

ASU
CARS
IPRL
From automation...
...to autonomy

Waymo Self-Driving Car

Intuitive DaVinci Surgical Robot

Apollo Robot at MPI for Intelligent Systems

Boston Dynamics – Spot Mini

Astrobee - NASA

Zipline

9/26/22
Course goals

• To learn the *theoretical*, *algorithmic*, and *implementation* aspects of main techniques for robot autonomy. Specifically, the student will
  1. Gain a fundamental knowledge of the “autonomy stack”
  2. Be able to apply such knowledge in applications / research by using ROS
  3. Devise novel methods and algorithms for robot autonomy
The see-think-act cycle

- **Knowledge**
  - Localization
    - Map Building
  - Information extraction
    - raw data
  - Sensing

- **Position**
  - Global map

- **Decision making**
  - Motion planning
    - Trajectory
    - Trajectory execution
      - actuator commands
      - Actuation

- **Actuation**

- **Real world environment**
Course structure

• Four modules, roughly of equal length
  1. motion control and planning
  2. robotic perception
  3. localization and SLAM
  4. state machines and system architecture

• Extensive use of the Robot Operating System (ROS)

• Requirements
  • CS 106A or equivalent
  • CME 100 or equivalent (for calculus, linear algebra)
  • CME 106 or equivalent (for probability theory)
  • See also the pre-knowledge quiz on the course website
## Schedule

<table>
<thead>
<tr>
<th>Week</th>
<th>Topic</th>
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| 1    | Course overview, mobile robot kinematics  
      | Introduction to the Robot Operating System (ROS)  
      | Thursday: HW1 out |
| 2    | Trajectory optimization  
      | Trajectory tracking & closed loop control |
| 3    | Motion planning I: graph search methods  
      | Motion planning II: sampling-based methods  
      | Tuesday: HW1 due, HW2 out |
| 4    | Robotic sensors & introduction to computer vision  
      | Camera models & camera calibration |
| 5    | Image processing, feature detection & description  
      | Information extraction & classic visual recognition  
      | Tuesday: HW2 due, HW3 out |
| 6    | Intro to localization & filtering theory  
      | Parameteric filtering (KF, EKF, UKF) |
| 7    | Tuesday: No lecture (Democracy Day)  
      | Nonparameteric filtering (PF)  
      | Thursday: Final project released  
      | Tuesday: HW3 due, HW4 out |
| 8    | Object detection / tracking, EKF localization  
      | Simultaneous localization and mapping (SLAM) |
| N/A  | Thanksgiving Break |
| 9    | Multi-sensor perception & sensor fusion I (by Daniel Watzenig)  
      | Multi-sensor perception & sensor fusion II (by Daniel Watzenig)  
      | Tuesday: HW4 due |
| 10   | Stereo vision  
      | State machines  
      | Tuesday: Final project check-in due |
| 11   | Final Project Presentation and Demo  
      | 12/15 3:30 - 6:30 PM |

In-Person attendance is not required!
Logistics - Lectures

• Tuesdays and Thursdays, 10:30am – 11:50 (Gates B1)
• Recordings will be made available to all students on Canvas.

• Course Materials in addition to Course Notes:
Logistics – Homework Assignments

• 4 assignments
• First Assignment out on Thursday
• ~2 weeks to submit on Gradescope
• Assignments are due Tuesdays which is when a new assignment will be released
• Budget of 6 late days, max 3 days per assignment
• Cooperation and discussion is encouraged, but solutions must be prepared individually. Add names of classmates who you collaborated with. Copying from other students or other sources is considered a case of academic dishonesty.
• Need to be typeset in Latex!
Logistics – Sections

• 2-hour, once-a-week sessions starting Week 2
• Hands-on exercises that complement the lecture material, build familiarity with ROS, develop skills necessary for the final project

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<td>(in-person) masonmc</td>
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• Section sign-up sheet coming soon!
Grading

• Course grade calculation
• (20%) final project
• (60%) homework
• (20%) sections
• (extra 5%) participation on Piazza
Logistics - Grades

• (20%) final project.
• (60%) homework.
• (20%) sections.
• (extra 5%) participation on Ed Discussion

4 or 3 units?

