MECH 464 / 563 / EECE 589
Introduction to Robotics

- **Instructor:** Prof. Tim Salcudean *tims@ece.ubc.ca.*

- **Teaching Assistant:** Alaa Eldin Abdelaal aabdelaal@ece.ubc.ca
- **Lectures:** MWF 11:00-12:00 by Zoom. Will record pre-lecture videos and tape the actual lectures – mainly Q&A. There will be pre-lecture slides and reading material.
- **Tutorial:** M 17:00-18:00 – only if needed, please keep open if possible.

- **UBC Canvas Web Page:**
  https://canvas.ubc.ca/courses/70761

What is a Robot?

Definitions:

1 (a) A machine that looks like a human being and performs various complex acts (as walking or talking) of a human being; also, a similar but fictional machine whose lack of capacity for human emotions is often emphasized (b) an efficient, insensitive person who functions automatically

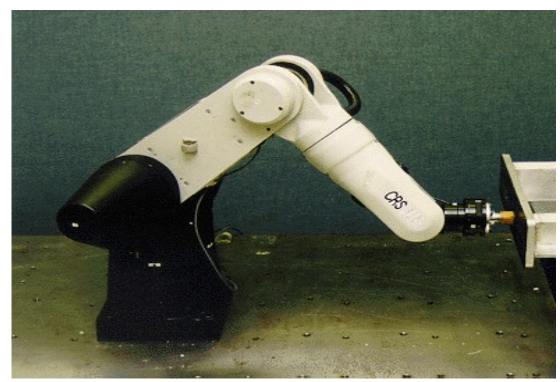
2 A device that automatically performs complicated often repetitive tasks

3 A mechanism guided by automatic controls

(source: www.m-w.com)

4: A **reprogrammable, multifunctional manipulator** designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks

(source: Robot Institute of America, 1979)



Why use a Robot instead of a human?

- Carry out dangerous tasks, minimizing risks to human life (e.g., movement of nuclear waste, bomb disposal, underwater exploration).
- Carry out tedious and repetitive tasks (e.g., autonomous lawnmowers, autonomous vacuums, household duties).
- Manufacture more consistent and better quality products.
- Increase productivity (through reduced downtime, greater throughput, etc.)
- Entertainment & Fun!

Robot Components

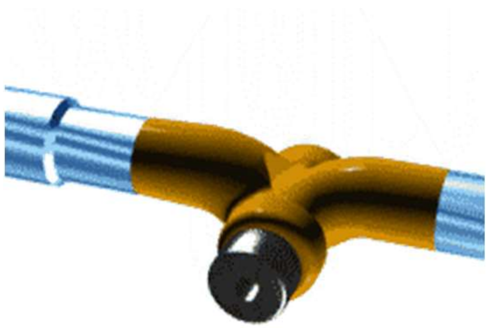
The **Manipulator** is a mechanical structure consisting of a sequence of rigid bodies (**links**) connected by a means of articulation (**joints**); a typical industrial manipulator is characterized by an **arm** that ensures mobility, a **wrist** for dexterity and an **end-effector** to carry out the task required of the robot.

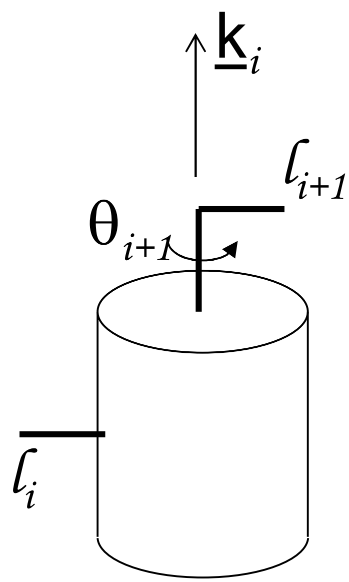
Actuators set the manipulator in motion through actuation of the joints; typical actuators include electric, hydraulic, pneumatic and piezoelectric actuation.

Sensors measure the status of the manipulator (proprioceptive sensors) and, if necessary, the status of the environment (exteroceptive sensors).

