# AA 274
# Principles of Robotic Autonomy

Course overview, mobile robot kinematics,

introduction to motion control

Stanford University

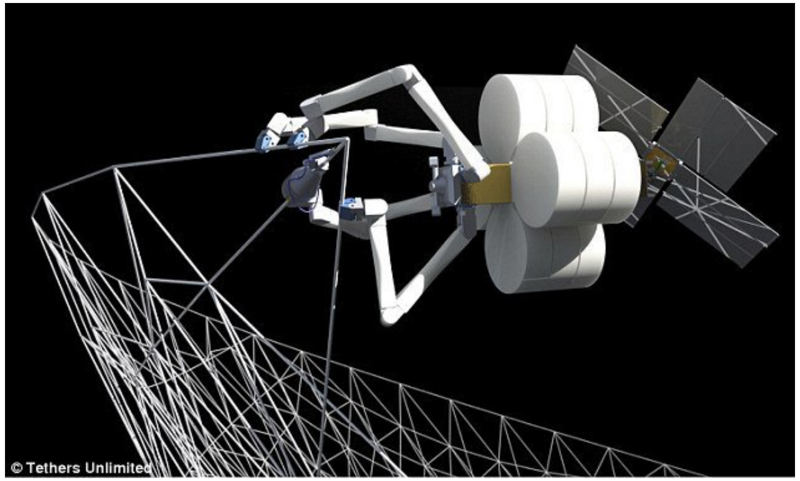
Autonomous Systems Lab

# Course goals

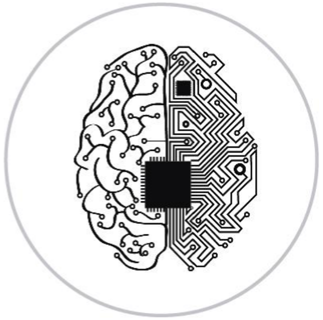
- To learn the *theoretical*, *algorithmic*, and *implementation* aspects of main techniques for robot autonomy. Specifically, the student will
    1. Gain a fundamental knowledge of the "autonomy stack"
    2. Be able to apply such knowledge in applications / research by using ROS
    3. Devise novel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

