اصول علم ربات – جلسه دوم

Fundamentals of Robotics – Lecture 02

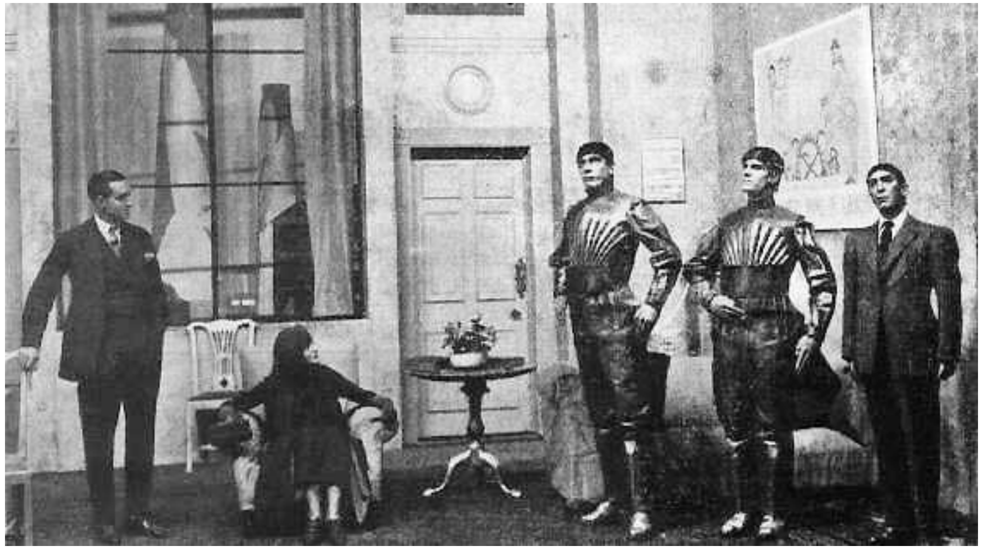
Course Roadmap-2

دکتر مهدی جوانمردی

زمستان و بهار ۱۴۰۱

[slides adapted from Gianni Di Caro, @CMU with permission]

Etymology of the term Robot



- R.U.R. (Rossum's Universal Robots): Theater 1920 sci-fi play by the Czech writer Karel Čapek
    - rabota = “obligatory work”
- From Proto-Slavic *orbota (“hard work, slavery”) derived from *orbъ (“slave”)
- After R.U.R., the commonly used term *automaton* started to be substituted with **robot**

DOMIN: Sulla, let Miss Glory have a look at you.

HELENA: (*stands and offers her hand*) Pleased to meet you. It must be very hard for you out here, cut off from the rest of the world.

SULLA: I do not know the rest of the world Miss Glory please sit down

HELENA: (*sits*) Where are you from?

SULLA: From here, the factory

HELENA: Oh, you were born here.

SULLA: Yes I was made here.

HELENA: (*startled*) What?

DOMIN: (*laughing*) Sulla isn’t a person, Miss Glory, she’s a robot.

HELENA: Oh, please forgive me . . .

DOMIN: (*puts his hand on Sulla’s shoulder*) Sulla doesn’t have feelings. You can examine her. Feel her face and see how we make the skin.

HELENA: Oh, no, no!

DOMIN: It feels just the same as human skin. Sulla even has the sort of down on her face that you’d expect on a blonde. Perhaps her eyes are a bit small, but look at that hair. Turn around, Sulla.

HELENA: Stop it!

DOMIN: Talk to our guest. We’re very honoured to have her here.

SULLA: Please sit down miss. (*both sit*) Did you have a good crossing.

More than 150 Years in the collective imaginary

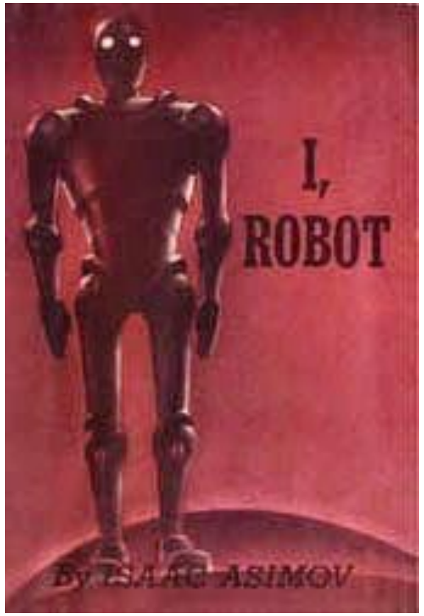
Sci-fi Robots & co.

A multitude of shapes,
attitudes, capabilities

Bubo, from the Clash of the Titans (1981)

The Steam Man of the Prairies (1868)

The Wizard of Oz (1939)



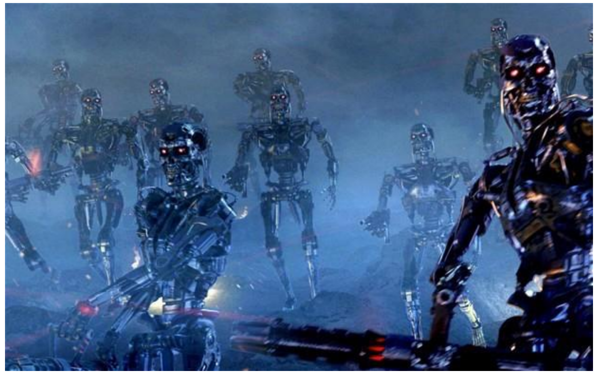
A complete illustrated history http://www.filmsite.org/robotsinfilm.html

More than 150 Years in the collective imaginary

Good robots
human / animal shaped

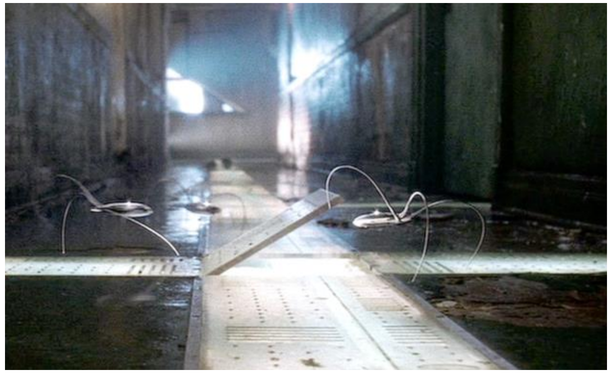
Nasty (more human?) robots
human / animal shaped

The Jetsons,
1962



Terminator,
1984

Star
Wars,
1977



Minority Report,
2002

Road map

- Robots?
- Robotics as a field of study
- Robotics in this course
- What will you learn
- Practical aspects of the course

A robot….?

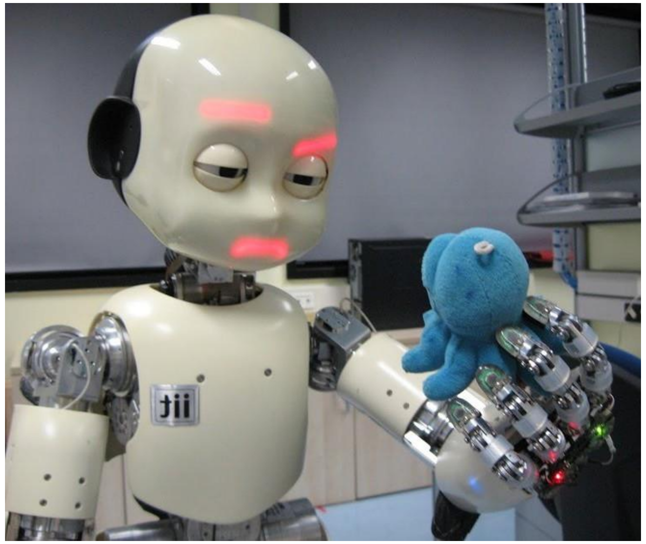
A robot....?

A **robot** (*mechanism*):

- is a machine which exists in the physical world,
- has movable parts,
- can sense its external and internal environment,
- can make decisions (fully or partially autonomous),
- acts upon the environment to achieve some goals,
- is designed to do a job by itself.

Links and joints

- **PHYSICALLY EMBEDDED**: exists in the 3D physical world, subject to the laws of physics (e.g., it does not live in a computer)
- **MOVEABLE PARTS**: made of multiple (rigid or soft) **bodies** (links) connected by **joints**, so that *relative motion* between adjacent links becomes possible.
  Actuation of the joints (e.g., by electric motors), causes the robot to move and exert forces in desired ways
- **ACT ON ITS ENVIRONMENT**: it has physical effectors/actuators, made out of links and joint



Links and joints

Rigid body / link :
The relative distance between any two points (e.g., in a link) remains unchanged

Soft body / link :
The relative distance between any two points can change

Effectors and Actuators

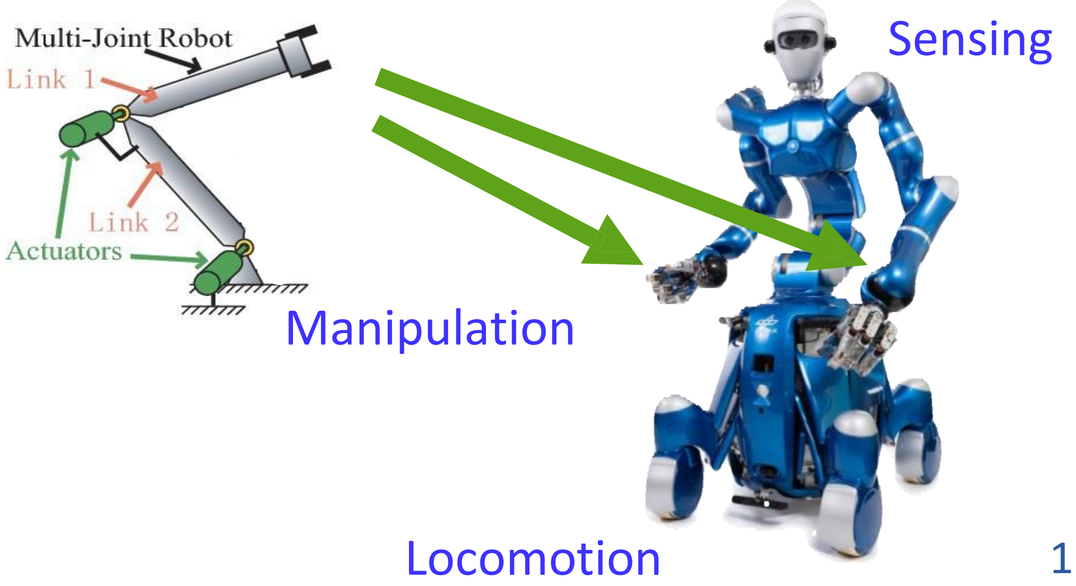
Action: Do physical things in the real world

EFFECTORS: Electro-mechanical parts that enable a robot to act, such as wheels, tracks, legs, arms, grippers, fingers, wings, flippers, … also devices for soldering, cutting, heating, melting ... An effector determines an effect on the environment

ACTUATORS: The underlying electro-mechanical mechanisms that physically enable the effectors to execute an action or movement, such as motors, (artifitial) muscles, rotors, hydraulic or pneumatic cylinders, chemically-sensitive materials, …

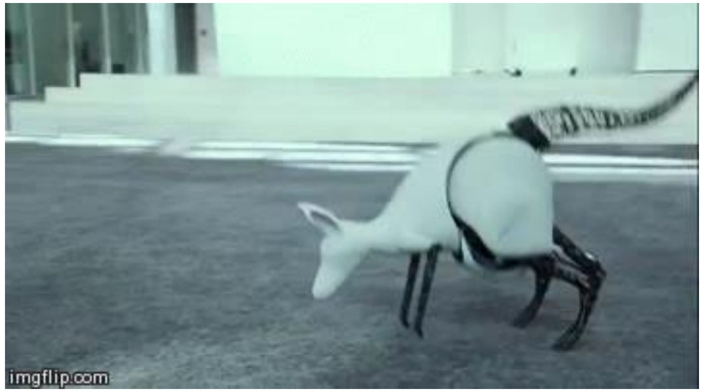
Three main categories of activities:

- ✓ **Locomotion**: moving around
- ✓ **Sensing**: gather environment's information
- ✓ **Manipulation**: handling, acting upon objects



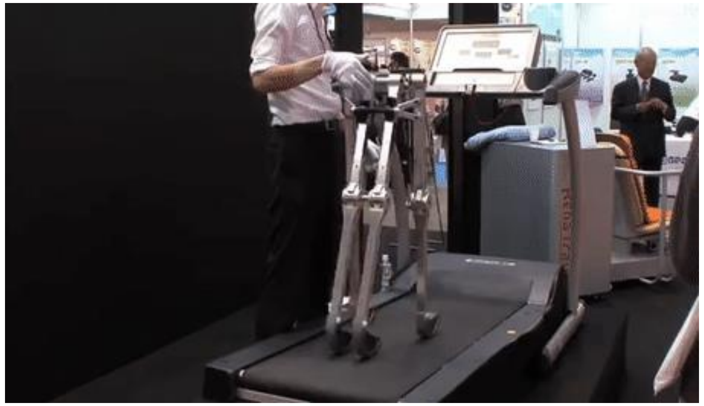
Active vs. passive actuation

ACTIVE ACTUATION: the action of effectors and actuators is performed through the direct consumption of energy to provide power, in the forms of fuel, batteries, springs, …



PASSIVE ACTUATION: exploiting the potential energy in the mechanics of the effector and its interaction with the environment instead of active power consumption

It needs a downward slope!



