

Principles of Robot Autonomy I

Course overview, mobile robot kinematics



Stanford
University



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

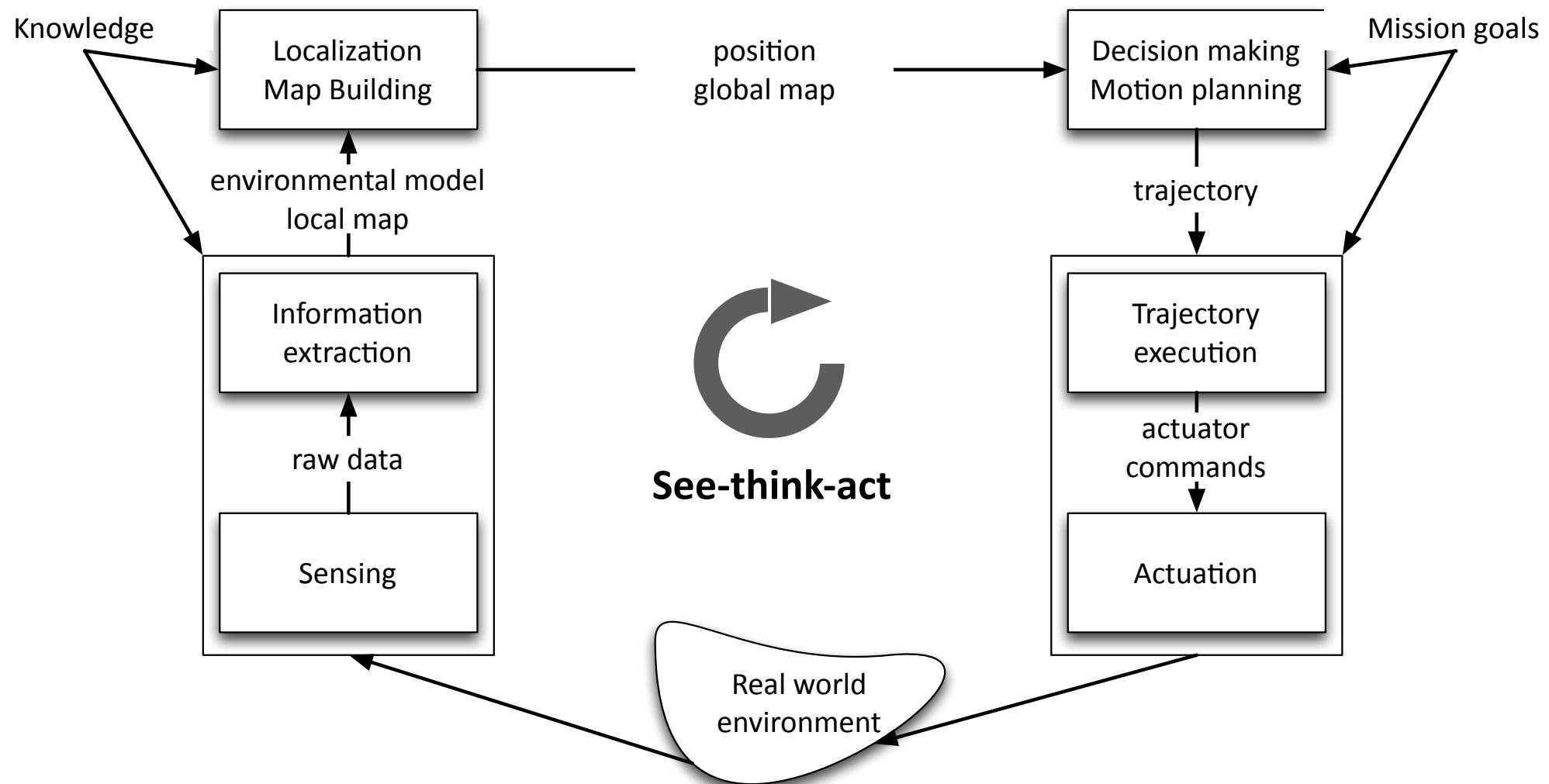
From automation...