• AA174A: 4 units
• AA 274A/CS 237A/EE 260A: 3 or 4. Taking this class for 4 units entails completing an additional homework problem per problem set and also writing a one-page review of a paper at the end of the quarter.
Logistics

• Office hours:
  • Prof. Jeannette Bohg: Friday, 1-2pm (Gates 244 and Zoom)
  • CAs: Mondays 1 – 3pm (in-person), garydai, ...
           Tuesdays 2pm – 4pm (virtual) masonmc, snewdick,
           Thursdays 6pm – 8pm (virtual) alvinsun, bdobkows.
           Friday 10am – 12pm (virtual) alvinsun, li2053.

• Course websites:
  • For course content: http://asl.stanford.edu/aa274a/
  • For course-related questions: https://edstem.org/us/courses/28635
  • For homework submissions: https://www.gradescope.com/courses/439779
  • For announcements and lecture videos: https://canvas.stanford.edu/courses/159179
  • To contact the AA274 staff, use the email: cs237a-aut2223-staff@lists.stanford.edu

• Syllabus has all the info!

9/26/22   AA 274A | Lecture 1
Mobile robot kinematics

• Aim
  • Understand motion constraints
  • Learn about basic motion models for wheeled vehicles
  • Gain insights for motion control

• Readings
Motion Planning and Control
Constraints in Motion Planning and Control

How to Parallel Park Like a Pro

I'M TERRIBLE AT PARALLEL PARKING.

Futurama - Put Your Head on My Shoulders [S02E10]
https://tenor.com/view/parallel-park-parking-proper-gif-13789379
Generalized Coordinates

• Let $\xi = [\xi_1, \ldots, \xi_n]^T$ denote the configuration of a robot (e.g., $\xi = [x, y, \theta]^T$ for a wheeled mobile robot)
Kinematic constraints

$$a_i(\xi, \dot{\xi}) = 0, \quad i = 1, \ldots, k < n$$

- constrain the instantaneous admissible motion of the mechanical system
- generally expressed in Pfaffian form, i.e., linear in the generalized velocities

$$a_i^T(\xi) \dot{\xi} = 0, \quad i = 1, \ldots, k < n$$
Holonomic constraints

- $h_i(\xi) = 0$, for $i = 1, \ldots, k < n$
- Reduce space of accessible configurations to an $n - k$ dimensional subset
- If all constraints are holonomic, the mechanical system is called holonomic
- Generally, the result of mechanical interconnections
Examples of Holonomic constraints

Xiang, Qin, Mo et al., "SAPIEN: A SimulAted Part-based Interactive ENvironment", CVPR 2020
Kinematic constraints

\[ a_i(\xi, \dot{\xi}) = 0, \quad i = 1, \ldots, k < n \]

• constrain the instantaneous admissible motion of the mechanical system

• generally expressed in Pfaffian form, i.e., linear in the generalized velocities

\[ a_i^T(\xi) \dot{\xi} = 0, \quad i = 1, \ldots, k < n \]

• \( k \) holonomic constraints imply the existence of an equal number of kinematic constraints

\[ \frac{d}{dt} h_i(\xi) = \frac{\partial}{\partial \xi} h_i(\xi) \dot{\xi} = 0, \quad i = 1, \ldots, k < n \]

• However, the converse is not true in general...
Nonholonomic constraints

• If a kinematic constraint is not integrable in the form $h_i(\xi) = 0$, then it is said nonholonomic -> nonholonomic mechanical system

• Nonholonomic constraints reduce mobility in a completely different way. Consider a single Pfaffian constraint

$$a^T(\xi) \dot{\xi} = 0$$

• Holonomic
  • Can be integrated to $h(\xi) = 0$
  • Loss of accessibility, motion constrained to a level surface of dimension $n - 1$

