Introduction

December 9, 2009

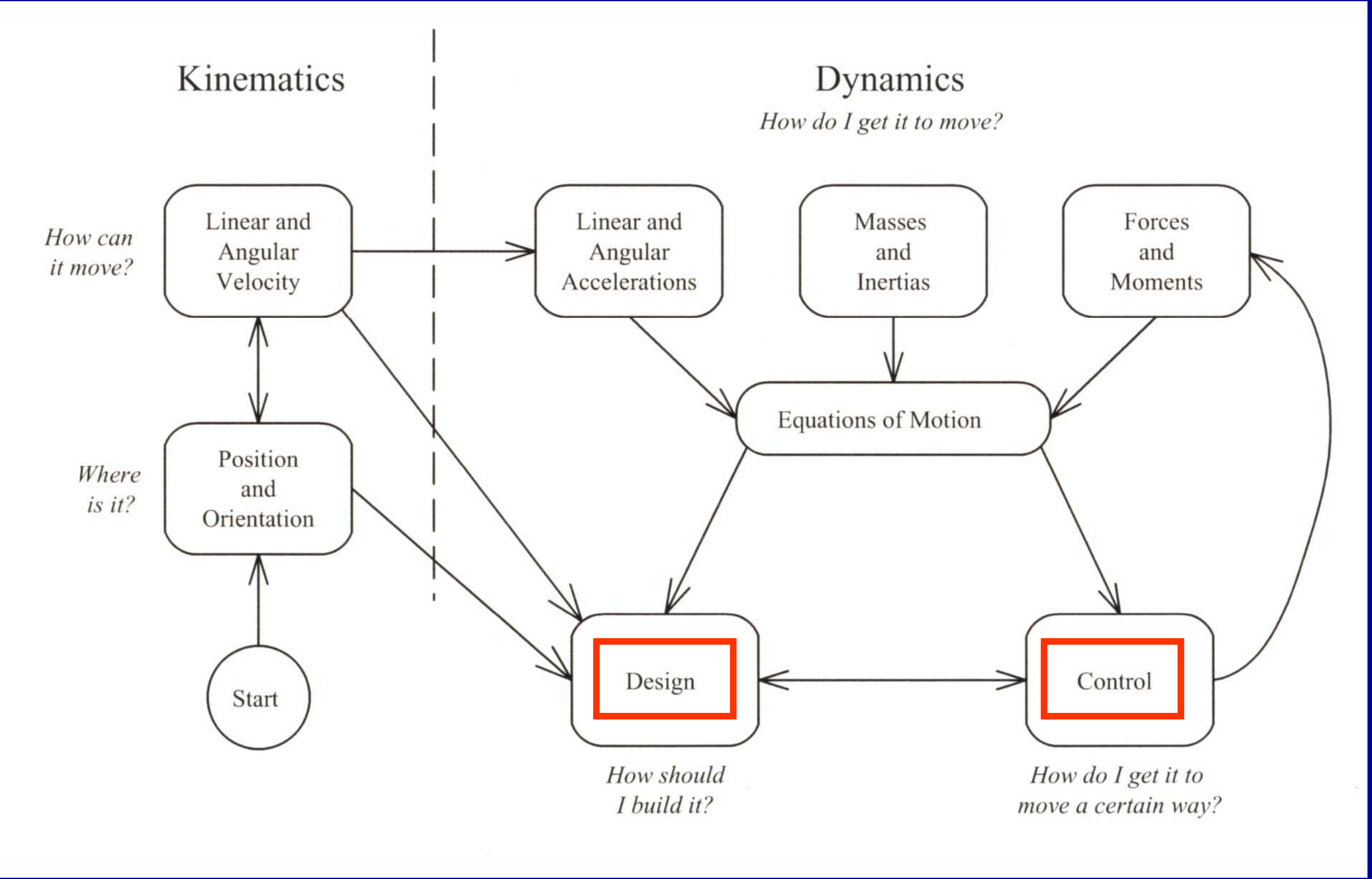
Background

- Focuses on the mechanics and control of the mechanical manipulator
- Robotics is not a new science, but merely a collection of topics taken from mechanical engineering, mathematics, control theory, electrical engineering, and computer science.

Networked Robots

- IEEE Society of Robotics and Automation's Technical Committee
- A robotic device connected to a communications network such as the Internet or LAN. The network could be wired or wireless, and based on any of a variety of protocols such as TCP, UDP, or 802.11.
- http://networked-robots.cs.umn.edu/

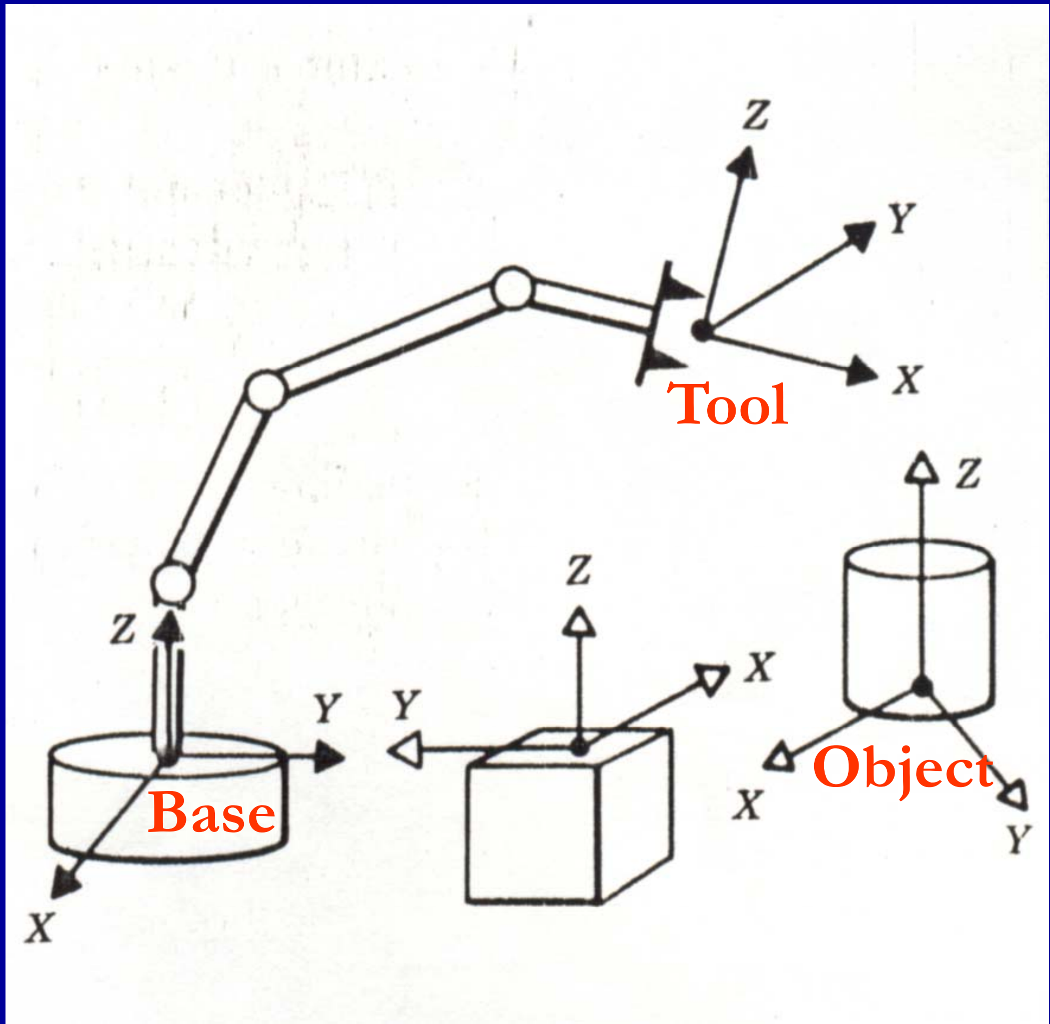
Theoretical Developments Schematic



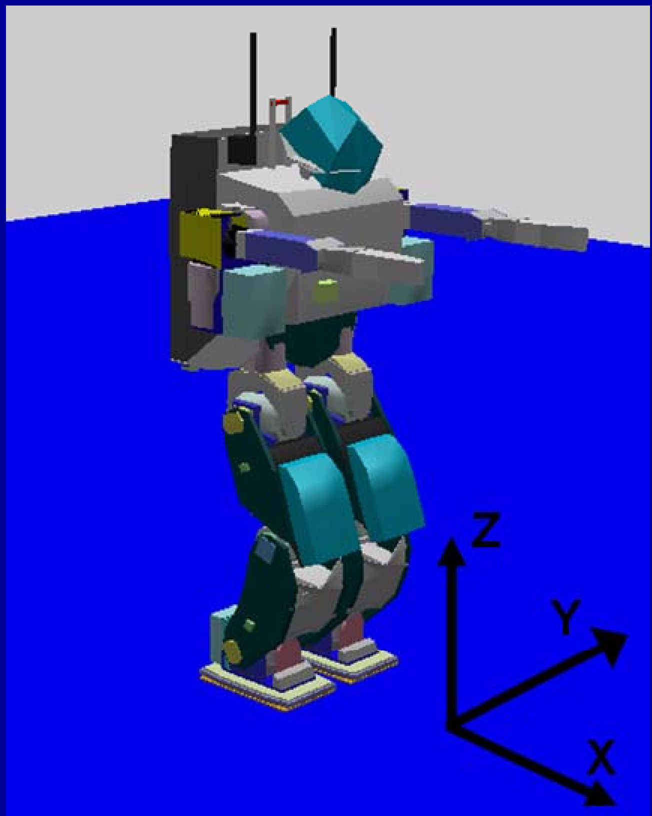
Description of position and orientation

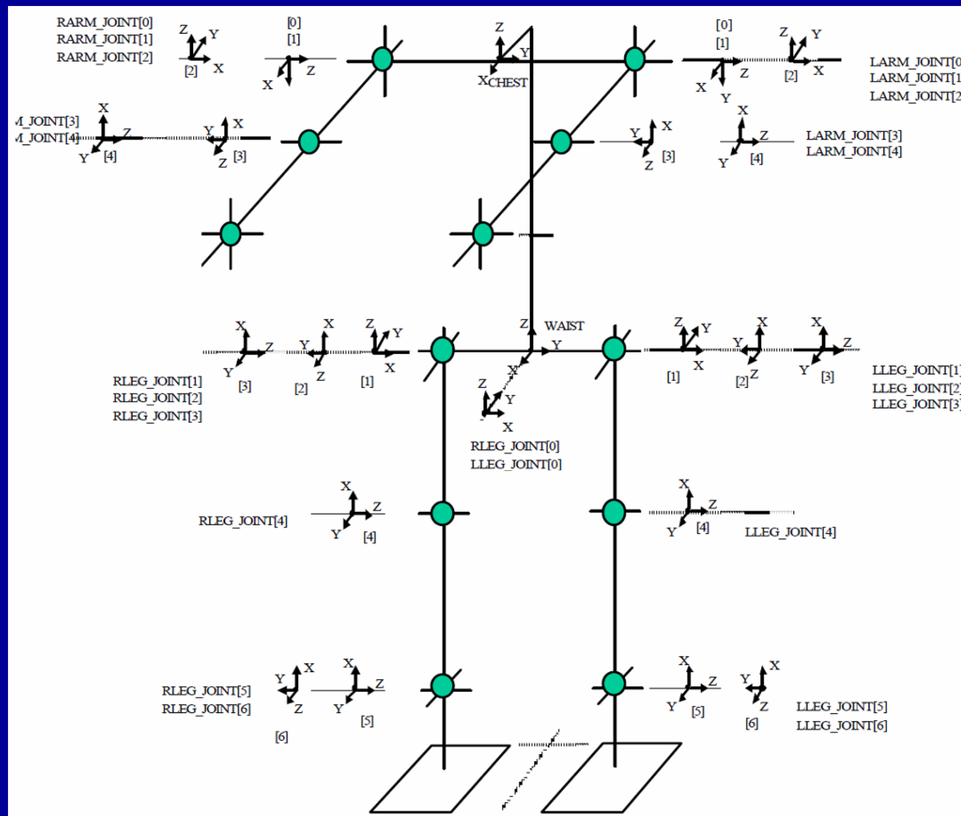
- Objects in 3D space are described by two attributes: position and orientation.
- Always attach a coordinate system (or frame) rigidly to the object: stationary or in motion
- Various reference coordinate systems: tool, base, object, world,…
- Transforming the description

Coordinate Systems or Frames



Coordinate Systems or Frames

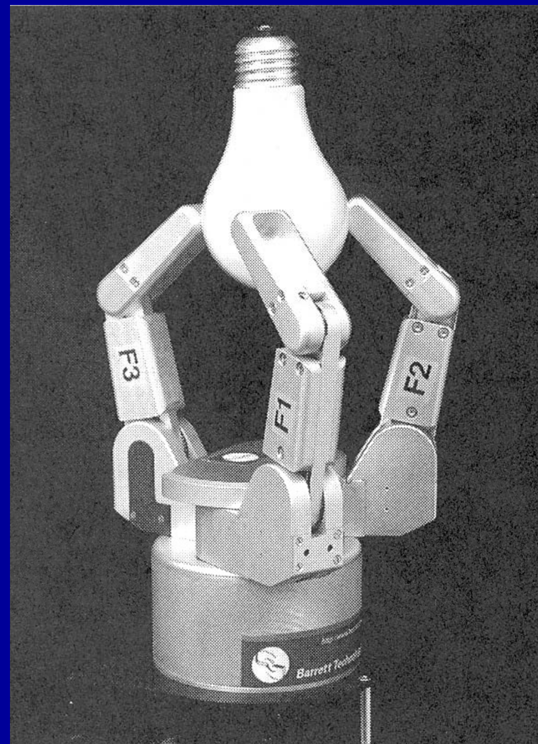




End-effectors

Grippers

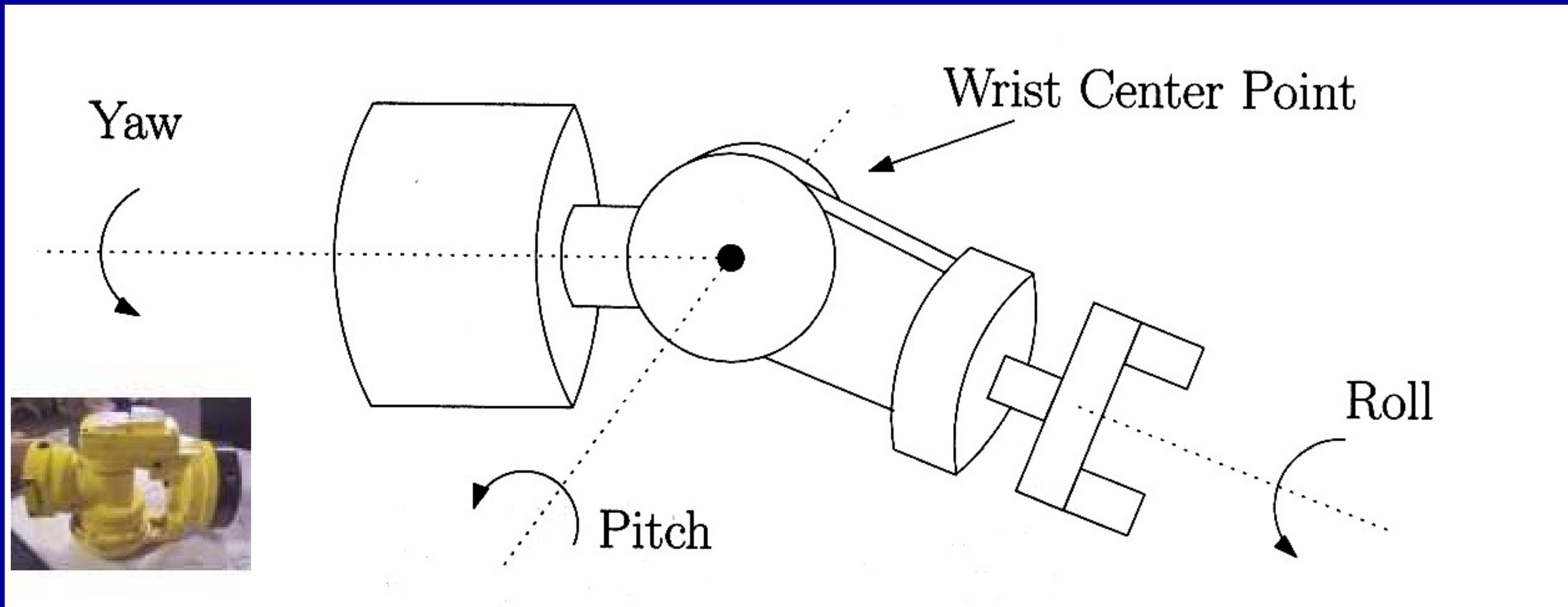
End arm effector, BTM



Anthropomorphic hand, Barrett Technology

Serial Wrists

Three joint axes intersect at a common point, known as the wrist center point.