...to autonomy



The see-think-act cycle



Course structure

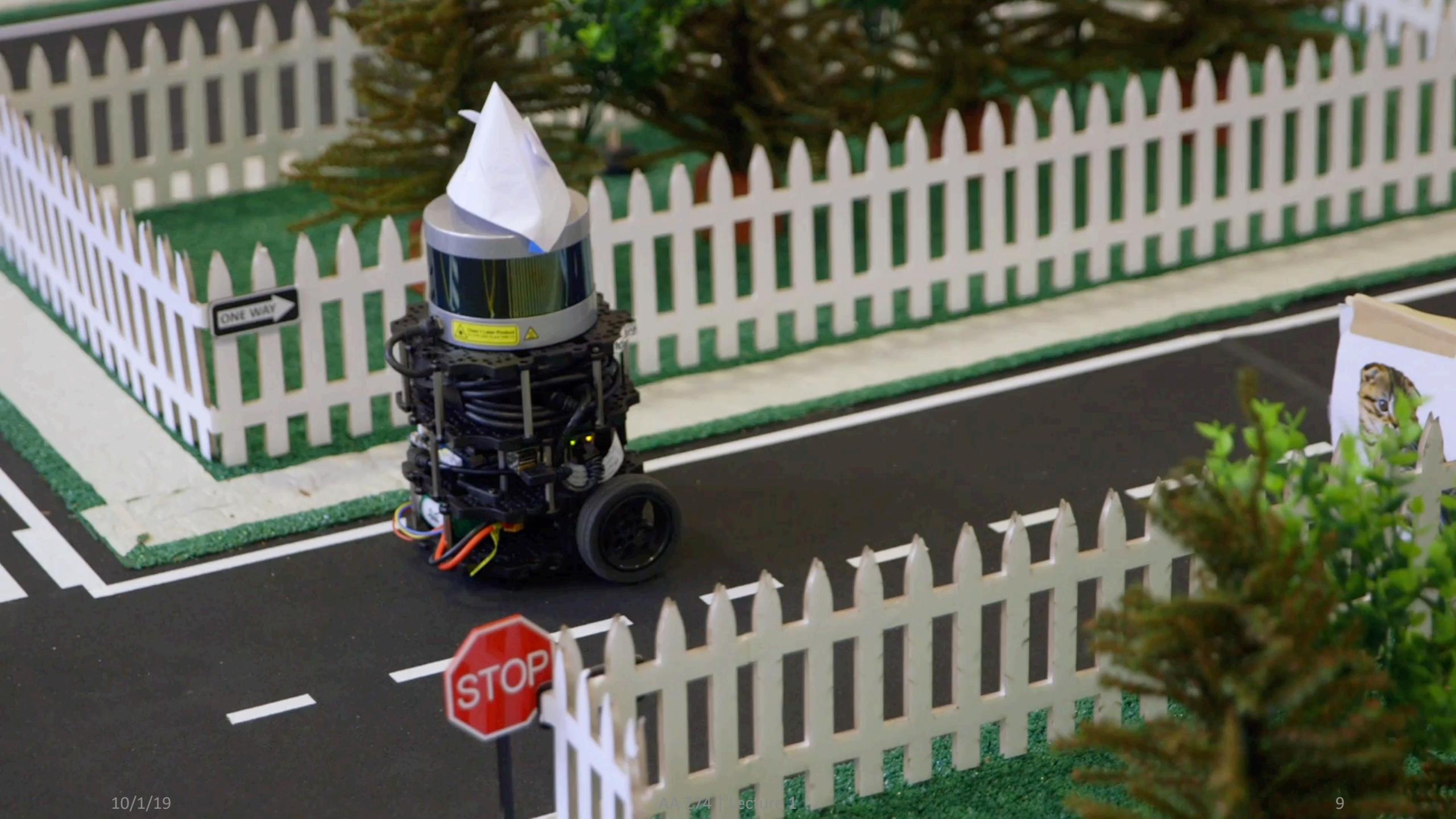
- Four modules, roughly of equal length
 1. motion control and planning
 2. robotic perception
 3. localization and SLAM
 4. state machines, decision making, and system architecture
- Extensive use of the Robot Operating System (ROS)
- Requirements
 - CS 106A or equivalent
 - CME 100 or equivalent (for linear algebra)
 - CME 106 or equivalent (for probability theory)

