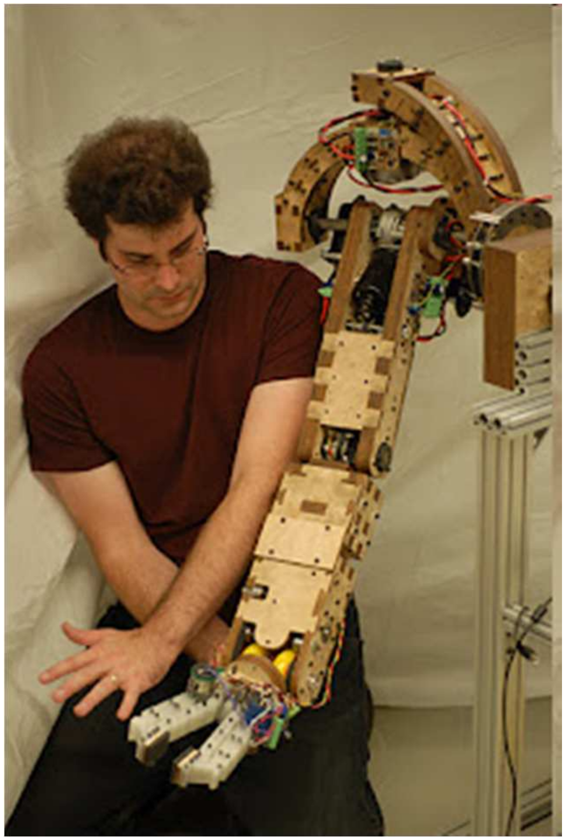
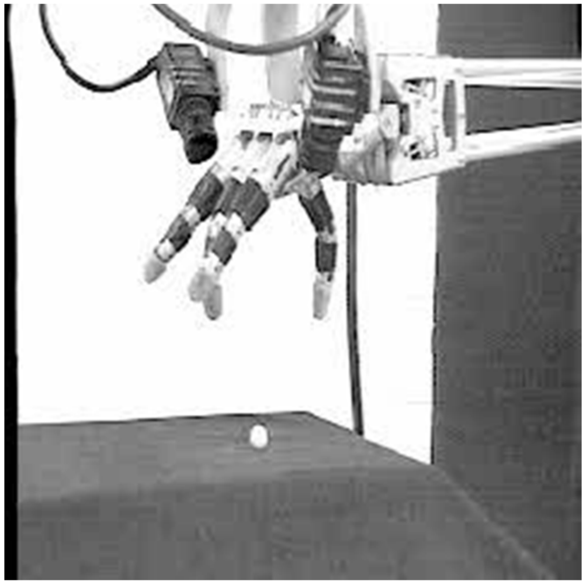
Robot Arms, Hands:



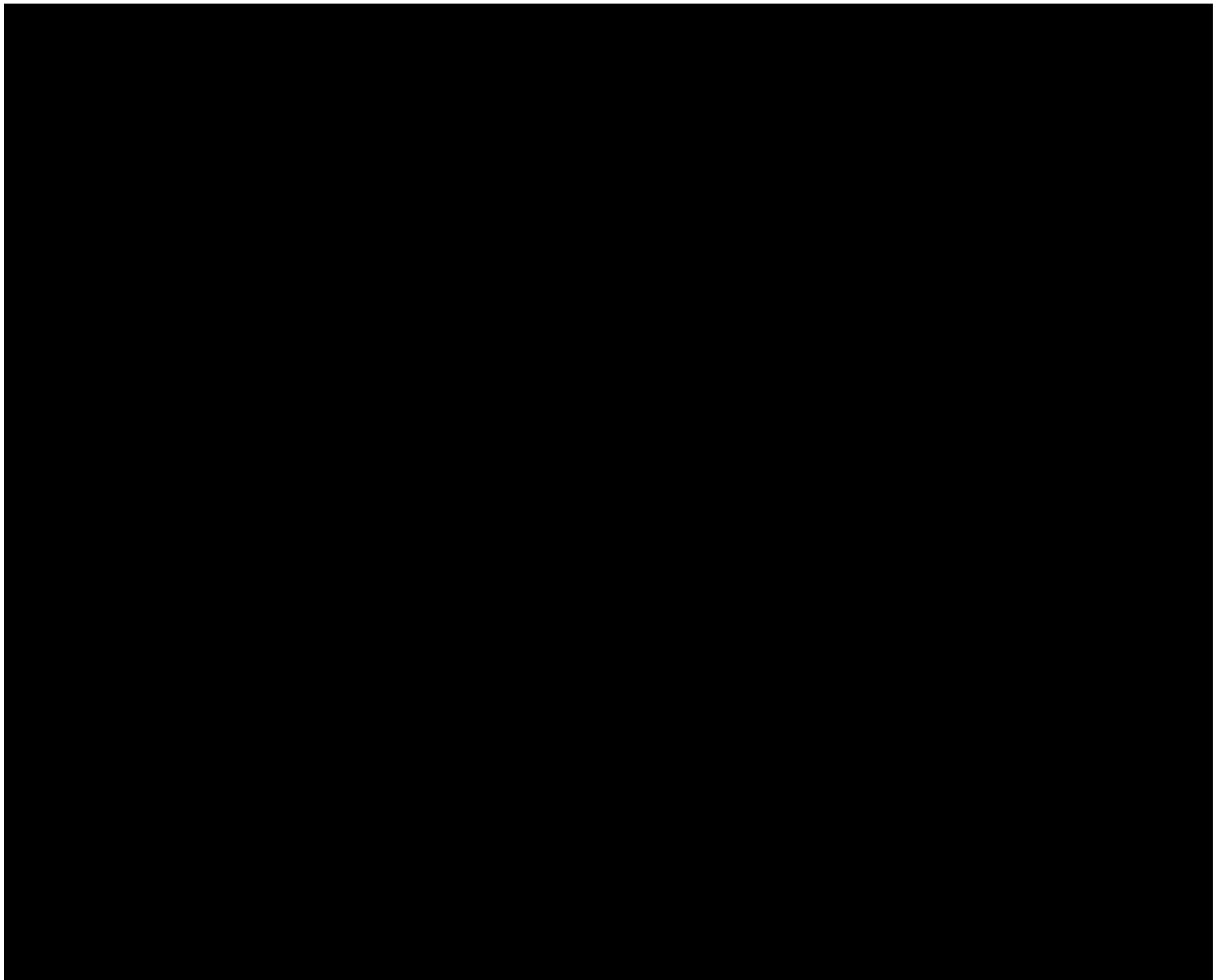
With slides from

What a robot arm and hand can do



- Martin 1992-’97 PhD work

What a robot arm and hand can do

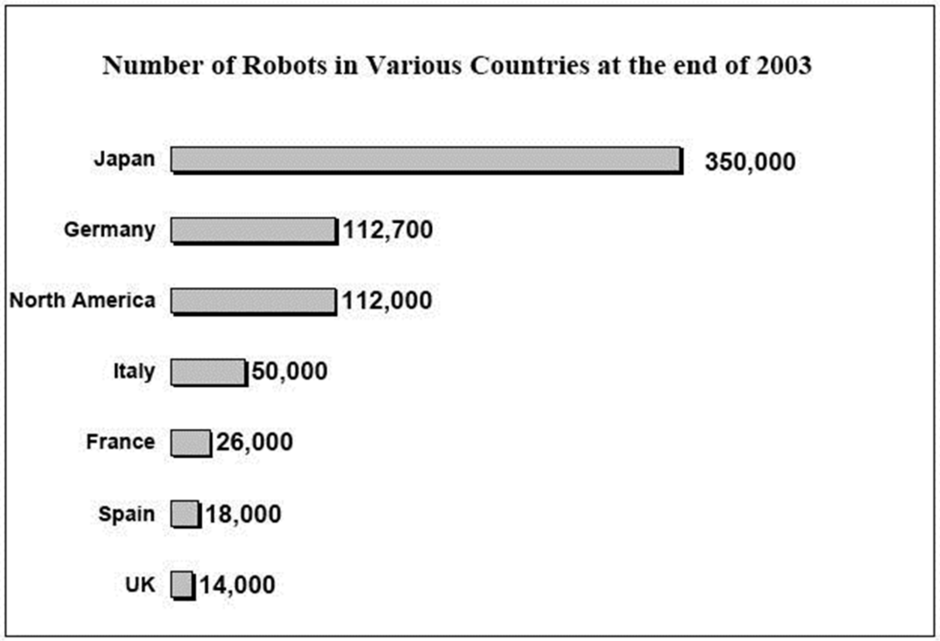


- Camilo 2011-? PhD work

Robotics field .

- 6 Million mobile robots
  - From $100 roomba to $millions Mars rovers
- 1 million robot arms
  - Usually $20,000-100,000, some $millions (Canadaarm)
- Value of industrial robotics sector: $25 billion
  - Roomba: $142M in sales
  - Industrial arms $17.5billion in sales
- Arms crucial for these industries:
  - Automotive (Welding, painting, some assembly)
  - Electronics (Placing tiny components on PCB) http://www.youtube.com/watch?v=DG6A1Bsi-lg
  - General: Pack boxes, move parts from conveyor to machines

Robots in everyday use and popular culture



- Chances are, something you eat, wear, or use was made by a robot

http://www.robotuprising.com/

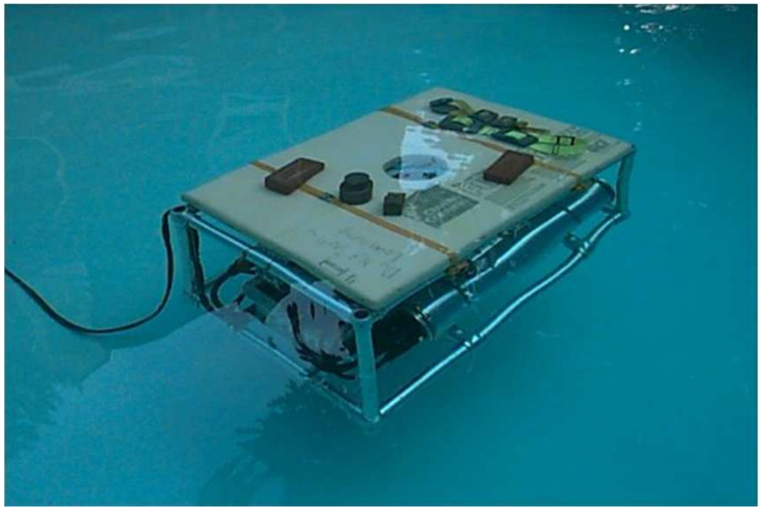
Common applications

- Industrial
  - Robotic assembly
- Commercial
  - Household chores
- Military
- Medical
  - Robot-assisted surgery