# From automation…

# …to autonomy

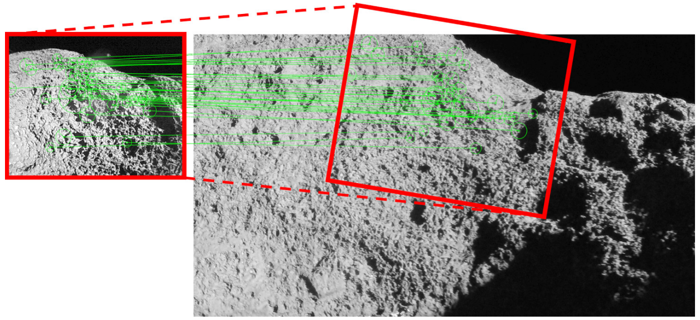

# ASL research



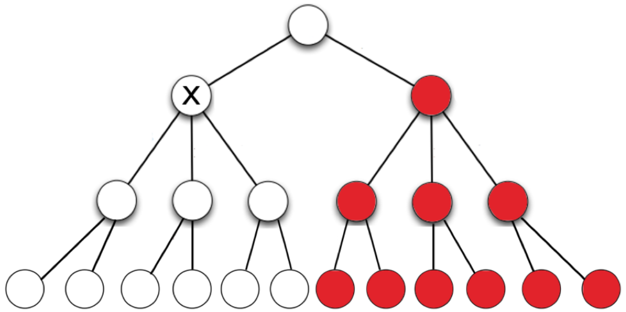
Trustworthy autonomy

Agile motion planning

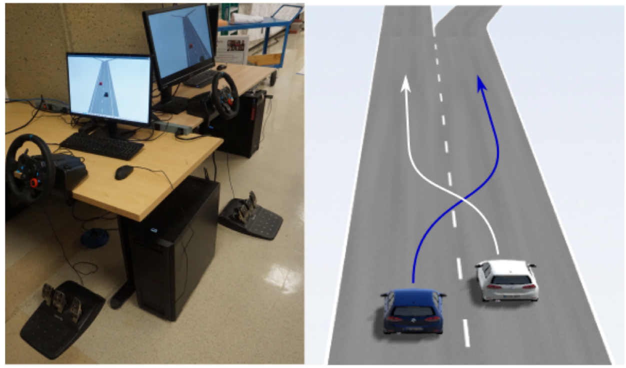
System-level coordination



Interplay with perception



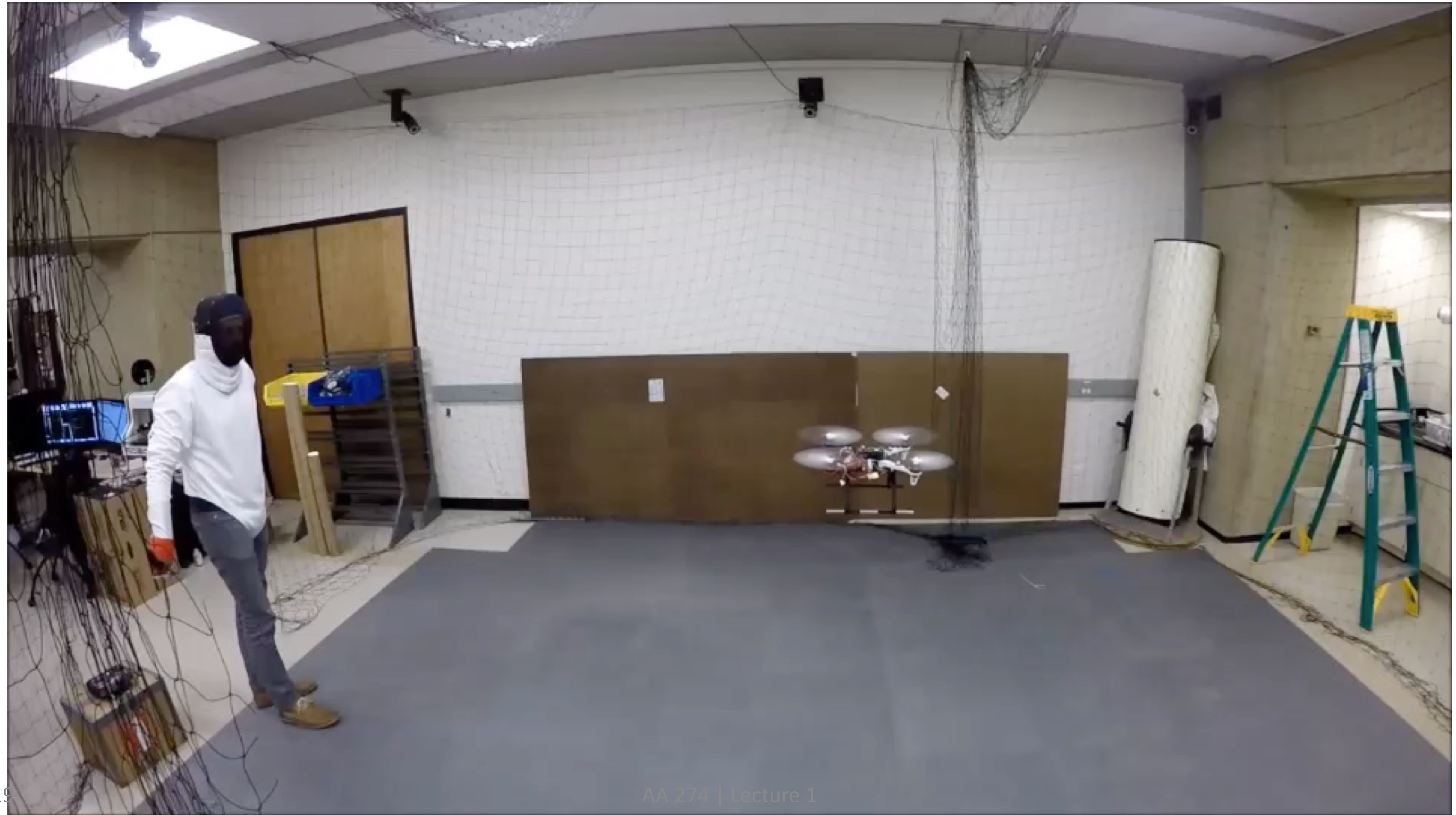