Parallel Wrists

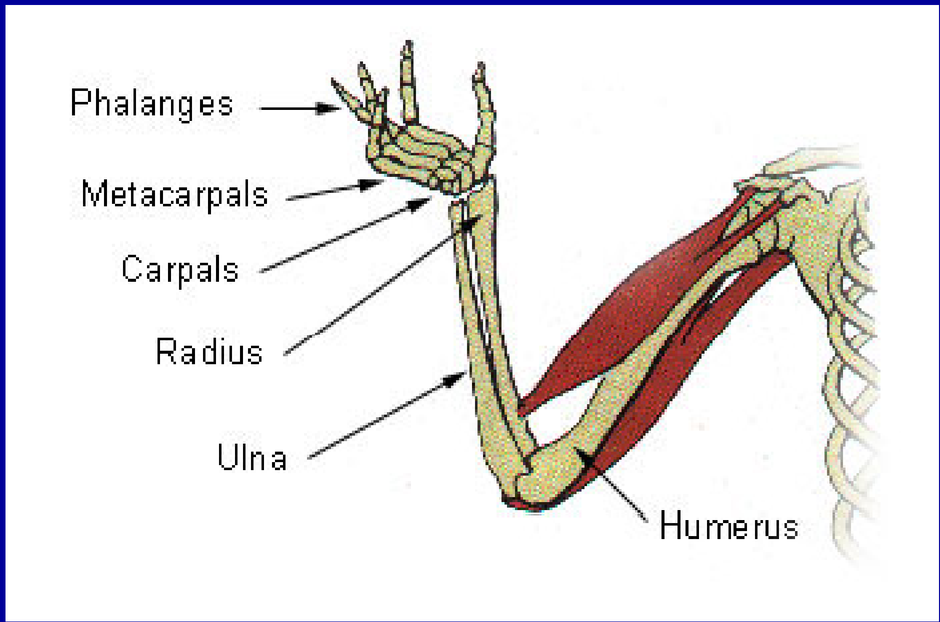
A 3-DOF 3-RRR spherical parallel manipulator

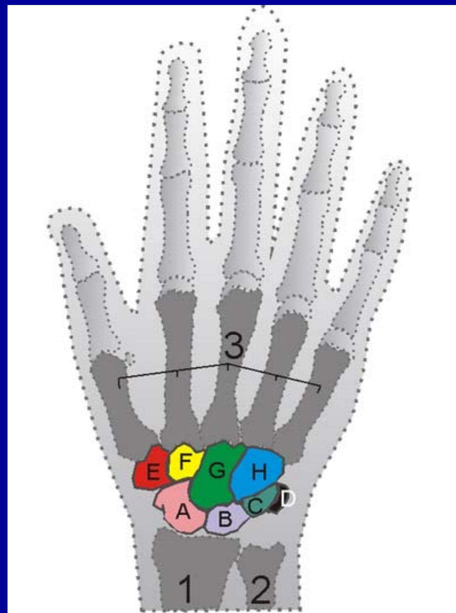
actuated

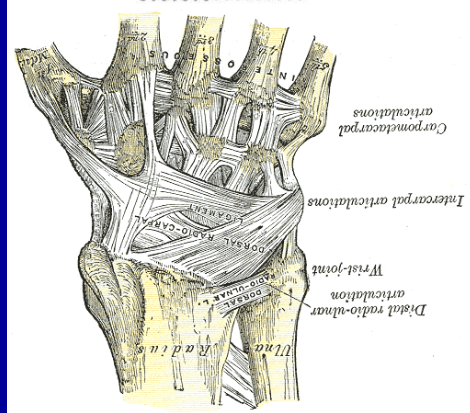
Laval University

A 2-DOF version (without torsional rotation about its vertical axis)

Upper Extremity

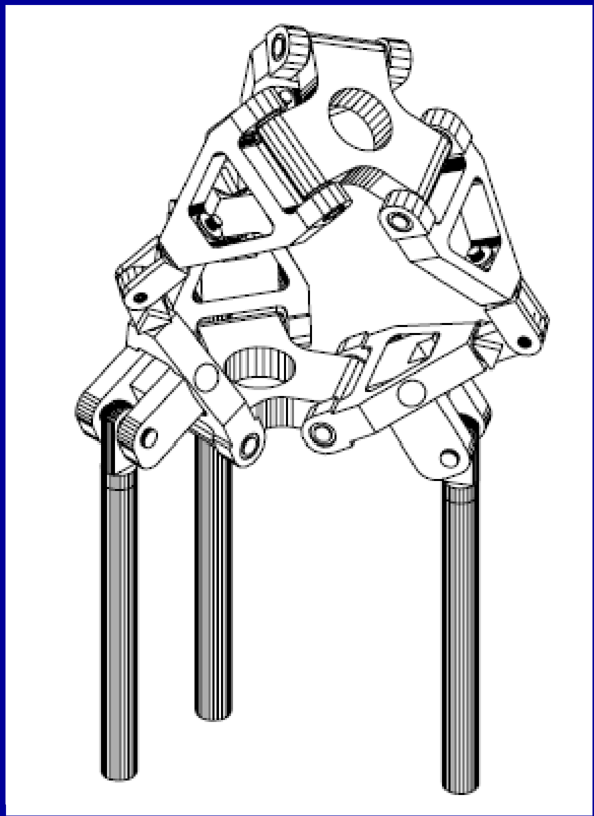






<Wikipedia>

Carpal Wrist



Vanderbilt University

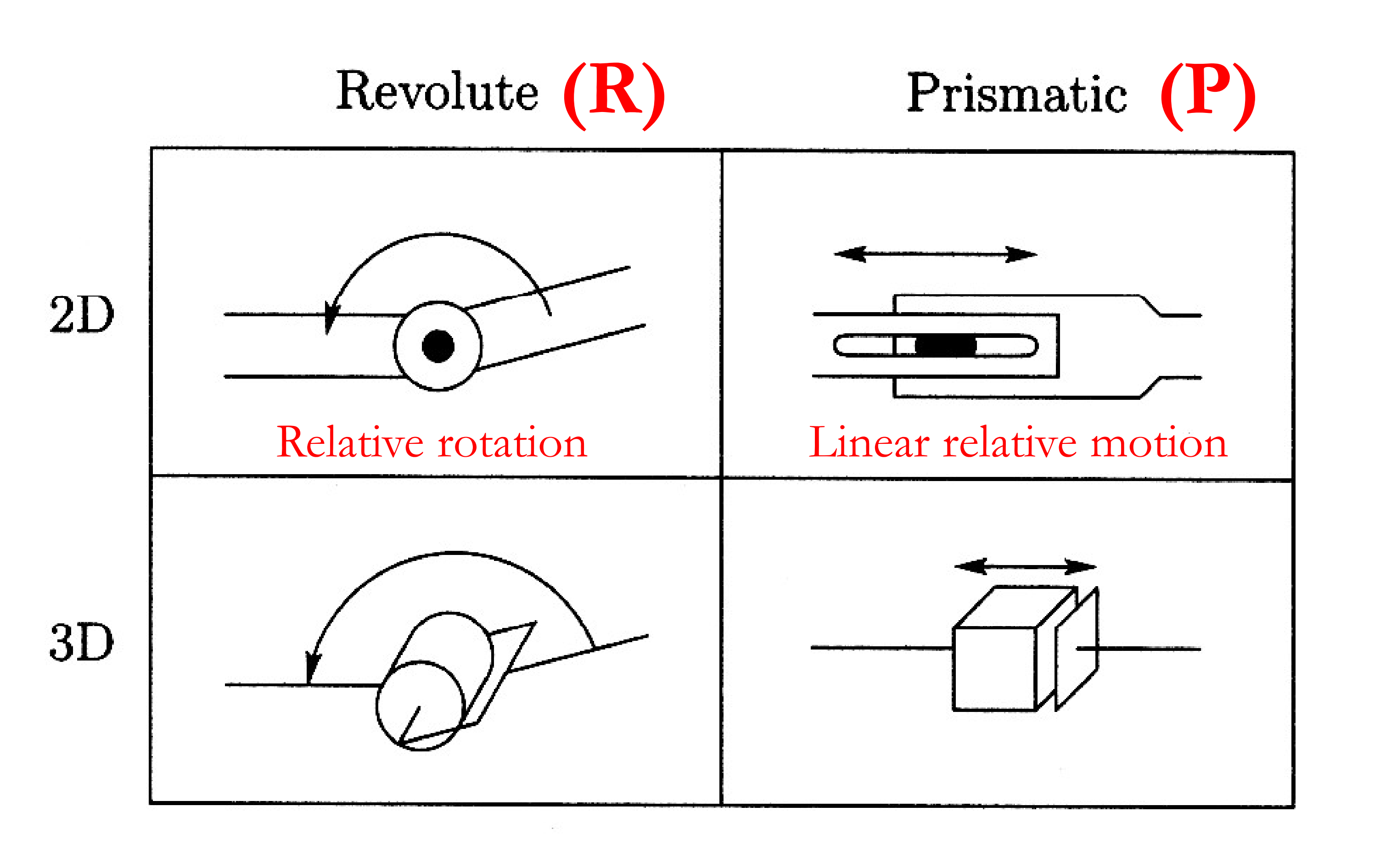
Kinematics

- The science of motion that treats motion without regard to the forces which cause it
- The position, velocity, acceleration, and all higher order derivatives of the position variables
- Refers to all the geometrical and time-based properties of the motion

Symbolic Representation of Robots

- Robot manipulators are composed of links connected by joints to form a kinematic chain.
- Joints are typically rotary (revolute) or linear (prismatic). (knuckle, spherical)
- Each joint allows a single degree of freedom of motion between adjacent links.

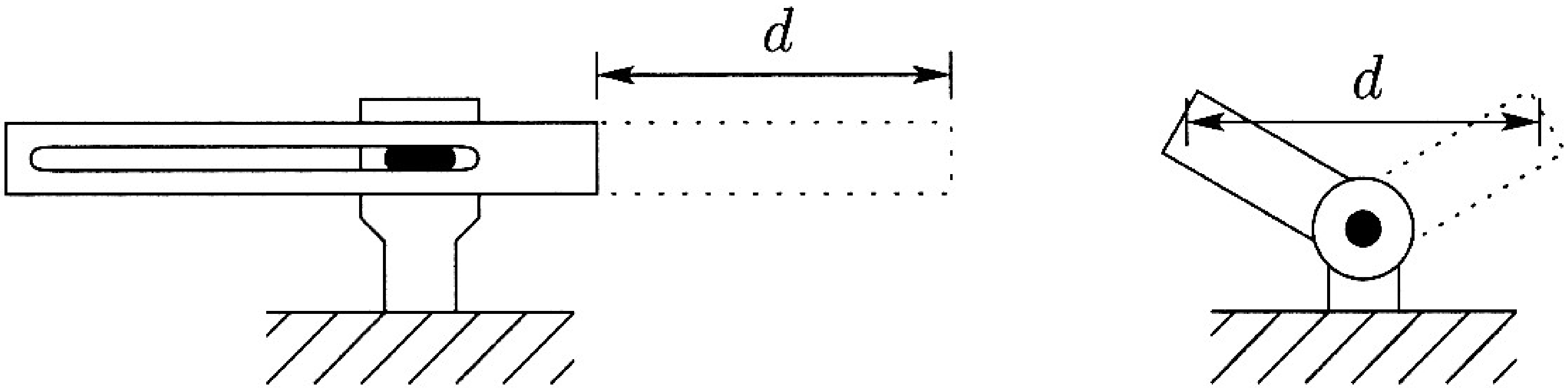
Representation of Robot Joints



Linear vs. Rotational Link Motion

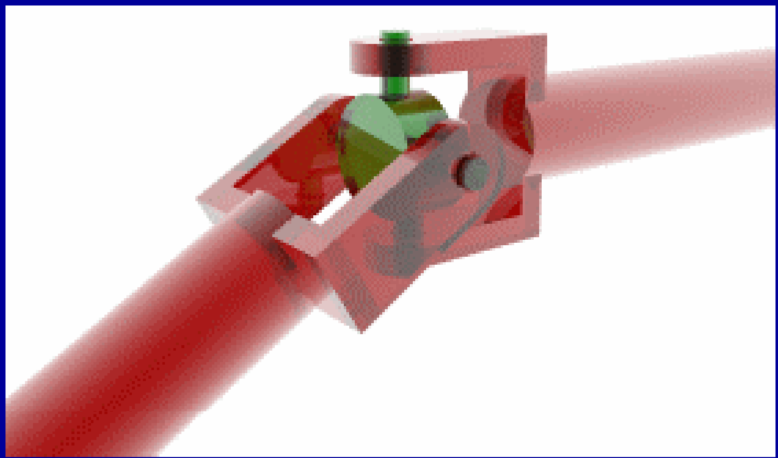
- Linear axes (prismatic joints) typically have higher resolution than revolute joint.
- Rotational axes usually result in a large amount of kinematic and dynamic coupling among the links, with a resultant accumulation of errors and a more difficult control problem.
- Why revolute joints? Increased dexterity and compactness.

Linear vs. Rotational Link Motion



A smaller revolute joint can cover the same distance ***d*** as a larger prismatic joint. The tip of a prismatic link can cover a distance equal to the length of the link. The tip of a rotational link of length ***a*** can cover a distance of *2a* by rotating 180 degrees.

Universal Joint



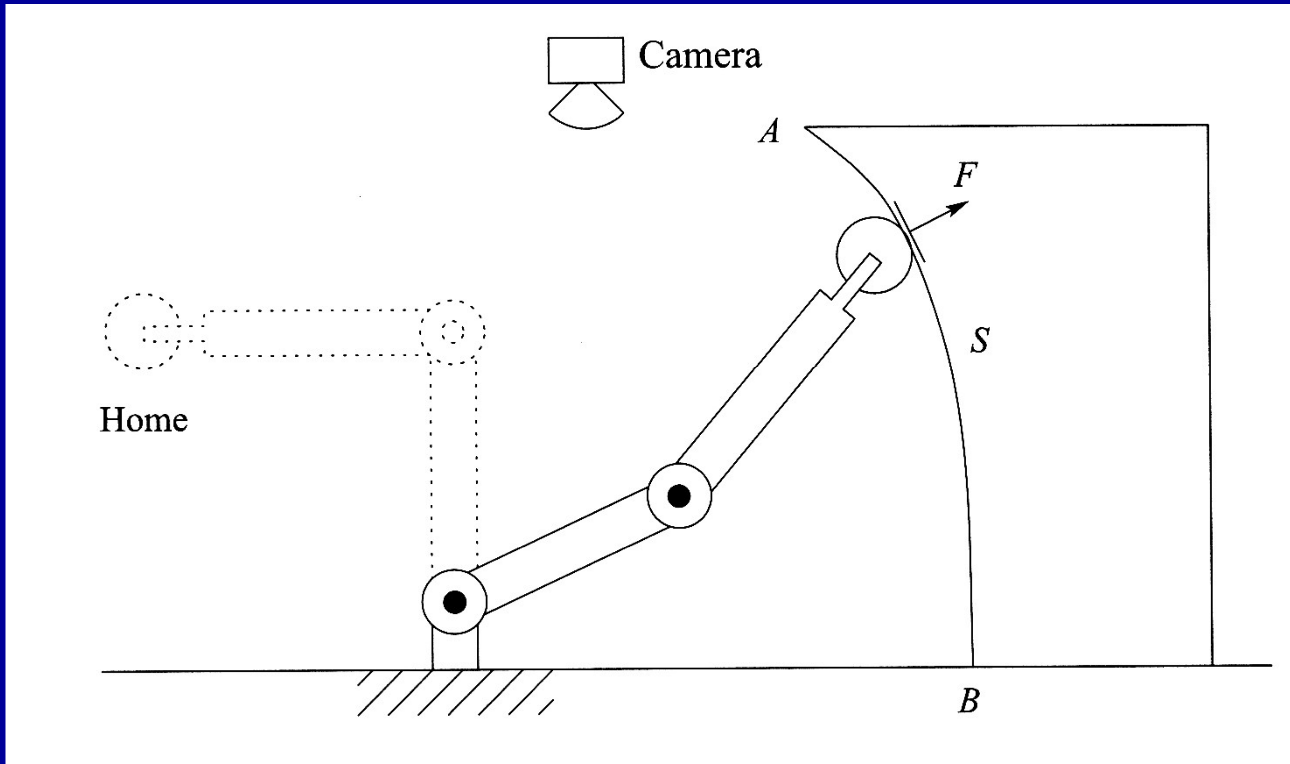
A joint in a rigid rod that allows the rod to bend in any direction

<Wikipedia>

Accuracy and Repeatability

- Accuracy- how close the manipulator can come to a given point within its workspace (computational errors, machining accuracy, flexibility effects, gear backlash, static/dynamic effects)
- Repeatability- how close a manipulator can return to a previously taught point (controller resolution)
- Resolution- computed as the total distance traveled divided by 2^n, where *n* is the number of bits of encoder accuracy. (the smallest increment of motion that the controller can sense)