• Nonholonomic
  • Velocities constrained to belong to a subspace of dimension $n - 1$, the null space of $a^T(\xi)$
  • No loss of accessibility
Example of nonholonomic system

• System: disk that rolls without slipping
• \( \xi = [x, y, \theta]^T \)

• No side slip constraint
  \[ [\dot{x}, \dot{y}] \cdot \begin{bmatrix} \sin \theta \\ -\cos \theta \end{bmatrix} = \dot{x} \sin \theta - \dot{y} \cos \theta = [\sin \theta, -\cos \theta, 0] \dot{\xi} = 0 \]

• Facts:
  • No loss of accessibility
  • Wheeled vehicles are generally nonholonomic
Types of wheels

• Standard wheels (four types)

- Standard wheel -- fixed or steerable
- Standard, off-centered wheel (caster) -- passive or active

• Special wheels: achieve omnidirectional motion (e.g., Swedish or spherical wheels)
Kinematic models

• Assume the motion of a system is subject to \( k \) Pfaffian constraints
  \[
  \begin{bmatrix}
  a_1^T(\xi) \\
  \vdots \\
  a_k^T(\xi)
  \end{bmatrix} \; \dot{\xi} := A^T(\xi)\dot{\xi} = 0
  \]

• Then, the admissible velocities at each configuration \( \xi \) belong to the \((n - k)\)-dimensional null space of matrix \( A^T(\xi) \)

• Denoting by \( \{ g_1(\xi), \ldots, g_{n-k}(\xi) \} \) a basis of the null space of \( A^T(\xi) \), admissible trajectories can be characterized as solutions to

\[
\dot{\xi} = \sum_{j=1}^{n-k} g_j(\xi)u_j = G'(\xi)u
\]

Input vector
Example: unicycle

- Consider pure rolling constraint for the wheel:
  \[
  \dot{x} \sin \theta - \dot{y} \cos \theta = [\sin \theta, -\cos \theta, 0] \dot{\xi} = a^T(\xi) \dot{\xi} = 0
  \]

- Consider the matrix
  \[
  G(\xi) = [g_1(\xi), g_2(\xi)] = \begin{bmatrix}
  \cos \theta & 0 \\
  \sin \theta & 0 \\
  0 & 1
  \end{bmatrix}
  \]

  where \([g_1(\xi), g_2(\xi)]\) is a basis of the null space of \(a^T(\xi)\)

- All admissible velocities are therefore obtained as linear combination of \(g_1(\xi)\) and \(g_2(\xi)\)
The kinematic model of the unicycle also applies to the differential drive vehicle, via the one-to-one input mappings:

\[
\begin{align*}
    v &= \frac{r}{2}(\omega_r + \omega_l), \\
    \omega &= \frac{r}{L} (\omega_r - \omega_l)
\end{align*}
\]
Simplified car model

\[
\begin{pmatrix}
\dot{x} \\
\dot{y} \\
\dot{\theta}
\end{pmatrix}
= \begin{pmatrix}
v \cos \theta \\
v \sin \theta \\
v/L \tan \phi
\end{pmatrix}
\]

|v| \leq v_{\text{max}}, \quad |\phi| \leq \phi_{\text{max}} < \frac{\pi}{2}

v \in \{-v_{\text{max}}, v_{\text{max}}\}, \quad |\phi| \leq \phi_{\text{max}} < \frac{\pi}{2}

v = v_{\text{max}}, \quad |\phi| \leq \phi_{\text{max}} < \frac{\pi}{2}

From kinematic to dynamic models

• A kinematic state space model should be interpreted only as a subsystem of a more general dynamical model

• Improvements to the previous kinematic models can be made by placing integrators in front of action variables

• For example, for the unicycle model, one can set the speed as the integration of an action $a$ representing acceleration, that is

$$\begin{align*}
\dot{x} &= v \cos \theta, \\
\dot{y} &= v \sin \theta, \\
\dot{\theta} &= \omega, \\
\dot{v} &= a
\end{align*}$$
Next time