Safe and robust decision making and learning



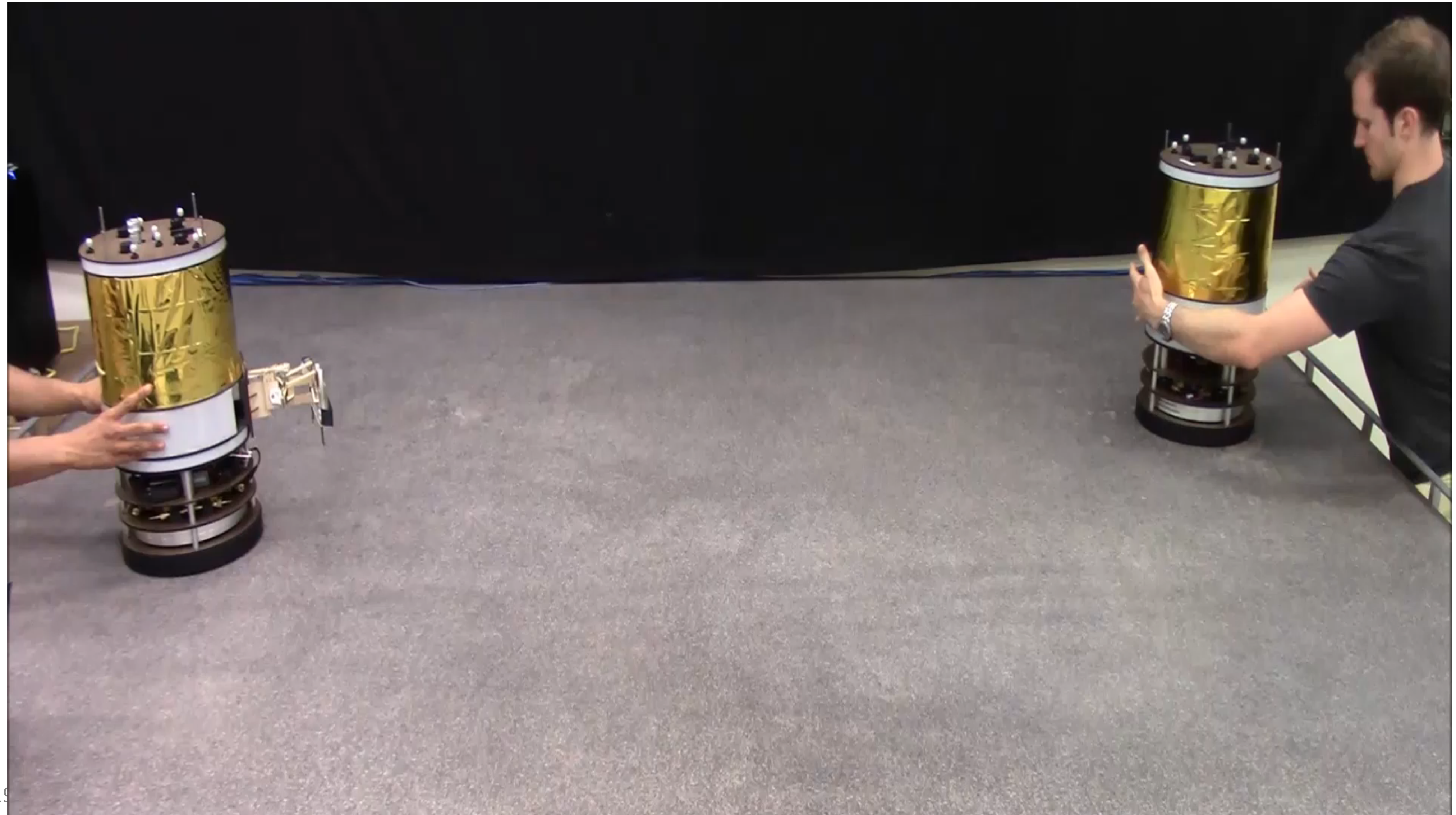
Safe interactions with humans

# Sample of ASL research

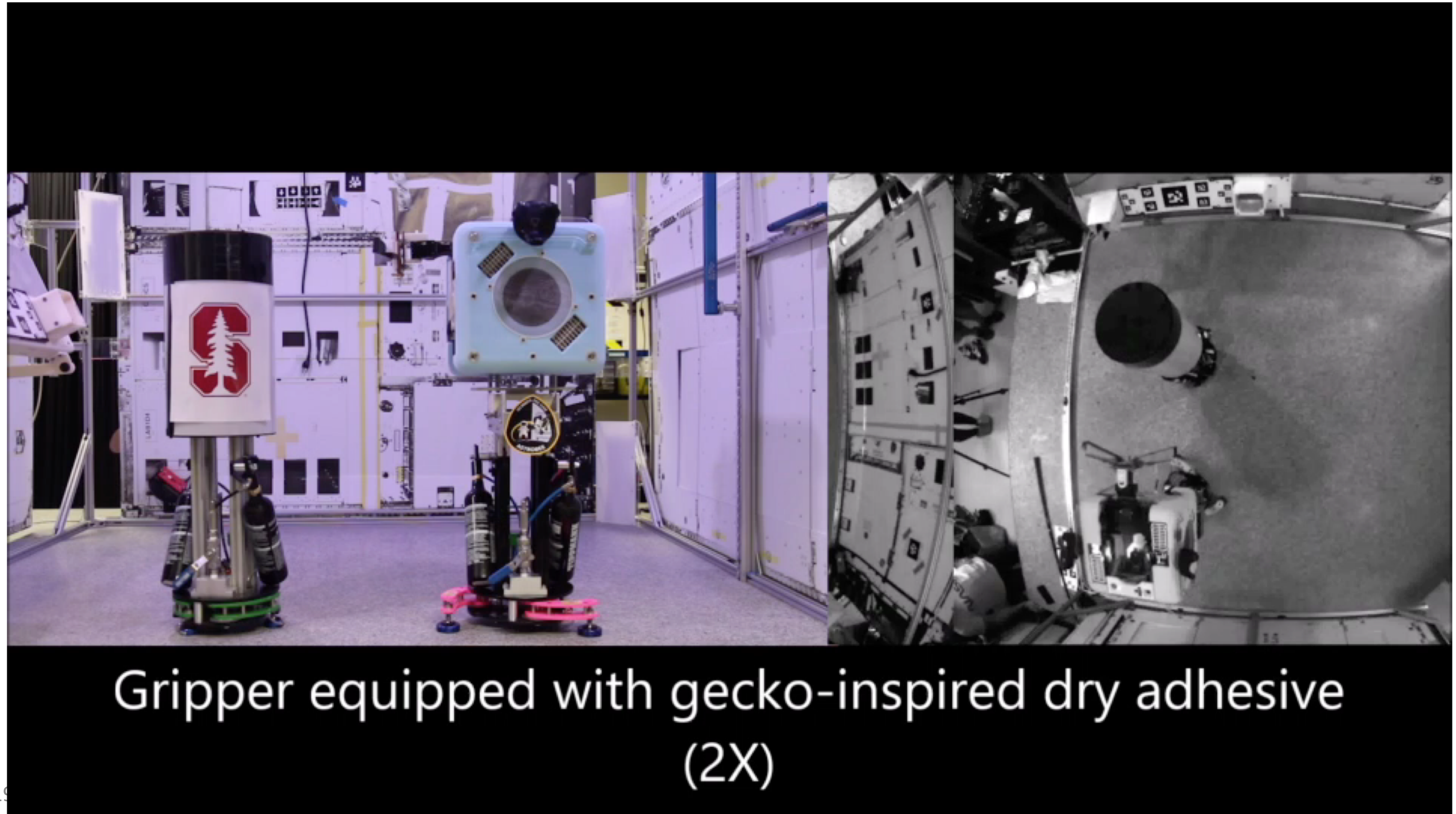
# Sample of ASL research



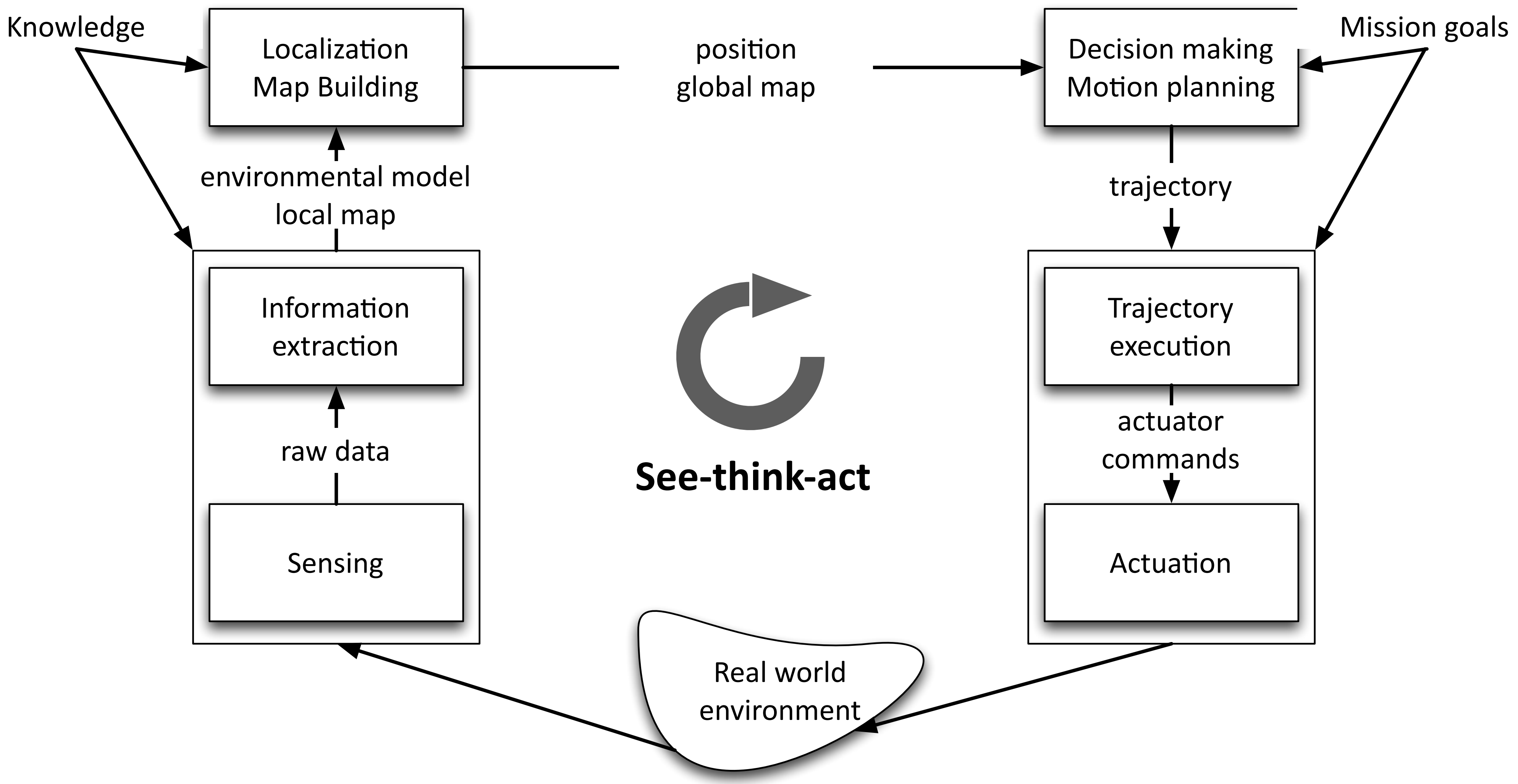
# Sample of ASL research



# Sample of ASL research

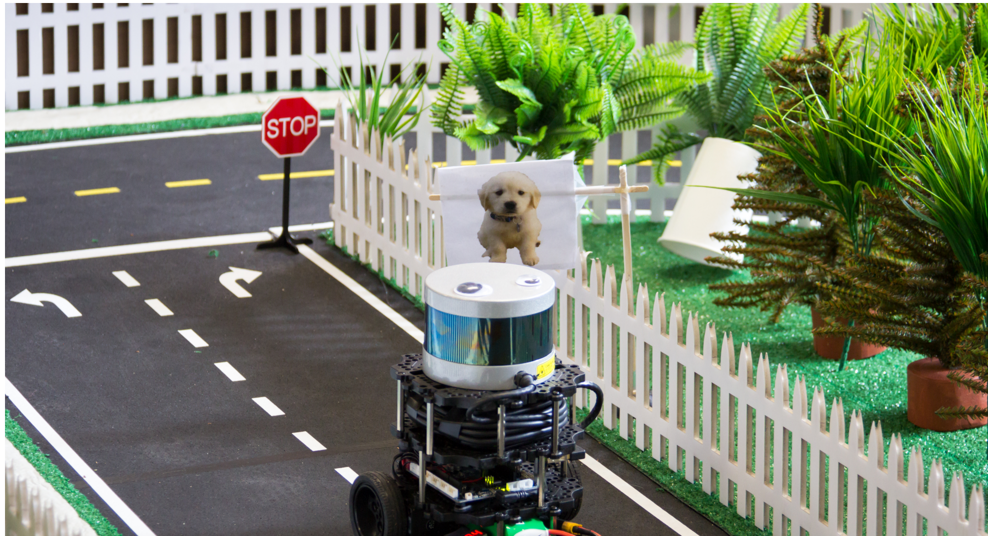