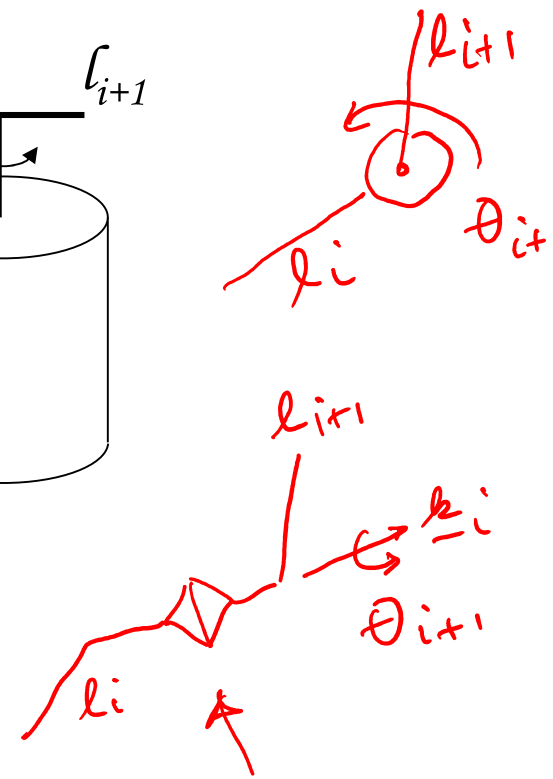
The **Control System** enables automated control and supervision of manipulator motion.