Logistics

- Lectures:
 - Tuesday and Thursday, 10:30am -11:50am; Friday 1:30pm - 2:50pm (NVIDIA Auditorium)
 - Friday lectures are optional for those enrolled in AA 174A
- Sections
 - Monday, Wednesday, 10:30am - 12:30pm (Skilling Lab space)
 - Monday, 3:00pm – 5:00pm (Skilling Lab space)
 - Tuesday, 4:00pm – 6:00pm (Skilling Lab space)
 - Thursday, 2:00pm – 4:00pm (Skilling Lab space)
- Office hours:
 - Prof. Pavone: Tuesday, 1:00 - 3:00pm (Durand 261), after class, and by appointment
 - CAs: Tuesday, 2:00 – 4:00pm; Thursday, 4:00 – 6:00pm (Durand 023)
- Course websites:
 - <http://asl.stanford.edu/aa274/>
 - <https://piazza.com/stanford/fall2019/aa174aaa274acs237aee260a>
 - <https://www.gradescope.com/courses/59890>
 - <https://canvas.stanford.edu/courses/105756>
- To contact the AA274 staff, use the email: aa274a-aut1920-staff@lists.stanford.edu

Grading

- Course grade calculation
 - 15% midterm I
 - 15% midterm II
 - 15% final project
 - 40% homework (four problem sets)
 - 15% sections
 - Extra 5%: participation on Piazza



Team

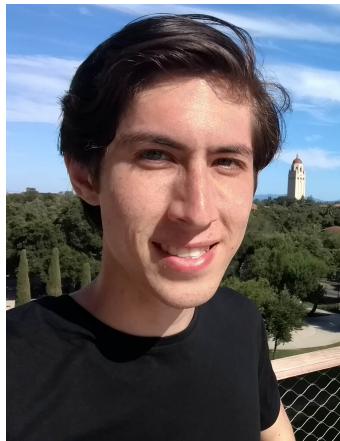
Instructor



Marco Pavone
Associate Professor AA,
and CS/EE (by courtesy)

CAs

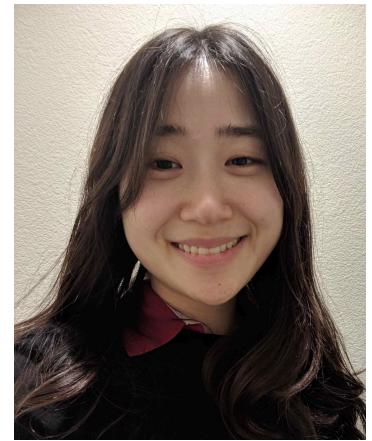
Andrew Bylard



Boris Ivanovic

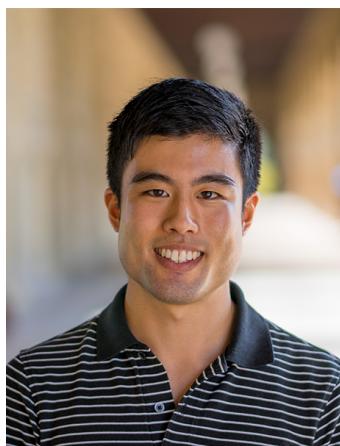


Jenna Lee



Collaborators:

- Benoit Landry
- Karen Leung
- Daniel Watzenig



Toki Migimatsu



Apoorva Sharma

Schedule

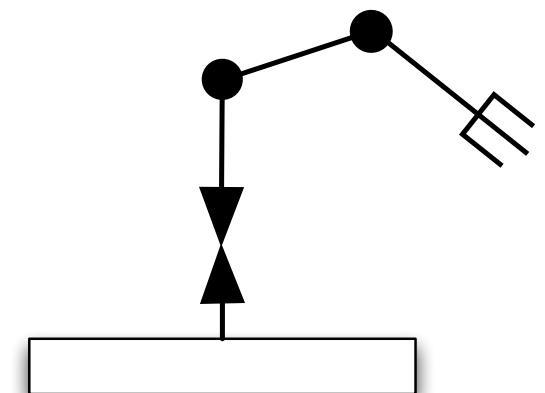
Date	Topic	Assignment	
09/24	Course overview, mobile robot kinematics		
09/26	Introduction to the Robot Operating System (ROS)		
09/27	★ Autonomy in the wild (seminar)	HW1 out	
10/01	Trajectory optimization		
10/03	Trajectory tracking & closed loop control		
10/04	★ Advanced methods for trajectory optimization		
10/08	Motion planning I: graph search methods	HW1 due, HW2 out	
10/10	Motion planning II: sampling-based methods		
10/11	Midterm I		
10/15	Robotic sensors & introduction to computer vision		
10/17	Camera models & camera calibration		
10/18	★ Stereo vision	HW2 due, HW3 out	
10/22	Image processing, feature detection & description		
10/24	Information extraction & classic visual recognition		
10/25	★ Modern robotic perception		
10/29	Intro to localization & filtering theory		HW3 due, HW4 out
10/31	Parameteric filtering (KF, EKF, UKF)		
11/01	★ Nonparameteric filtering (PF)		
11/05	EKF localization		Final project released
11/07	EKF SLAM		
11/08	★ Monte Carlo localization and particle filter SLAM		
11/12	Multi-sensor perception & sensor fusion		
11/14	Software for autonomous systems I		
11/15	★ Software for autonomous systems II		
11/19	State machines		HW4 due
11/21	Decision making under uncertainty		
11/22	Midterm II		Final project check-in
11/26	Thanksgiving Recess (no classes)		
11/28	Thanksgiving Recess (no classes)		
11/29	Thanksgiving Recess (no classes)		
12/03	Reinforcement learning		
12/05	Conclusions		
12/06	Final Project Demo		

Mobile robot kinematics

- Aim
 - Understand motion constraints
 - Learn about basic motion models for wheeled vehicles
 - Gain insights for motion control
- Readings
 - R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to Autonomous Mobile Robots. MIT Press, 2nd Edition, 2011. Sections 3.1-3.3.
 - B. Siciliano, L. Sciavicco, L. Villani, G. Oriolo. Robotics: Modelling, Planning, and Control. Springer, 2008 (chapter 11).

Holonomic constraints

- Let $\xi = [\xi_1, \dots, \xi_n]^T$ denote the configuration of a robot (e.g., $\xi = [x, y, \theta]^T$ for a wheeled mobile robot)
- *Holonomic* constraints
 - $h_i(\xi) = 0$, for $i = 1, \dots, k < n$
 - 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



Kinematic constraints

- Kinematic constraints

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

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

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

- Clearly, k holonomic constraints imply the existence of an equal number of kinematic constraints

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

- However, the converse is not true in general...

Nonholonomic constraints

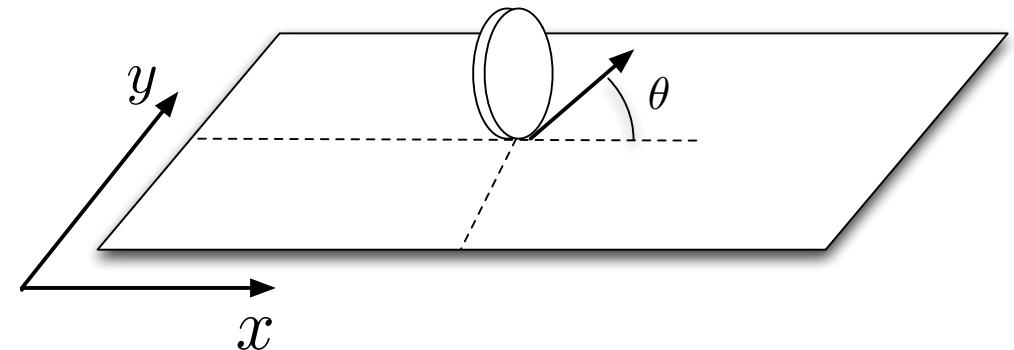
- If a kinematic constraint is not integrable in the form $h_i(\xi) = 0$, then it is said *nonholonomic* -> nonholonomic mechanical system
- Nonholonomic constraints reduce mobility in a completely different way. Consider a single Pfaffian constraint