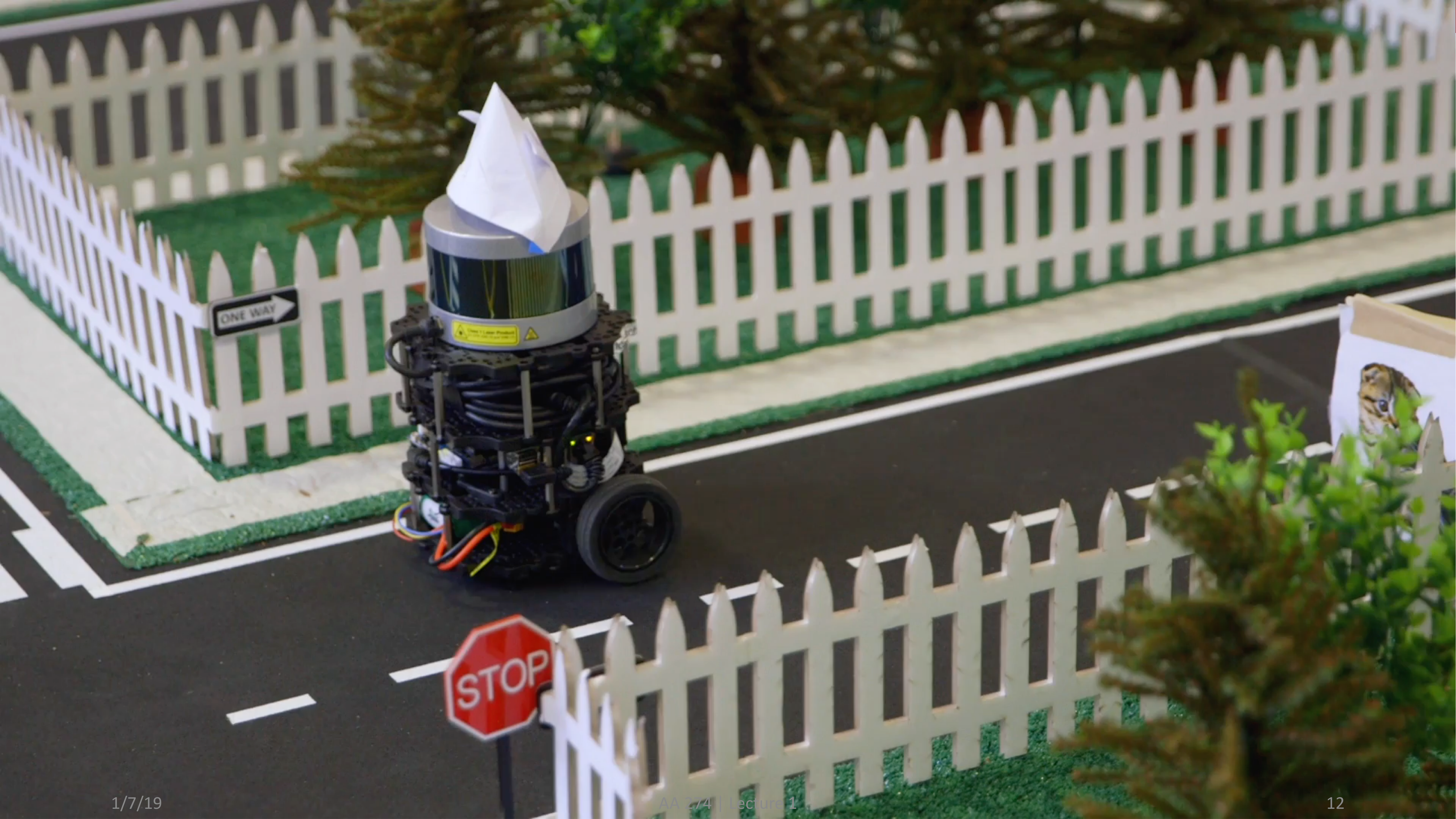
# The see-think-act cycle



# Course structure

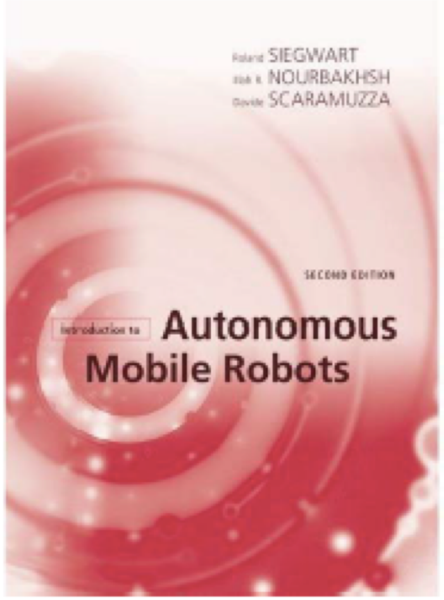
- Four modules, roughly of equal length
    1. motion control
    2. perception, from classic to deep learning approaches
    3. localization and SLAM
    4. planning, decision making, and system architecting
- Extensive use of the Robot Operating System (ROS)
    - Requirement: familiarity with programming (e.g., CS 106A or equivalent)
- Course grade calculation
    - 72% homework (four problem sets)
    - 23% final project
    - 5% scribe quality
    - Extra 5%: participation on Piazza