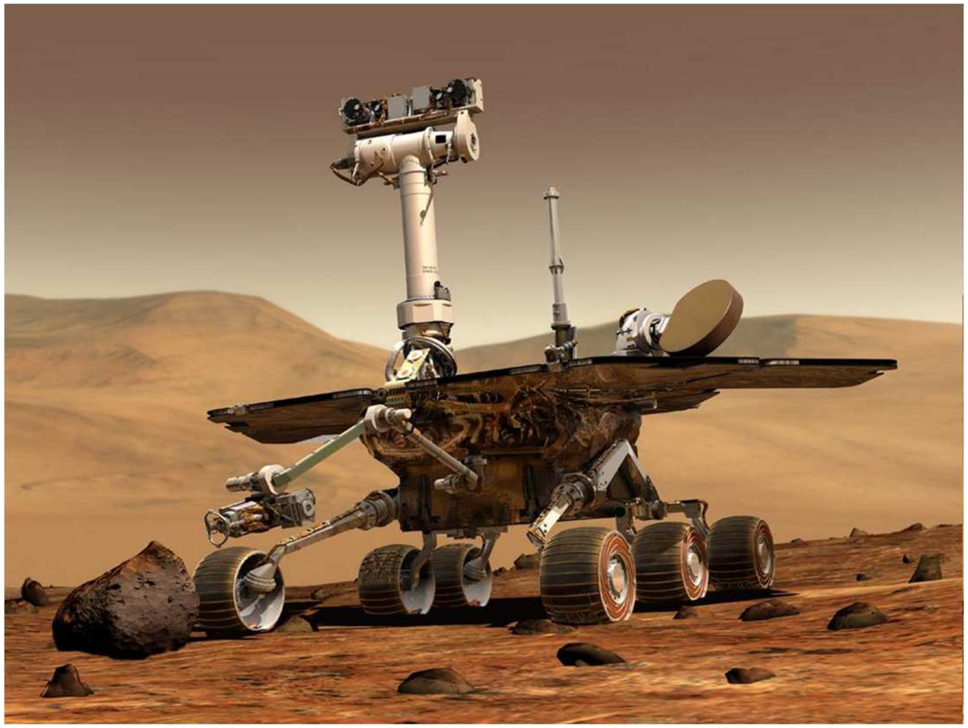
Picture of Roomba

Common applications

- Planetary Exploration
  - *Fast, Cheap, and Out of Control*
  - Mars rover
- Undersea exploration

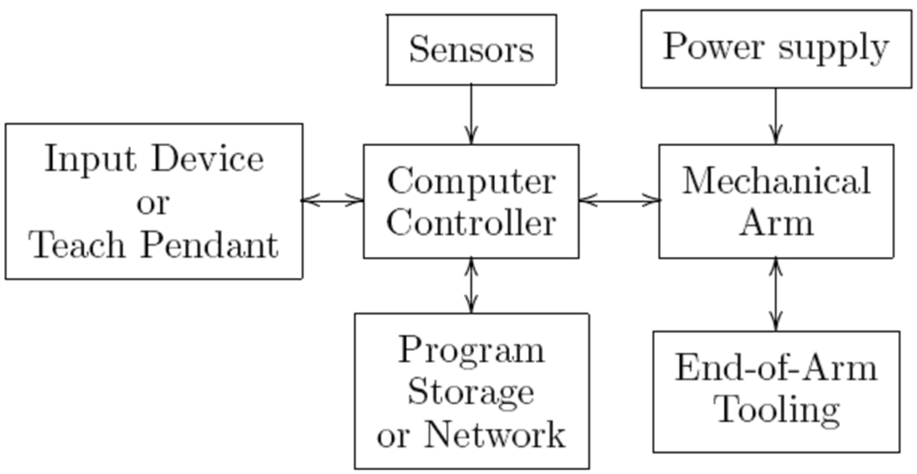


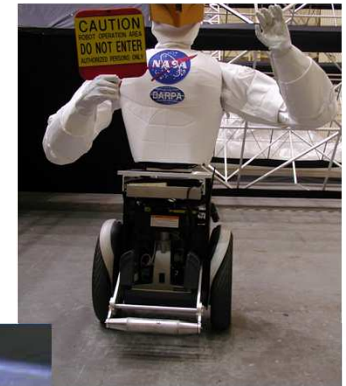
JHUROV; Johns Hopkins



Industrial robots

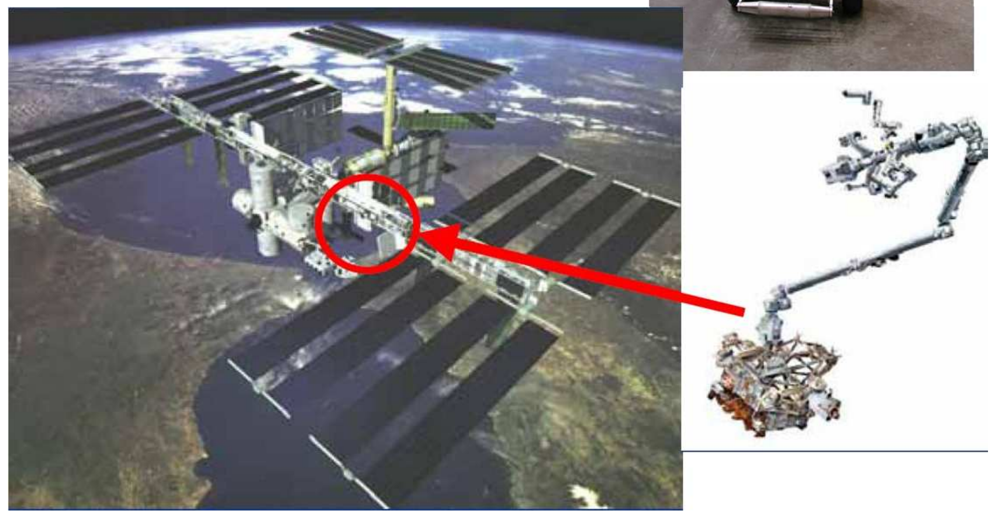
- High precision and repetitive tasks
  - Pick and place, painting, etc
- Hazardous environments



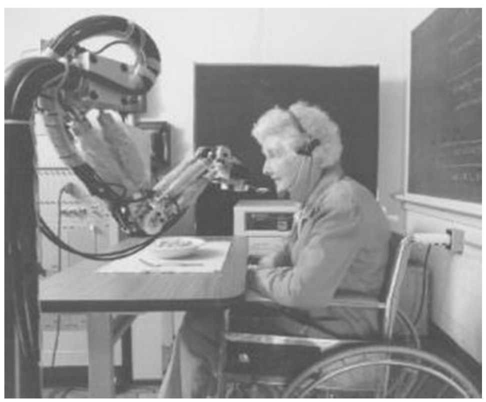


Emerging Robotics Applications

Space - in-orbit, repair and maintenance, planetary exploration anthropomorphic design facilitates collaboration with humans



Basic Science - computational models of cognitive systems, task learning, human interfaces



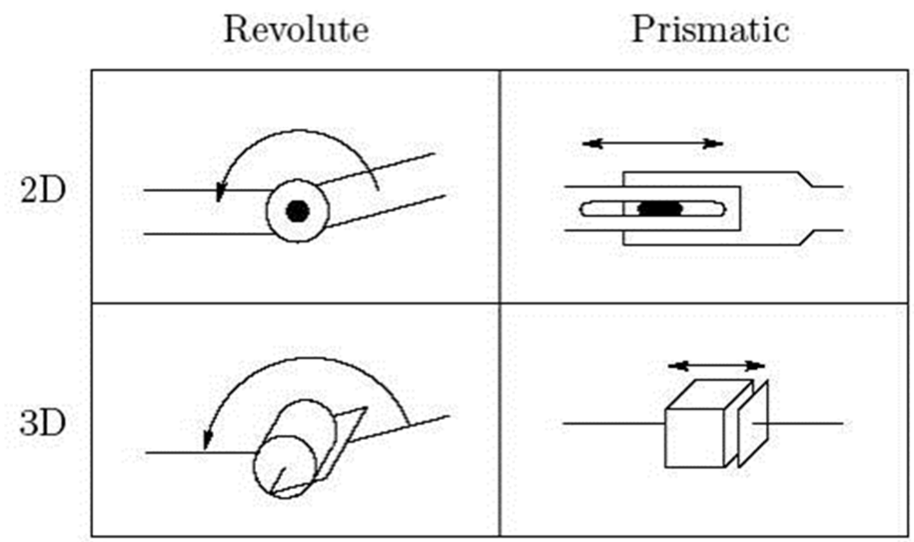
Health - clinical applications, "aging-in-place," physical and cognitive prosthetics in assisted-living facilities

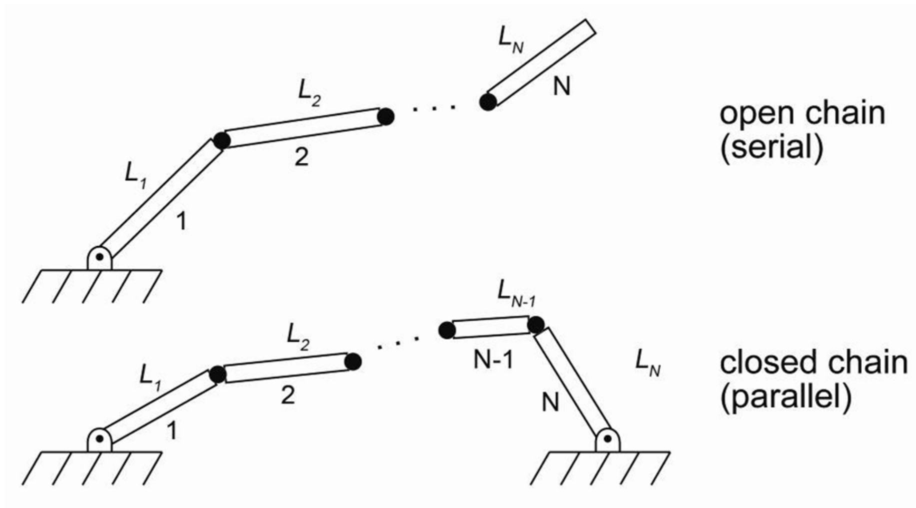
Military or Hazardous - supply chain and logistics support, re-fueling, bomb disposal, toxic/radioactive cleanup

No or few robots currently operate reliably in these areas!