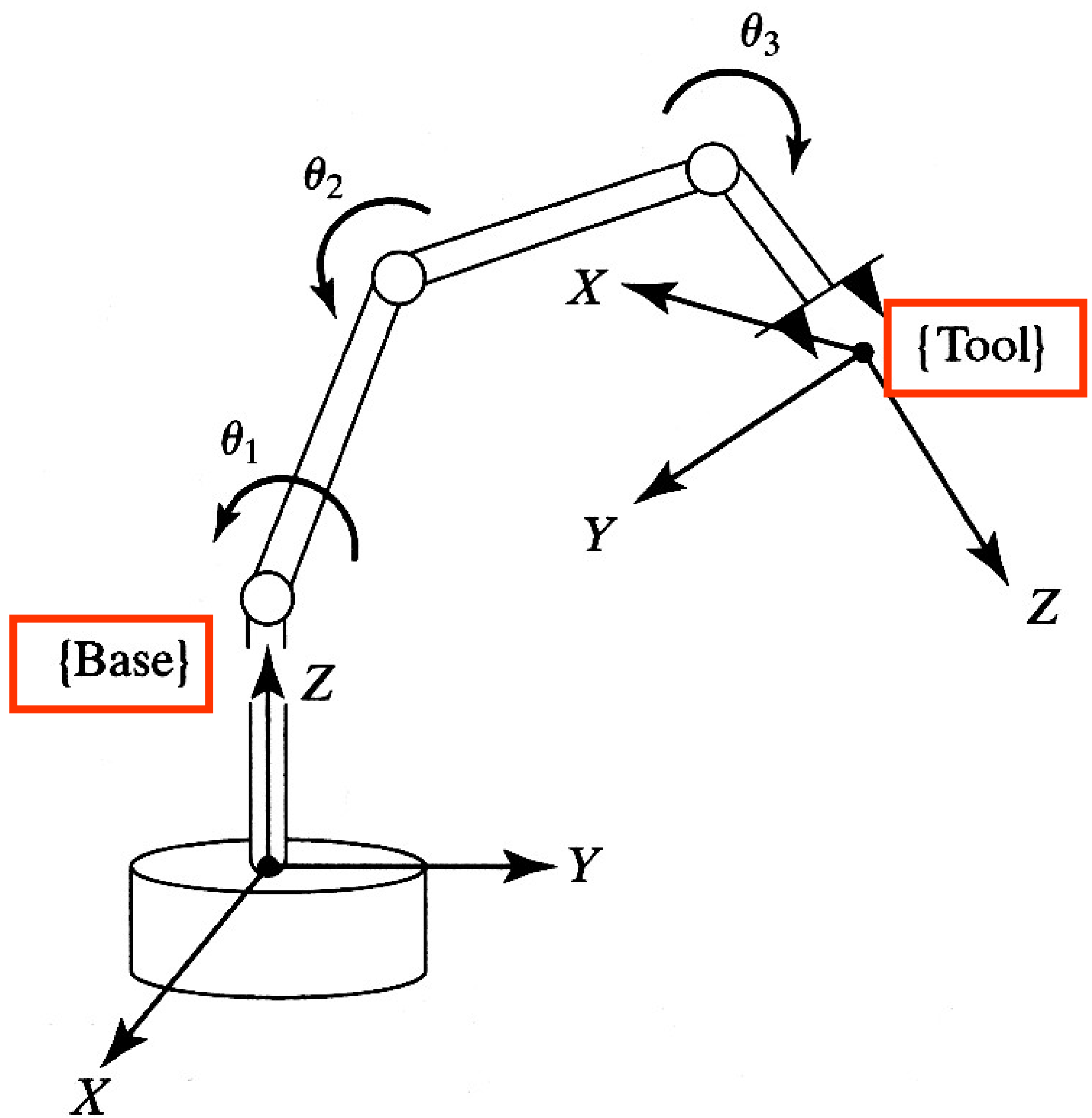
Two-link Planar Robot Example



We wish to move the manipulator from its home position to position *A*, from which point the robot is to follow the contour of the surface *S* to the point *B*, at constant velocity, while maintaining a prescribed force *F* normal to the surface.

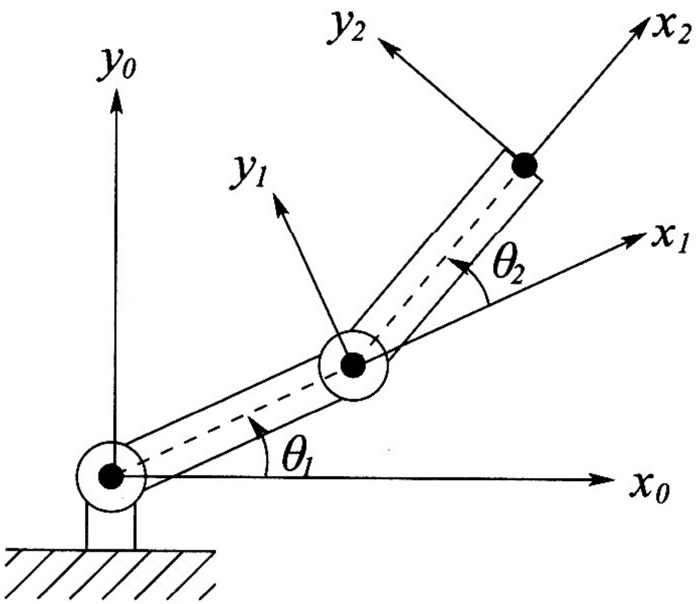
Forward Kinematics

- Degrees of freedom: free space 6, a plane 3
- Given: a set of joint angles
- Find: the position and orientation of the tool frame relative to the base frame
- Changes the representation of manipulator position from a joint space description into a Cartesian space description.



θ_3
θ_2
X
{Tool}
θ_1
Y
Z
{Base}
Z
Y
X

Forward Kinematic Equations: Nonlinear



Position of the tool frame

$$x_2 = a_1 \cos\theta_1 + a_2 \cos(\theta_1 + \theta_2)$$

$$y_2 = a_1 \sin\theta_1 + a_2 \sin(\theta_1 + \theta_2)$$

Orientation of the tool frame

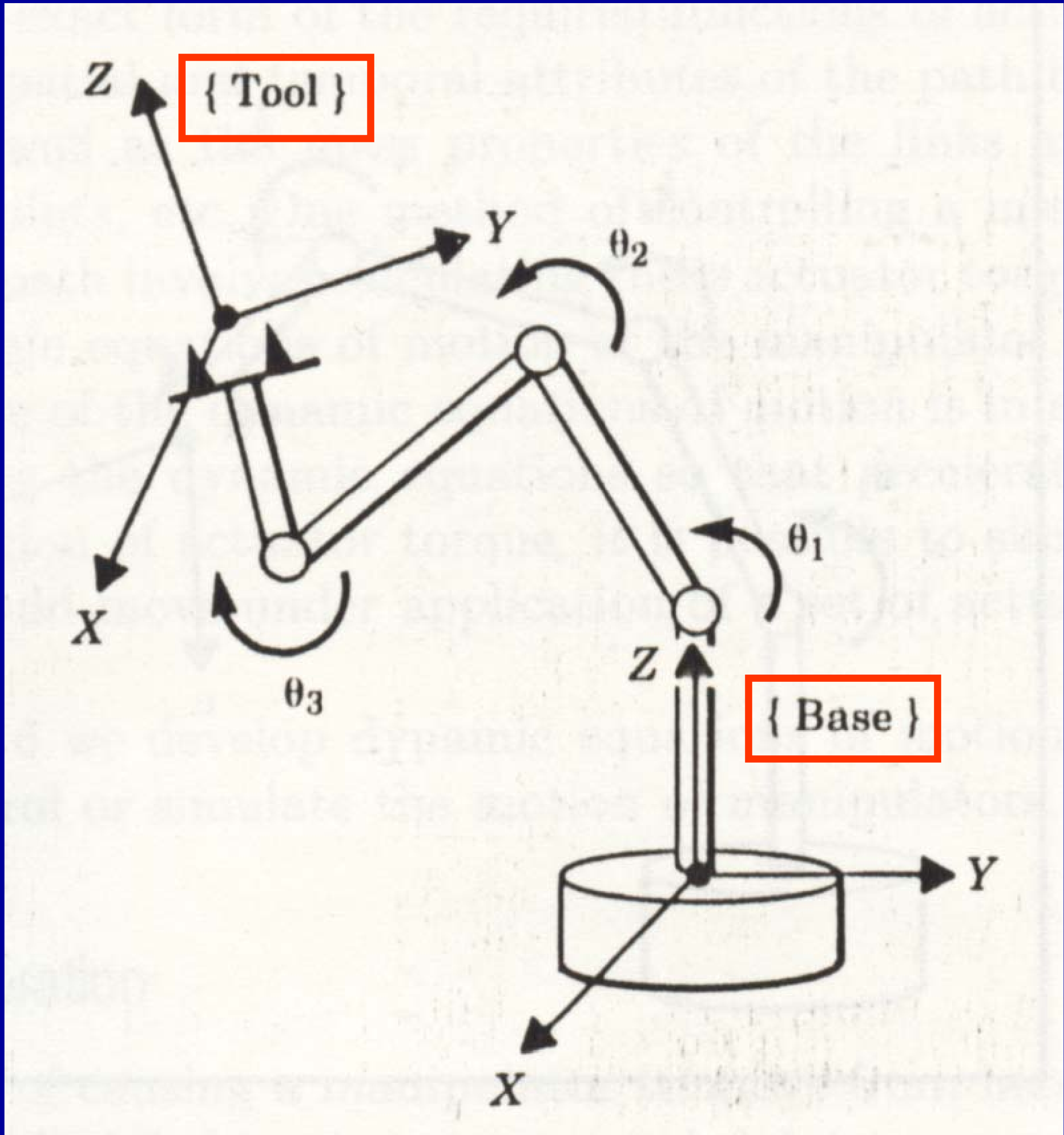
$$x_2 \cdot x_0 = \cos(\theta_1 + \theta_2); \quad y_2 \cdot x_0 = -\sin(\theta_1 + \theta_2)$$

$$x_2 \cdot y_0 = \sin(\theta_1 + \theta_2); \quad y_2 \cdot y_0 = \cos(\theta_1 + \theta_2)$$

$$\begin{bmatrix} x_2 \cdot x_0 & y_2 \cdot x_0 \\ x_2 \cdot y_0 & y_2 \cdot y_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta_1 + \theta_2) & -\sin(\theta_1 + \theta_2) \\ \sin(\theta_1 + \theta_2) & \cos(\theta_1 + \theta_2) \end{bmatrix}$$

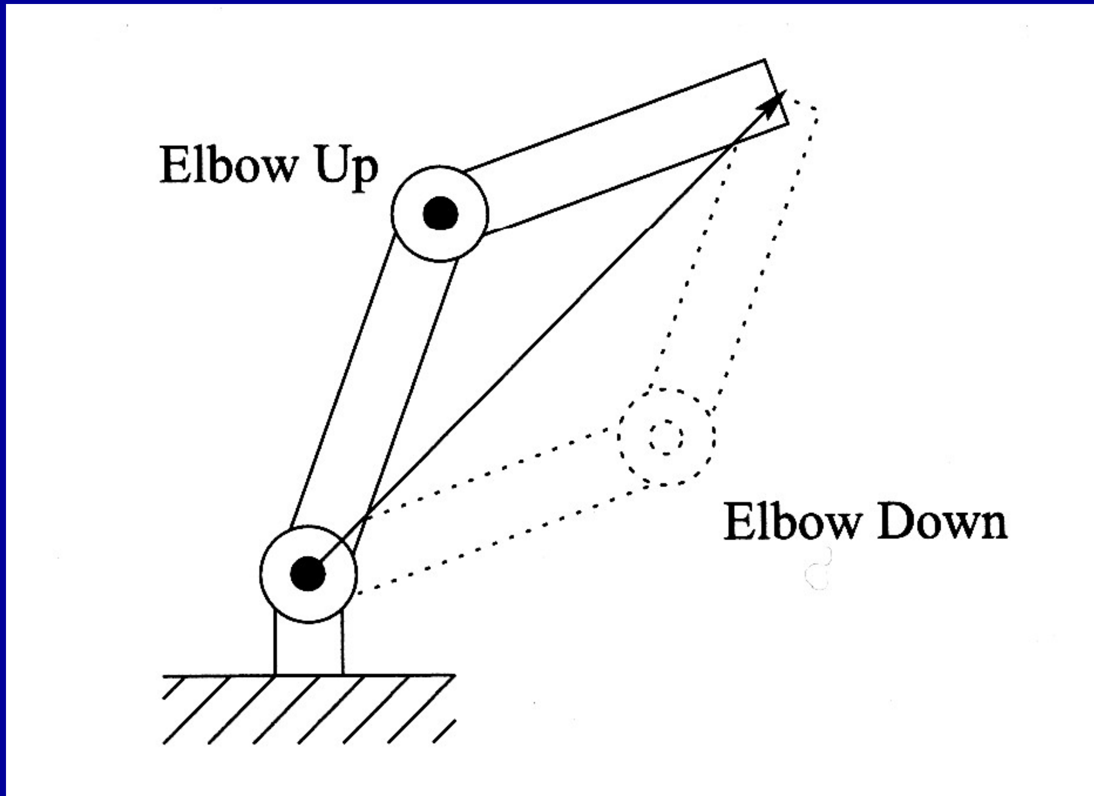
Inverse Kinematics

- Given: the position and orientation of the end-effector of the manipulator
- Find: all possible sets of joint angles that could be used to attain the given position and orientation
- Mapping of locations in 3D Cartesian space to locations in the robot's joint space
- Workspace: the existence of a kinematic solution

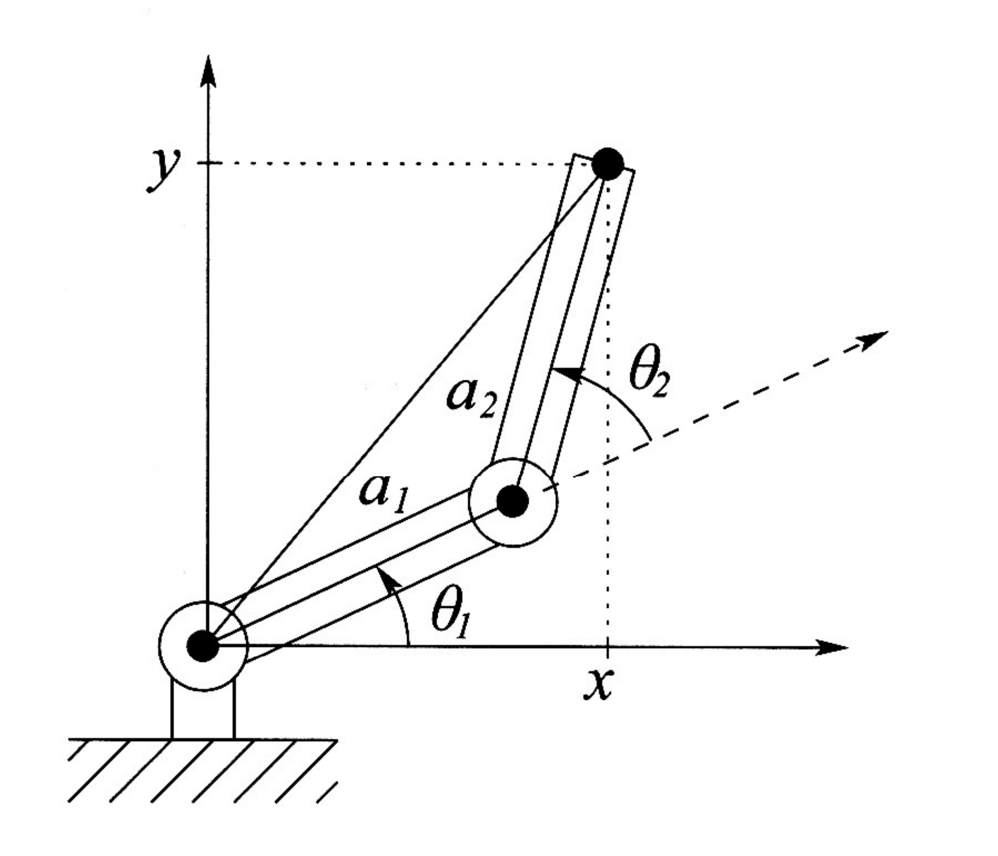


Since the forward kinematic equations are nonlinear, a solution may not be easy to find, nor is there a unique solution in general.