ONE WAY
STOP

# Recommended textbook

- R. Siegwart, I. R. Nourbakhsh, D. Scaramuzza. Introduction to Autonomous Mobile Robots. MIT Press, 2nd Edition, 2011.




- Additional reading material:
  - S. Thrun, W. Burgard, D. Fox. Probabilistic Robotics. MIT Press, 2005.
  - P. Goebel. ROS By Example. 2013.

# Schedule

| Date | Topic | Assignment | Readings |
|---|---|---|---|
| 01/07 | Course overview, mobile robot kinematics, introduction to motion control | | SNS:3.1-3:5; |
| 01/09 | The Robot Operating System (ROS) | HW1 out | Lecture notes |
| 01/11 | *Recitation*: Python (optional) | | |
| 01/14 | Open-loop and closed-loop motion control | | SNS:3.6 |
| 01/16 | Robotic sensors and introduction to computer vision | | SNS:4.1-4.2 |
| 01/18 | *Recitation*: dynamical systems (optional) | | |
| 01/21 | Martin Luther King, Jr., Day (no classes) | | |
| 01/23 | Camera models and camera calibration | HW2 out, HW1 due | SNS:4.2 |
| 01/25 | *Recitation*: advanced Python (optional) | | |
| 01/28 | Stereo vision and image processing | | SNS:4.3-4.5 |
| 01/30 | Feature detection & description, information extraction, and "classic" visual recognition | | SNS:4.7 |
| 02/05 | Machine learning for robot autonomy | | Lecture notes |
| 02/06 | Deep learning for visual recognition | | Lecture notes |
| 02/11 | Localization I | HW3 out, HW2 due | SNS:5:1-5:4 |
| 02/13 | Localization II | | SNS:5.5-5.6 |
| 02/18 | Presidents' Day (no classes) | | |
| 02/20 | Localization III | | SNS:5.6-5.7 |
| 02/25 | SLAM I | | SNS:5.8 |
| 02/27 | SLAM II | | SNS:5.8 |
| 03/04 | Motion planning I: combinatorial motion planning | HW4 out, HW3 due | SNS:6.1-6.5 |
| 03/06 | Motion planning II: sampling-based motion planning | | Lecture notes |
| 03/11 | Decision making and reinforcement learning | | Lecture notes |
| 03/13 | State machines and "architecting" the autonomy stack | HW4 due | Lecture notes |
| TBD | **Final project**, TBD | | |

# Team

**Instructor**

Marco Pavone

**Collaborators**:

- Andrew Bylard
- Patrick Goebel
- Boris Ivanovic
- Benoit Landry
- Joseph Steven Lorenzetti

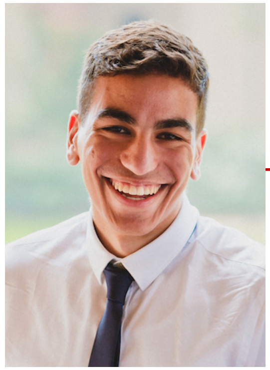
**Labs**:

ASL Autonomous Systems Lab

CARS Center for Automotive Research at Stanford

**CAs**

Christopher Covert



Amine Elhafsi

Karen Leung

Apoorva Sharma

# Logistics

- Location / time: 420-041, Mondays and Wednesdays, 1:30 -- 2:50pm
- Office hours:
  - Prof. Pavone: Mondays, 3:00 -- 5:00pm, after class, and by appointment
  - CAs (homework support): Tuesdays and Fridays, 2:00 -- 4:00pm, location TBD
  - CAs (ROS support): Mondays, Wednesdays, and Thursdays, 5:00 -- 7:00pm, location TBD

- Course website:
  - http://asl.stanford.edu/aa274/
  - https://piazza.com/stanford/winter2019/aa274
  - https://www.gradescope.com/courses/35120

- To contact the AA274 staff, use the email: aa274-win1819-staff@lists.stanford.edu

# Mobile robot kinematics

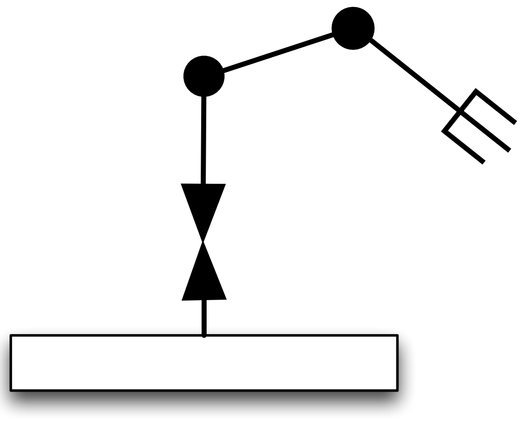
- Aim
  - Understand motion constraints
  - Learn about basic motion models for wheeled vehicles
  - Gain insights for motion control