Representations

- For the majority of this class, we will consider robotic manipulators as open or closed chains of links and joints
  - Two types of joints: revolute (θ) and prismatic (d)



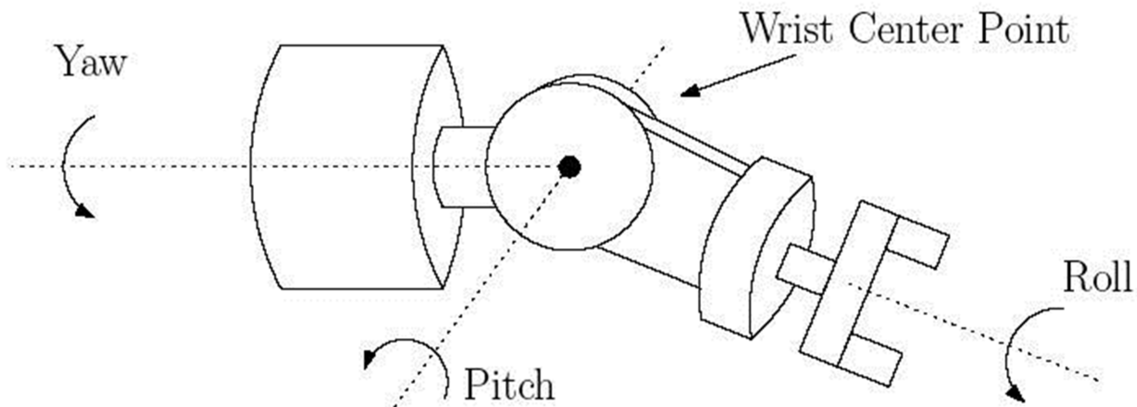


Definitions

- End-effector/Tool
  - Device that is in direct contact with the environment. Usually very task-specific
- Configuration
  - Complete specification of every point on a manipulator
  - set of all possible configurations is the *configuration space*
  - For rigid links, it is sufficient to specify the configuration space by the joint angles $q = [q_1 \quad q_2 \quad \ldots \quad q_n]^T$
- State space
  - Current configuration (joint positions *q*) and velocities $\dot{q}$
- Work space
  - The reachable space the tool can achieve
    - Reachable workspace
    - Dextrous workspace

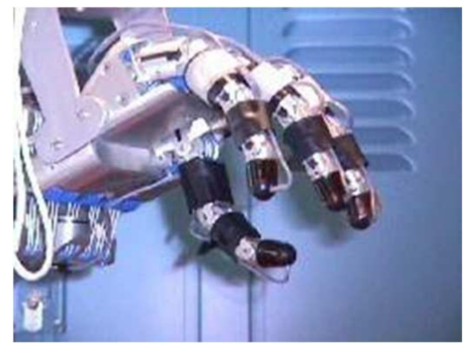
Common configurations: wrists

- Many manipulators will be a sequential chain of links and joints forming the ‘arm’ with multiple DOFs concentrated at the ‘wrist’

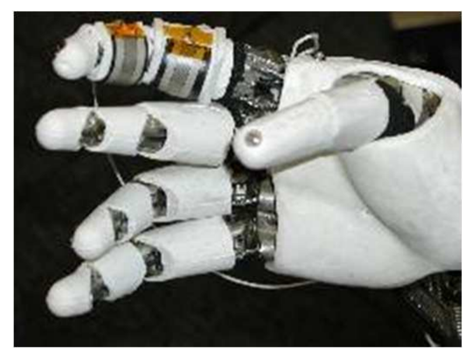


Example end-effector: Grippers

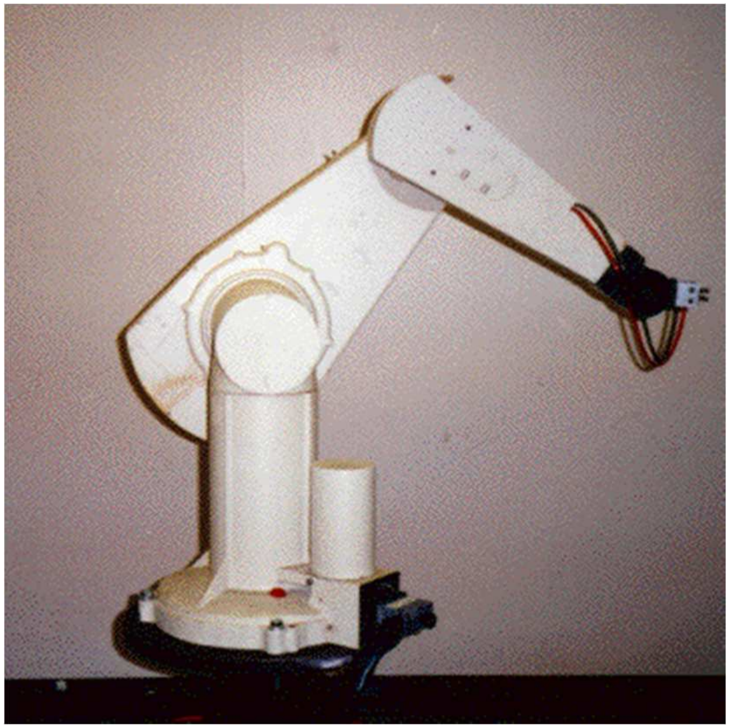
- Anthropomorphic or task-specific
  - Force control v. position control

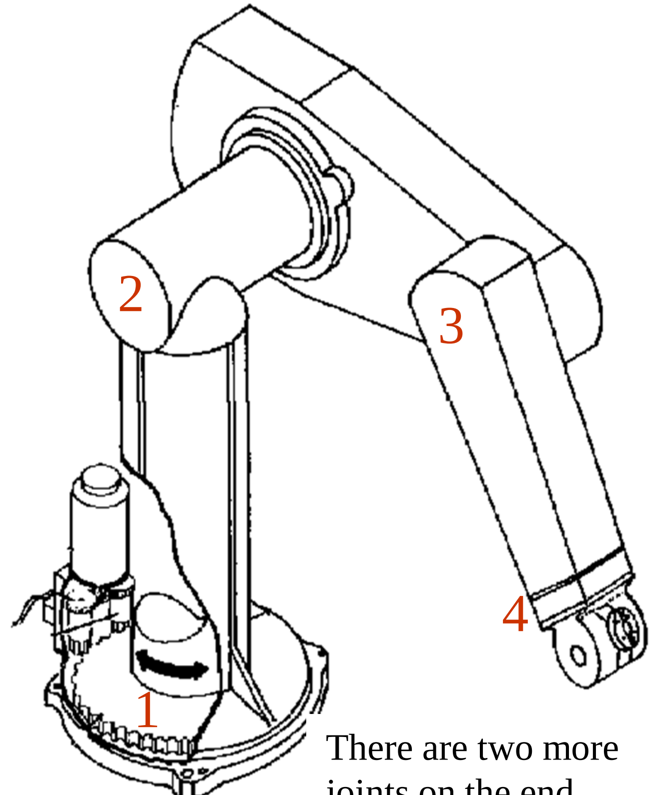


Utah MIT hand



An classic arm - The PUMA 560



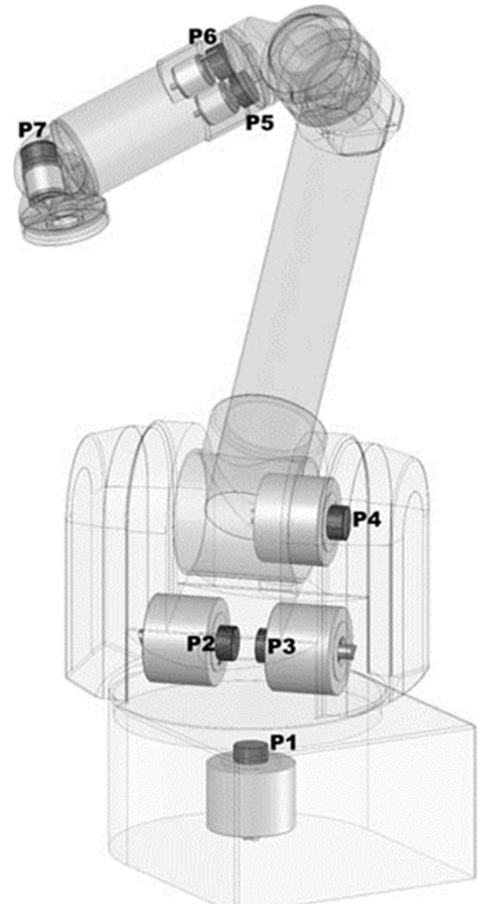


There are two more joints on the end effector (the gripper)