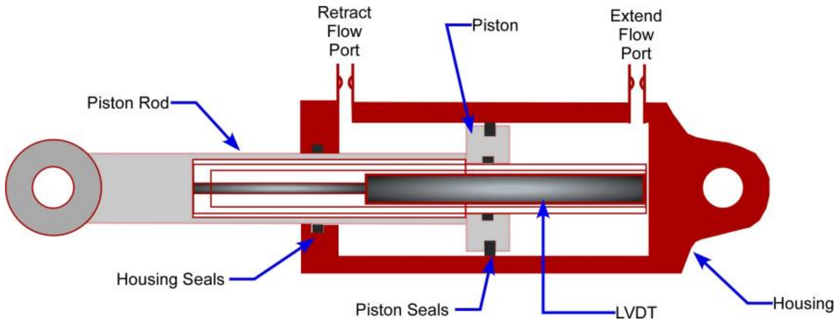
Types of actuators

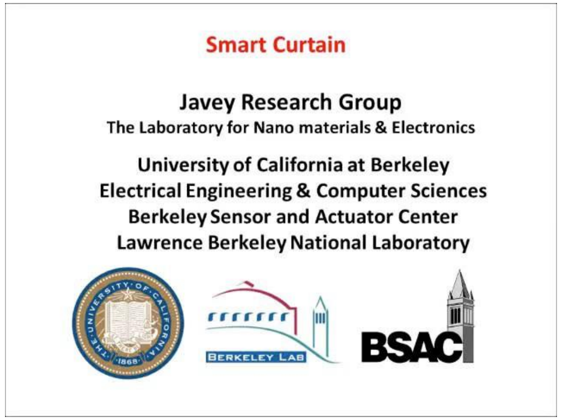
- ELECTRIC MOTORS
- HYDRAULICS
- PNEUMATICS
- MAGNETIC FIELDS
- PHOTO-REACTIVE MATERIALS
- CHEMICALLY-REACTIVE

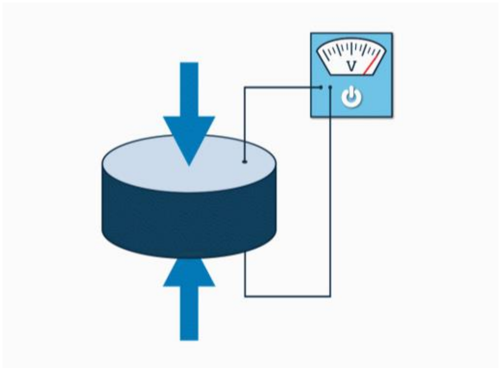
MATERIALS ○ THERMALLY-REACTIVE

MATERIALS ○ PIEZOELECTRIC

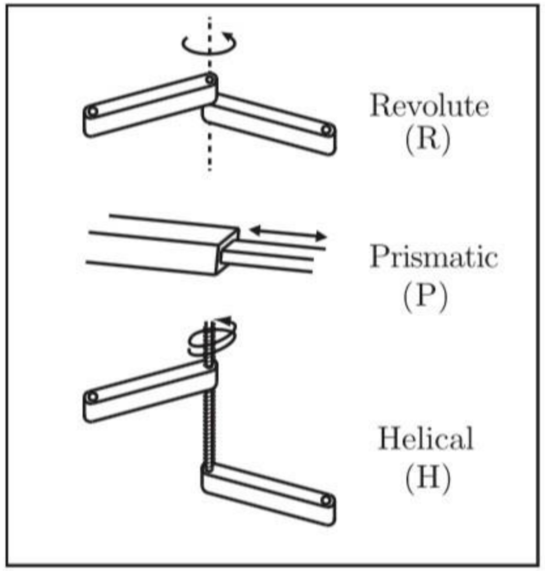
MATERIALS

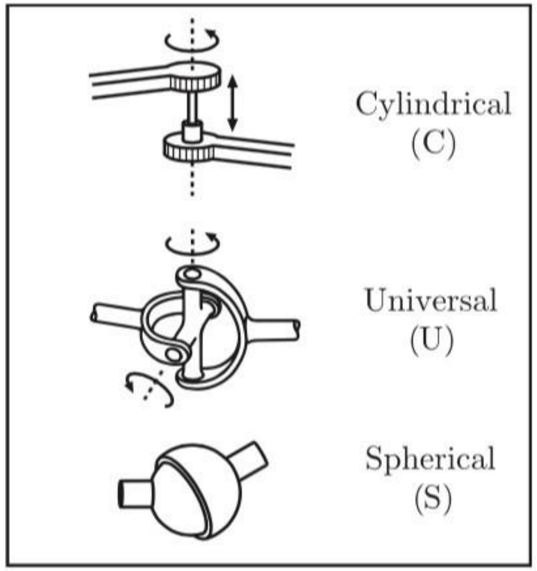


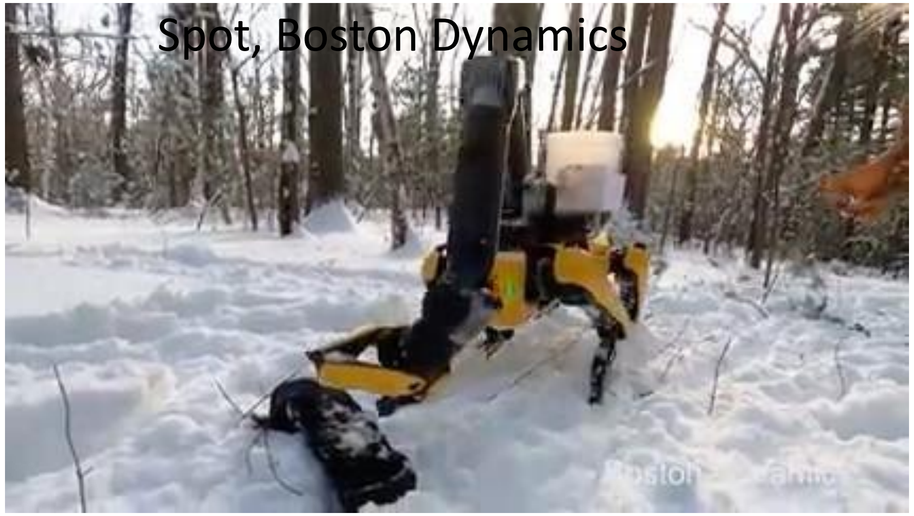


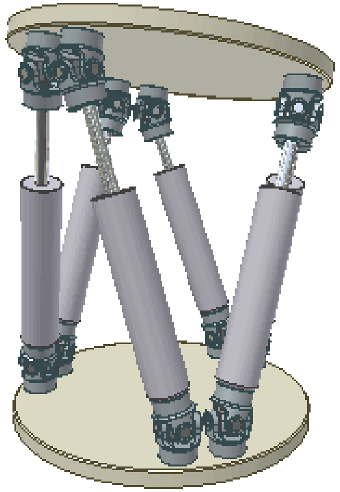


Typical robot joints and arrangements



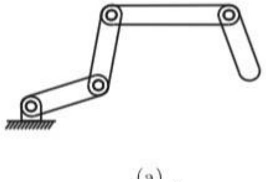


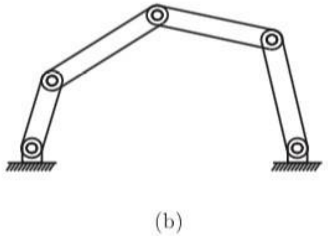




Stewart–Gough platform

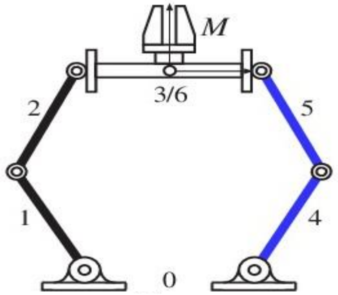
Open-chain

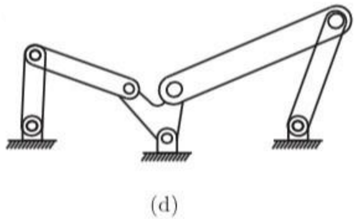




Closed-chain

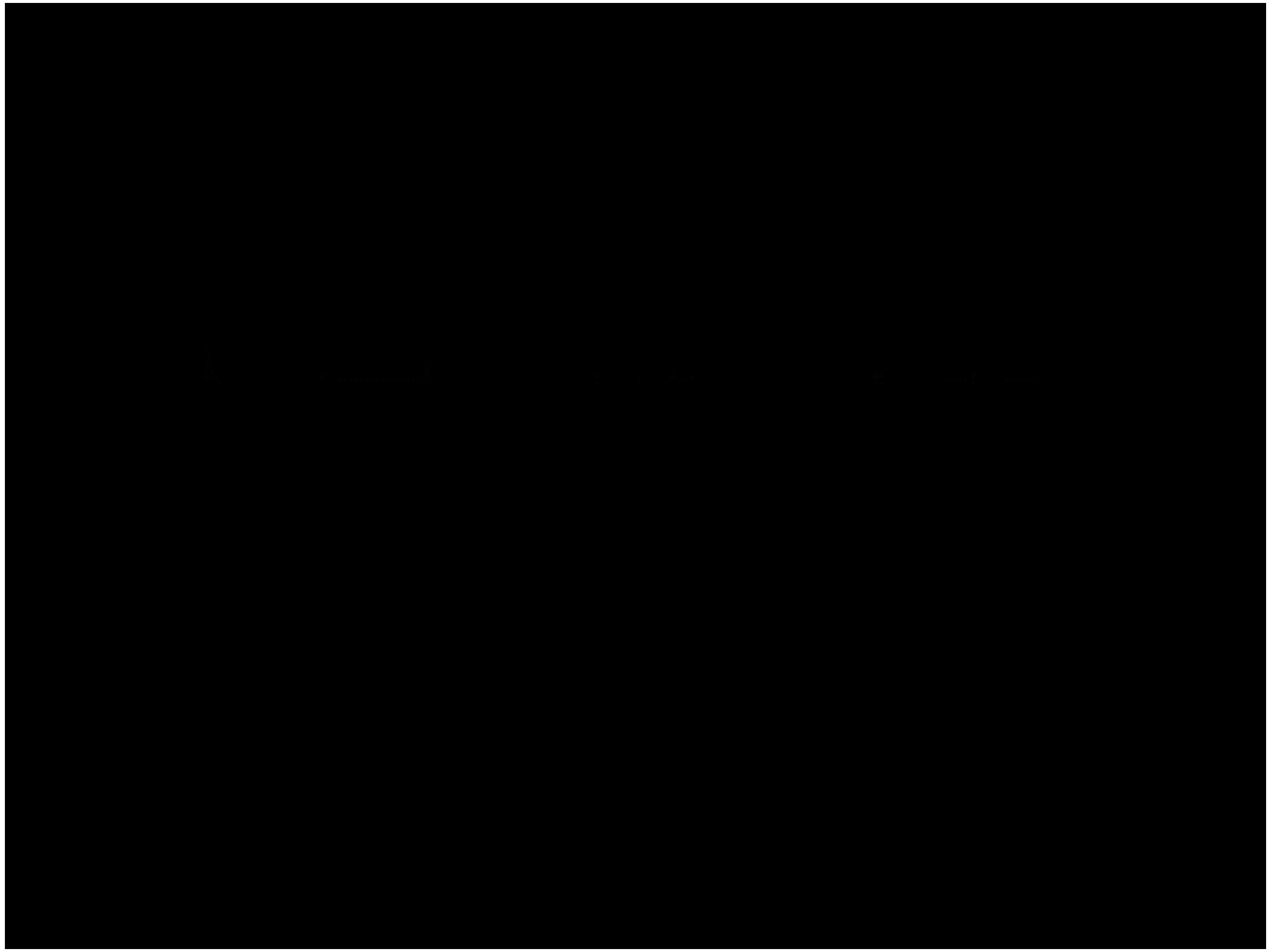
Parallel-chain





Locomotion can be obtained in many ways …

- Walk
- Run
- Fly
- Swim
- Dive
- Drive
- Jump
- Crawl
- Roll
- Slide
- Flow
- ….