Basic Joint Types: Revolute

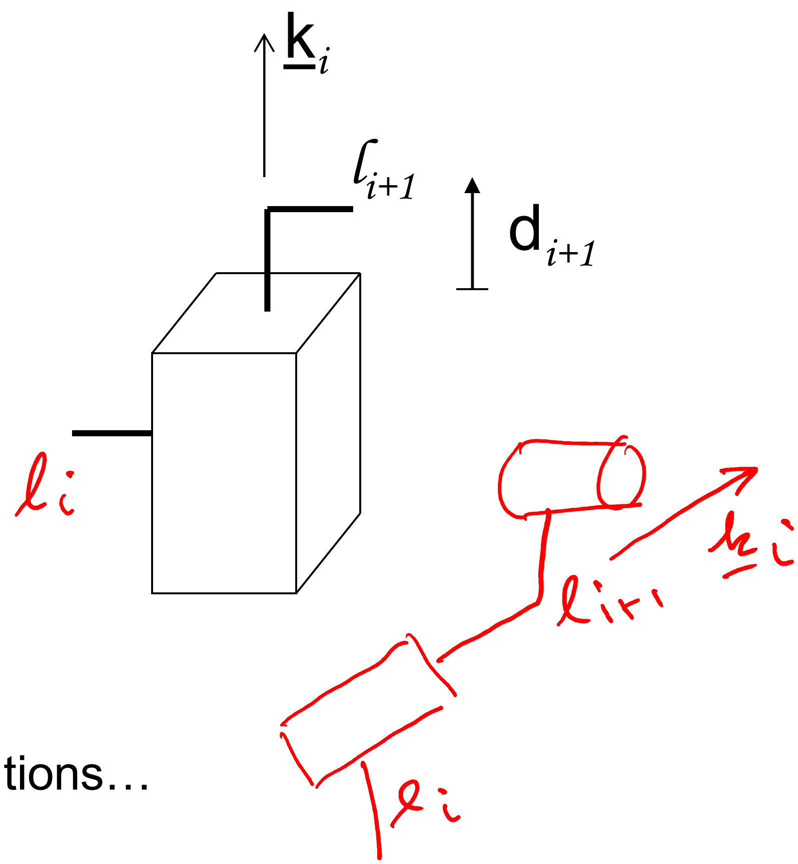




Other notation conventions…

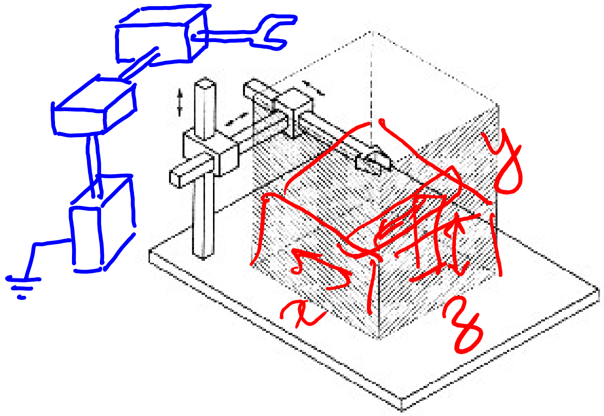


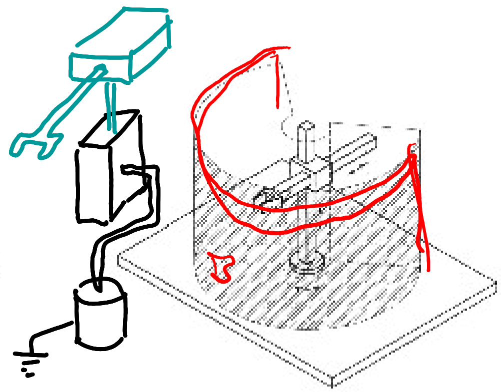
Basic Joint Types: Prismatic

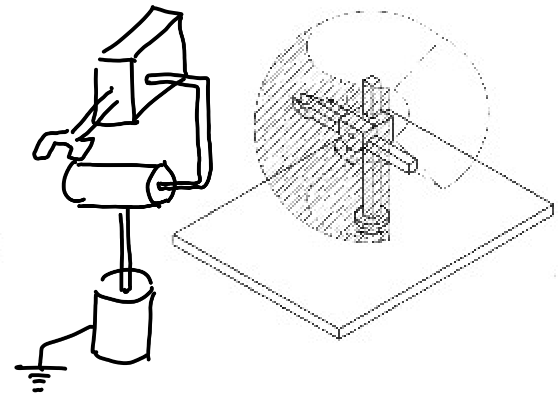


Other notation conventions…

Common Manipulator Structures



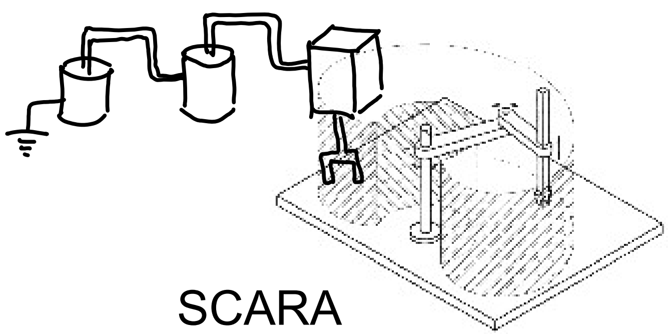




Cartesian (15% of market)

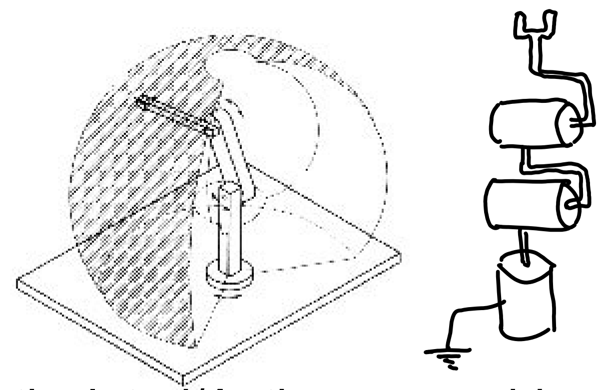
Cylindrical (47%)

Spherical (13%)



SCARA
(Selective Compliant Assembly Robot)

(25% together)



Articulated/Anthropomorphic

Some examples from Epson http://www.youtube.com/watch?v=vBZZPXCstdw&feature=related