Elbow Robot: Two Solutions



Inverse Kinematics



Quiz #1 (1 pt.) – Due Today

- Show that θ_1 and θ_2 are given as

$$\theta_2 = \tan^{-1}\frac{\pm\sqrt{1-D^2}}{D}, \quad D := \frac{x^2+y^2-a_1^2-a_2^2}{2a_1a_2}$$

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

Hint: Law of Cosines

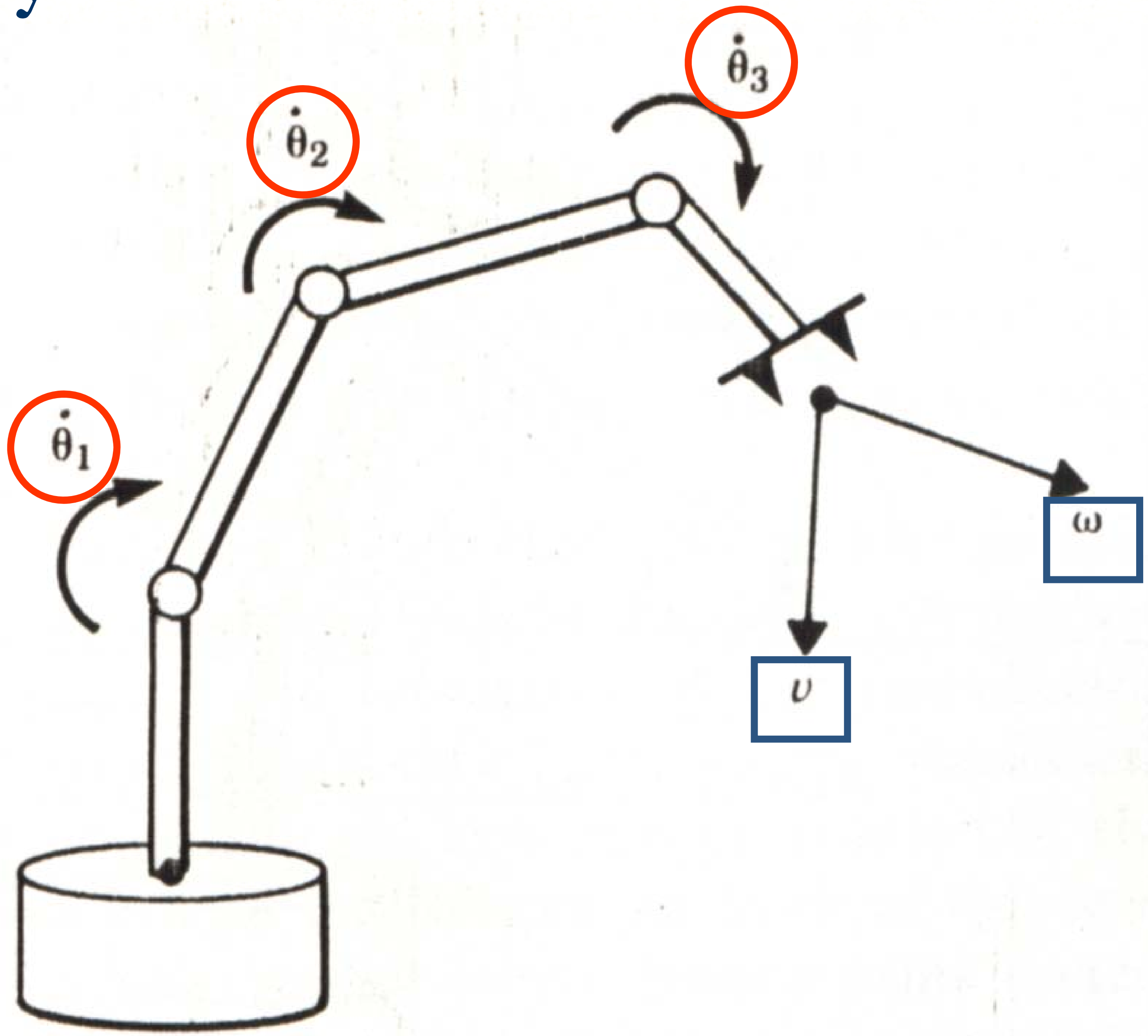
- If a triangle has sides of length a, b, and c, and θ is the angle opposite the side of length c, then

$$c^2 = a^2 + b^2 - 2ab\cos\theta$$

Velocities, static forces, singularities

- Jacobian: a mapping from velocities in joint space to velocities to Cartesian space.
- Singularities: the mapping is not invertible
- What set of joint torques are required to generate a desired contact force and moment?

Velocity Kinematics



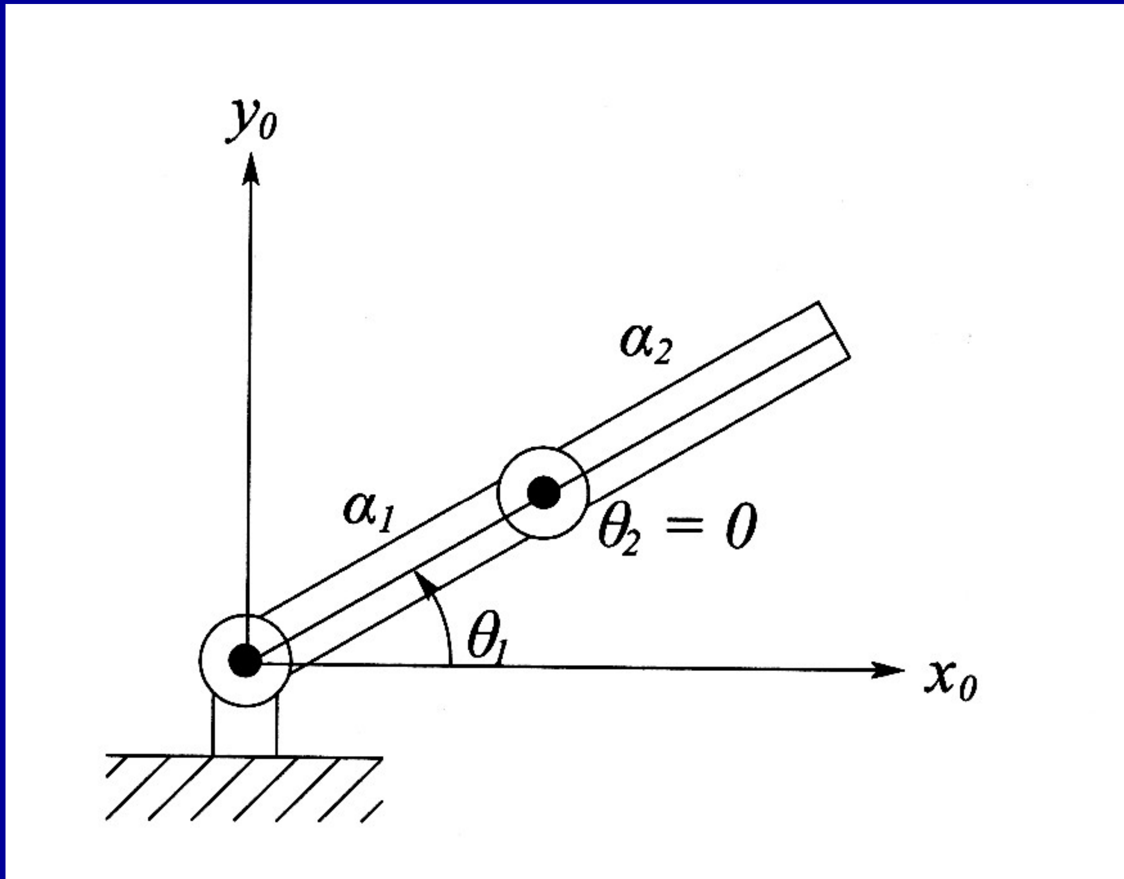
$$\dot{x} = -a_1 \sin\theta_1 \cdot \dot{\theta}_1 - a_2 \sin(\theta_1 + \theta_2)(\dot{\theta}_1 + \dot{\theta}_2)$$
$$\dot{y} = a_1 \cos\theta_1 \cdot \dot{\theta}_1 + a_2 \cos(\theta_1 + \theta_2)(\dot{\theta}_1 + \dot{\theta}_2)$$

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

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

This Jacobian does not have an inverse when $\theta_2 = 0$ or $\theta_2 = \pi$, in which case the manipulator is said to be in a *singular configuration*.

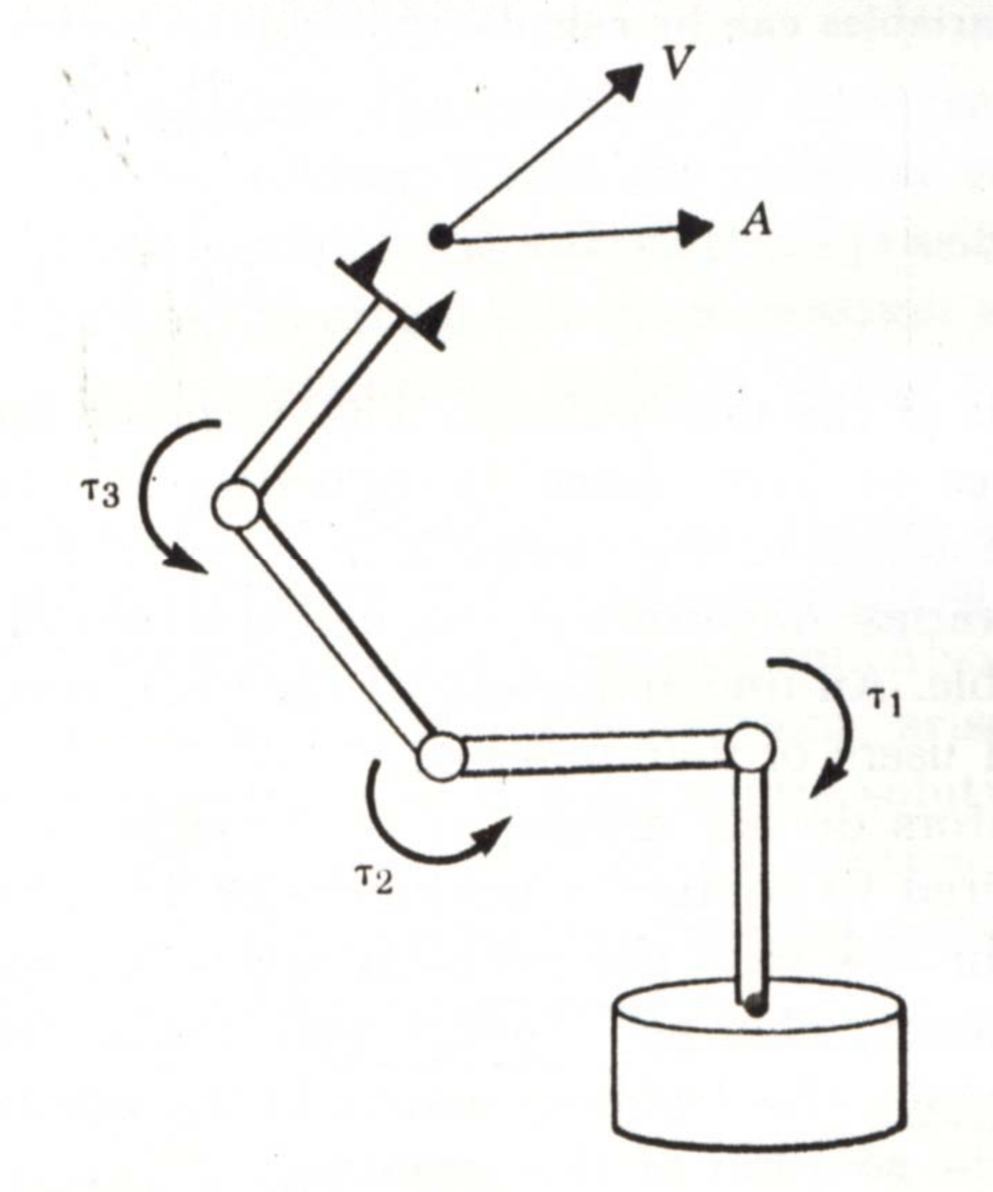
A Singular Configuration



Cannot move in certain directions.

Dynamics

- Studying the forces required to cause motion: Coriolis, Centripetal, Inertial, Gyroscopic
- Torques = *f*(path, mass, payload, friction)
- The dynamic equations of motion: Lagrangian Method, Recursive Newton-Euler Method



The dynamic equations of motion:

The relationship between the torque applied by the actuators and the resulting motion of the manipulator

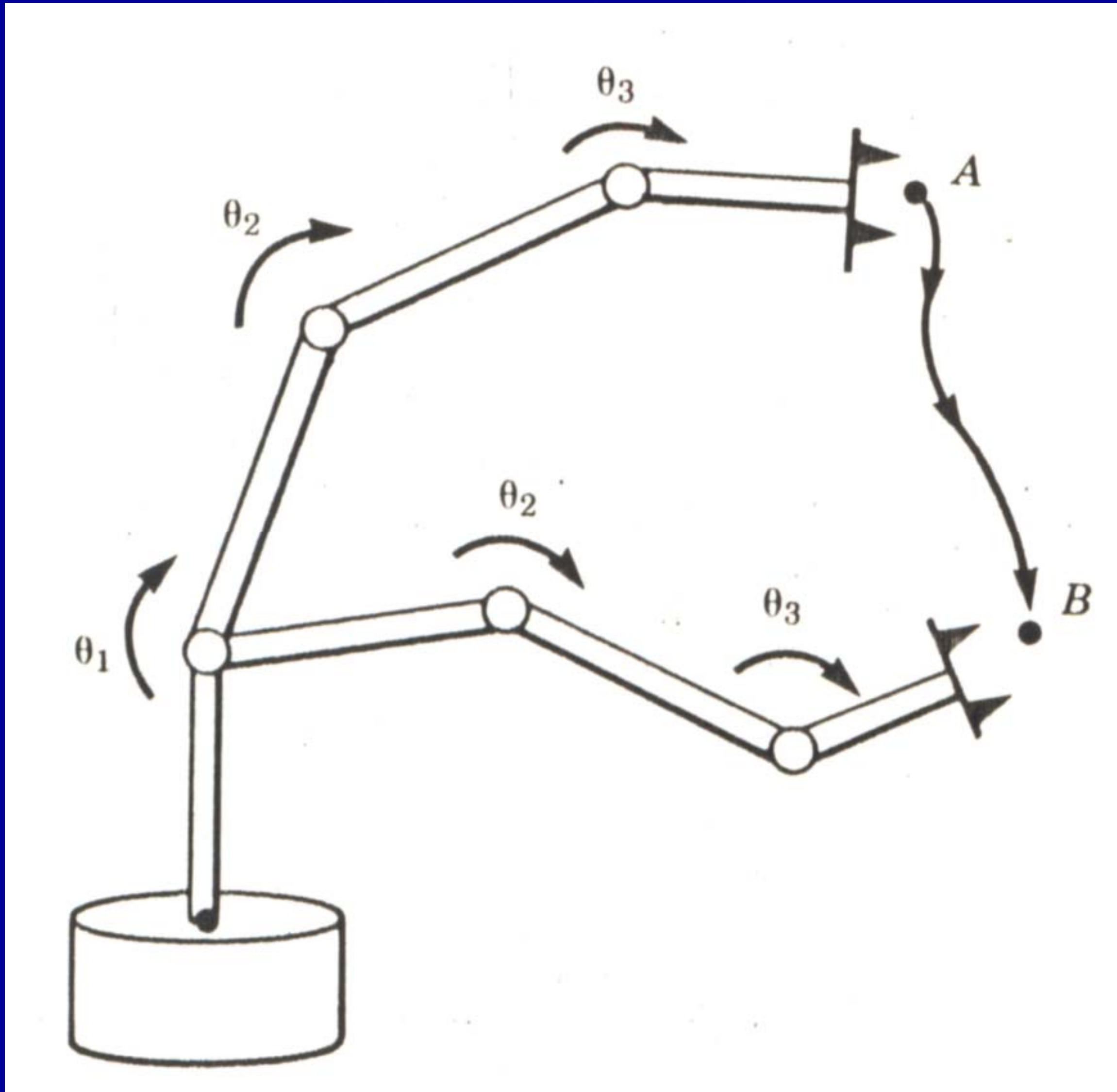
Possible to simulate the motion of a manipulator.

Path Planning and Trajectory Generation

- The robot control problem is typically decomposed hierarchically into three tasks: path planning, trajectory generation, and trajectory tracking.