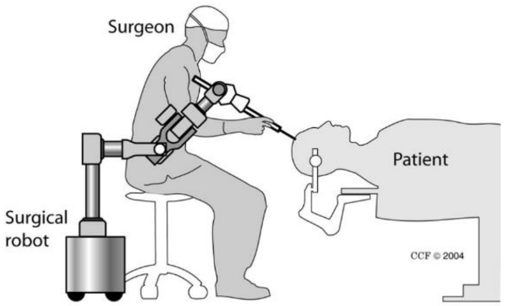
On purpose and autonomy of the robot

- **ACHIEVE GOALS:** it is not a random or meaningless entity, it has *purpose*

- ***AUTONOMOUS* SYSTEM:** acts based on its own (programmed or learned) decisions, and is not (*fully*) controlled by a human

  - **MANUAL CONTROL:** Fully operated by a human (maybe not a *true* robot)

✓ **Augmented system:**
- enhanced sensory data
- haptic



Robot and surgeon remains jointly in control. The surgeon remains in control of the procedure while the robot provides steady-hand manipulation of the instrument.

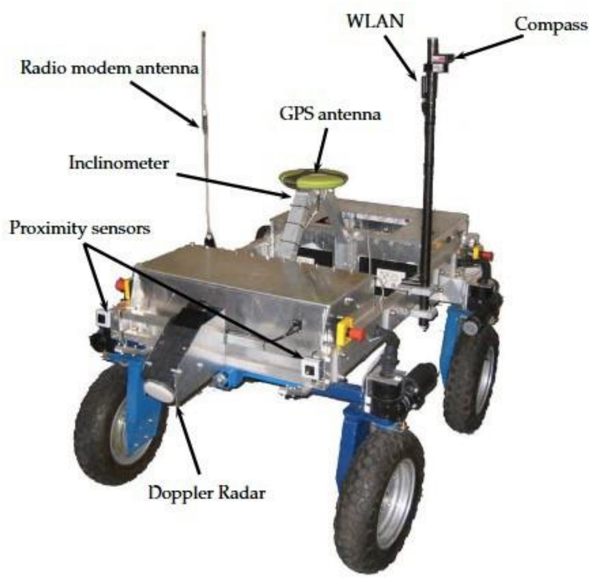
  - **AUTONOMOUS CONTROL:** No human intervention is possibly required for deciding and performing actions

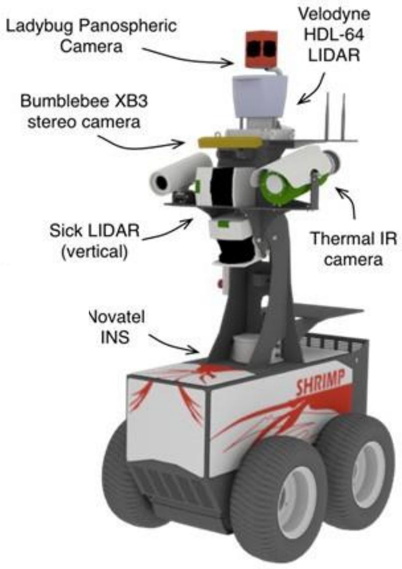
  - **SHARED CONTROL:** Part is on the robot side, part is on the human side

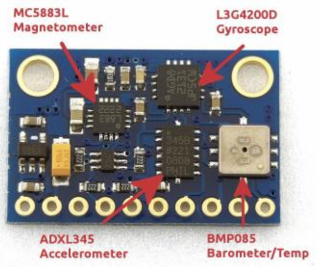
Control and sensing

- **OPEN-LOOP CONTROL:** Sensory input (feedback) from the environment the robot is acting upon is not considered, decisions are issued as **pre-programmed**
  - ➢ Environment should be practically deterministic, the robot should move with high precision, the cost of gathering and processing data should be high, … no surprises!

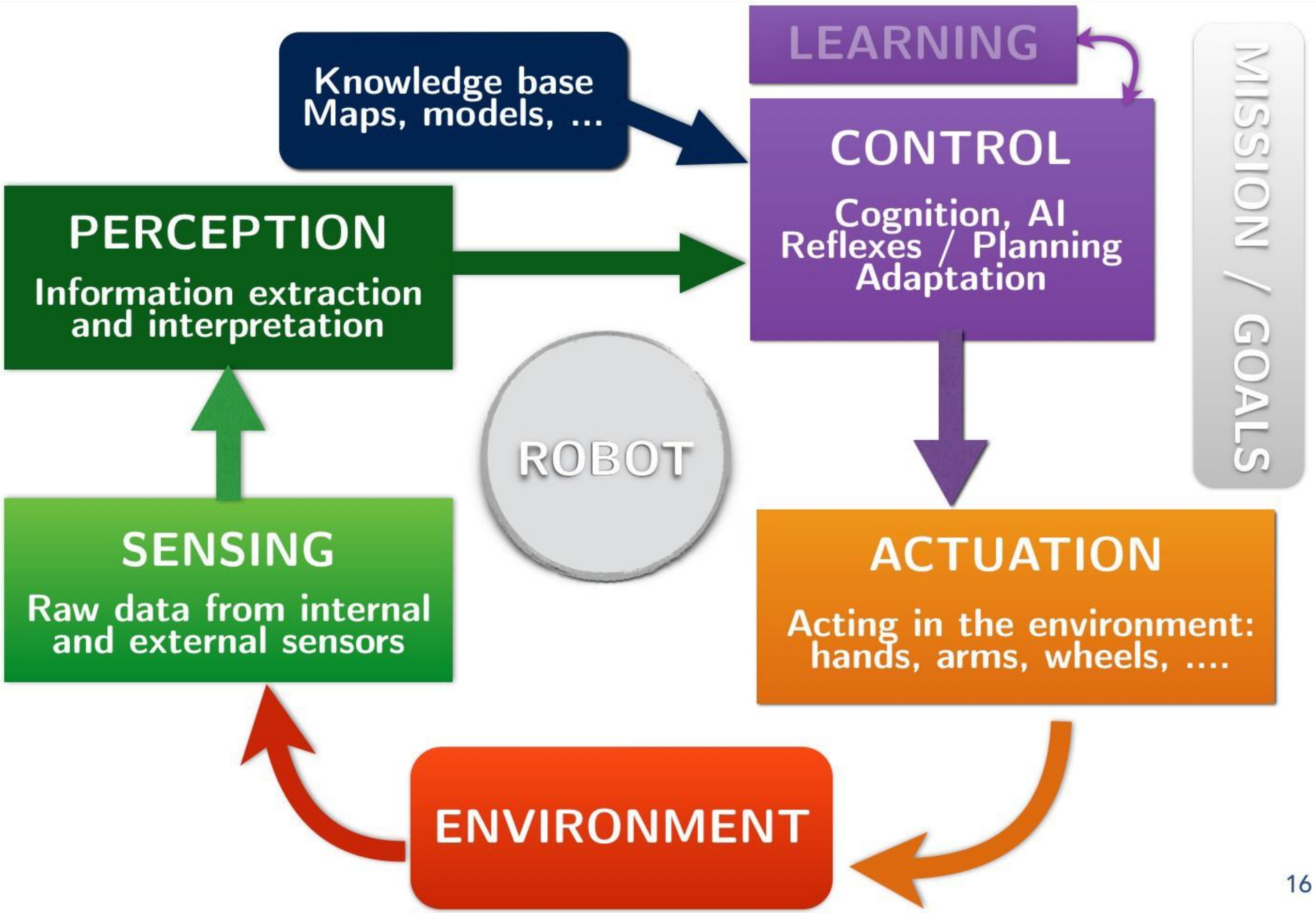
- **CLOSED-LOOP CONTROL:** Sensory feedback information from the environment (**exteroceptive sensing**) and from the robot itself (**proprioceptive sensing**) is used to **adapt decision-making** accordingly



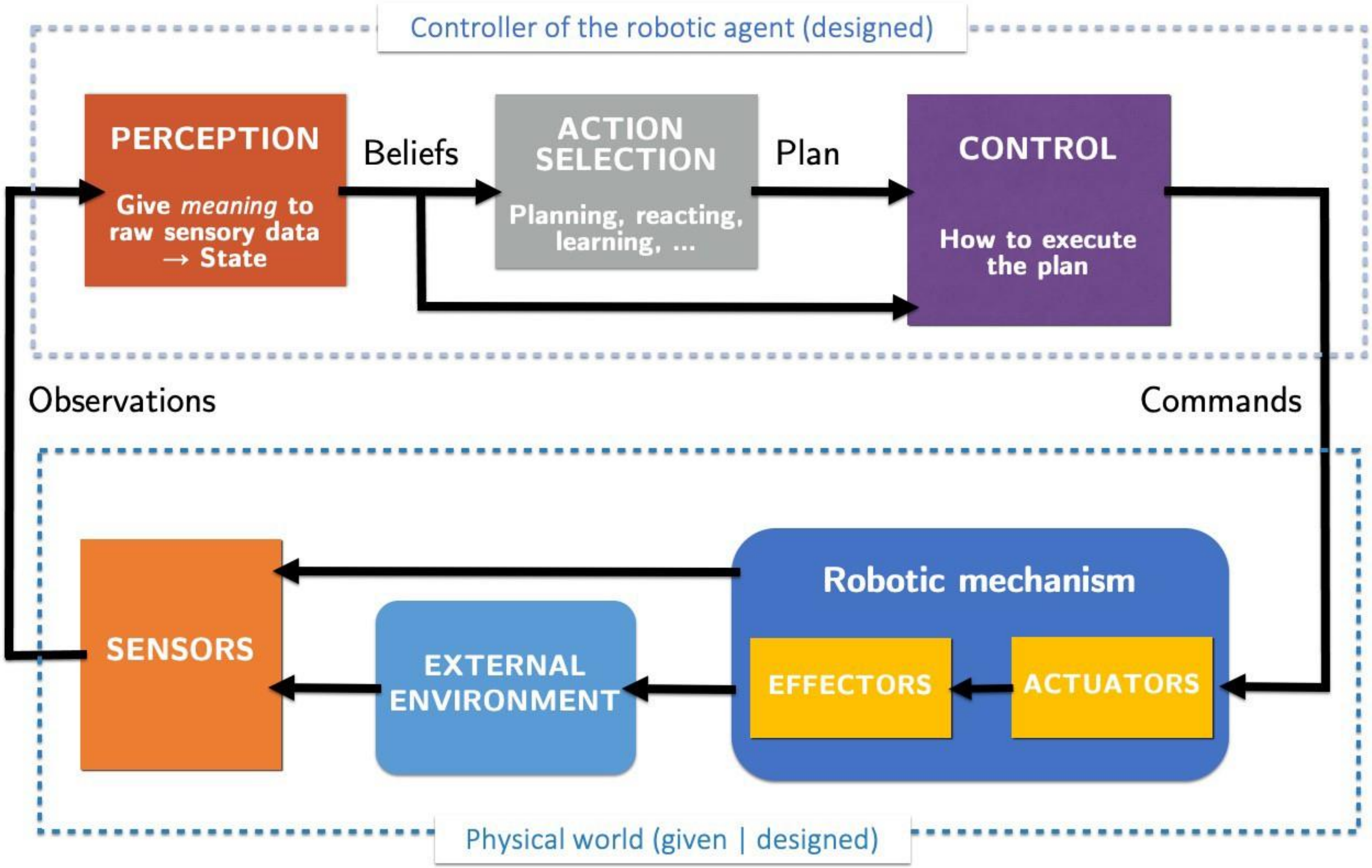




A general view of a robotic system architecture



Embodied agent + (intelligent) controller



So, what robotics is about?