The PUMA 560 has SIX revolute joints

A revolute joint has ONE degree of freedom (1 DOF) that is defined by its angle

An modern arm - The Barrett WAM

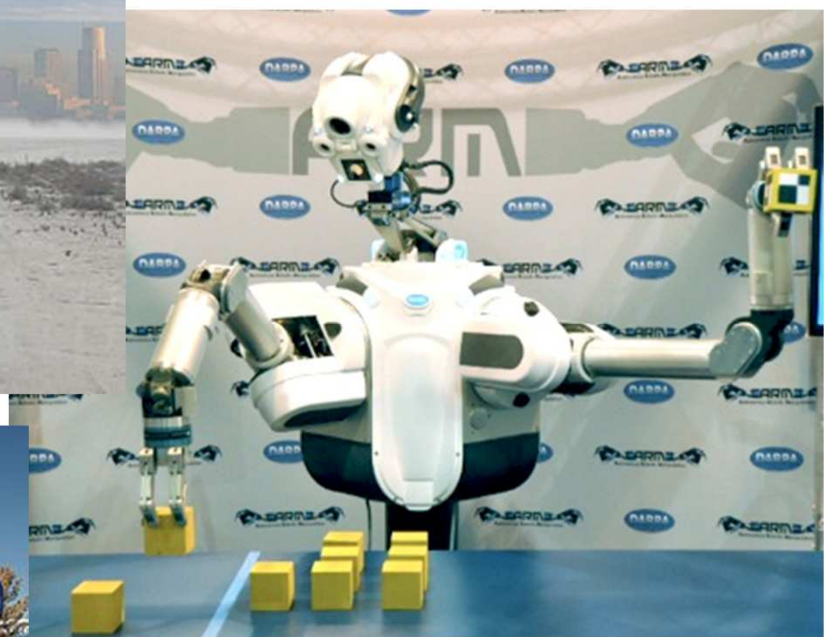


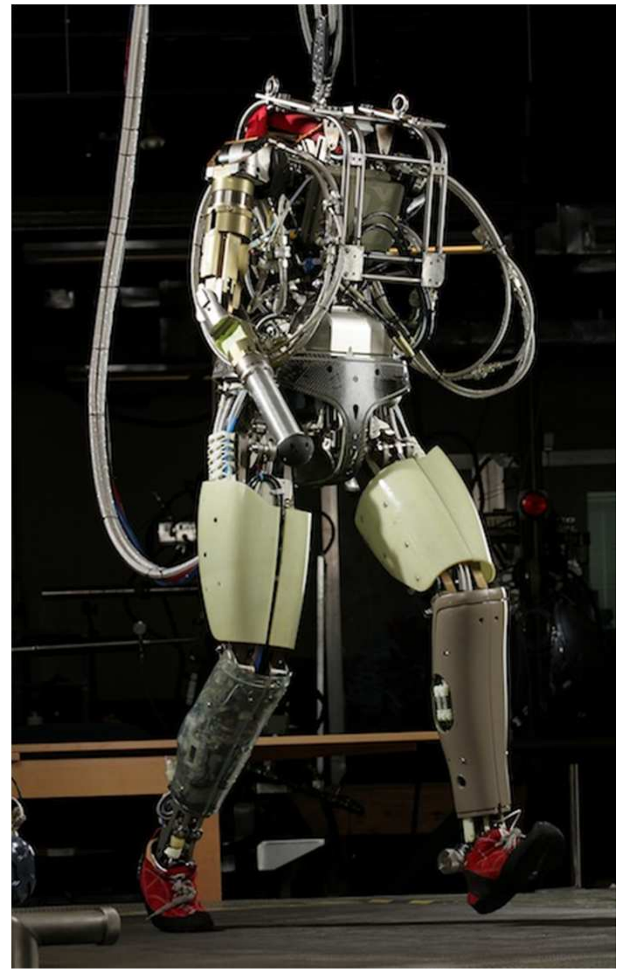
- The WAM has SEVEN revolute joints.
- Similar motion (Kinematics) to human

UA Robotics Lab platform
2 arm mobile manipulator

- 2 WAM arms, steel cable transmission and drive
- Segway mobile platform
- 2x Quad core computer platform.
- Battery powered, 4h run time.

Robotics challenges





Manipulation ‘11-14

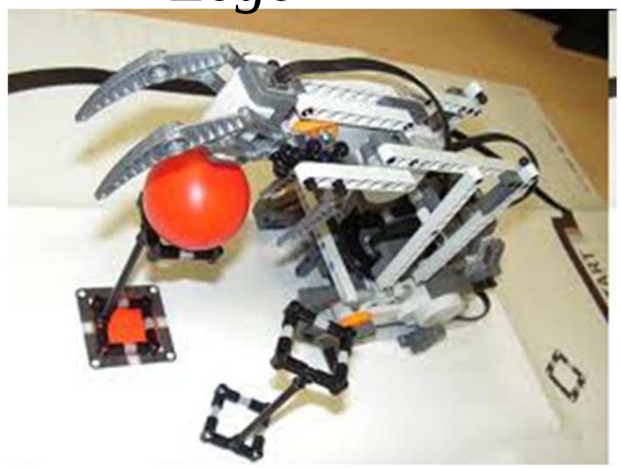
Navigation ‘05

Humanoids ’12-

Build or buy?

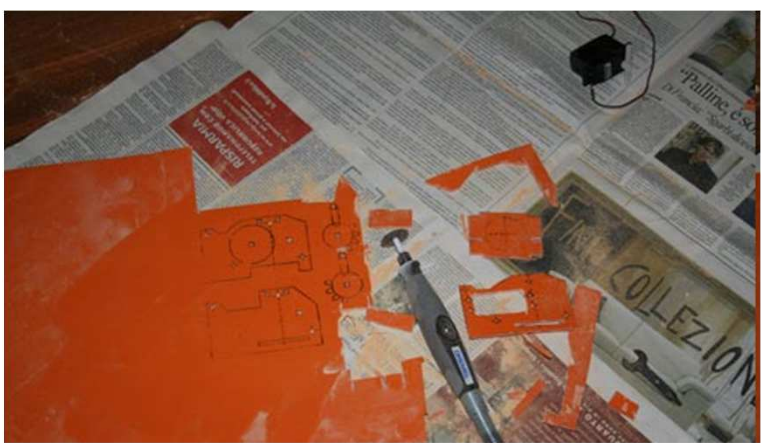
- Off the shelf kits:

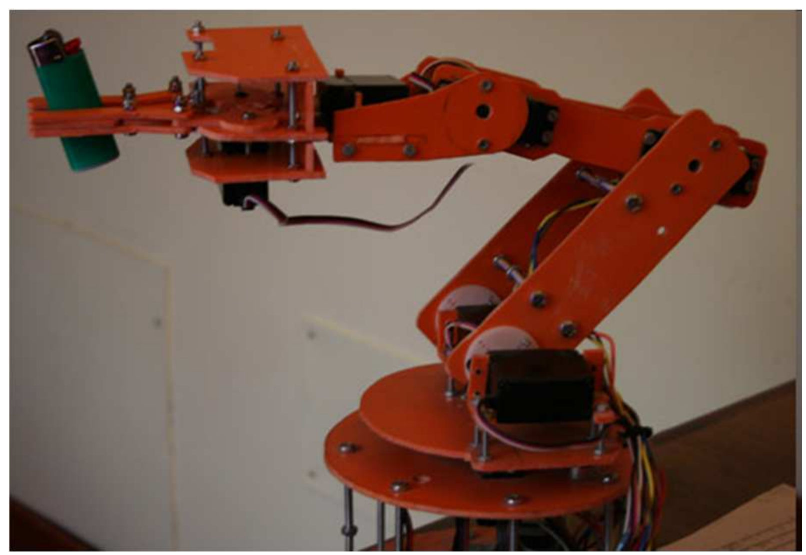
Lego



Lynxmotion

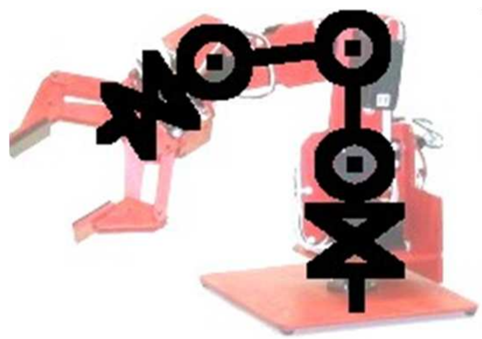
- Build your own:

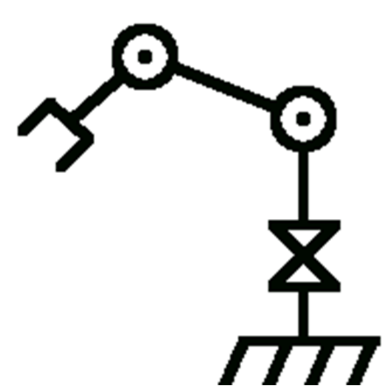




Mathematical modeling

Robot





Abstract model

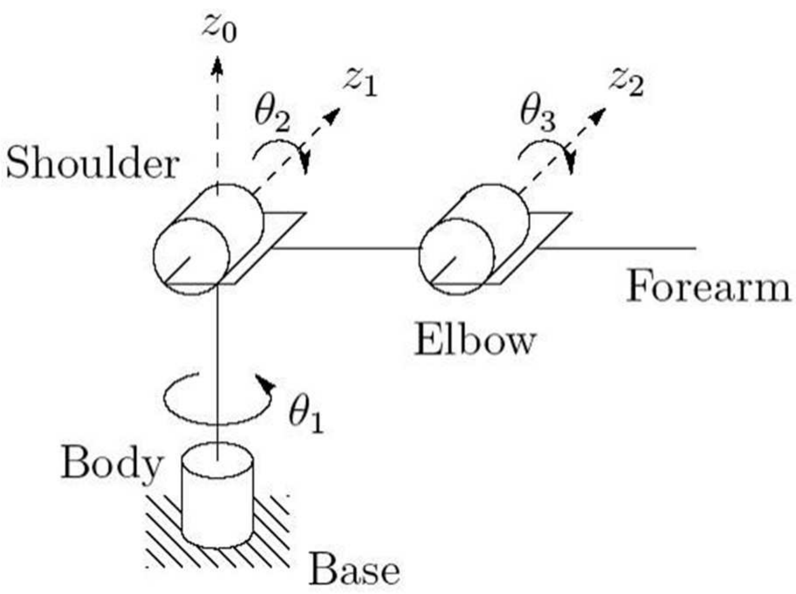
Strategy:

1. Model each joint separately
2. Combine joints and linkage lengths

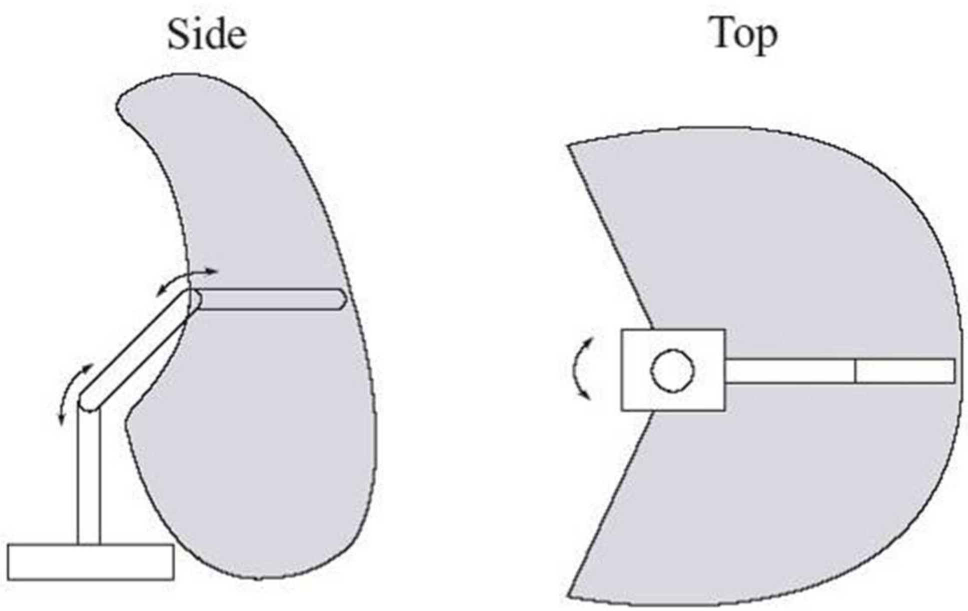
http://www.societyofrobots.com/robot_arm_tutorial.shtml

Common configurations: elbow manipulator

- Anthropomorphic arm: ABB IRB1400
- Very similar to the lab arm (RRR)