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

- 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

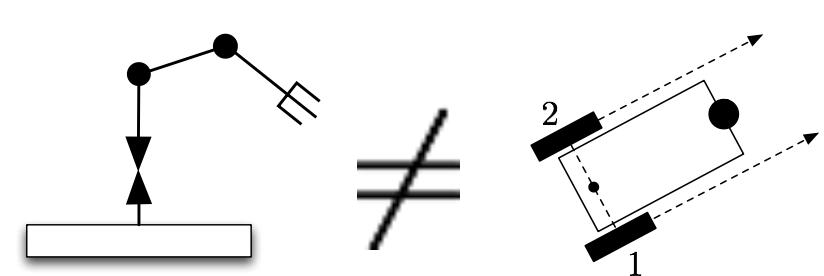
- System: disk that rolls without slipping
- $\xi = [x, y, \theta]^T$



- No side slip constraint

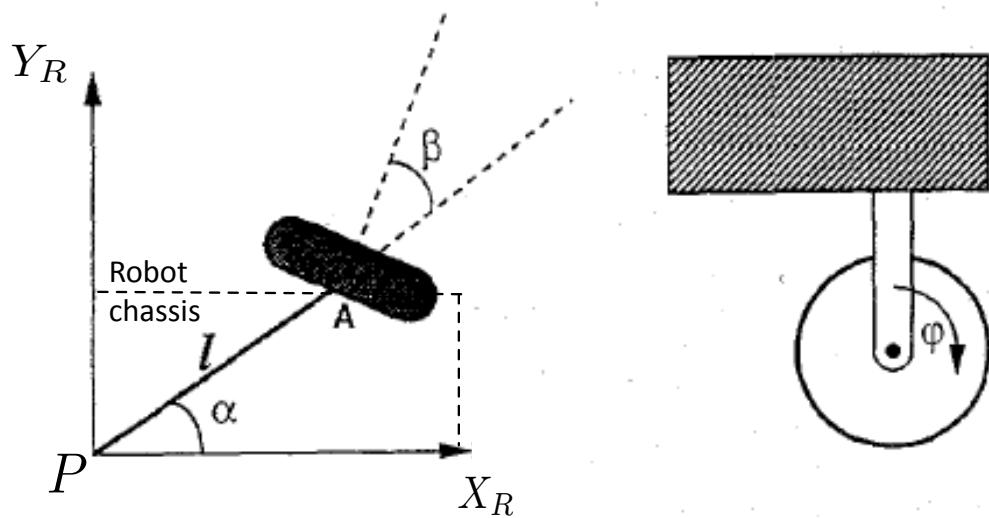
$$[\dot{x}, \dot{y}] \cdot \begin{bmatrix} \sin \theta \\ -\cos \theta \end{bmatrix} = \dot{x} \sin \theta - \dot{y} \cos \theta = [\sin \theta, -\cos \theta] \dot{\xi} = 0$$

- Facts:
 - No loss of accessibility
 - Wheeled vehicles are generally nonholonomic