- **Robot making**
  - Design
  - Mechatronics
  - Materials
  - Sensors
  - Actuators
  - …
- **Actuation**
  - Wheels
  - Arms
  - Hands
  - Joints
  - Legs
  - Heads
  - Rotors, blades
  - Motors
  - …
- **Robot control**
  - Cybernetics Control
  - theory
  - Automation Artificial
  - Intelligence
  - Knowledge representation
  - Probabilistic reasoning
  - Estimation theory
  - Decision-making Self-
  - organization
- **Sensing and perception**
  - Machine vision
  - Speech recognition/generation
  - Range finders
  - Dead reckoning
  - Localization techniques
  - Mapping
  - …
- **Software, interfaces, testing**
  - Device drivers
  - Inter-process
  - communications Multi-
  - process arbitration Interfaces
  - for status access Status / data
  - logging Simulation of robot(s) and environment physics
  - Benchmarks, data analysis
  - Safety and security
  - Dependability
  - …

We can't do everything!!!!

General topics considered in the course

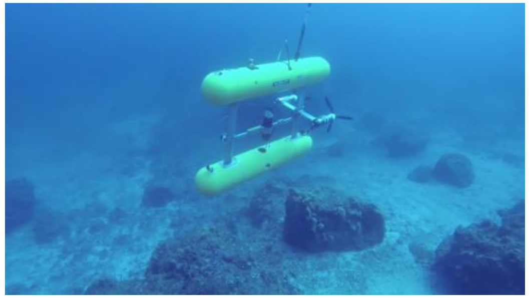
- **Robot making**
  - Design
  - Mechatronics
  - Materials
  - Sensors
  - Actuators
  - ...
- **Actuation**
  - Wheels
  - Arms
  - Hands
  - Joints
  - Legs
  - Heads
  - Rotors, blades
  - Motors
  - ...
- **Robot control**
  - Cybernetics
  - Control theory
  - Automation
  - Artificial Intelligence
  - Knowledge representation
  - Probabilistic reasoning
  - Estimation theory
  - Decision-making
  - Self-organization
- **Sensing and perception**
  - Machine vision
  - Speech recognition/generation
  - Range finders
  - Dead reckoning
  - Localization techniques
  - Mapping
  - ...
- **Software, interfaces, testing**
  - Device drivers
  - Inter-process communications
  - Multi-process arbitration
  - Interfaces for status access
  - Status / data logging
  - Simulation of robot(s) and environment physics
  - Benchmarks, data analysis
  - Safety and security
  - Dependability
  - ...

20

What type of robots should we study?

Industrial / Arm Robotics:
Complex, but fundamental

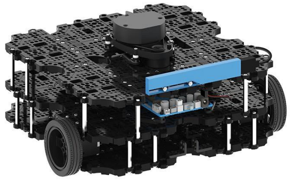
Humanoid / Legged Robotics:
Very complex and specialistic



Aerial / Water Robotics:
Ad hoc, require infrastructure

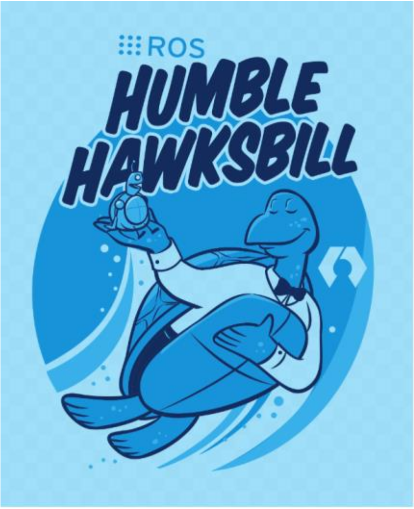
Mobile, wheeled robotics
+
Arm robotics (some)
+
AI robotics (some)
+
ROS, Gazebo

GAZEBO



ROS
Open Source Robotics Found...

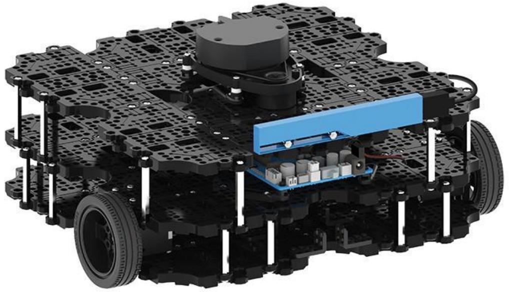
Our robot hw /sw tools



ROS 2 Humble

GAZEBO

TurtleBot 2



TurtleBot 3

Erle Rover

Anki Cozmo

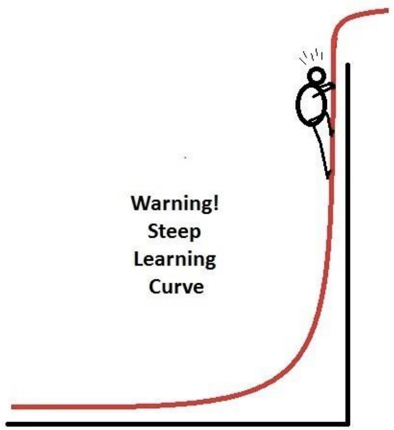
PhantomX Reactor Robot Arm

https://ros2-industrial-workshop.readthedocs.io/en/latest/_source/navigation/ROS2-Turtlebot.html

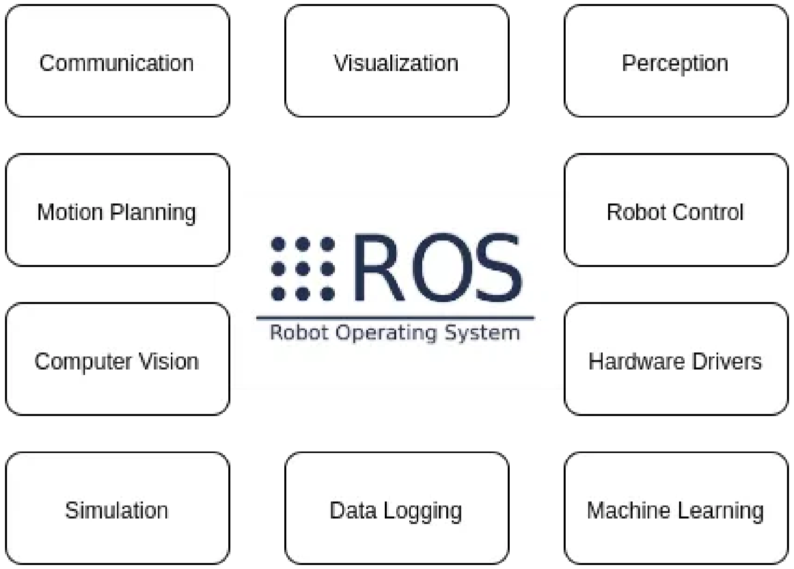
ROS (Robot Operating System)

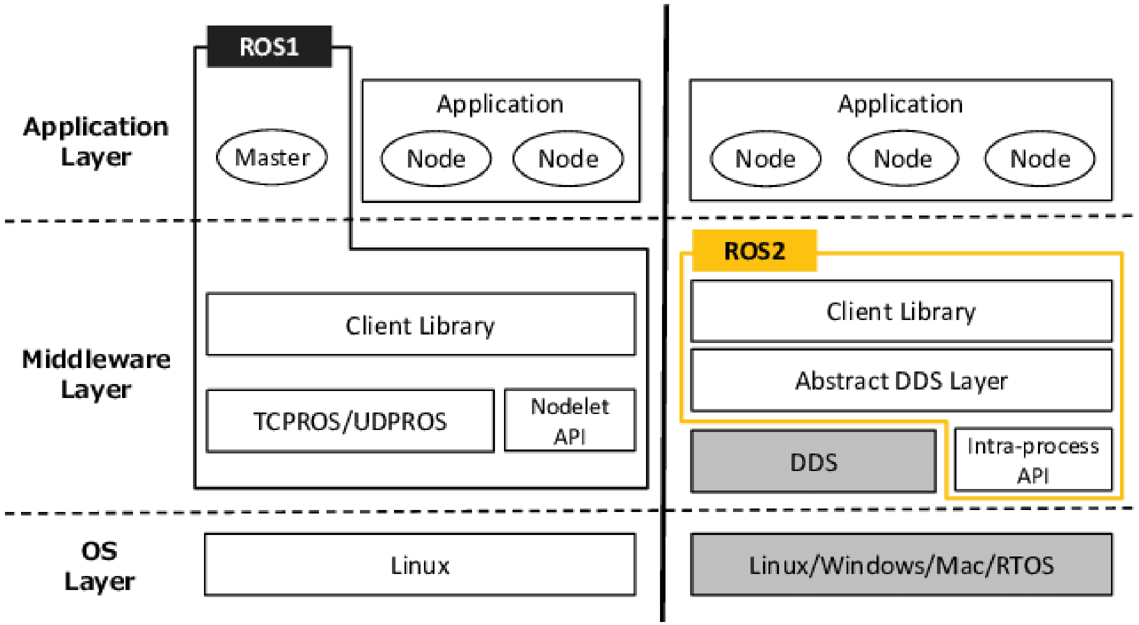
An open-source, middleware for your robot

Tools for programming robots. Its primary goal was/is to enable code reuse in robotics research and development



- Implementation of commonly-used functionality
- Inter-process communication (middleware)
- Hardware abstraction
- Visualization tools
- Package management
- ROS community