Path Planning and Trajectory Generation

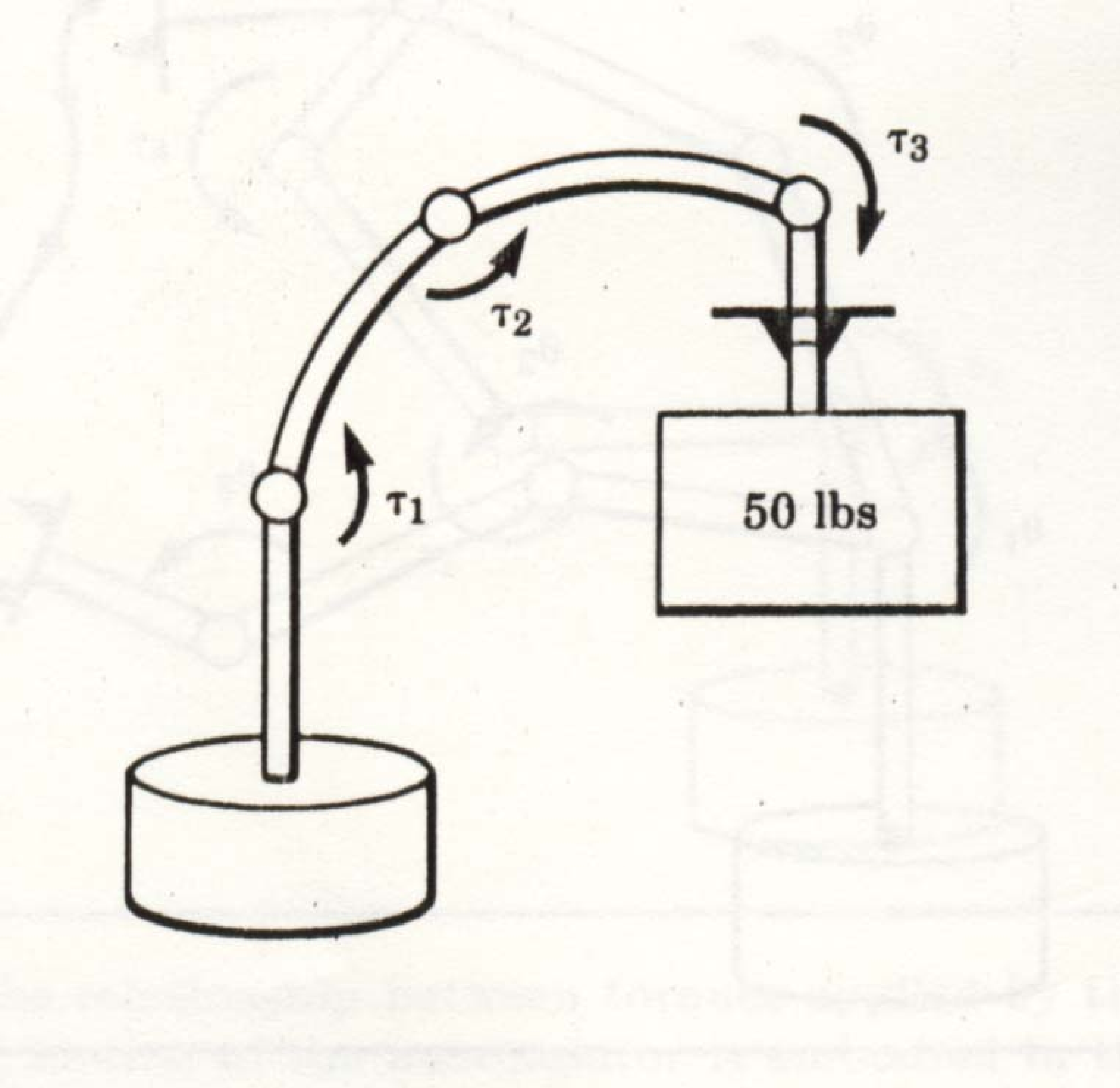
- PP determines a path in task space (or configuration space) to move the robot to a goal position while avoiding collisions with objects in its workspace. (without timing considerations)
- TG generates reference trajectories that determine the time history of the robot along a given path or between initial and final configurations. (Polynomial interpolation schemes)



Must generate a smooth trajectory in the joint space.

Manipulator design and sensors

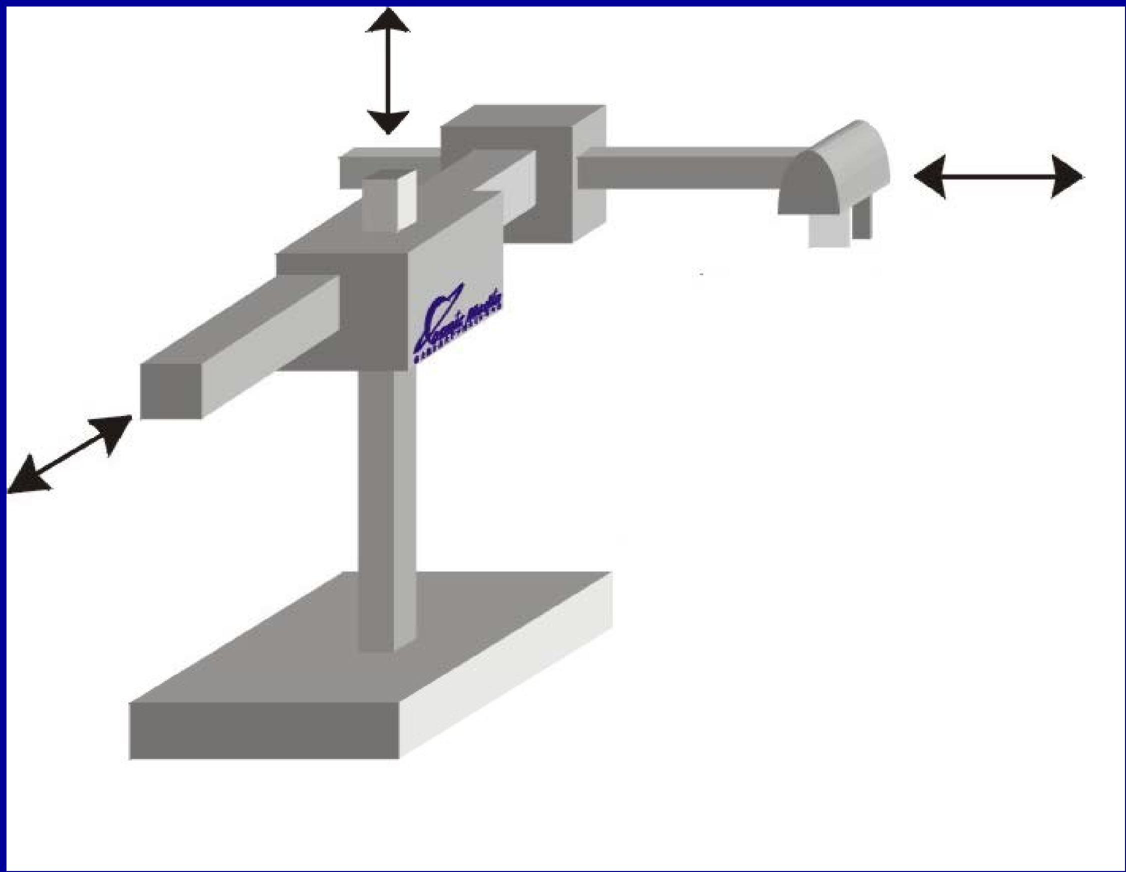
- The number of joints and their geometric arrangements
- Workspace, stiffness of the structure
- Specialized vs. universal robots
- The choice and location of actuators, transmission systems, and position sensors



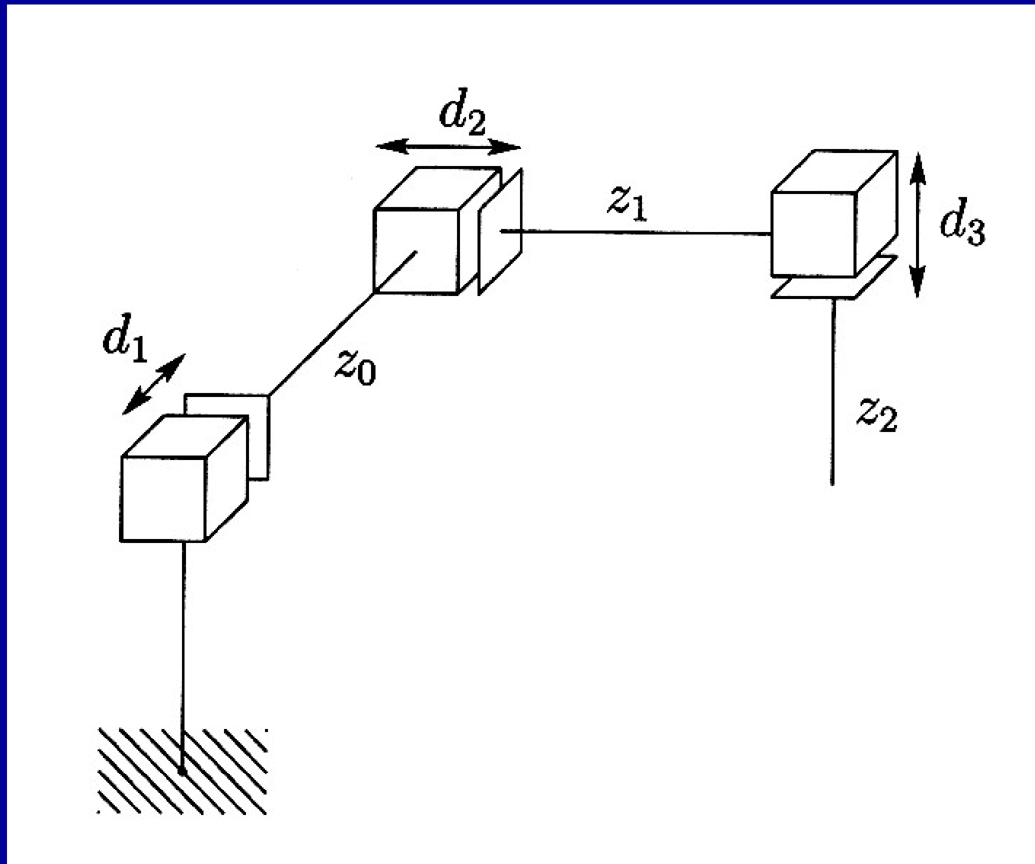
Design issues:

actuator choice, location, transmission system, structural stiffness, sensor location, and more

Cartesian Robot



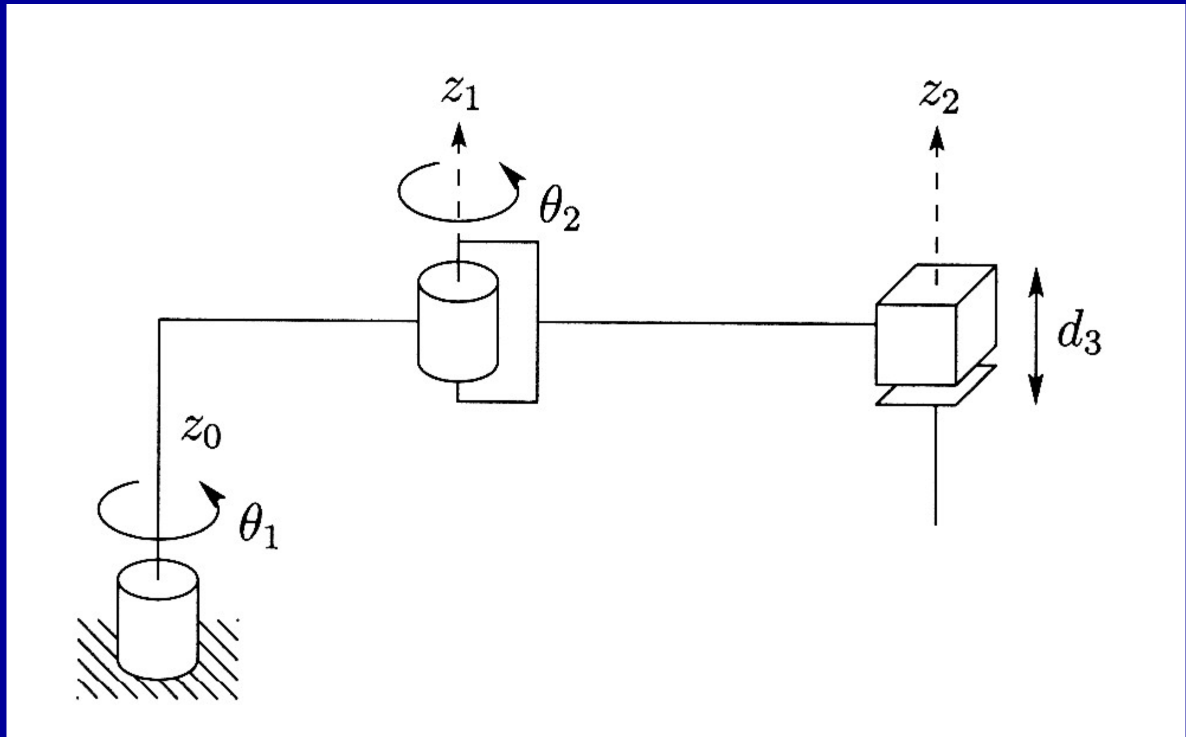
Cartesian Manipulator (PPP)



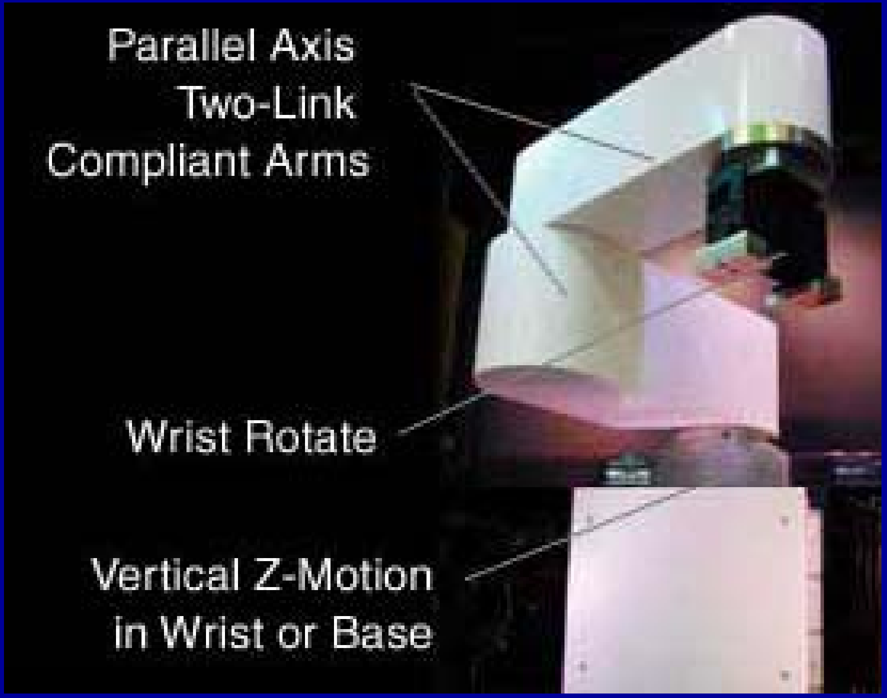
SCARA Manipulator

Selective **C**ompliant **A**rticulated **R**obot for **A**ssembly

SCARA Manipulator (RRP)



Ideal for table top assembly, pick-and-place tasks, and certain types of packaging applications.

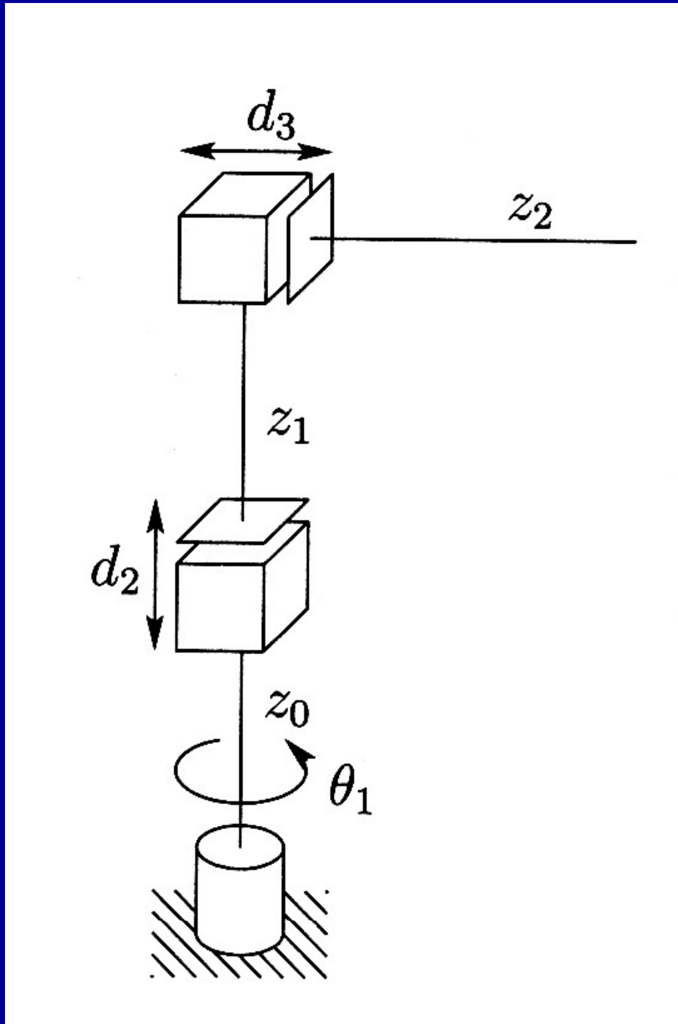


- Slightly compliant in the X-Y direction but rigid in the Z direction. Advantageous for many types of assembly operations, e.g., inserting a round pin in a round hole without binding.

- Allows the arm to extend into confined areas and then retract or fold up out of the way. Advantageous for transferring parts from one cell to another or for loading/unloading process stations that are enclosed.