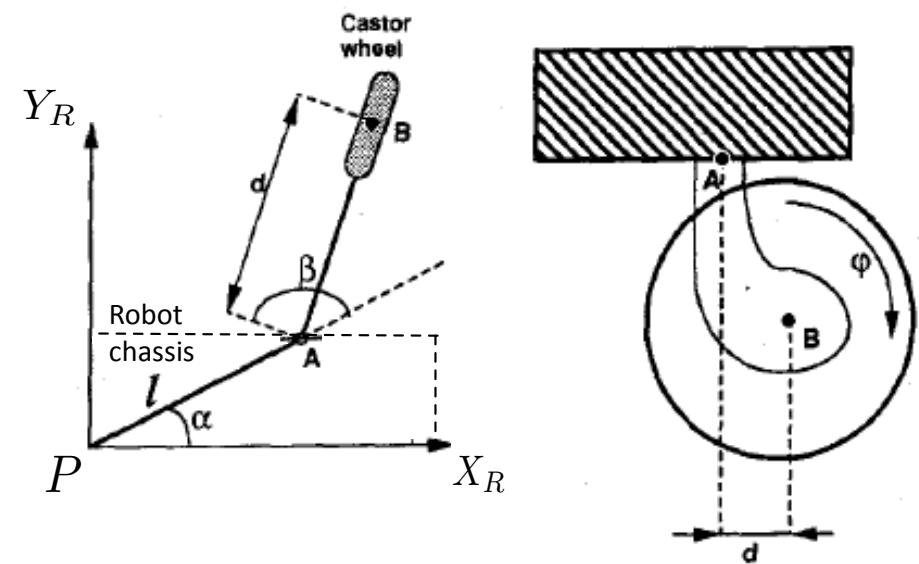


Types of wheels

- 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 ξ belong to the $(n - k)$ -dimensional null space of matrix $A^T(\xi)$
- Denoting by $\{g_1(\xi), \dots, g_{n-k}(\xi)\}$ 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

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

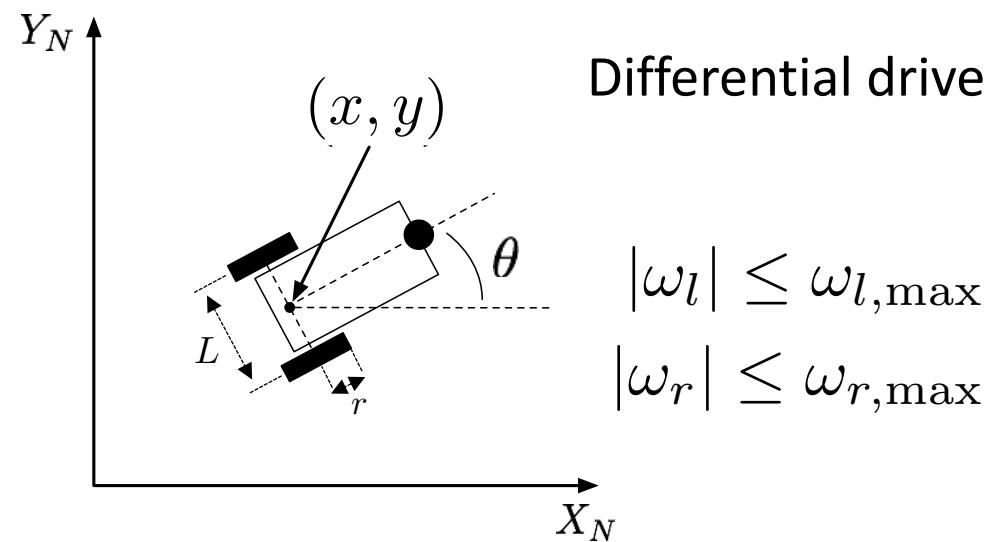
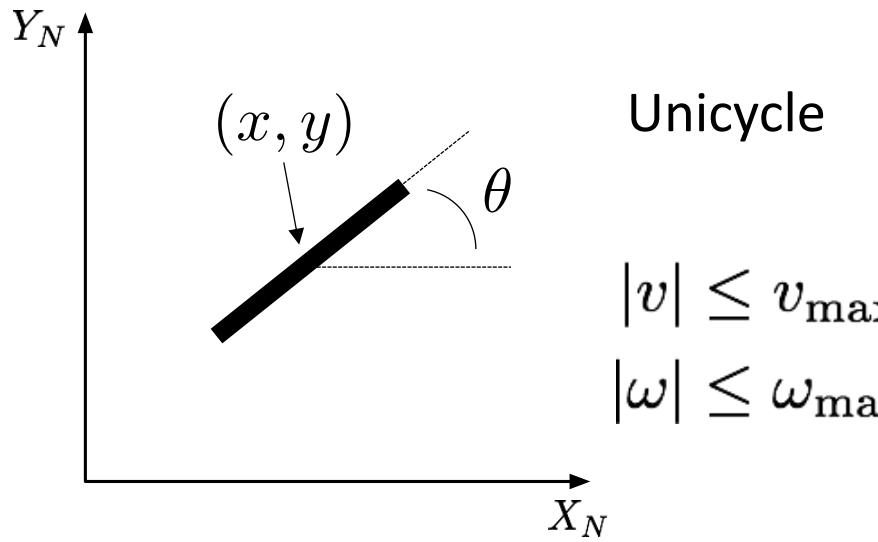
where $[g_1(\xi), g_2(\xi)]$ is a basis of the null space of $a^T(\xi)$