Autonomous mobile robotics

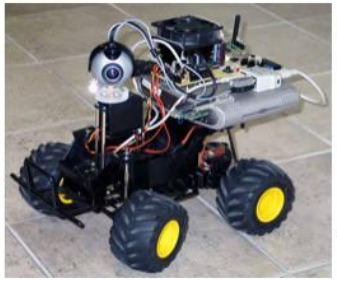
Mobile → *Wheeled* robots

***Design* and *Automatic Control* of a potentially large zoo of vehicles ...**

2- and 4-wheel
Differential driving

Tricyle

Murata Boy and Girl
Bicycle and Unicycle



Car-like
Ackermann

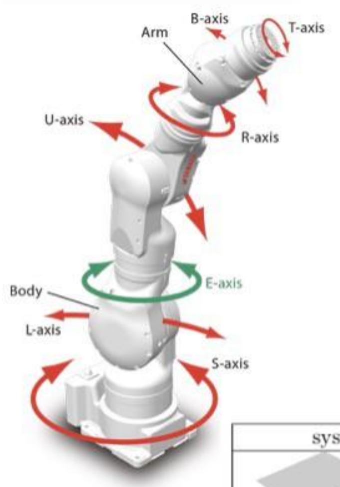
6-wheel
space rovers

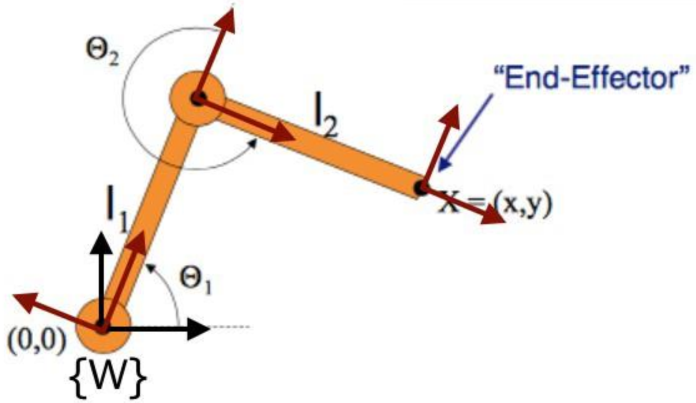
4-wheel
steering

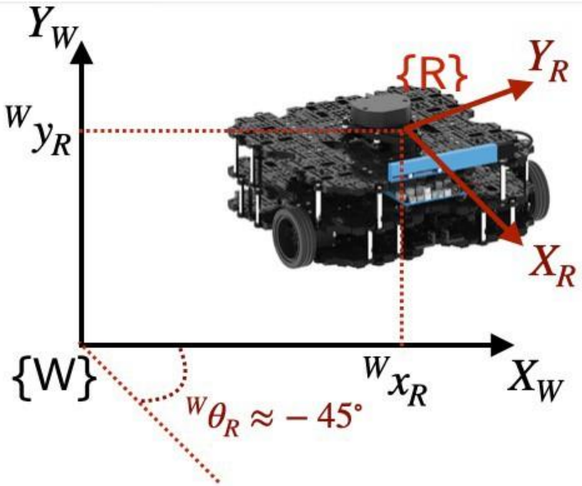
Tri-bots
Omniwheels

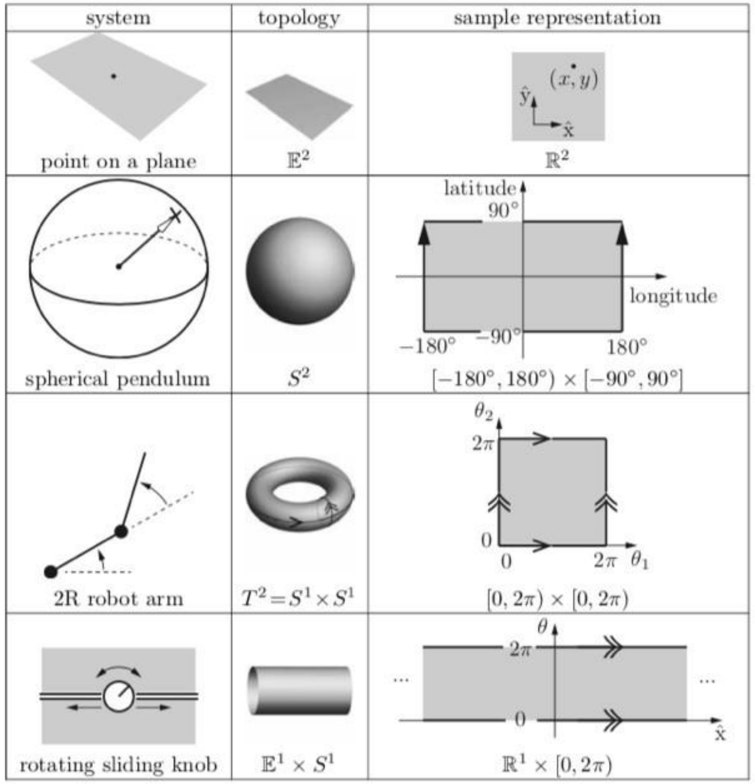
2

Journey starts by representing robot configuration, DOF, pose

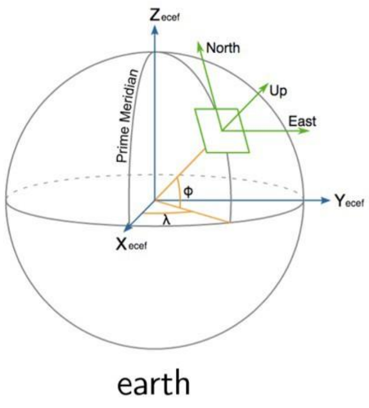


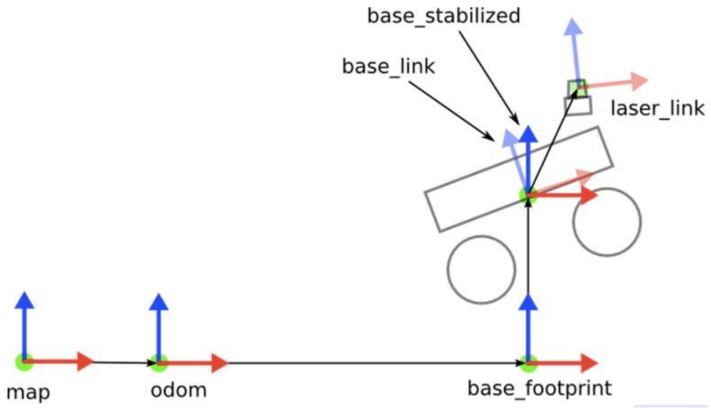




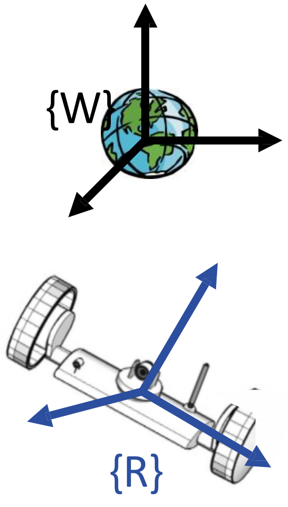


Journey starts by representing robot configuration, DOF, pose

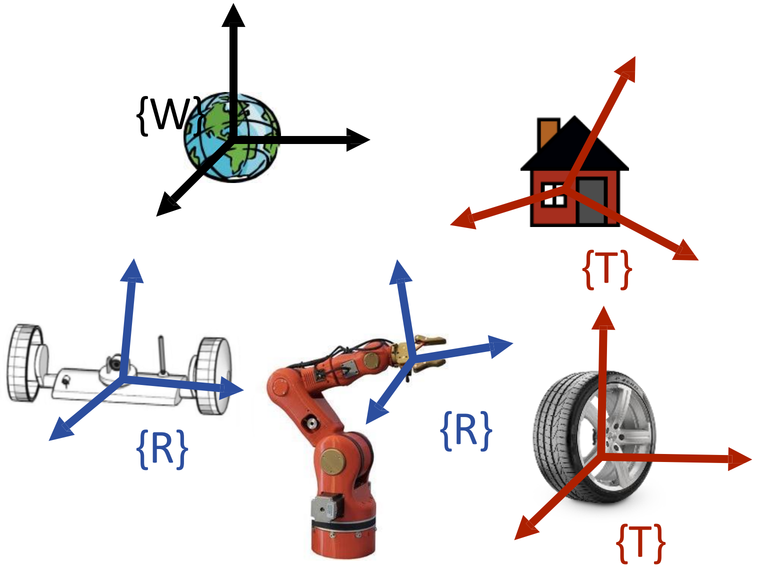




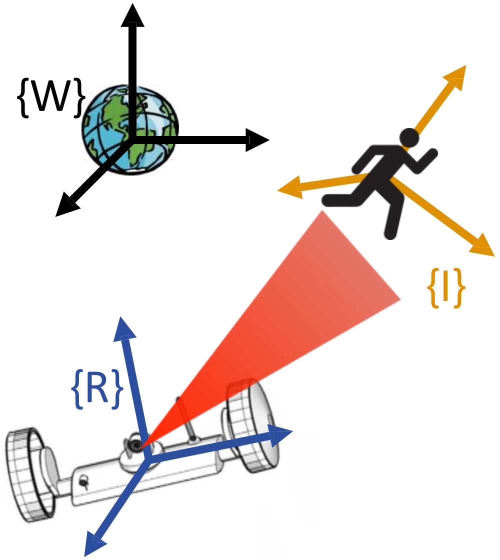
Where's the robot? What is robot's pose with respect to the world reference frame {W}?



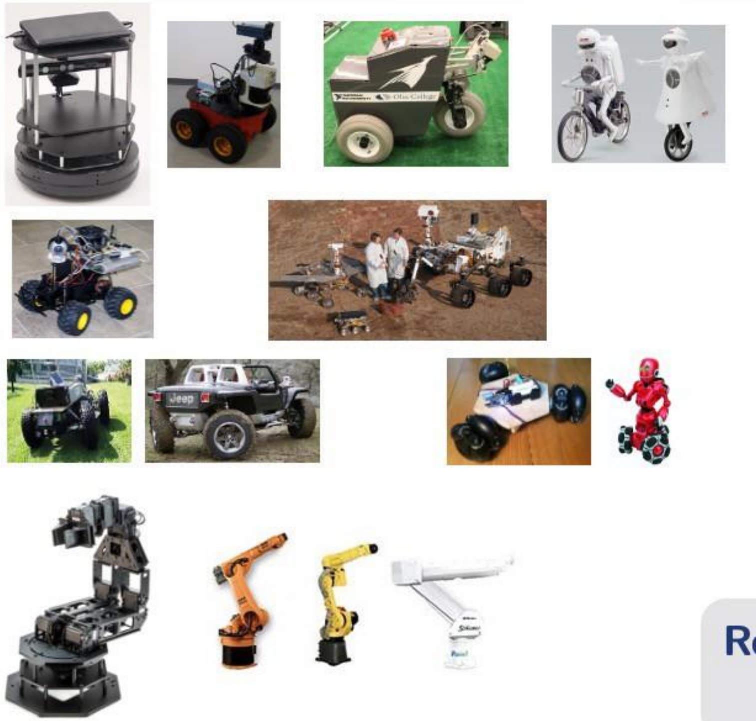
Robot's pose with respect to the external frame {T} (e.g., a target) ?



What is intruder's pose, observed using robot's lateral camera, in the world frame {W}?