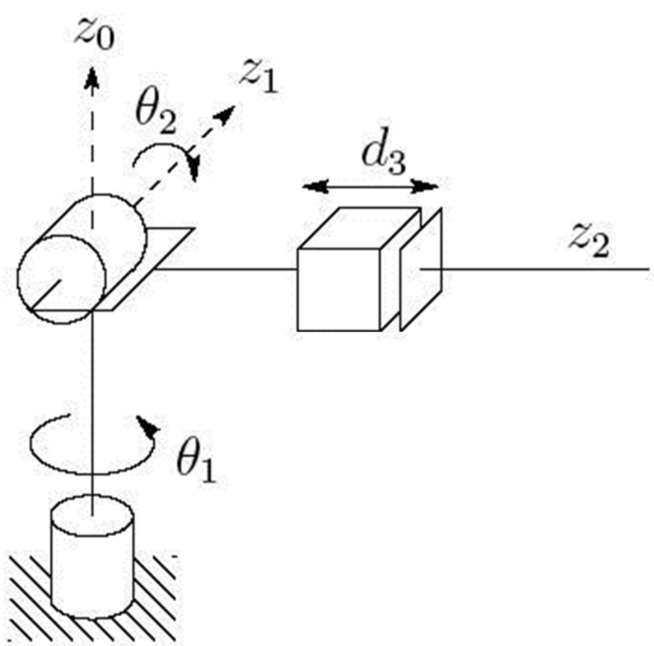


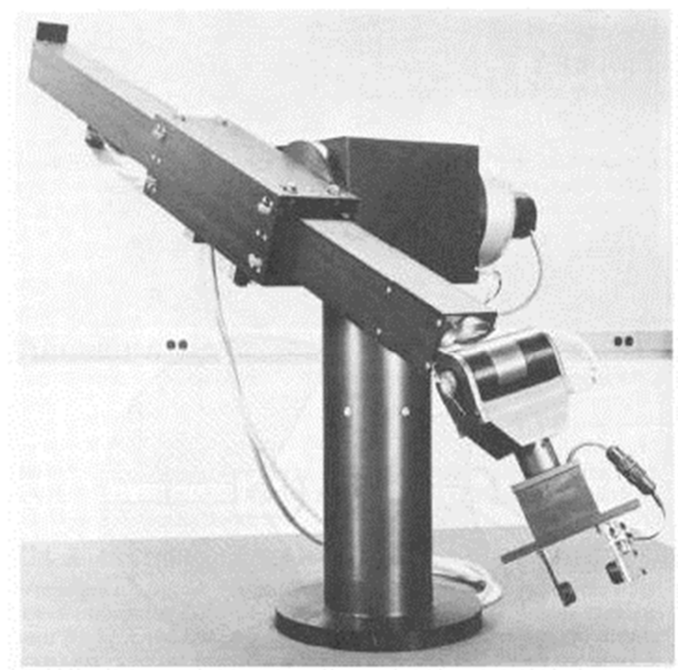
Workspace: elbow manipulator



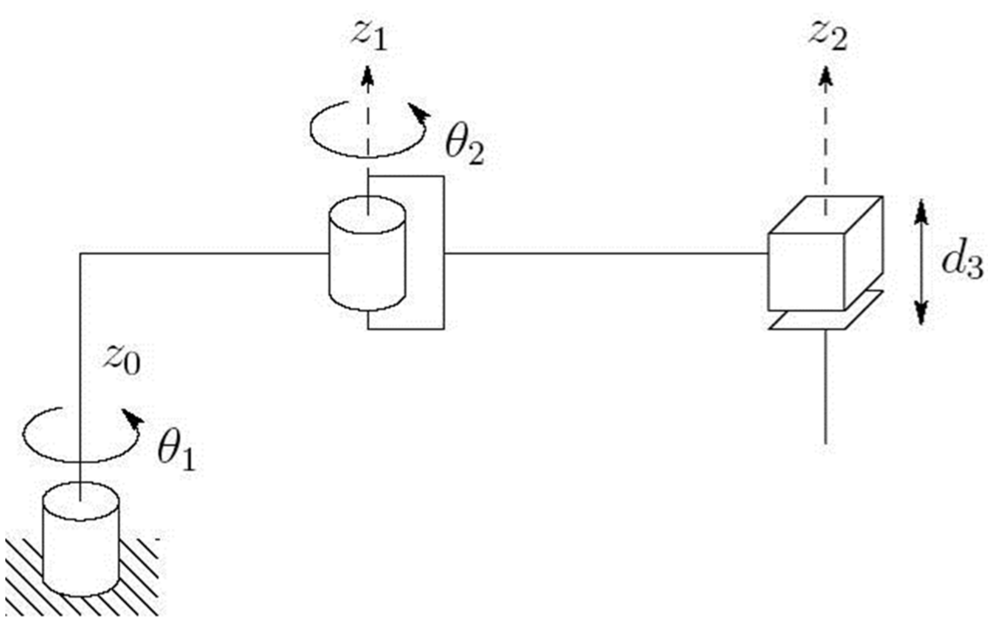
Common configurations: Stanford arm (RRP)

- Spherical manipulator (workspace forms a set of concentric spheres)





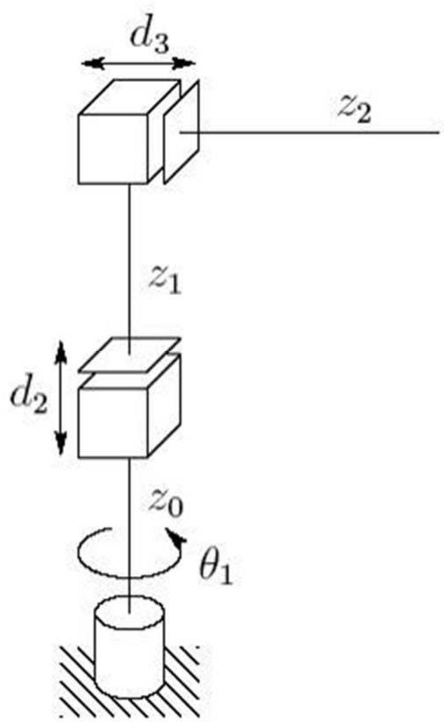
Common configurations: SCARA (RRP)

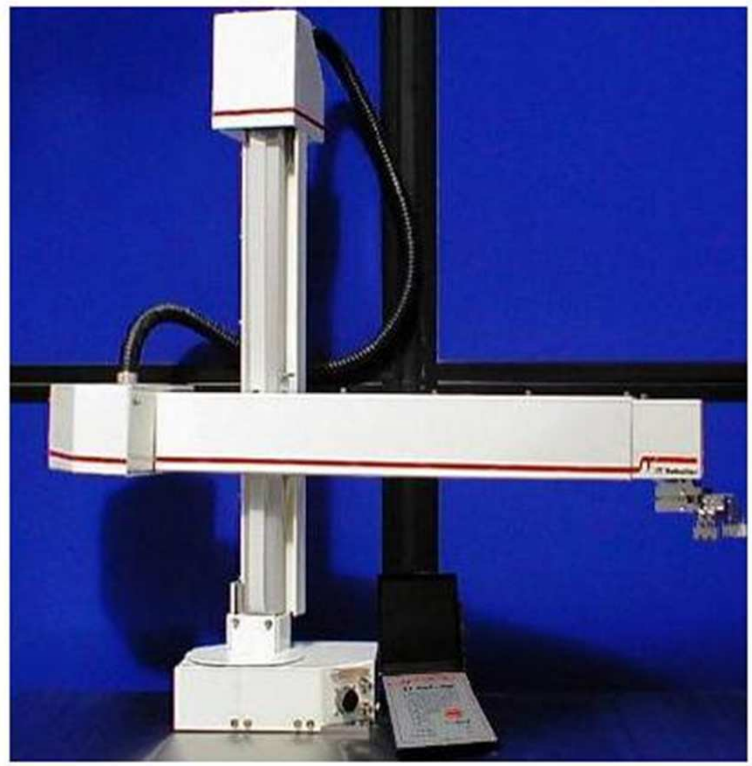


Adept Cobra Smart600 SCARA robot

Common configurations: cylindrical robot (RPP)

- workspace forms a cylinder

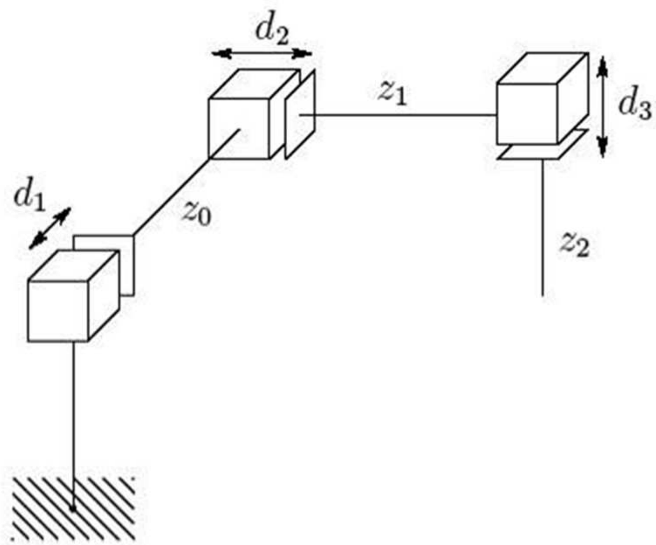




Seiko RT3300 Robot

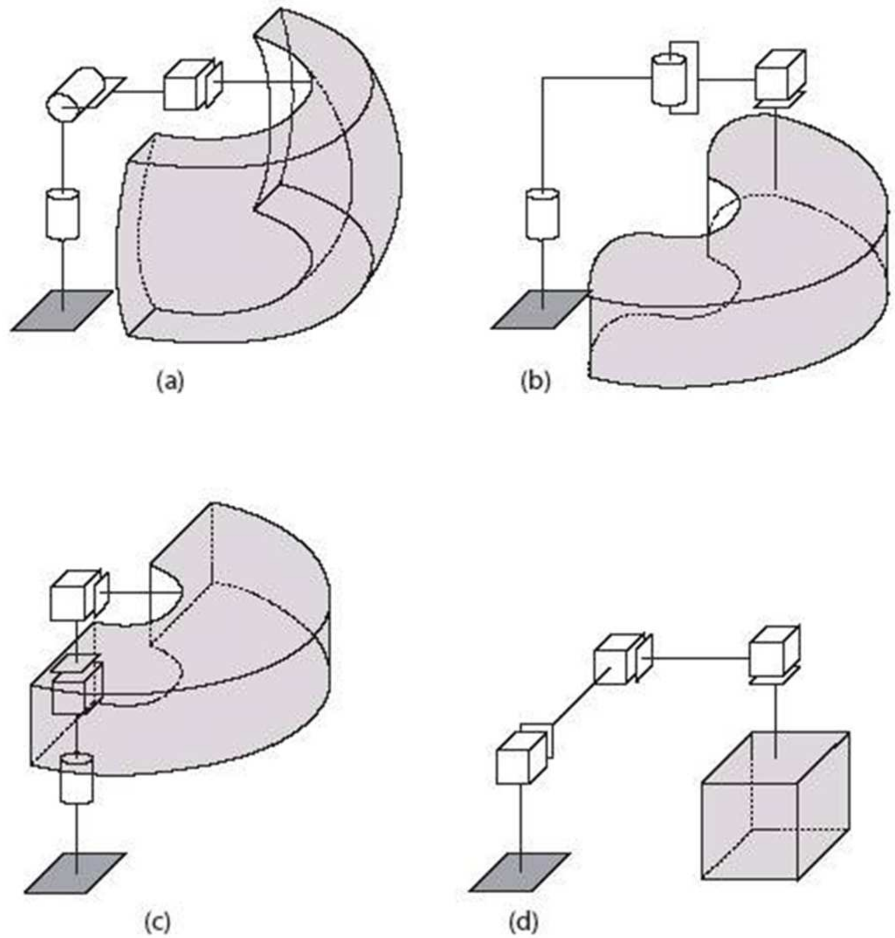
Common configurations: Cartesian robot (PPP)