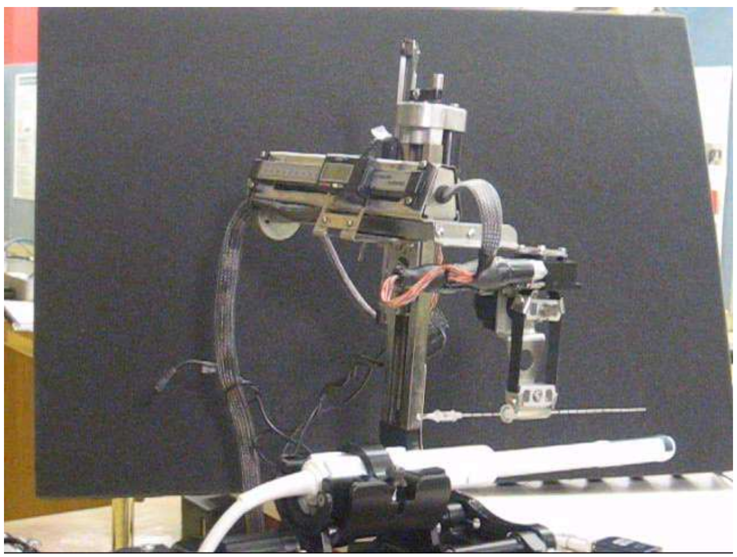
Not-so-common manipulator structures

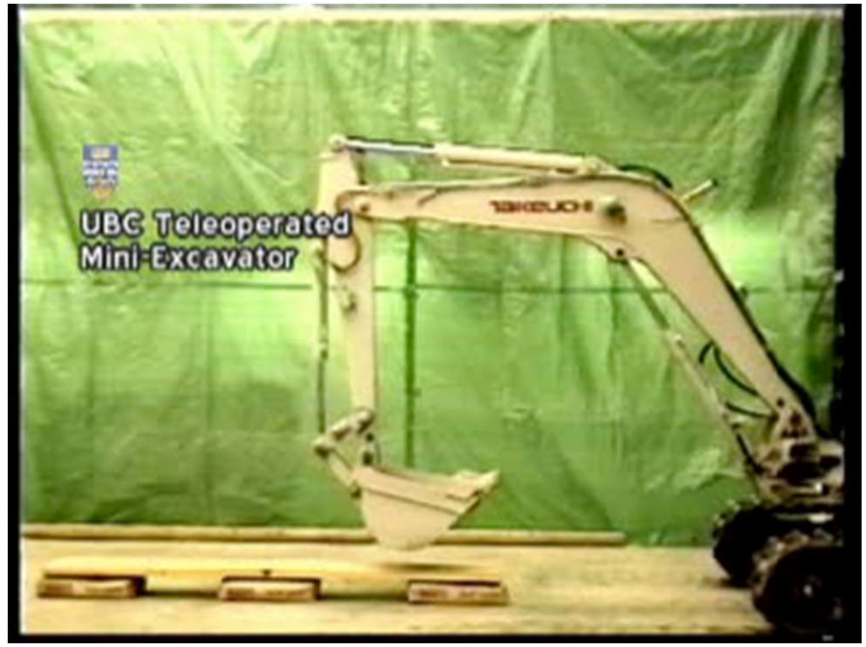
[Adept parallel robot]

[Snake robots for inspection/pipes]

Robotic excavators

Needle insertion robots





Degrees-of-freedom (DOF): The number of parameters required to specify the spatial configuration of the manipulator.

How many DOFs does a rigid body in 2-D space have?
How about a rigid body in 3-D?

How about the human arm

- excluding joints in the hand but including the shoulder, elbow and wrist?
- including joints in the hand?

Comments:

1. For serial manipulator, # of DOFs = # of joints.
2. Get *kinematic redundancy* if the number of parameters required to specify the end-effector position/orientation is less than the DOFs of the manipulator.
3. Some roboticists do not consider the end-effector as a DOF.
4. A joint where movement is not controlled continuously is sometimes assigned a ½ DOF.

Why have kinematic redundancy?

Reachable Workspace: The set of points achievable by the end-effector.
Dextrous Workspace: The set of points achievable by the end-effector *with arbitrary orientation.*

Consider a planar 2-link manipulator, with links of different lengths. What is the reachable workspace? What is the dexterous workspace?

Consider a planar 3-link manipulator, with links of different lengths. What is the reachable workspace? What is the dexterous workspace?

Common Specifications

Primary:

- Workspace
- Repeatability
- Resolution
- Accuracy
- Payload

Others, less often used:

- Stiffness
- Bandwidth (disturbance rejection)
- Cleanliness
- Impedance (mechanical) range – “Z-width”

Problems studied

- Direct kinematics: find end-effector location given joint angles
- Inverse kinematics: find joint angles given end-effector location

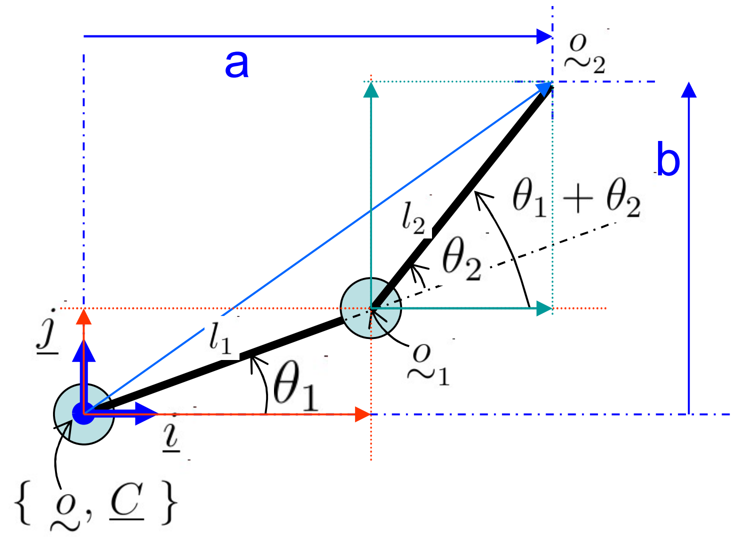
- Direct velocity kinematics: find end-effector velocity given joint rates
- Inverse velocity kinematics: find joint rates given end-effector velocity

- Direct dynamics: find end-effector acceleration given joint forces and torques
- Inverse dynamics: find joint forces and torques given end-effector acceleration

- Manipulator control: move end-effector to set-point or along specified trajectory. Requires kinematics and dynamics

Direct kinematics example: 2D SCARA

- Given the joint angles, find the location of the gripper in base coordinates.