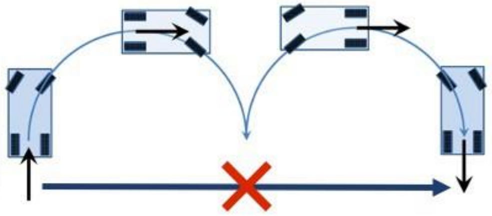
Next step: Kinematics models



Many types of wheels and of wheel arrangements

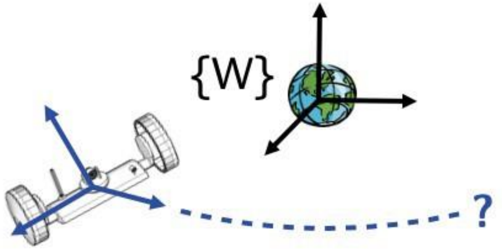
Different types of robotic arms

Kinematic constraints on the robot motion



Two-moves car parking: no side-way motion

Reference frame transformations
Kinematic models



$$\dot{x} = v(t)\cos(\theta(t))$$
$$\dot{y} = v(t)\sin(\theta(t))$$
$$\dot{\theta} = \omega(t)$$

$$\dot{\xi}_W = R^{-1}(\theta)\dot{\xi}_R = R^{-1}(\theta)\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix}$$

$$R(\theta) = \begin{bmatrix}\cos(\theta) & \sin(\theta) & 0\\ -\sin(\theta) & \cos(\theta) & 0\\ 0 & 0 & 1\end{bmatrix}$$

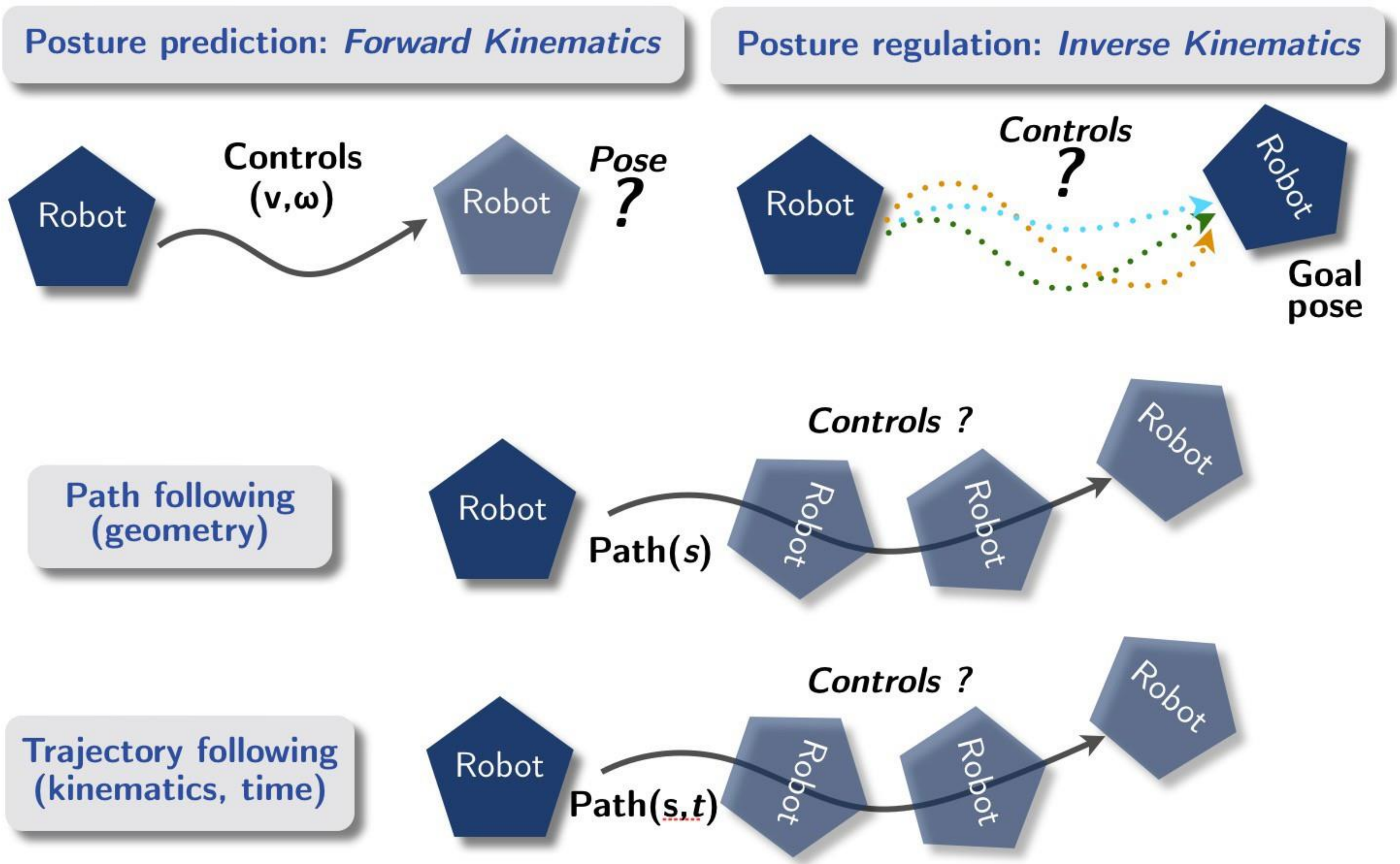
$$x(t) = \int_0^t v(t)\cos(\theta(t))dt$$
$$y(t) = \int_0^t v(t)\sin(\theta(t))dt$$
$$\theta(t) = \int_0^t \omega(t)dt$$

Generic robot

$$x(t) = \frac{1}{2}\int_0^t (v_R(t) + v_L(t))\cos(\theta(t))dt$$
$$y(t) = \frac{1}{2}\int_0^t (v_R(t) + v_L(t))\sin(\theta(t))dt$$
$$\theta(t) = \frac{1}{2\ell}\int_0^t (v_R(t) - v_L(t))dt$$

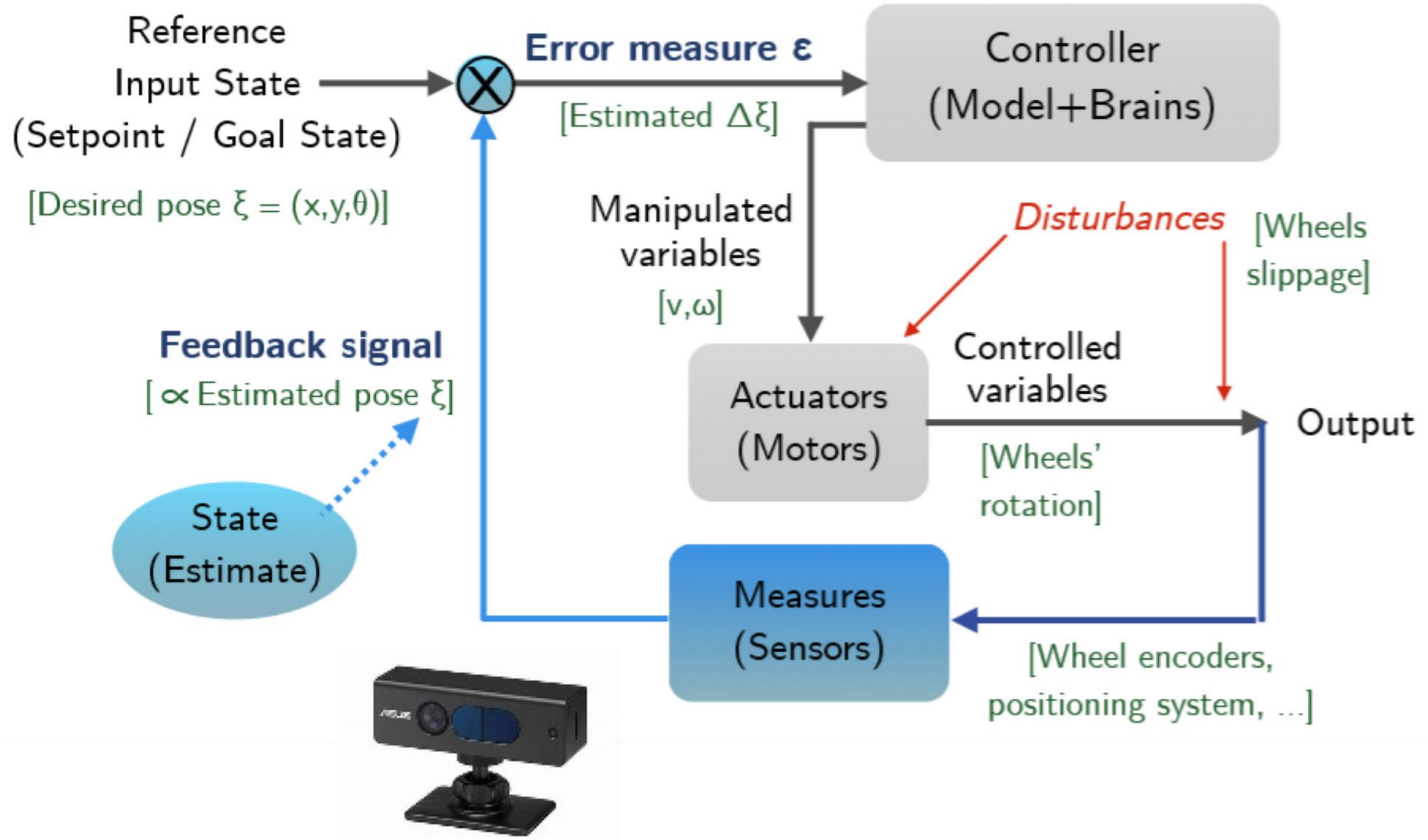
Differential steering robot

Forward / Inverse Kinematics + Controls

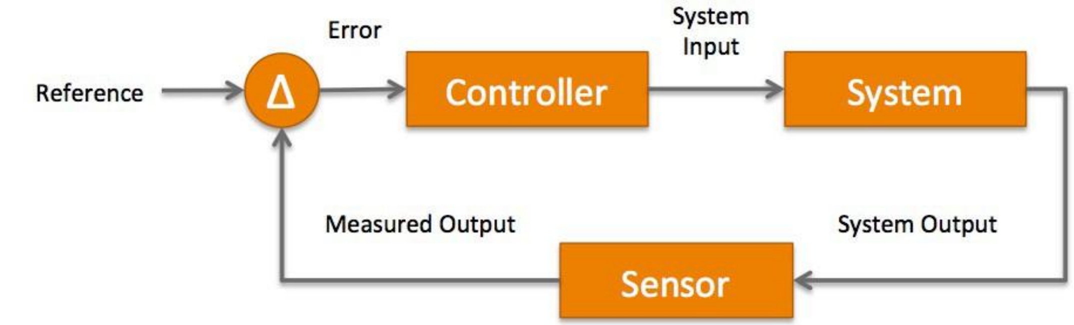


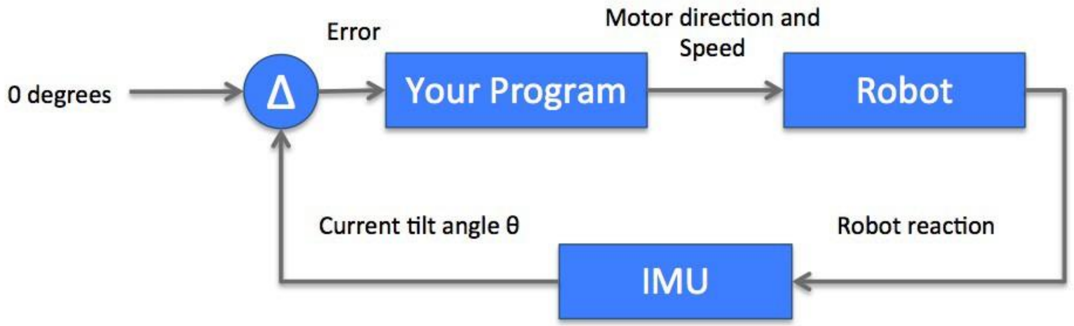
Next: Closed-loop control for error correction