- Increased structural rigidity, higher precision
  - Pick and place operations



Workspace comparison

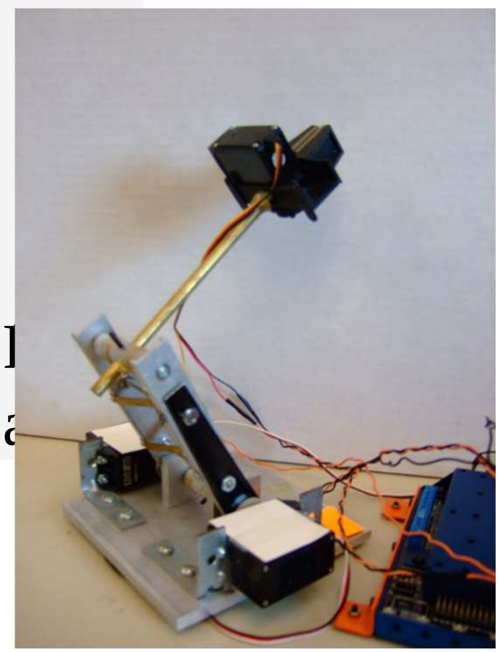
(a) spherical
(b) SCARA
(c) cylindrical
(d) Cartesian



Linkage configuration

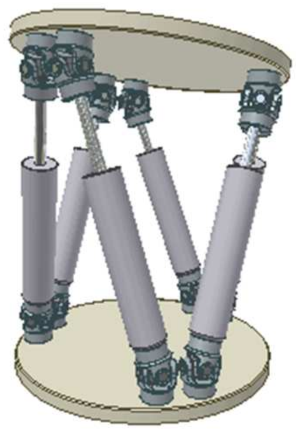
- Motors serially in arm
- Each motor carries the weight of previous
- Heavy

- Motors at base
- Lightweight and faster
- More complex transmission



Parallel manipulators

- some of the links will form a closed chain with ground
- Advantages:
  - Motors can be proximal: less powerful, higher bandwidth, easier to control
- Disadvantages:
  - Generally less motion, kinematics can be challenging



6DOF Stewart platform

ABB IRB6400

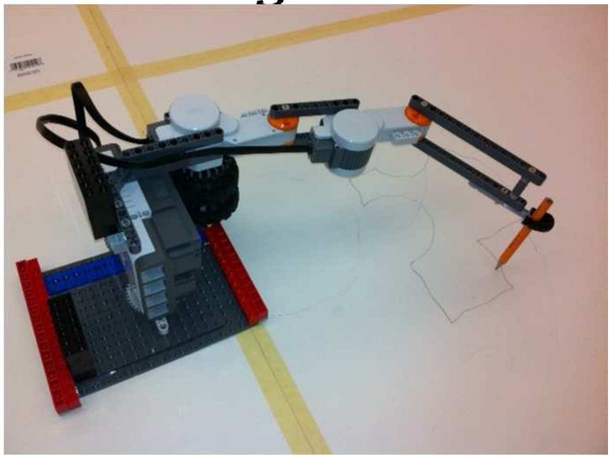
ABB IRB940 Tricept

How to build your Lego robot

- Minimize loading of motors from weight of other motors.

Solutions:

- SCARA

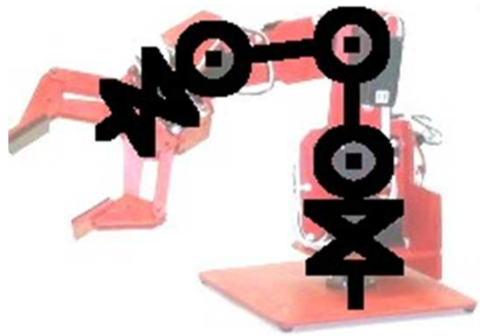


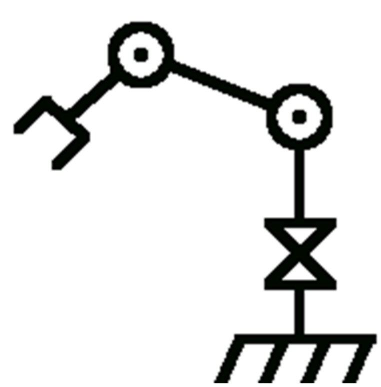
- Parallelogram linkage

(Similar to a Phantom 1)

Mathematical modeling

Robot





Abstract model

Strategy:

1. Model each joint separately
2. Combine joints and linkage lengths

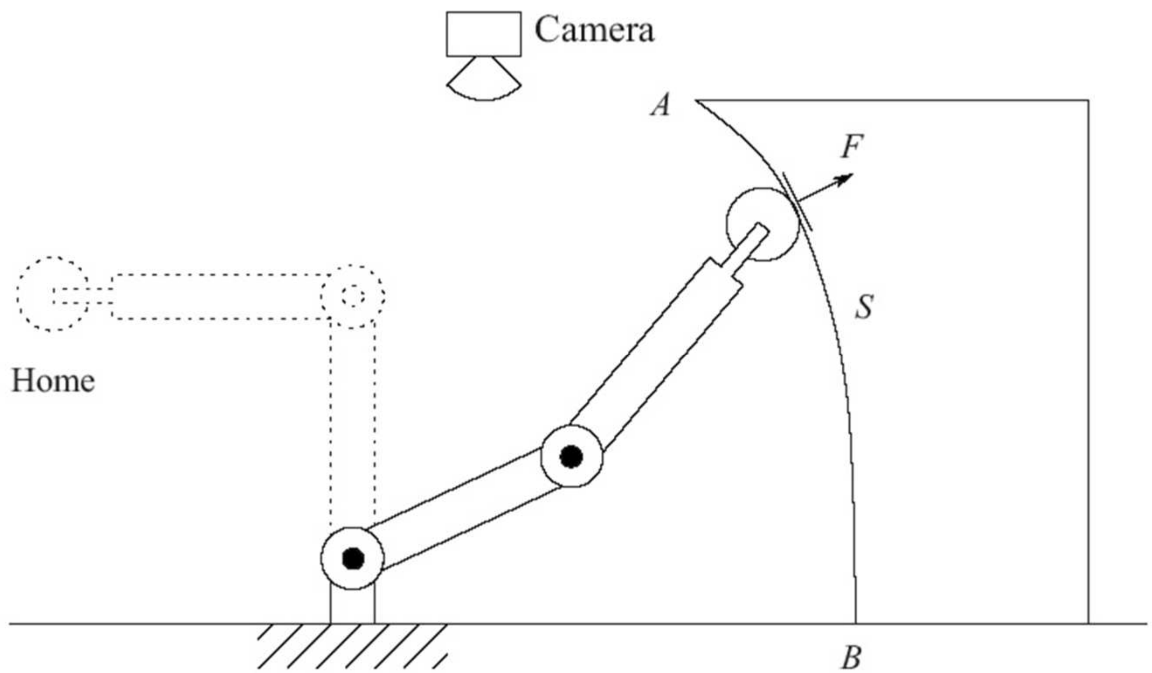
A simple example follows here.

More general treatment of next lecture

http://www.societyofrobots.com/robot_arm_tutorial.shtml

Simple example: Modeling of a 2DOF planar manipulator

- Move from ‘home’ position and follow the path AB with a constant contact force *F* all using visual feedback



Coordinate frames & forward kinematics

- Three coordinate frames: 0 1 2
- Positions:

$$\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \begin{bmatrix} a_1 \cos(\theta_1) \\ a_1 \sin(\theta_1) \end{bmatrix}$$

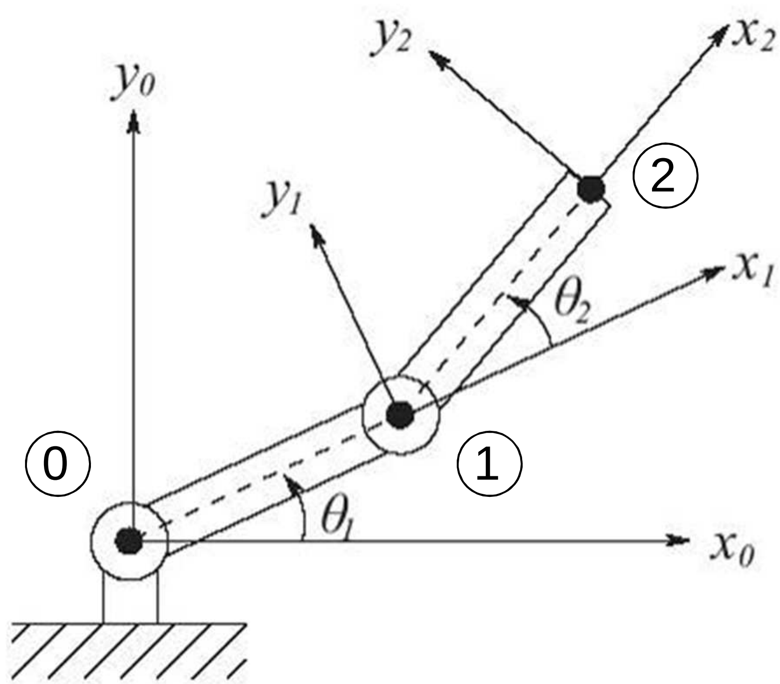
$$\begin{bmatrix} x_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} a_1 \cos(\theta_1) + a_2 \cos(\theta_1 + \theta_2) \\ a_1 \sin(\theta_1) + a_2 \sin(\theta_1 + \theta_2) \end{bmatrix} \equiv \begin{bmatrix} x \\ y \end{bmatrix}_t$$