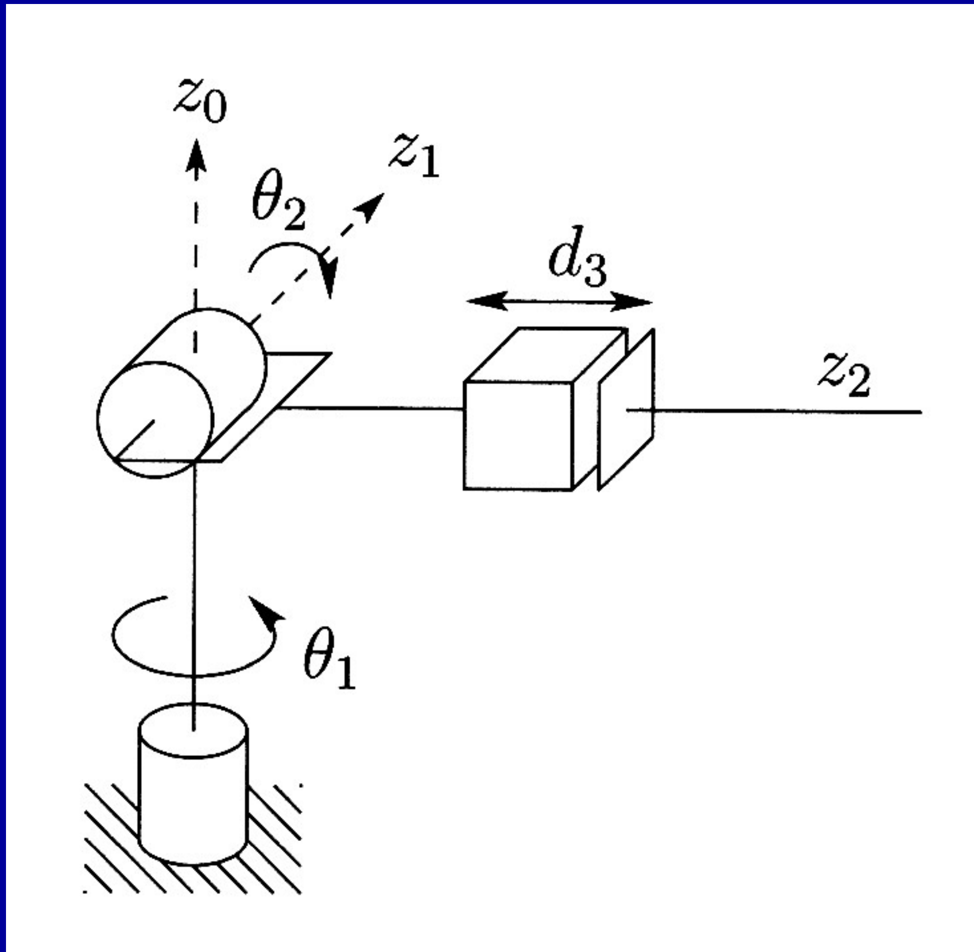
Cylindrical Manipulator

Cylindrical Manipulator (RPP)



Spherical Robot

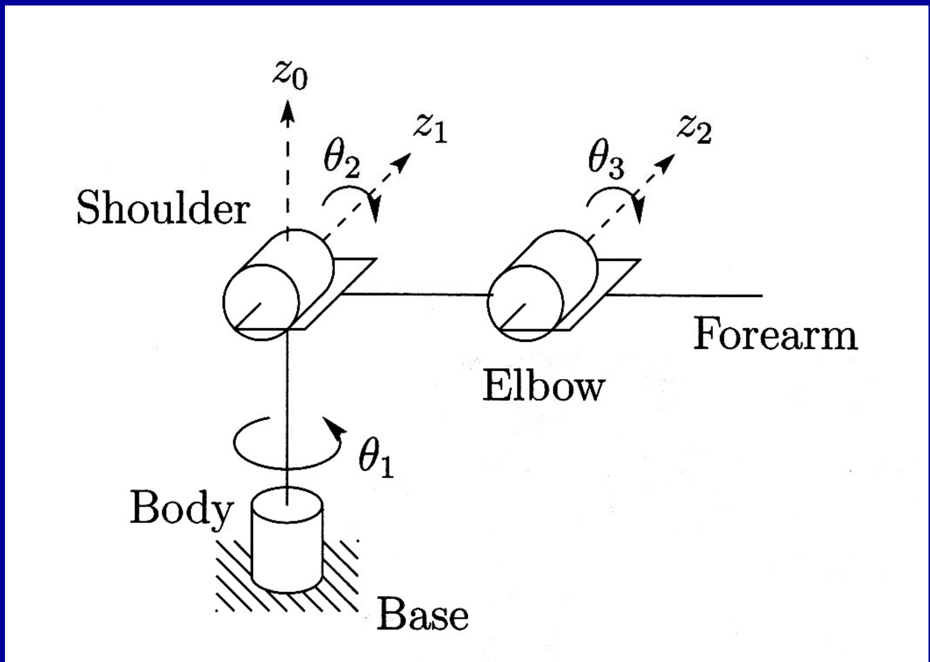
Spherical Manipulator (RRP)

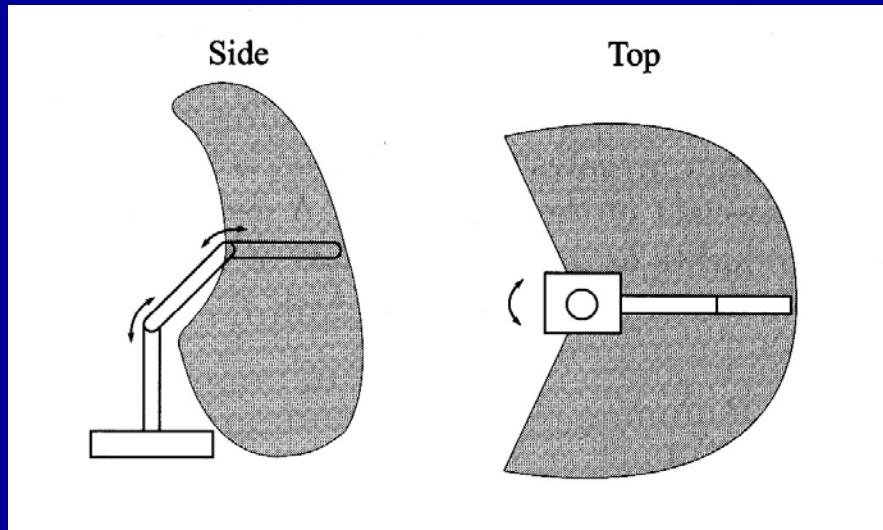


Articulated Robot

Mitsubishi Heavy Industries PA-10

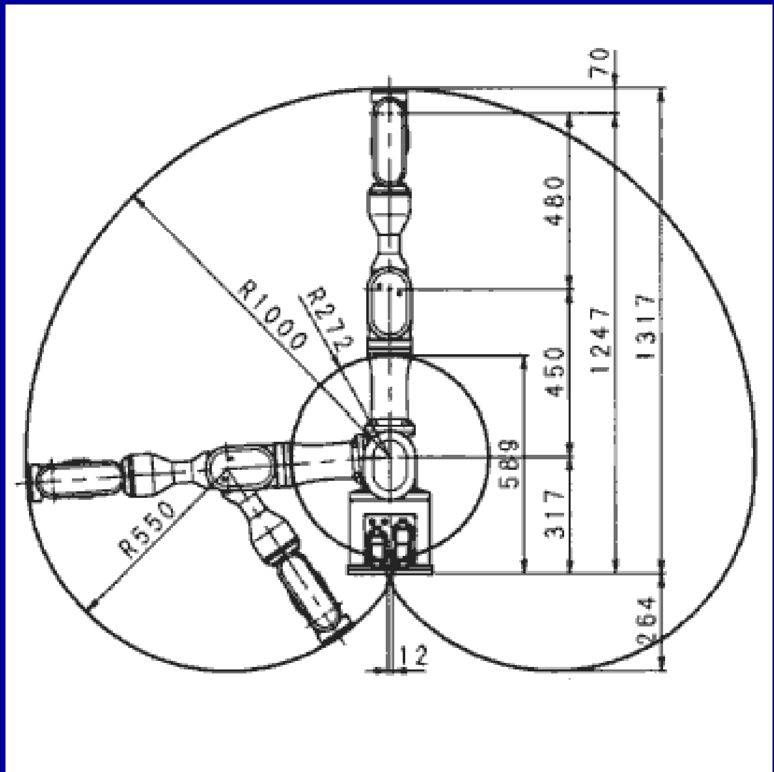
Articulated Robot (RRR)

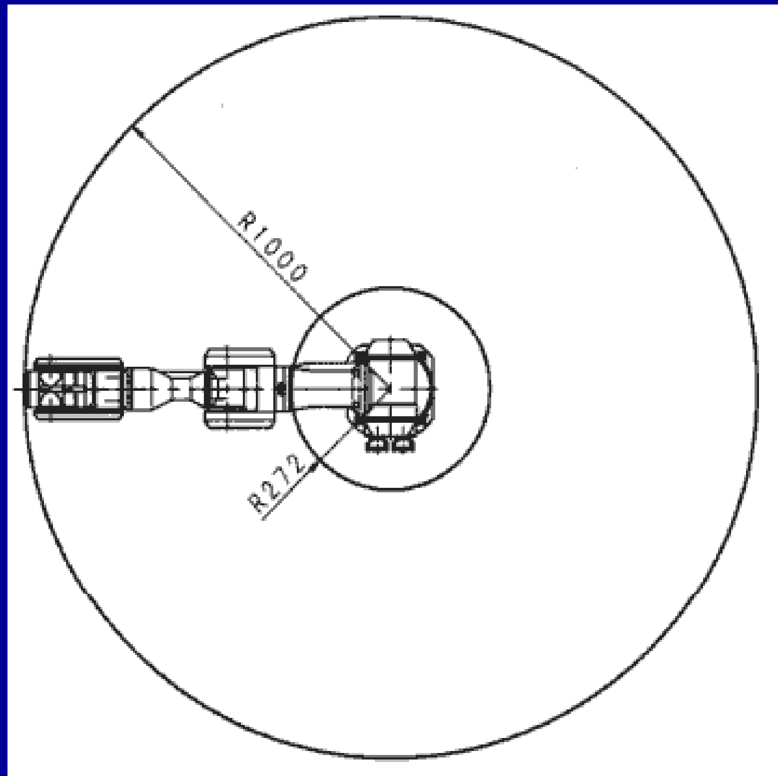




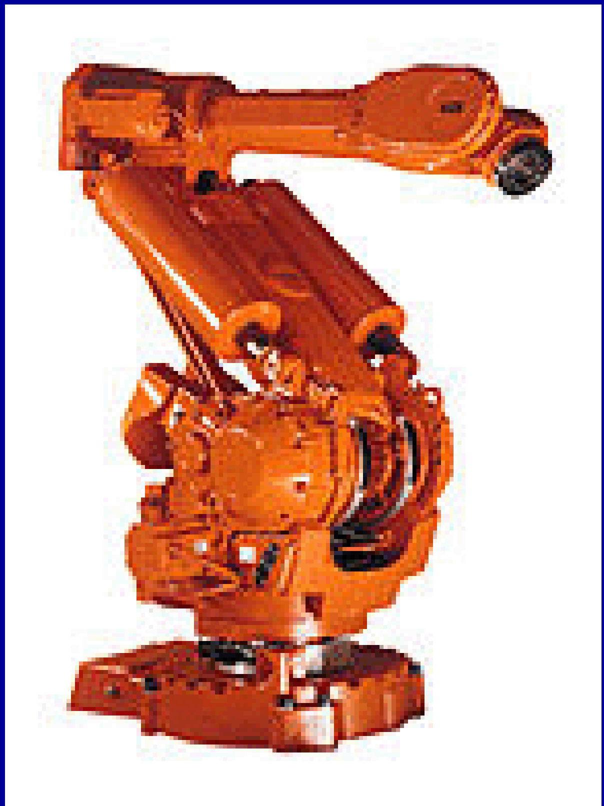
Provides for relatively large freedom of movement in a compact space

MHI PA-10





Parallelogram Linkage (RRR)



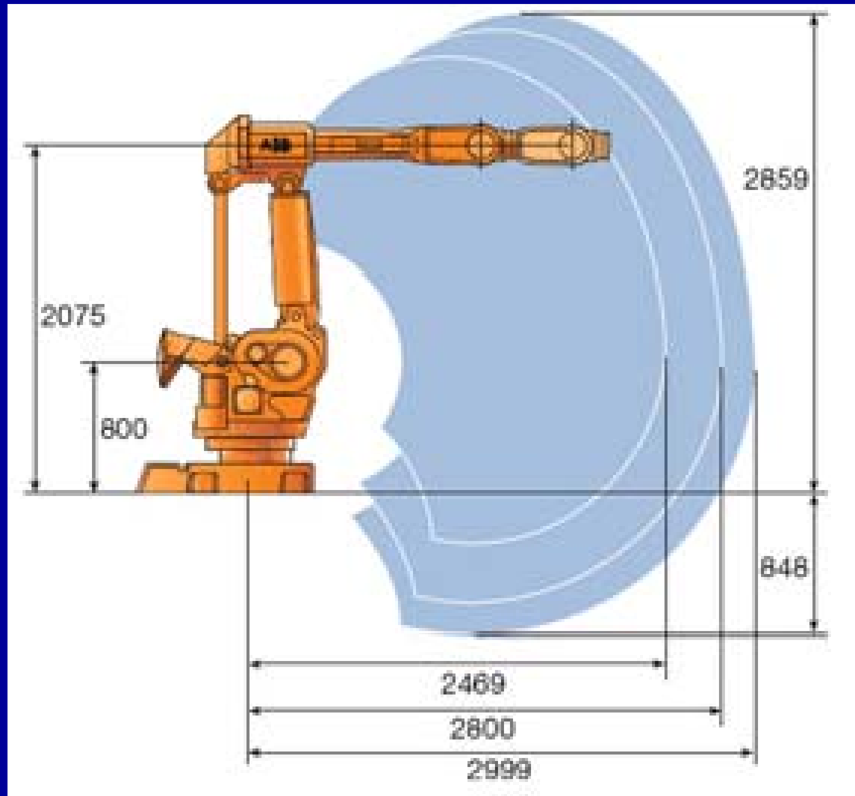


ABB IRB 6400RF

Why Parallelogram Linkage?

- Less dexterous than the elbow manipulator
- Actuator for joint 3 is located on link 1
- Links 2 and 3 can be made more lightweight and the motors themselves can be less powerful
- The dynamics are simpler than those of the elbow manipulator (easier to control)

Parallel Robot

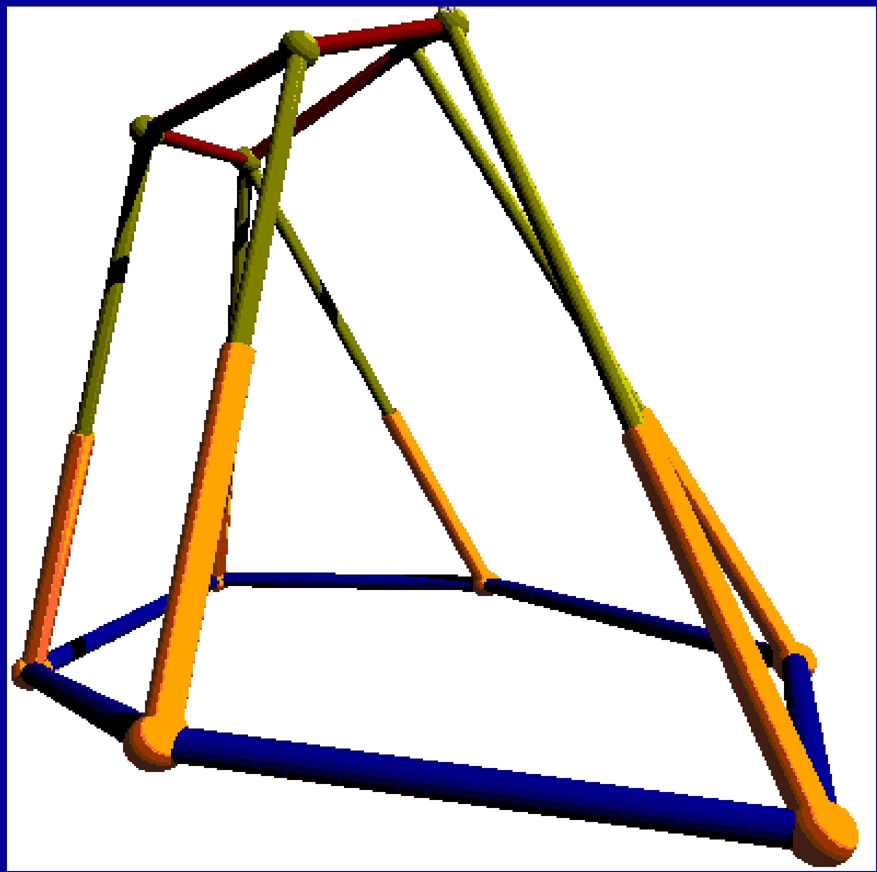


ABB IRB940

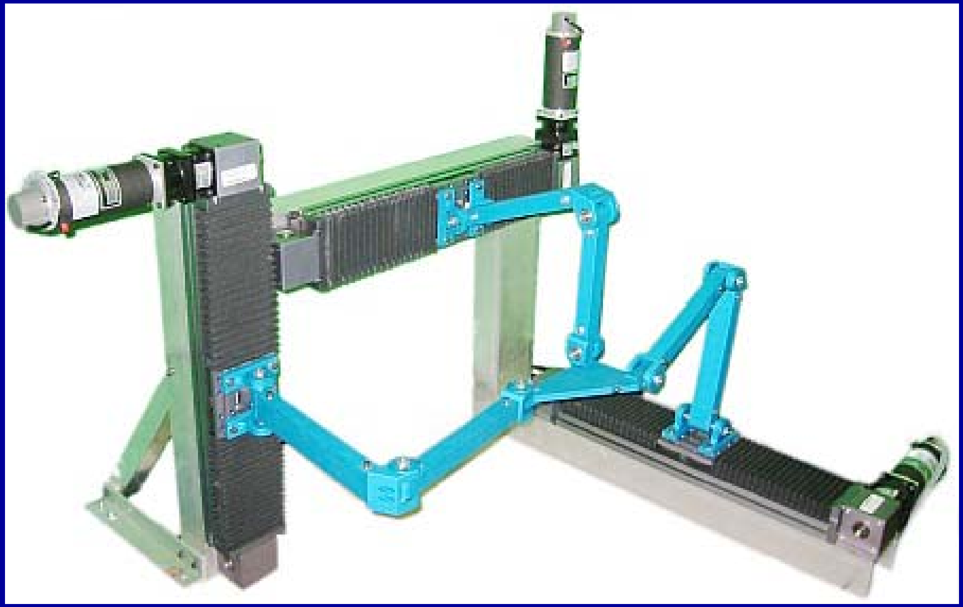
The closed chain kinematics of parallel robots can result in

- greater structural rigidity
- greater accuracy

than open chain robots.