- Readings
  - SNS: 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

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

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

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

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

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

- However, the converse is not true in general…

# Nonholonomic constraints

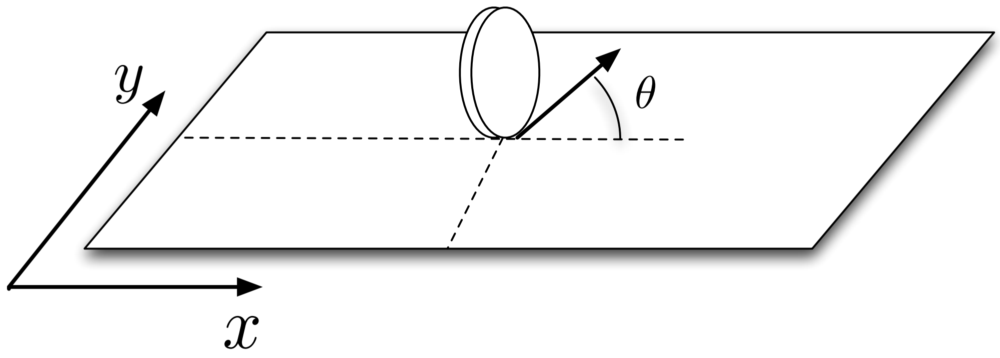
- If a kinematic constraint is not integrable in the form $h_i(\xi) = 0$, then it is said *nonholonomic* -> nonholonomic mechanical system
- Nonholonomic constraints reduce mobility in a completely different way. Consider a single Pfaffian constraint

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

- 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 $a^T(\xi) = 0$
  - No loss of accessibility

# Example of nonholonomic system

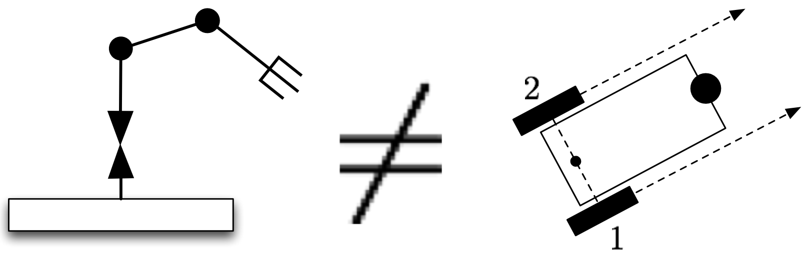
- System: disk that rolls without slipping
- $\xi = [x, y, \theta]^T$




- No side slip constraint

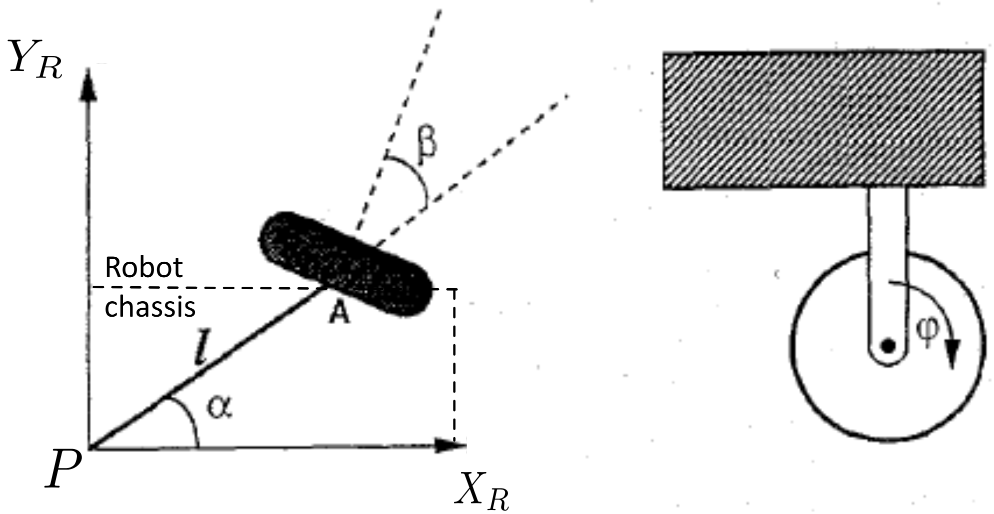
$$[\dot{x},\, \dot{y}] \cdot \begin{bmatrix} \sin\theta \\ -\cos\theta \end{bmatrix} = \dot{x}\sin\theta - \dot{y}\cos\theta = [\sin\theta, -\cos\theta, 0]\,\dot{\xi} = 0$$