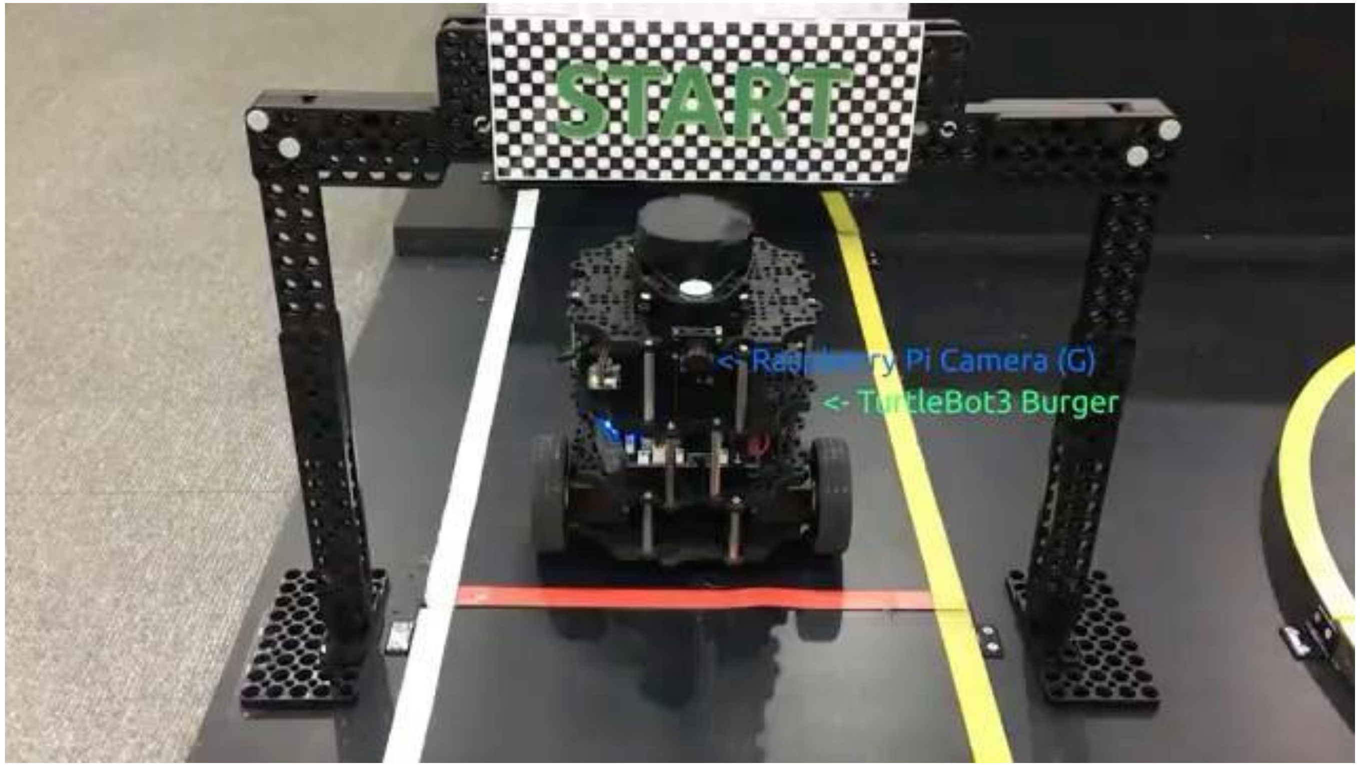
Things might (<u>will!</u>) go wrong, open-loop controls needs to be replaced by **closed-loop control** (using kinematic models)



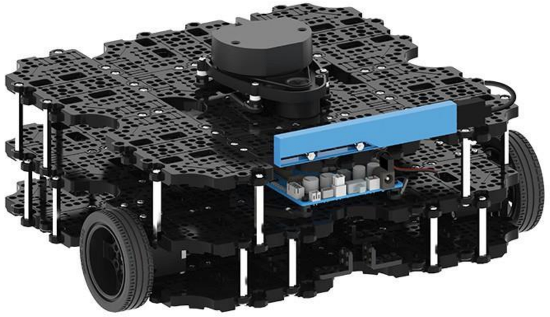
Feedback-based control







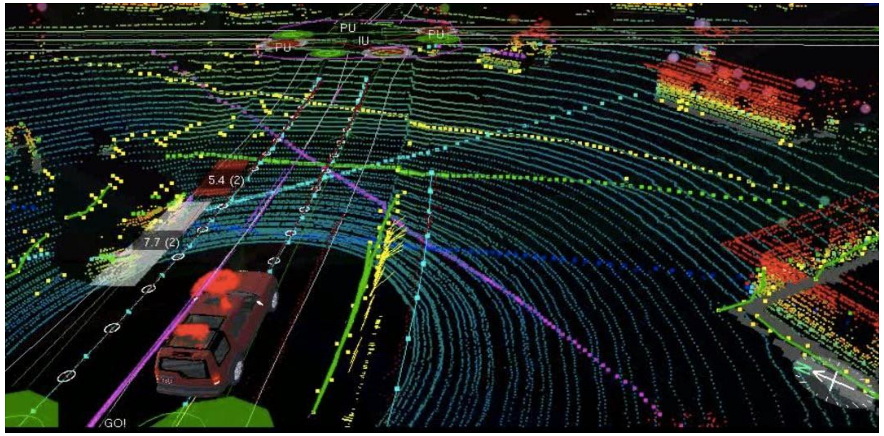
Feedback needs data! Sensors: from raw data to perception

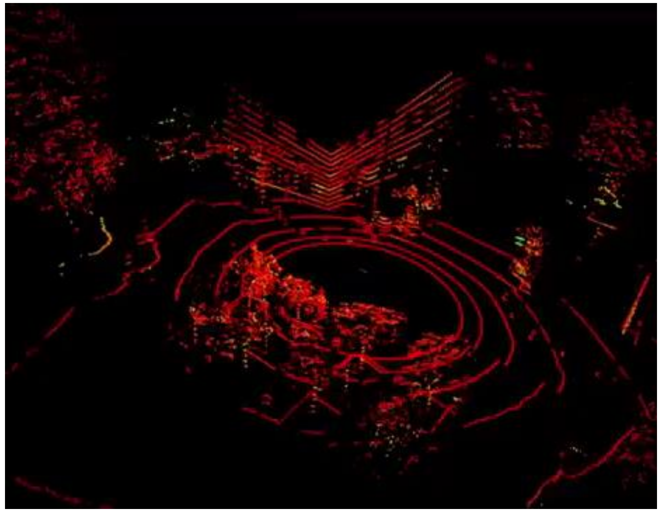


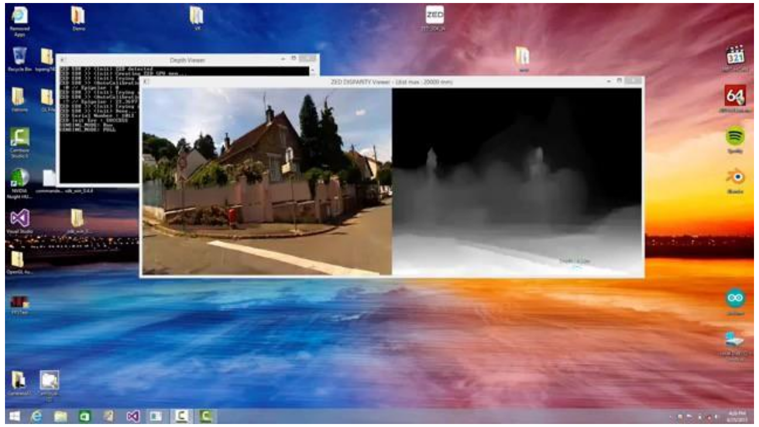
- Proprioceptive sensors
- Exteroceptive sensors

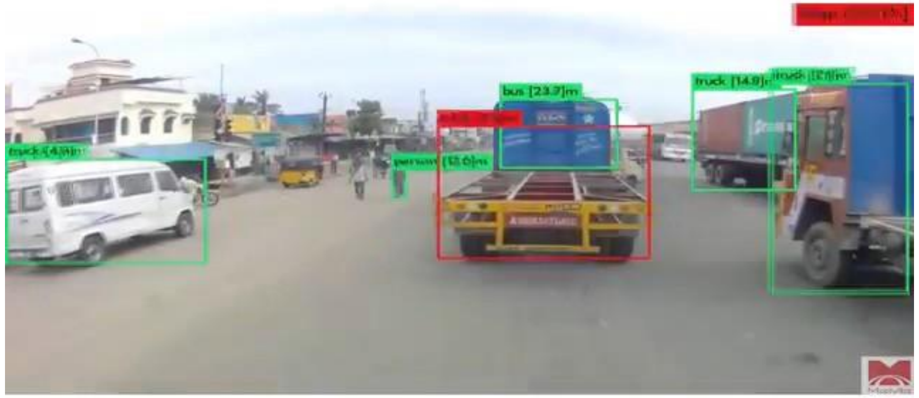
Sensors: from raw data to perception

1.3 million data points per second with a 360° horizontal field-of-view and a 26.8° vertical field-of-view.









Fundamental problems in mobile autonomous robotics

Where am I?

Localization + **Sensing**

(State estimation)

Kalman filter
Extended Kalman filter
Particle filter

Where am I going?

Representation
+
Landmark-based **Mapping** and **SLAM**

EKF, Monte Carlo, Perception

How do I get there?

Planning (Deliberative) + **Path Execution**

Exact and Probabilistic
Non-holonomic constraints
Closed-loop controls

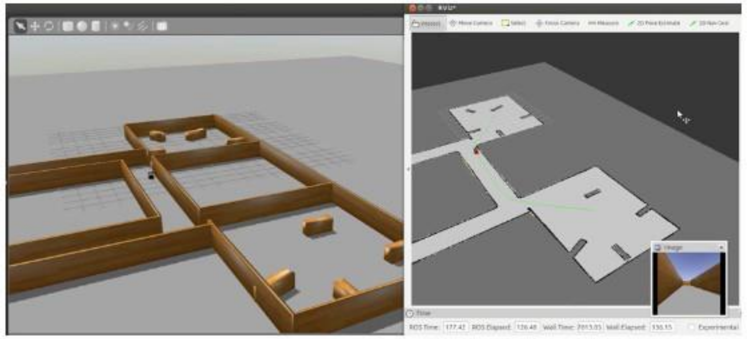
To finish with a touch on AI Olympics

Robot navigation and control using:

Reinforcement learning, Supervised learning, Deep learning

Balancing theory & hands-on

Experiment with the models in physics-based realistic *simulation* learning and exploiting ROS and GAZEBO tools



ROS

Open Source Robotics Foundation

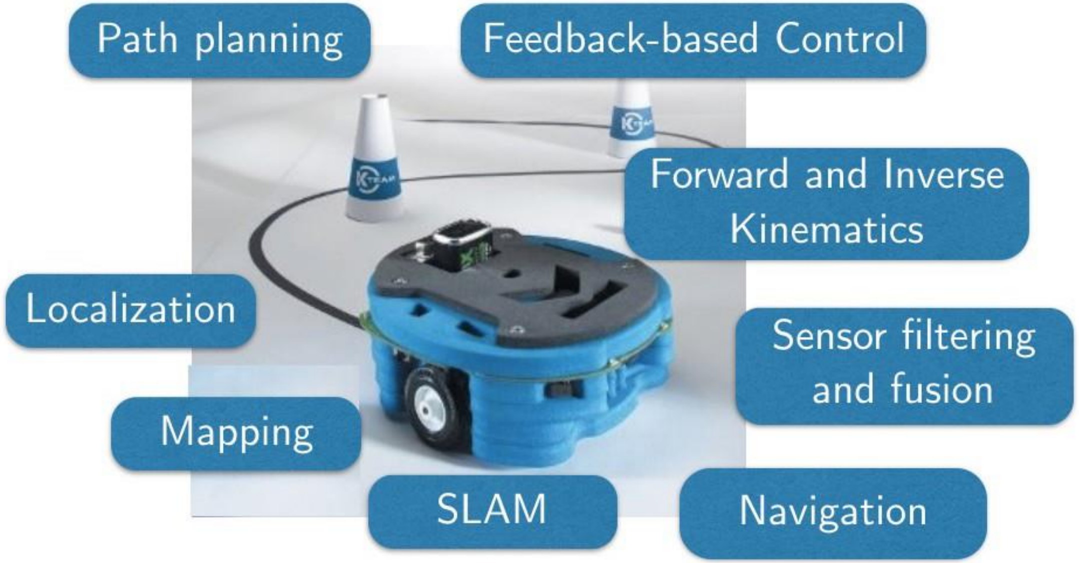
GAZEBO

Face the challenges of real-world

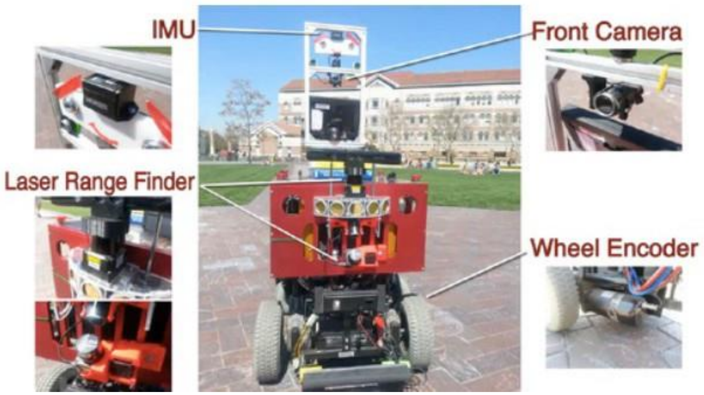
***Theory* classes on mathematical and computational *models* about *fundamental problems in* robotics**

What will you take-home?