Tripteron

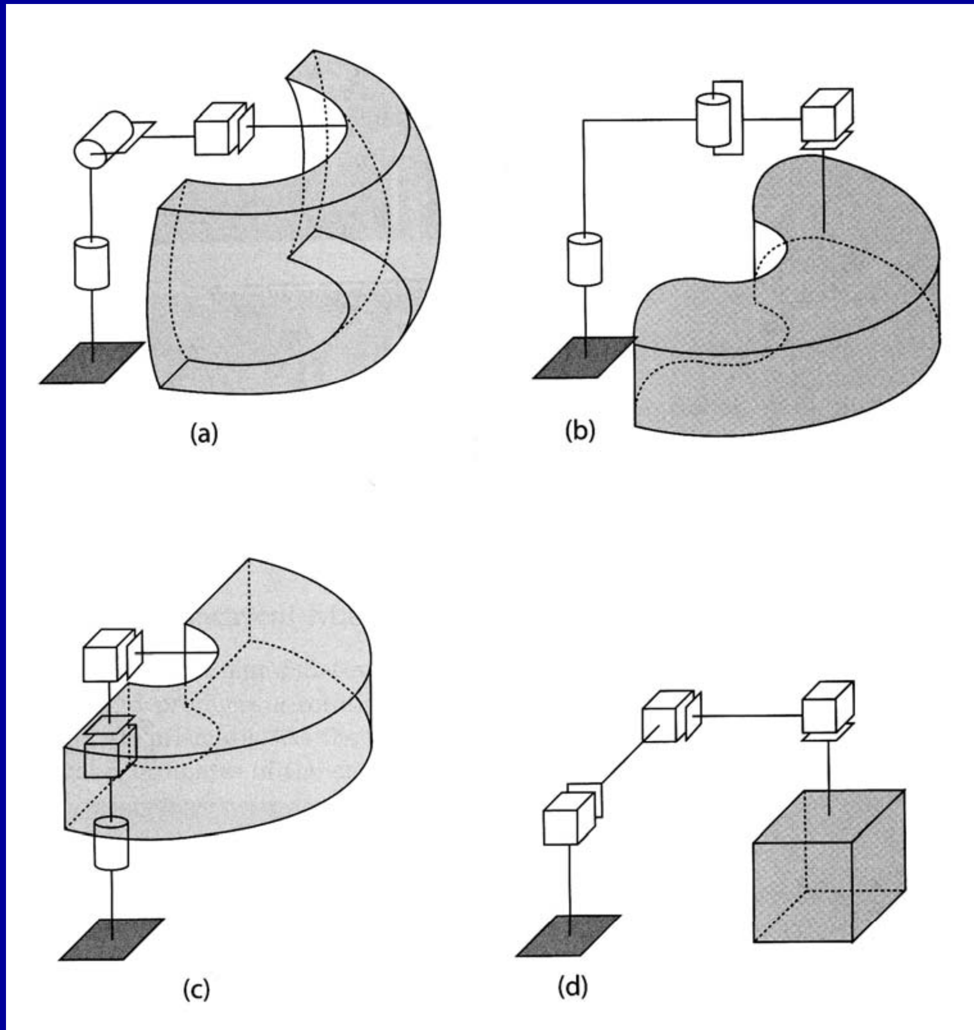
A 3-DOF Translational Parallel Mechanism (PRRR)



Quadrupteron

3 translation (PRRU) +
1 rotation along the vertical axis (PRRR)

Comparison of the workspaces



Homework #3 (1 pt.)- Due Dec. 16

- Evaluate each of the three-link manipulators in terms of its workspace.

Sensor Options

Physical Property	Technology
Contact	Bump, Switch
Distance	Ultrasound, Radar, Infra red
Light level	Photocells, Cameras
Sound level	Microphones
Strain	Strain gauges
Rotation	Encoders
Magnetism	Compasses
Smell	Chemical
Temperature	Thermal, Infra red
Inclination	Inclinometer, Gyroscopes
Pressure	Pressure gauges
Altitude	Altimeters

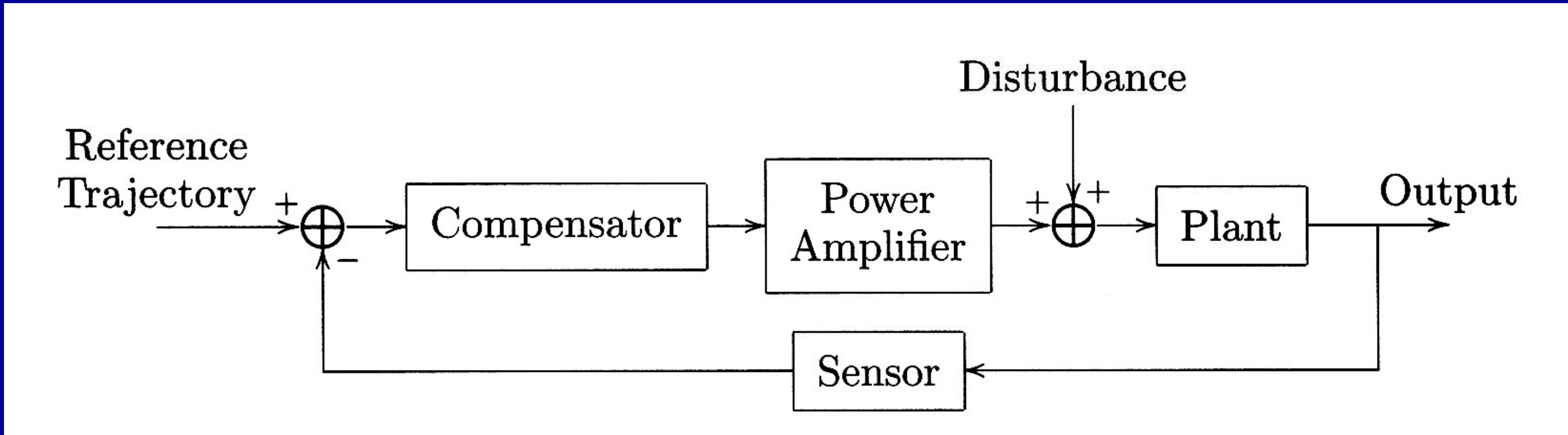
Homework #4 (1 pt.)- Due Dec. 16

- Explain the principles of operation of the following sensors: potentiometers, optical encoders, force, infrared, ultrasonic, laser, gyroscopes, accelerometers, magnetometers/compass (a minimum of five)

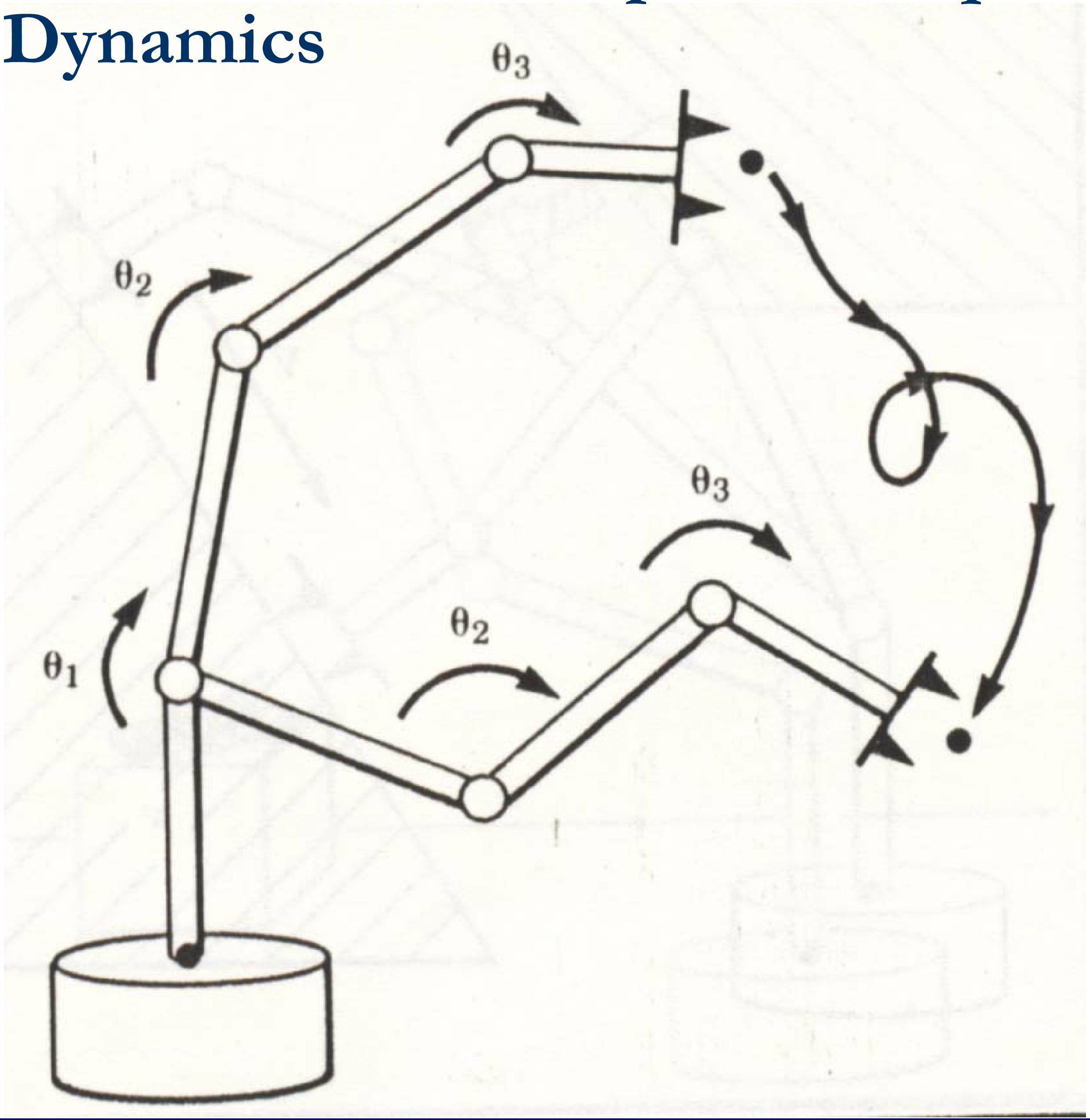
Position Control

- Compensate for errors in knowledge of the parameters of a system
- Suppress disturbances
- Linear position control
- Nonlinear position control

SISO Feedback Control: Tracking and Disturbance Rejection



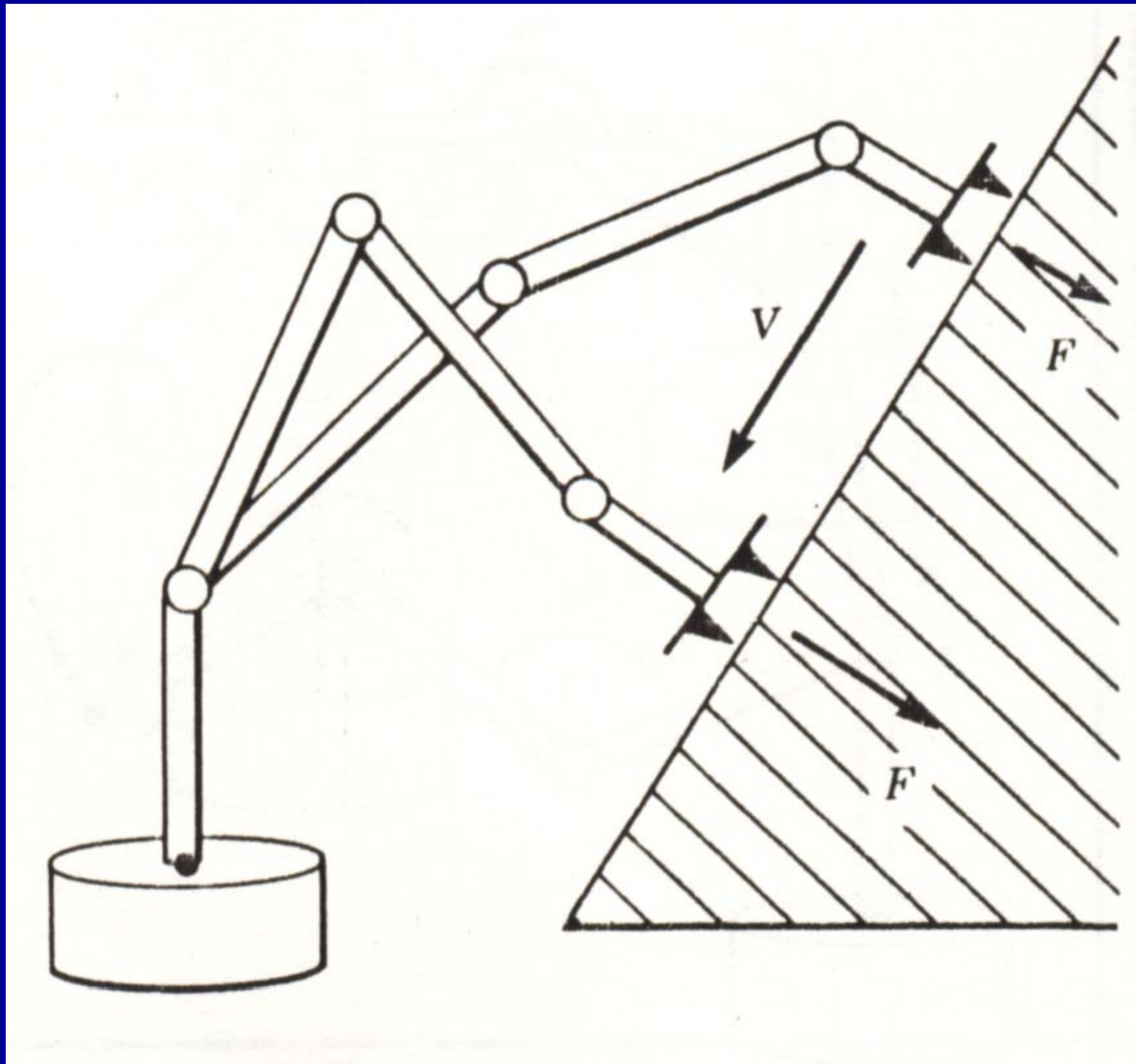
Multivariable Control: Computed Torque and Inverse Dynamics



Force Control

- Control forces of contact
- Hybrid control and impedance control

A hybrid position-force control system

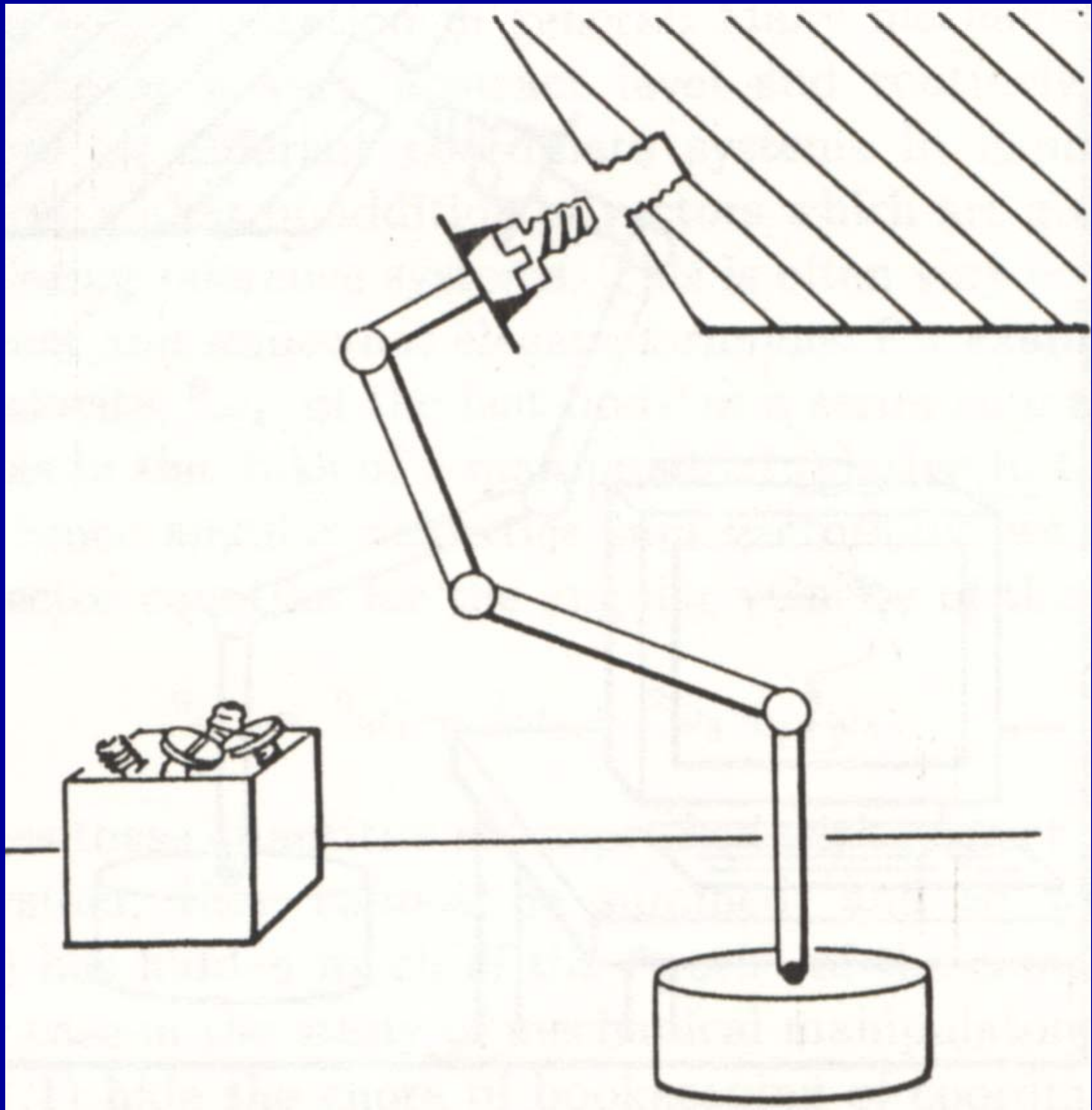


Vision-Based Control

- Cameras can be used not only to measure the position of the robot but also to locate objects in the robot's workspace.
- May wish to control the motion of the robot manipulator relative to some target as the end-effector moves through free space. (force control cannot be used)
- Image-Based Visual Servo- an error measured in image coordinates is directly mapped to a control input