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

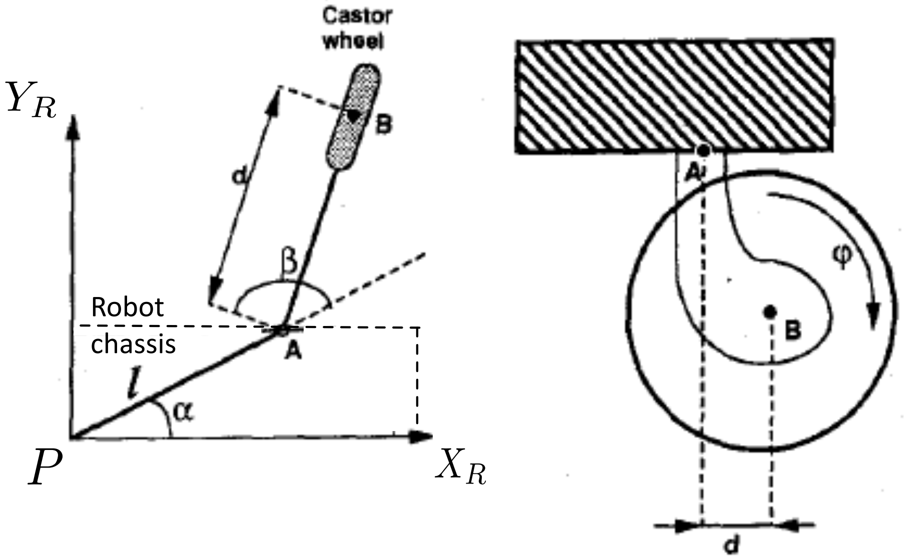


# Types of wheels

- Standard wheels (four types)




Standard wheel -- fixed or steerable



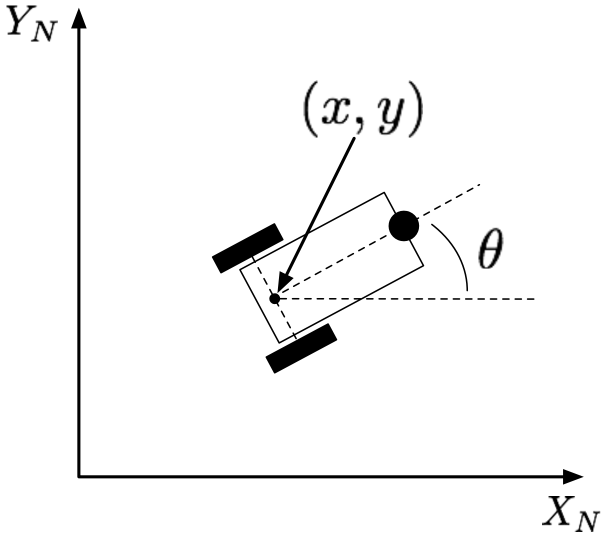

Standard, off-centered wheel (caster) -- passive or active

- Special wheels: achieve omnidirectional motion (e.g., Swedish or spherical wheels)

# Kinematic models (examples)

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

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \\ \dot{\zeta} \end{pmatrix} = \begin{pmatrix} \cos\zeta \ \cos\theta \\ \cos\zeta \ \sin\theta \\ \sin\zeta \\ 0 \end{pmatrix} u_1 + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} u_2$$

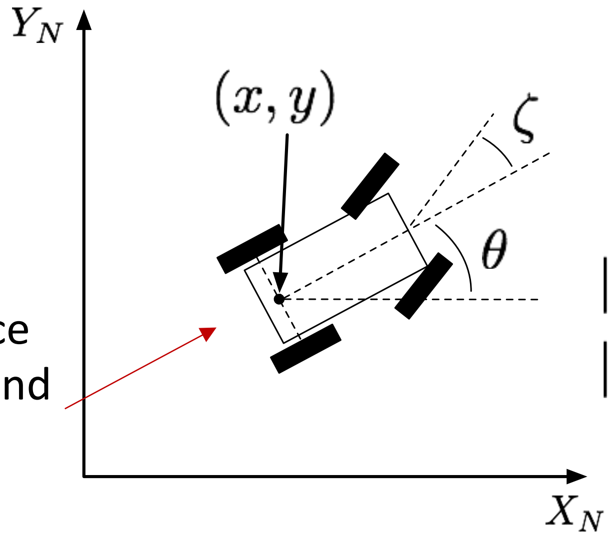



Unicycle or differential drive

$$|v| \leq v_{\max}$$

$$|\omega| \leq \omega_{\max}$$

Assume distance between rear and front axles is 1




Tricycle or simple car

$$|u_1| \leq u_{1,\max}$$

$$|u_2| \leq u_{2,\max}$$

$$|\zeta| \leq \zeta_{\max}$$

Warning: a kinematic state space model should be interpreted only as a subsystem of a more general dynamical model

# Simplified car models

- Assuming we do not care about the direction of the front wheels, set

$$v = u_1 \cos\zeta, \qquad \omega = u_1 \sin\zeta$$

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \\ \dot{\zeta} \end{pmatrix} = \begin{pmatrix} \cos\zeta \, \cos\theta \\ \cos\zeta \, \sin\theta \\ \sin\zeta \\ 0 \end{pmatrix} u_1 + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} u_2 \Rightarrow \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} \cos\theta \\ \sin\theta \\ 0 \end{pmatrix} v + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \omega$$

$|v| \leq u_{1,\max} \cos\zeta_{\max}, \;\; |\omega| \leq |v| \tan\zeta_{\max}$ $\longrightarrow$ Car-like robot

$|v| = u_{1,\max} \cos\zeta_{\max}, \;\; |\omega| \leq |v| \tan\zeta_{\max}$ $\longrightarrow$ Reeds&Shepp’s car

$v = u_{1,\max} \cos\zeta_{\max}, \;\; |\omega| \leq |v| \tan\zeta_{\max}$ $\longrightarrow$ Dubins’ car

- Reference: J.-P. Laumond. Robot Motion Planning and Control. 1998.

# Next time

ROS