A general overview of the ***fundamental problems***, and of their standard solution, in ***autonomous mobile robotics, arm robotics, AI robotics***

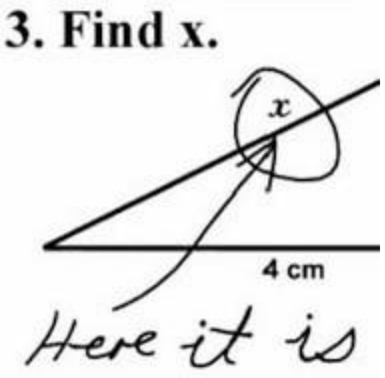


Some practical insights regarding ***robot design*** and the ***characteristics and the use of the basic sensors*** for relative and global localization, and for navigation



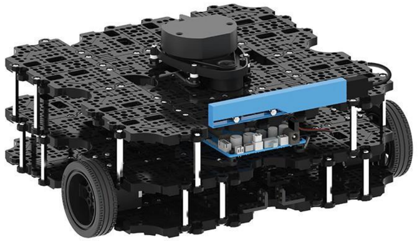
What will you take home?

Some general **mathematical tools** and techniques, and the "refreshment" of useful mathematical notions



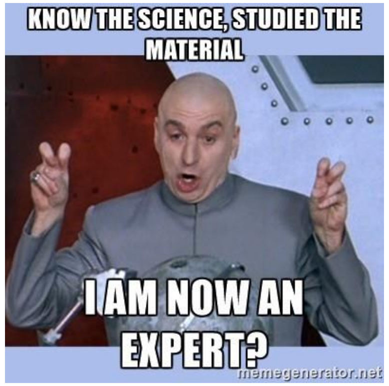
- Kinematics for controlled rigid bodies
- Statistical filters
- Kalman filter
- Extended Kalman filter
- Bayes + Monte Carlo techniques
- Jacobians
- Closed-loop control of dynamical systems
- Planning algorithms
- Topological notions
- A bit of AI and deep learning

Basic working knowledge of ROS and GAZEBO

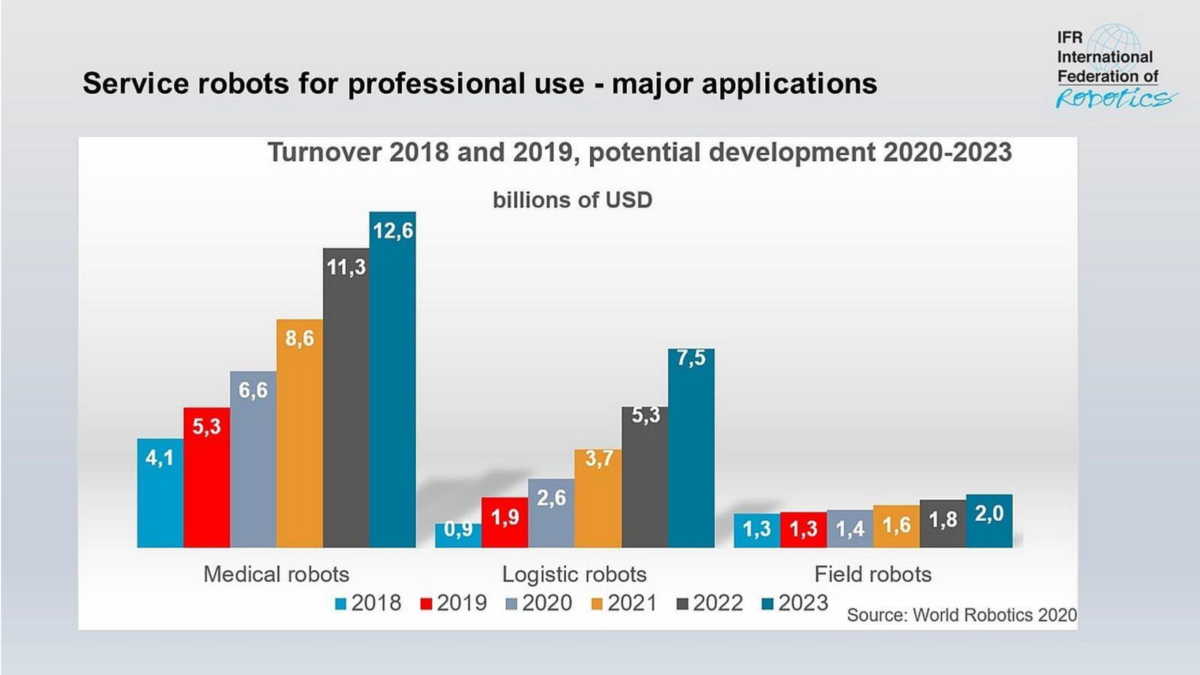


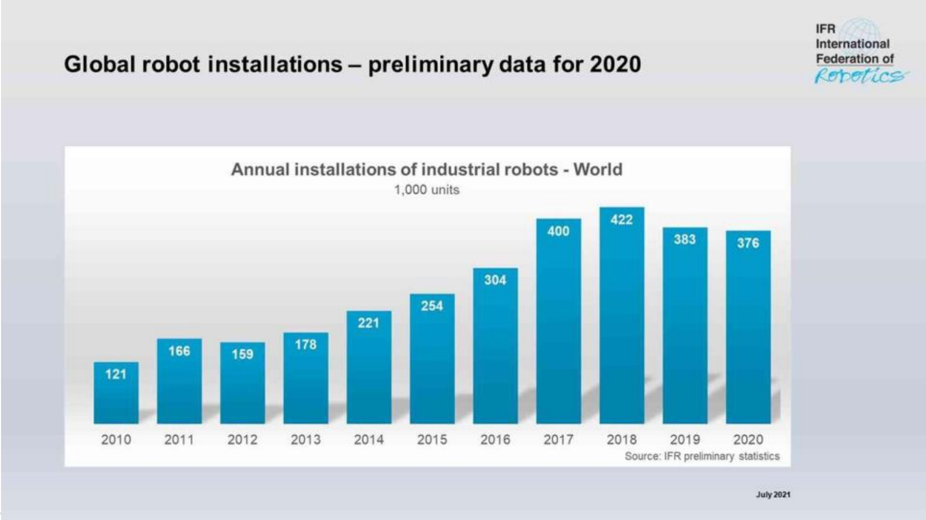
ROS
Open Source Robotics Foundation

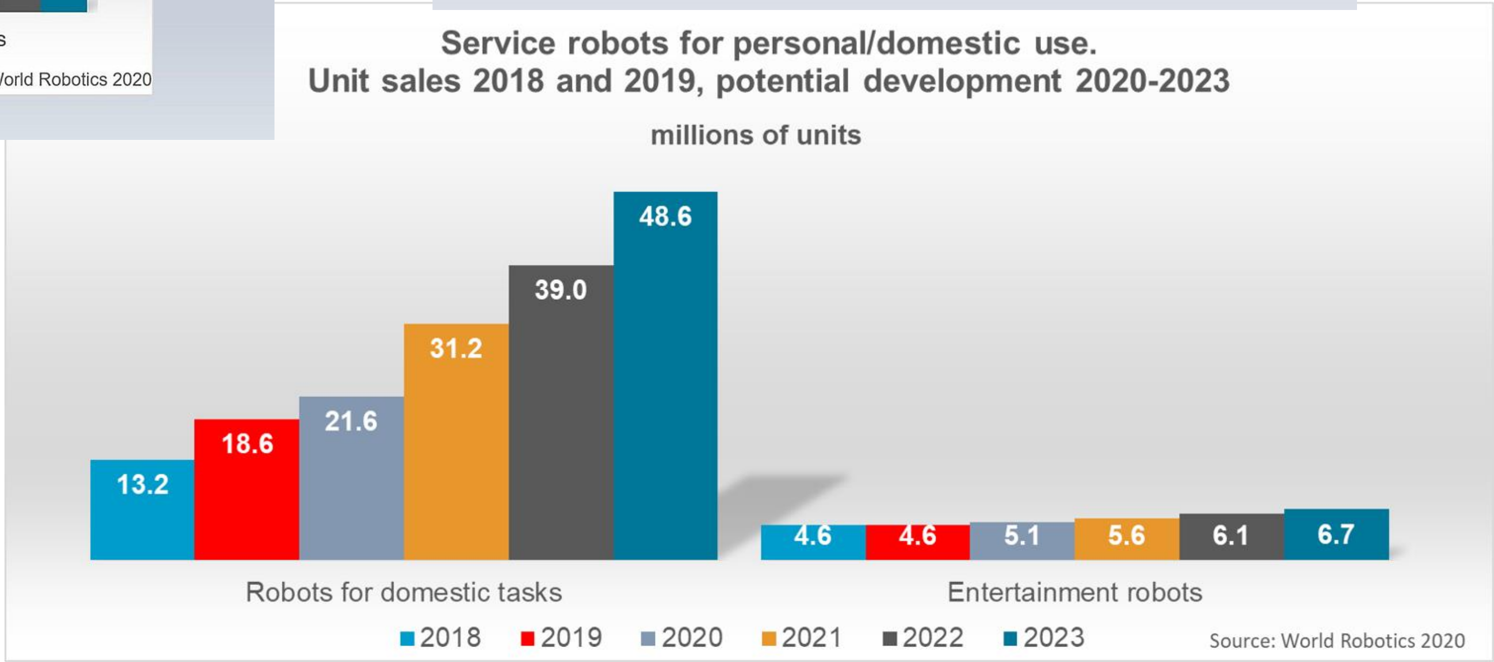
GAZEBO



Robotics hype: a growing world-wide trend!







It was (is) a long way (to go)

1961 — **First robot arm** went to work assembling cars at a General Motors plant, in NJ, USA

1968 — **First robot arm controlled by a digital computer**, from Marvin Minsky at MIT

1970 — Shakey, first **AI-based robot** that could move, sense, and reason on its environment, from SRI, Stanford

1977 — The Voyager 1 and 2 **NASA space probes** were launched to study Saturn and Jupiter

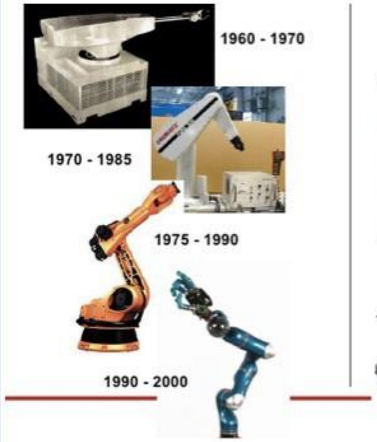
1996 — Honda researchers introduce P2/ASIMO, the **first complete human-like robot**

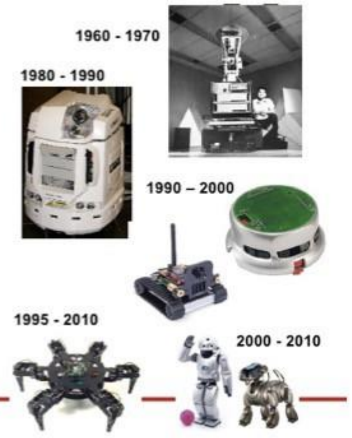
1999 — Sony developed AIBO, a **robotic dog** that could play and interact with people

2002 — Roomba, the **automatic vacuum** cleaner appears on the market

2005 — Boston Dynamics introduces BigDog, an **impressively stable quadrupede robot**

2011 — Willow Garage presents PR2, an **open source humanoid personal robot**





2012-

Baxter industrial robot: learn, collaborate

2013-2016 -

BD's **Atlas** humanoid robot for indoors and outdoors

2016 -

Uber starts **self-driving car service**

2012 -

Major **ROS** distributions