$$\underline{C} = [\,\underline{i}\ ,\ \underline{j}\,]$$

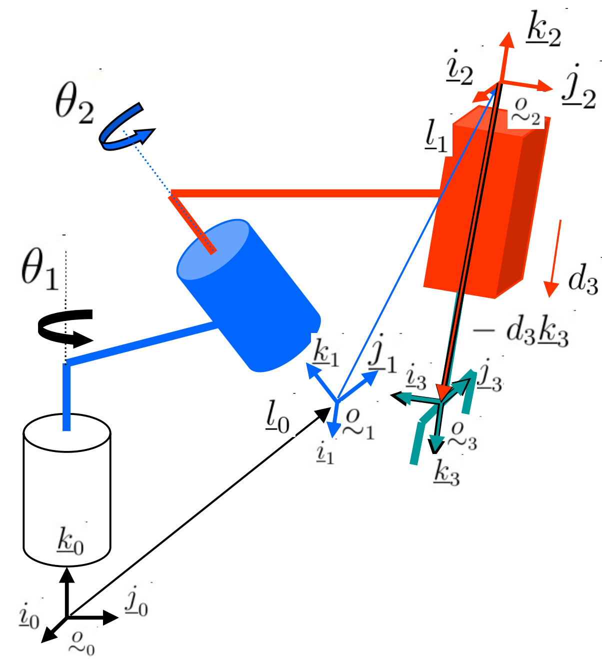
$$\underset{\sim}{o}_2 = \underset{\sim}{o} + a\underline{i} + b\underline{j}$$

$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} l_1 \cos\theta_1 \\ l_1 \sin\theta_1 \end{bmatrix}$$

$$+ \begin{bmatrix} l_2 \cos(\theta_1 + \theta_2) \\ l_2 \sin(\theta_1 + \theta_2) \end{bmatrix}$$

$$= \begin{bmatrix} l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) \\ l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) \end{bmatrix}$$

Direct kinematics, in general:



$$\underset{\sim}{o}_1 = \underset{\sim}{o}_0 + \underline{\underline{Rot}}(\underline{k}_0, \theta_1)\underline{l}_0$$

$$\underset{\sim}{o}_2 = \underset{\sim}{o}_1 + \underline{\underline{Rot}}(\underline{k}_1, \theta_2)\underline{l}_1$$

$$\underset{\sim}{o}_3 = \underset{\sim}{o}_2 - d_3\underline{k}_3$$

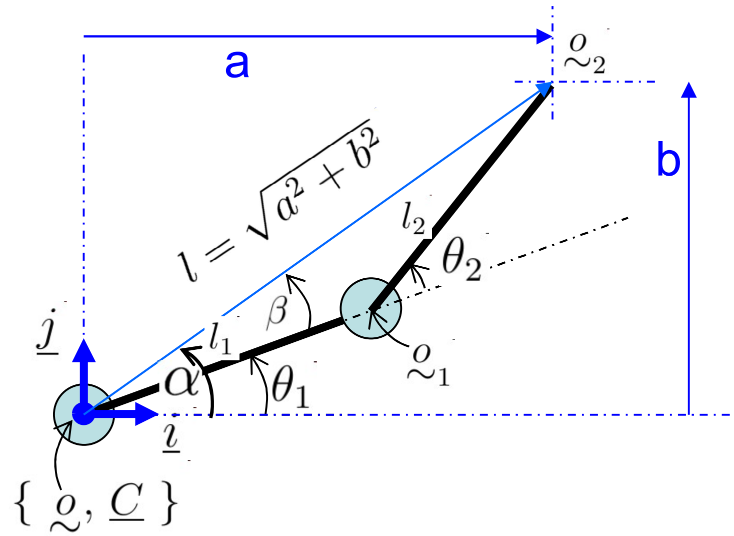
$$\underline{k}_1 = \underline{k}_1(\theta_1) = \underline{\underline{Rot}}(\underline{k}_0, \theta_1)\underline{k}_1(0)$$

$$\underline{k}_2 = \underline{k}_2(\theta_1, \theta_2) = \underline{\underline{Rot}}(\underline{k}_1, \theta_2)\underline{k}_2(0,0)$$

$$= \underline{\underline{Rot}}(\underline{\underline{Rot}}(\underline{k}_0, \theta_1)\underline{k}_1(0), \theta_2)\underline{k}_2(0,0)$$

Inverse kinematics, 2D SCARA example:

- Given the gripper coordinates in base coordinate system, find joint angles.



θ_2 - ?

From cosine law:

$$l^2 = l_1^2 + l_2^2 + 2 l_1 l_2 \cos\theta_2$$

θ_1 - ?