- Orientation of the tool frame:

$$\hat{x}_0 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \hat{y}_0 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$\hat{x}_2 = \begin{bmatrix} \cos(\theta_1 + \theta_2) \\ \sin(\theta_1 + \theta_2) \end{bmatrix}, \hat{y}_2 = \begin{bmatrix} -\sin(\theta_1 + \theta_2) \\ \cos(\theta_1 + \theta_2) \end{bmatrix}$$

$$R_2^0 = \begin{bmatrix} \hat{x}_2 \cdot \hat{x}_0 & \hat{y}_2 \cdot \hat{x}_0 \\ \hat{x}_2 \cdot \hat{y}_0 & \hat{y}_2 \cdot \hat{y}_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta_1 + \theta_2) & -\sin(\theta_1 + \theta_2) \\ \sin(\theta_1 + \theta_2) & \cos(\theta_1 + \theta_2) \end{bmatrix}$$

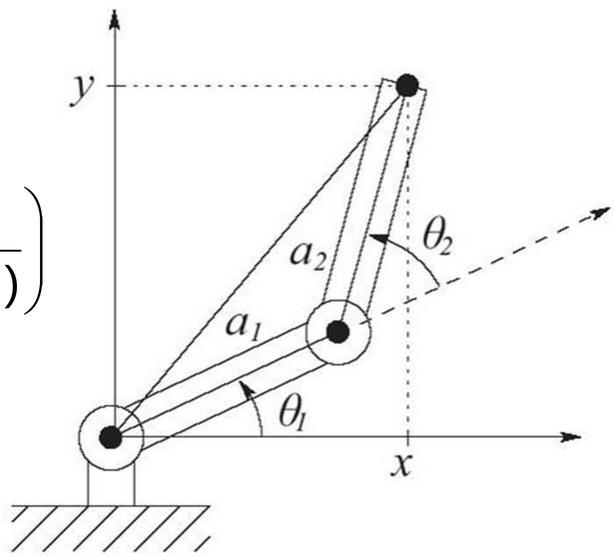


Inverse kinematics

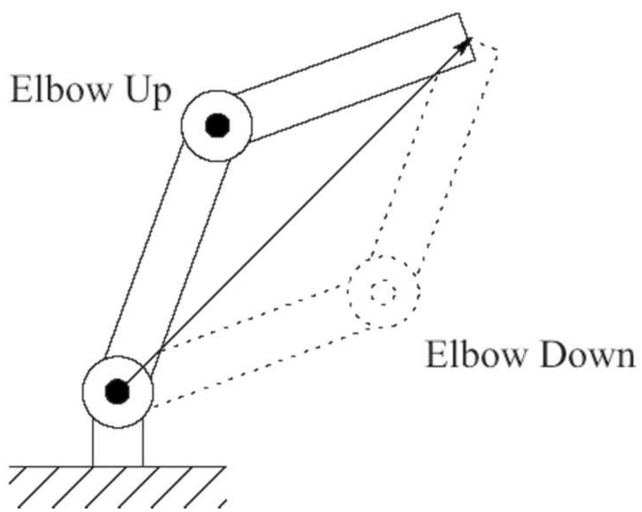
- Find the joint angles for a desired tool position

$$\cos(\theta_2) = \frac{x_t^2 + y_t^2 - a_1^2 - a_2^2}{2a_1a_2} \equiv D \Rightarrow \sin(\theta_2) = \pm\sqrt{1-D^2}$$

$$\theta_2 = \tan^{-1}\left(\pm\frac{\sqrt{1-D^2}}{D}\right) \quad \theta_1 = \tan^{-1}\left(\frac{y}{x}\right) - \tan^{-1}\left(\frac{a_2\sin(\theta_2)}{a_1 + a_2\cos(\theta_2)}\right)$$

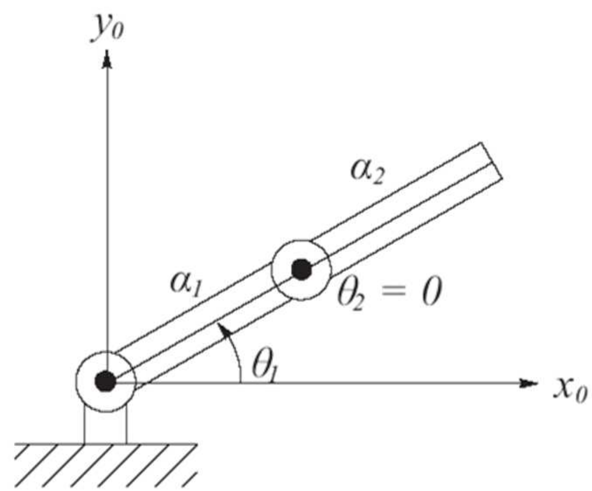


- Two solutions!: elbow up and elbow down



Velocity kinematics: the Jacobian

- State space includes velocity



$$\begin{bmatrix} \dot{x}_2 \\ \dot{y}_2 \end{bmatrix} = \begin{bmatrix} -a_1 \sin(\theta_1)\dot{\theta}_1 - a_2 \sin(\theta_1+\theta_2)(\dot{\theta}_1+\dot{\theta}_2) \\ a_1 \cos(\theta_1)\dot{\theta}_1 + a_2 \cos(\theta_1+\theta_2)(\dot{\theta}_1+\dot{\theta}_2) \end{bmatrix}$$

$$= \begin{bmatrix} -a_1 \sin(\theta_1) - a_2 \sin(\theta_1+\theta_2) & -a_2 \sin(\theta_1+\theta_2) \\ a_1 \cos(\theta_1) + a_2 \cos(\theta_1+\theta_2) & a_2 \cos(\theta_1+\theta_2) \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}$$

$$= J\dot{\vec{q}}$$

- Inverse of Jacobian gives the joint velocities:

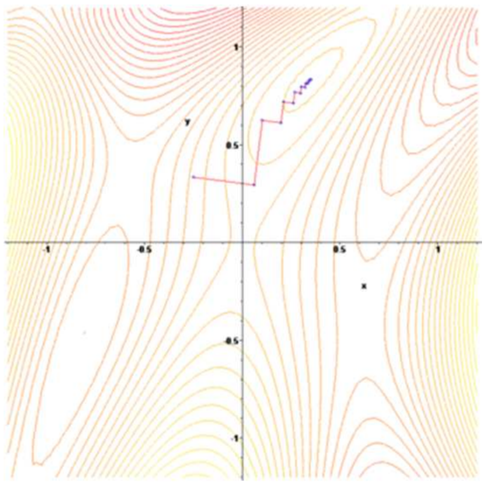
$$\dot{\vec{q}} = J^{-1}\dot{\vec{x}}$$

$$= \frac{1}{a_1 a_2 \sin(\theta_2)} \begin{bmatrix} a_2 \cos(\theta_1+\theta_2) & a_2 \sin(\theta_1+\theta_2) \\ -a_1 \cos(\theta_1) - a_2 \cos(\theta_1+\theta_2) & -a_1 \sin(\theta_1) - a_1 \sin(\theta_1+\theta_2) \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}$$

- This inverse does not exist when θ_2 = 0 or π, called singular configuration or singularity

Path planning

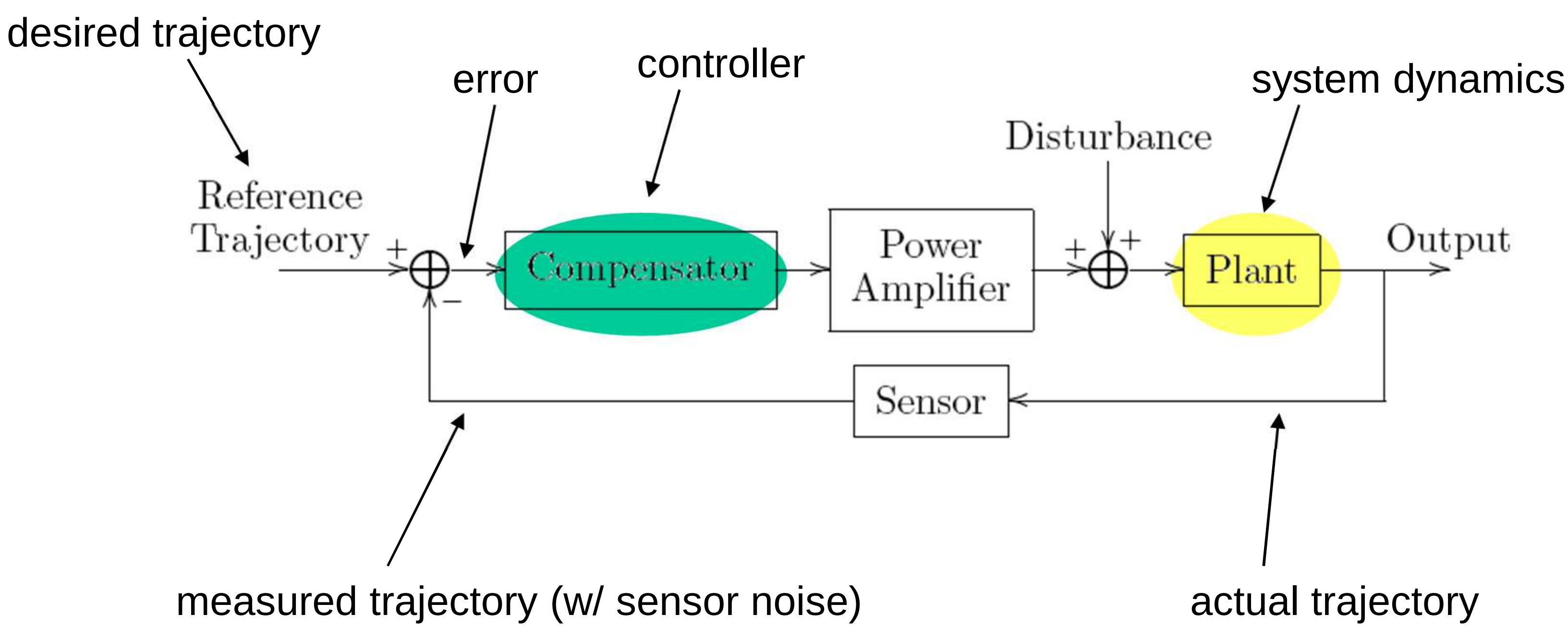
- In general, move tool from position A to position B while avoiding singularities and collisions
  - This generates a path in the work space which can be used to solve for joint angles as a function of time (usually polynomials)
  - Many methods: e.g. potential fields