- All admissible velocities are therefore obtained as linear combination of $g_1(\xi)$ and $g_2(\xi)$

Unicycle and differential drive models

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \cos \theta \\ \sin \theta \\ 0 \end{pmatrix} v + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \omega$$

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \frac{r}{2}(\omega_l + \omega_r) \cos \theta \\ \frac{r}{2}(\omega_l + \omega_r) \sin \theta \\ \frac{r}{L}(\omega_r - \omega_l) \end{pmatrix}$$

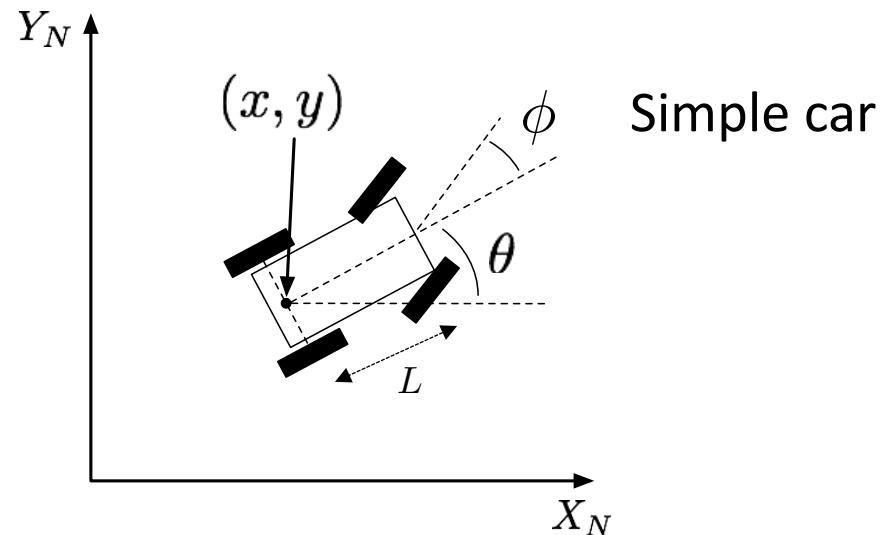


The kinematic model of the unicycle also applies to the differential drive vehicle, via the one-to-one input mappings:

$$v = \frac{r}{2}(\omega_r + \omega_l) \quad \omega = \frac{r}{L}(\omega_r - \omega_l)$$

Simplified car model

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} v \cos \theta \\ v \sin \theta \\ \frac{v}{L} \tan \phi \end{pmatrix}$$



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

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

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

- Simple car model
- Reeds&Shepp's car
- Dubins' car

References: (1) J.-P. Laumond. Robot Motion Planning and Control. 1998. (2) S. LaValle. Planning algorithms, 2006.

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

$$\dot{x} = v \cos \theta, \quad \dot{y} = v \sin \theta, \quad \dot{\theta} = \omega, \quad \dot{v} = a$$

Next time