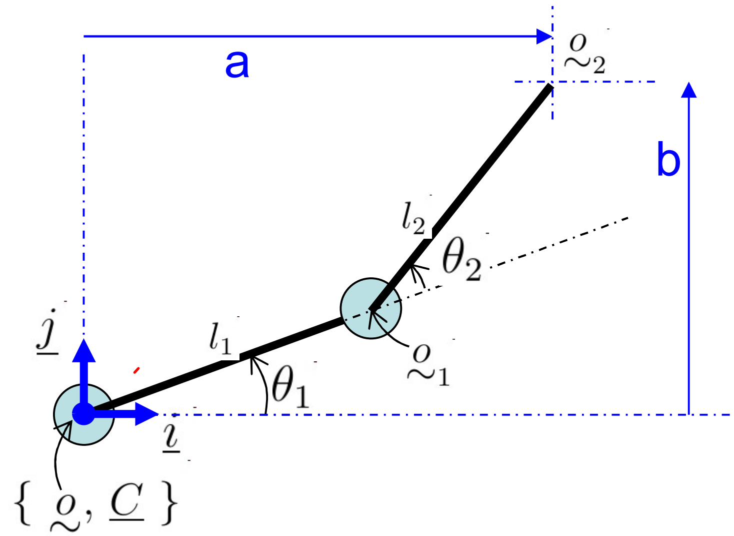
$$\alpha = \operatorname{atan}(a, b)$$

From cosine law:

$$l_2^2 = l_1^2 + l^2 - 2 l_1 l \cos\beta \qquad \theta_1 = \alpha - \beta$$

Cosine law does not work well for small angles…

Velocity kinematics, 2D SCARA example:



$$\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) \\ l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) \end{bmatrix}$$

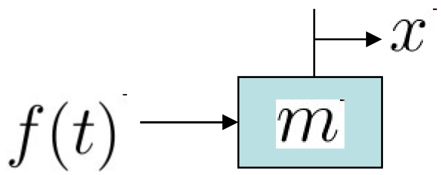
$$\frac{d}{dt}\begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} -l_1 \sin\theta_1\dot{\theta}_1 - l_2 \sin(\theta_1 + \theta_2)(\dot{\theta}_1 + \dot{\theta}_2) \\ l_1 \cos\theta_1\dot{\theta}_1 + l_2 \cos(\theta_1 + \theta_2)(\dot{\theta}_1 + \dot{\theta}_2) \end{bmatrix}$$

$$= \begin{bmatrix} -l_1 \sin\theta_1 - l_2 \sin(\theta_1 + \theta_2) \\ l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) \end{bmatrix}\dot{\theta}_1 + \begin{bmatrix} -l_2 \sin(\theta_1 + \theta_2) \\ l_2 \cos(\theta_1 + \theta_2) \end{bmatrix}\dot{\theta}_2$$

$$= J_1\dot{\theta}_1 + J_2\dot{\theta}_2$$

Inverse dynamics examples:

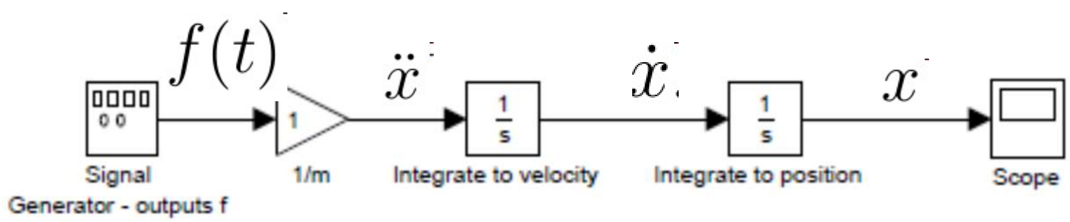
- Simple mass



$$m\ddot{x}(t) = f(t)$$

To compute forces from position, take second derivative of $x(t)$

To compute positions from forces, integrate the differential equation:



with initial conditions specified for each integrator block.

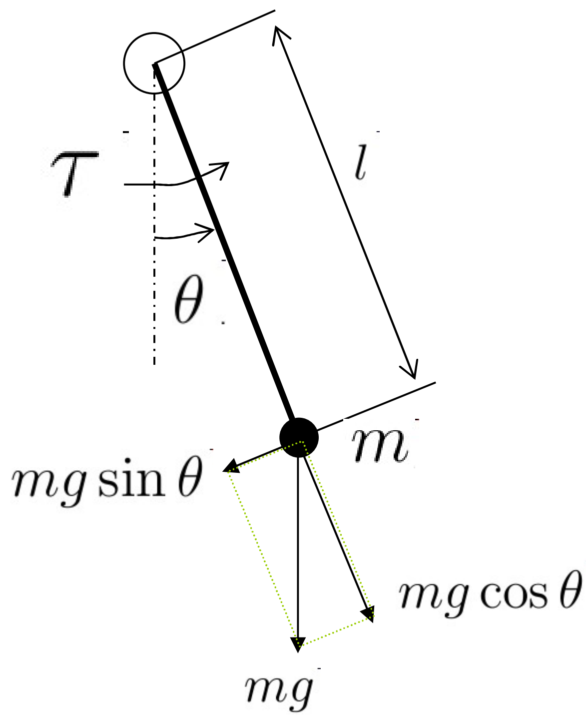
Inverse dynamics examples:

- Simple mass

Euler's law: $$ml^2\ddot{\theta} = \tau + \tau_{gravity}$$

$$ml^2\ddot{\theta} = \tau - lmg\sin\theta$$

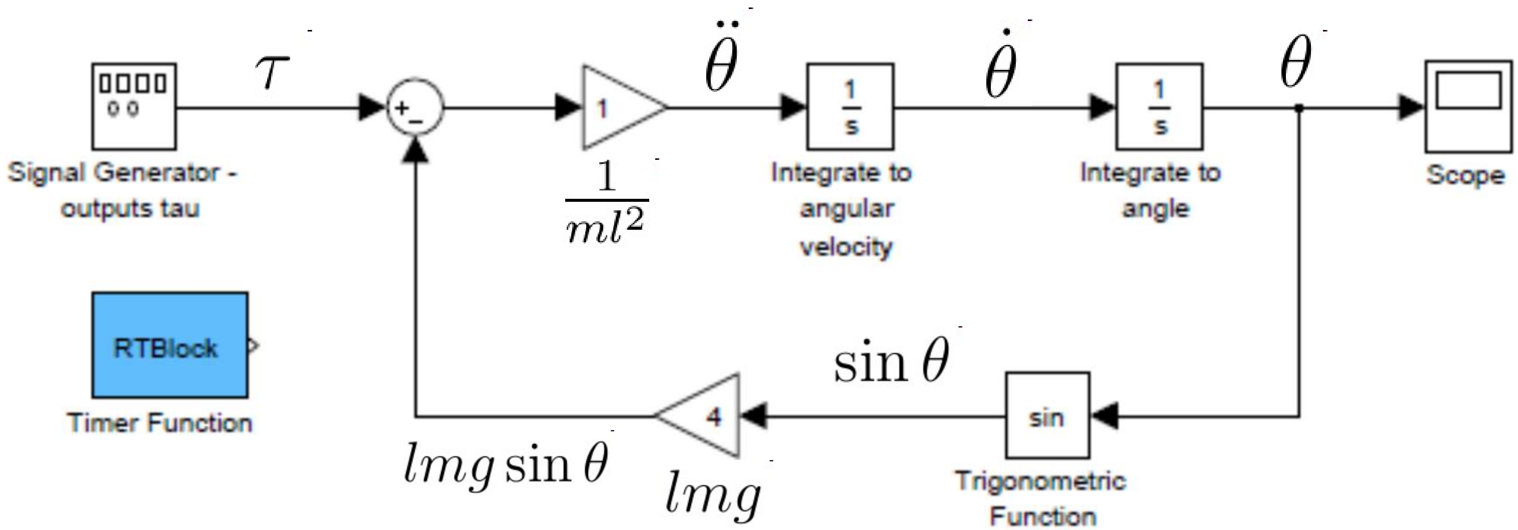
$$\ddot{\theta} + \frac{g}{l}\sin\theta = \frac{1}{ml^2}\tau$$