- Can apply to mobile agents or a manipulator configuration

Joint control

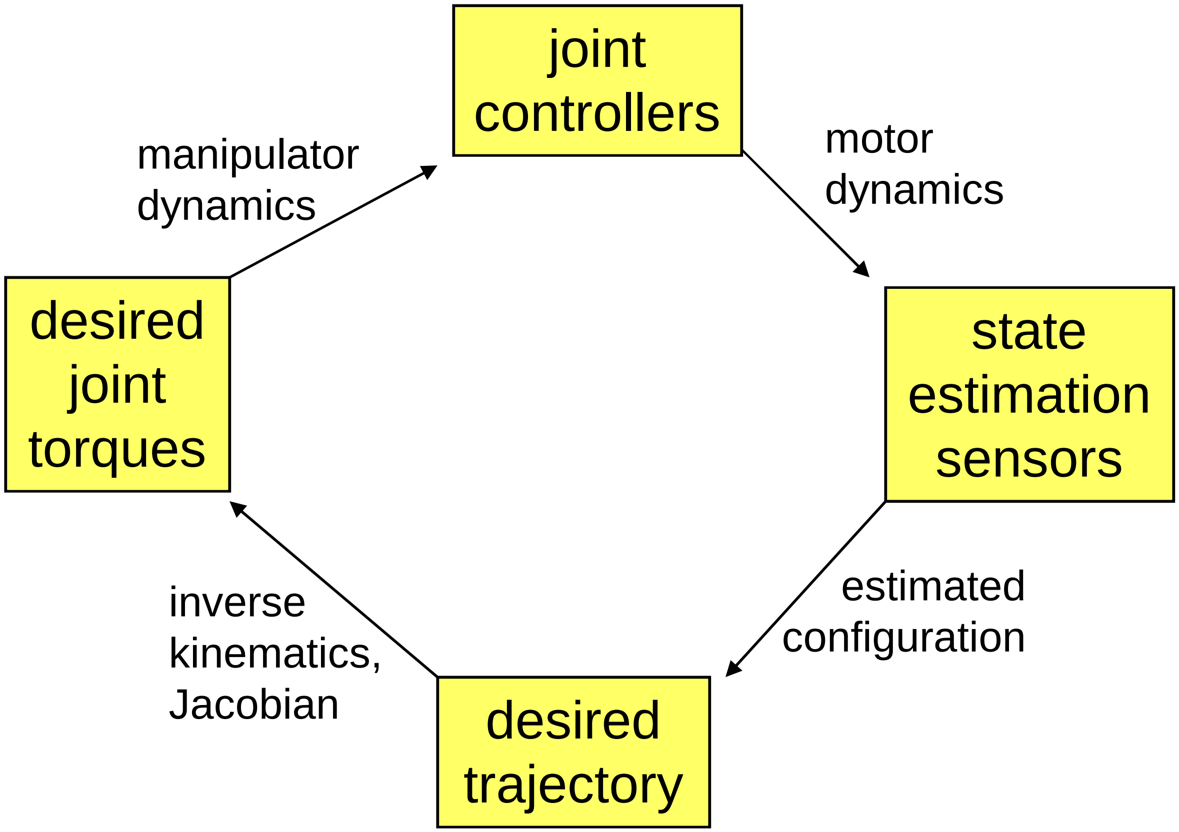
- Once a path is generated, we can create a desired tool path/velocity
  - Use inverse kinematics and Jacobian to create desired joint trajectories



Other control methods

- Force control or impedance control (or a hybrid of both)
  - Requires force/torque sensor on the end-effector
- Visual servoing
  - Using visual cues to attain local or global pose information
- Common controller architectures:
  - PID
  - Adaptive
  - Repetitive
- Challenges:
  - Underactuation
  - Nonholonomy (mobile agents)
  - nonlinearity

General multivariable control overview



Sensors and actuators

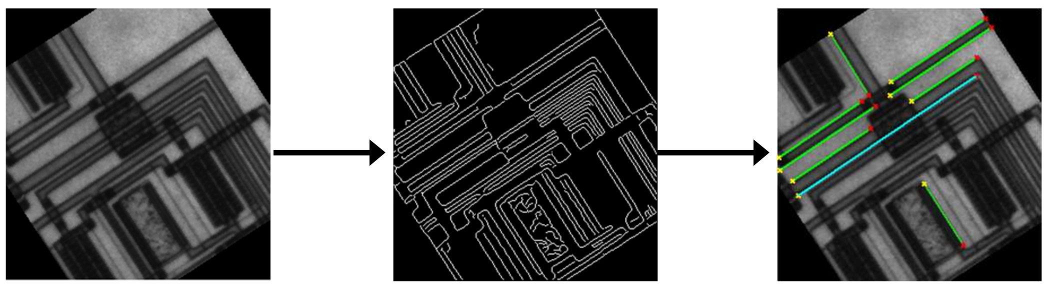
- sensors
  - Motor encoders (internal)
  - Inertial Measurement Units
  - Vision (external)
  - Contact and force sensors
- motors/actuators
  - Electromagnetic
  - Pneumatic/hydraulic
  - electroactive
    - Electrostatic
    - Piezoelectric

Basic quantities for both:

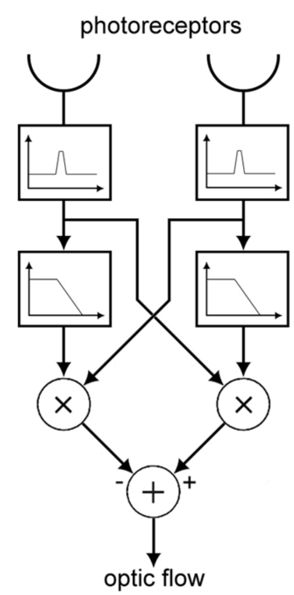
- Bandwidth
- Dynamic range
- sensitivity

Computer Vision

- Simplest form: estimating the position and orientation of yourself or object in your environment using visual cues
  - Usually a statistical process
  - Ex: finding lines using the Hough space

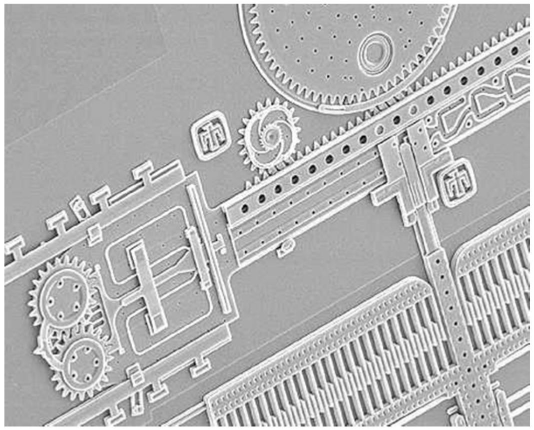


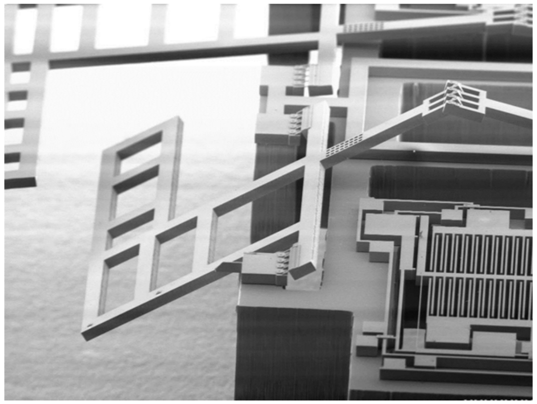
- More complex: guessing what the object in your environment are
- Biomimetic computer vision: how do animals accomplish these tasks:
  - Obstacle avoidance
    - Optical flow?
  - Object recognition
    - Template matching?

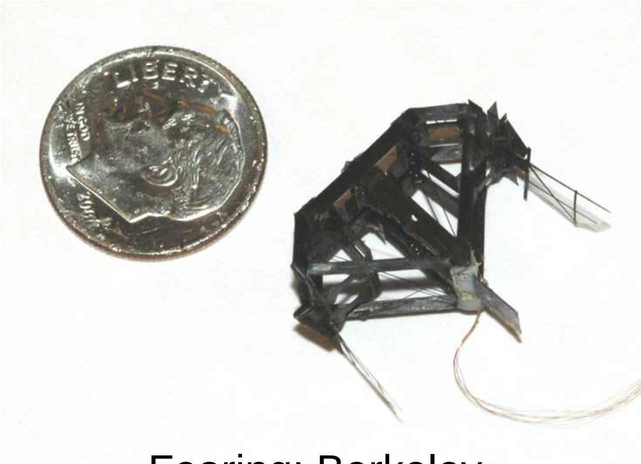


MEMS and Microrobotics

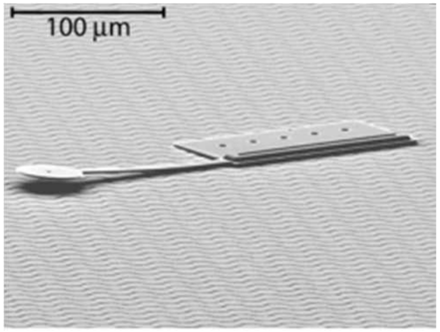
- Difficult definition(s):
  - Robotic systems with feature sizes < 1mm
  - Robotic systems dominated by micro-scale physics
- MEMS: Micro ElectroMechanical Systems
  - Modified IC processes to use ‘silicon as a mechanical material’







Fearing; Berkeley



Donald; Dartmouth

Pister; Berkeley

Surgical robotics

- Minimally invasive surgery
  - Minimize trauma to the patient
  - Potentially increase surgeon's capabilities
  - Force feedback necessary, tactile feedback desirable

Humanoid robots

- For robots to efficiently interact with humans, should they be anthropomorphic?

QRIO Sony

; Honda (video from Siegwart?)

Winning IROS 2000-2012 work

Next class…

- Homogeneous transforms as the basis for forward and inverse kinematics

Consider reading:

Craig, J.J., *Introduction to Robotics, Mechanics, and Control*

Chapter 3 (and 2 if math/geometry review needed)

Book available in library, bookstore or on-line

Other texts:
M. Spong, S. Hutchinson, and M. Vidyasagar, “Robot Modeling and Control”, Wiley
(In UA library)

Grad level:
Li, Murray, Sastry, “A Mathematical Introduction to Robotic Manipulation”, CRC Press
(Downloadable PDF on-line@Caltech)