Programming Language

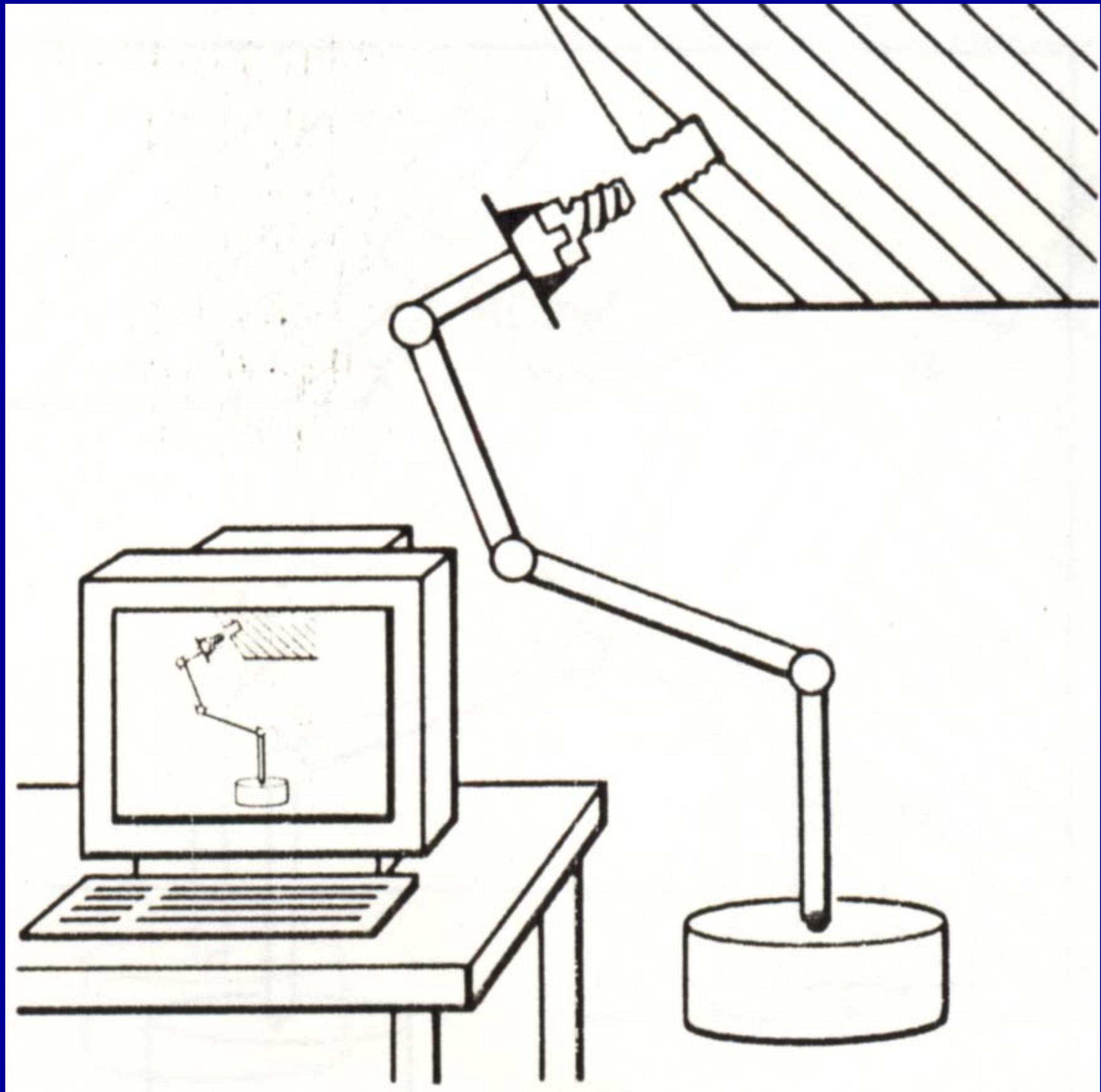
- The interface between the human user and the (industrial) robot
- Programmable = flexible
- Input to the trajectory generation problem is given in the robot programming language.



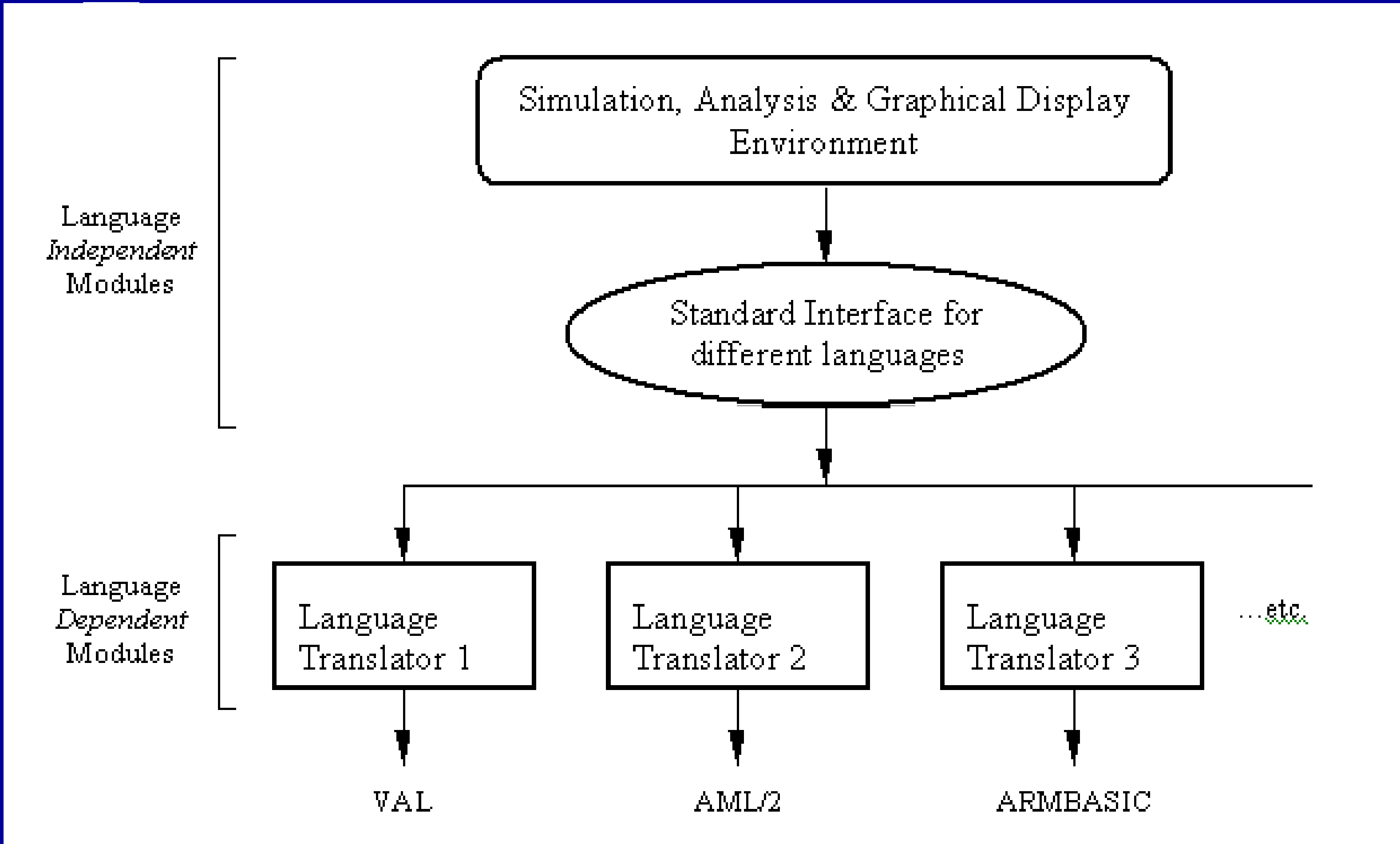
Desired motions of the manipulator and end-effector, desired contact forces, and complex manipulation strategies can be described in a robot programming language.

Offline Programming System

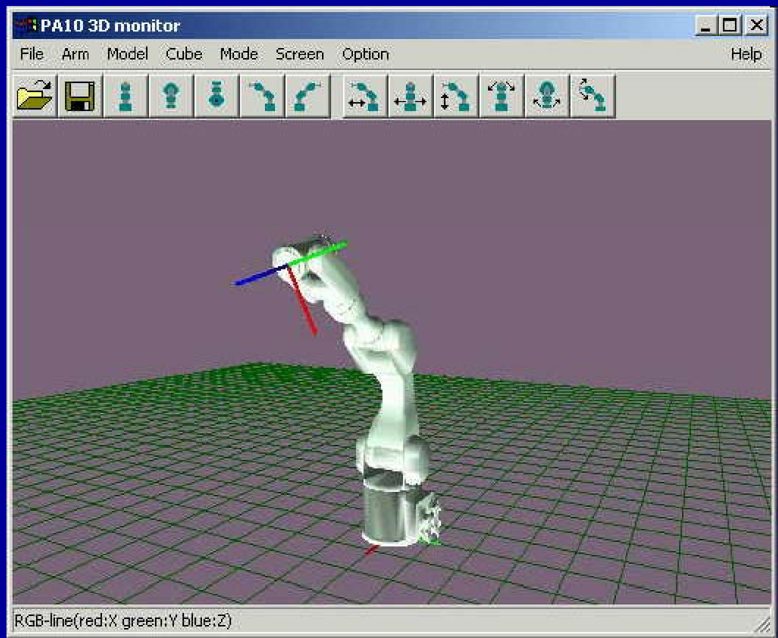
- A robot programming environment by means of computer graphics
- Will not cause the robot to be tied up when it needs to be reprogrammed
- Use of CAD data

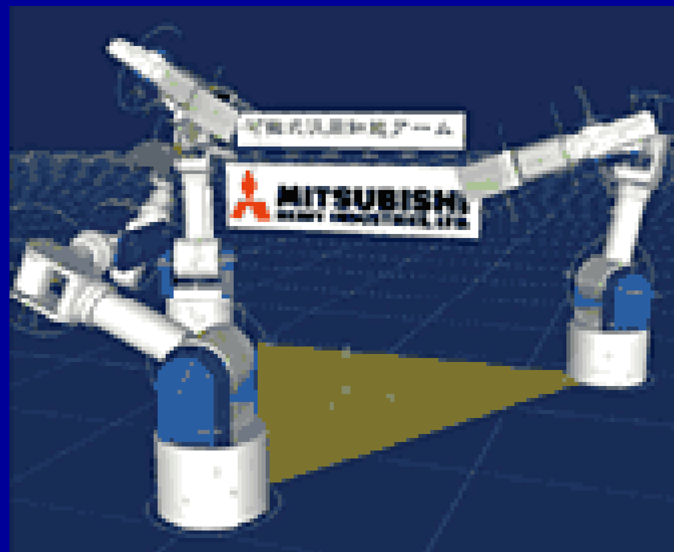


OLPs allow robots to be programmed without access to the robot itself during programming.

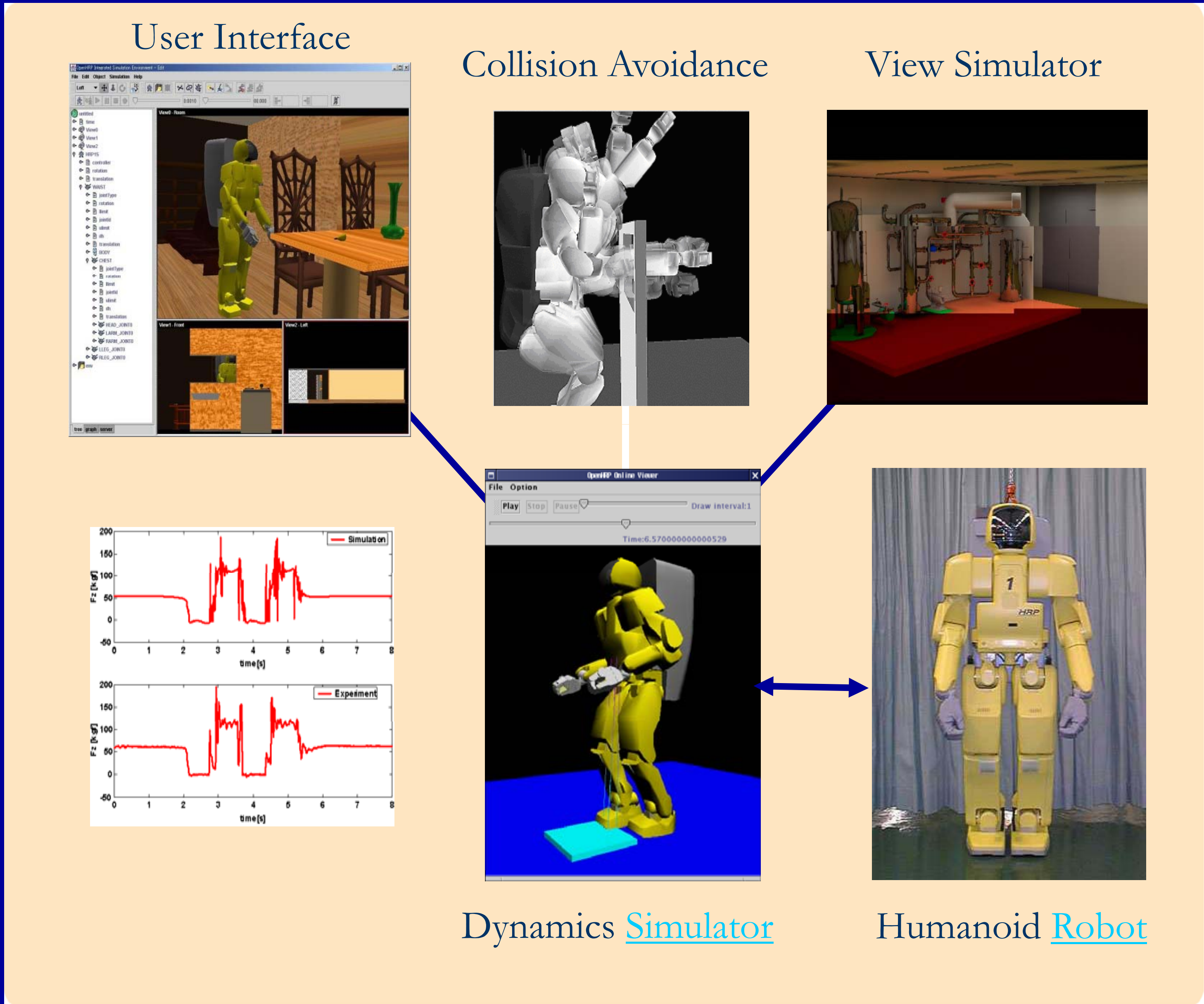

Simulation, Analysis & Graphical Display Environment
Standard Interface for different languages
Language *Independent* Modules
Language *Dependent* Modules
Language Translator 1
Language Translator 2
Language Translator 3
...etc.
VAL
AML/2
ARMBASIC

PA-10 Off-line Simulators





OpenHRP (AIST)



Notation

- Vectors or matrices in uppercase, scalars in lowercase
- Leading subscripts and superscripts: coordinate system
- Trailing superscripts: the inverse of transpose
- Trailing subscripts: a vector component
- Trigonometric functions: s1, c1