Inverse dynamics: $$\tau(t) = ml^2\ddot{\theta}(t) + lmg\sin\theta(t)$$

Direct dynamics: $$ml^2\ddot{\theta} = \tau - lmg\sin\theta$$

$$\ddot{\theta}(t) = \frac{1}{ml^2}(\tau(t) - lmg\sin\theta(t))$$

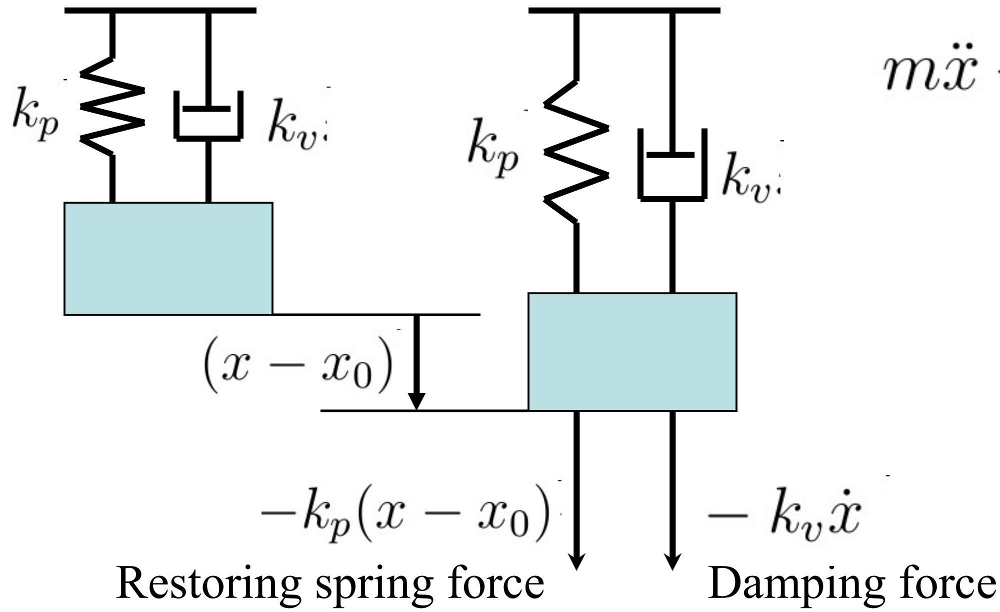


Control:

Newton's Law: $m\ddot{x} = f$

PD controller: $f = -k_p(x - x_0) - k_v\dot{x}$

$$m\ddot{x} + k_v\dot{x} + k_p x = k_p x_0$$



Energy function? $V(x, \dot{x}) = \frac{1}{2}k_p(x - x_0)^2 + \frac{1}{2}m\dot{x}^2$

Energy decreases, x_0 a stable equilibrium point of the closed loop system.

Course objective

To provide a solid foundation of the analysis tools required in the design of manipulators and their control systems. To understand the control and navigation methods used in robot manipulators, robotic vehicles and drones, and robot-assisted teleoperators.

- Course notes available on UBC Canvas.
- Textbook: Peter Corke, Robotics, Vision and Control, 2^{nd} Edition, 2017

Suggested References:

L. Sciavicco and B. Siciliano, “Modeling and Control of Robot Manipulators” (2nd Edition). Springer Verlag, 2000.

J.Craig, "Introduction to Robotics: Mechanics and Control" (3rd Edition). Addison-Wesley, 2005.

M.W. Spong, S. Hutchinson and M. Vidyasagar, "Robot Modeling and Control", Wiley 2005.

R.M. Murray, Z. Li and S.S. Sastry, “A Mathematical Introduction to Robotic Manipulation”. CRC Press, 1994 (closest text in notation).

Tentative lecture plan

- **[Week 1-2] Some** Course organization, introduction to the topic. Common robot configurations, technology and applications. Notational convention for rotational and prismatic joints. PD control of a simple mass. Energy interpretation. Pendulum example.
- **[Week 2-3]** Vectors, points, linear and affine transformations and their coordinate representations. Change of coordinates. Structure of rotations and reflections. Matrix exponential representation of rotation. Quaternions. Direct kinematics. Denavit-Hartenberg convention. Angular velocity. Addition of angular velocities. Velocity kinematics. Manipulator Jacobians. Singularities.
- **[Week 4]** The geometric approach to inverse kinematics. Prototype inverse kinematics problems. Wrist-arm decomposition. Examples (inverse kinematics of spherical wrist, PUMA, CRS, Stanford manipulators).
- **[Week 5-6]** The Newton-Euler approach to the dynamics of serial manipulators. The Euler-Lagrange approach to the dynamics of serial manipulators. Control-relevant properties of equations of motion for serial manipulators. Linearity in parameters.

Tentative lecture plan

- **[Week 7-8]** Drone dynamics and control. Manipulator position control in joint space: computed-torque, feedforward, and PD+gravity position control. Stability of PD+gravity control using Lyapunov's second method. Manipulator position control in task space: resolved acceleration control and stiffness control.
  [Week 8-9] Mobile robots: models, navigation, localization, mapping, simultaneous localization and mapping.
- **[Week 10-11]** Introduction to computer vision. Light and colour. Image formation. Basic Image processing. Feature extraction. Camera calibration. Introduction to vision-based robot control.
- **[Week 12]** Advanced topics (teleoperation, medical robotics, visual servoing?)
- **[Week 13]** Student Presentations.

Homework and grading

- **Homework:** Handed out as formal homework or as problems assigned in class.

- **Project Work:** There will be simple projects for undergraduate students, primarily using simulations, and more difficult projects for graduate students. Past examples include a motion planner for a 6DOF robot, teaching by demonstration using the da Vinci robot, design and control of a haptic interface (dual pantograph system), image guidance for an ultrasound robot, drone modelling and control.
- Given COVID-19 situation, we cannot have any projects involving more hardware than your laptop camera or a webcam. So the projects will involve simulation work and reports on technical literature.

- **Grading**: Homework 20%, project work, including a report and possible presentation, 20%, midterms 30%, final exam 30%. If the final exam is better than the midterms, the midterms will be worth 0% and the final 60%.