MCE/EEC 647/747: Robot Dynamics and Control

Lecture 1: Introduction

Reading: SHV Chapter 1

Robotics and Automation Handbook, Chapter 1

Assigned readings from several articles.

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Robots in Modern Industry and Society

- *Robot* comes from the Czech *robota*, which means “work”. Word used in 1920’s theater piece.
- A robot is a programmable mechanical device, typically powered by electric motors. In this course we concentrate on **manipulators**.
- The applications of robots have transcended the industrial (manufacturing) environment. Robotic devices are used in medicine, space exploration, entertainment and as household aides.
- The study of robotics comprises many highly-specialized sub-areas. Several of these are at the core of mechanical and electrical engineering.

Robotics in Mechanical and Electrical Engineering

- The structural design of the linkages and joint drivers is in itself a mechanical design problem. The manipulator must be light and possess high stiffness, while the design must maximize the useful workspace.
- The robot must be fitted with reliable sensors to be used as feedback by the motion/force control program.
- The geometry of the robot must be precisely modeled using a systematic approach allowing the solution of the *forward and inverse kinematic problems*.
- A dynamic model of the robot must be derived using a systematic approach, allowing analytical and simulation studies of the manipulator's behavior at high speeds and under the influence of external forces.
- Control algorithms must be designed on the basis of the dynamic model. These controllers are to be used to achieve precision motion profile following, possibly with additional force control requirements (Figure 1.19 in SHV).
- Visual and other sensory information must be used in autonomous path following and obstacle avoidance applications.

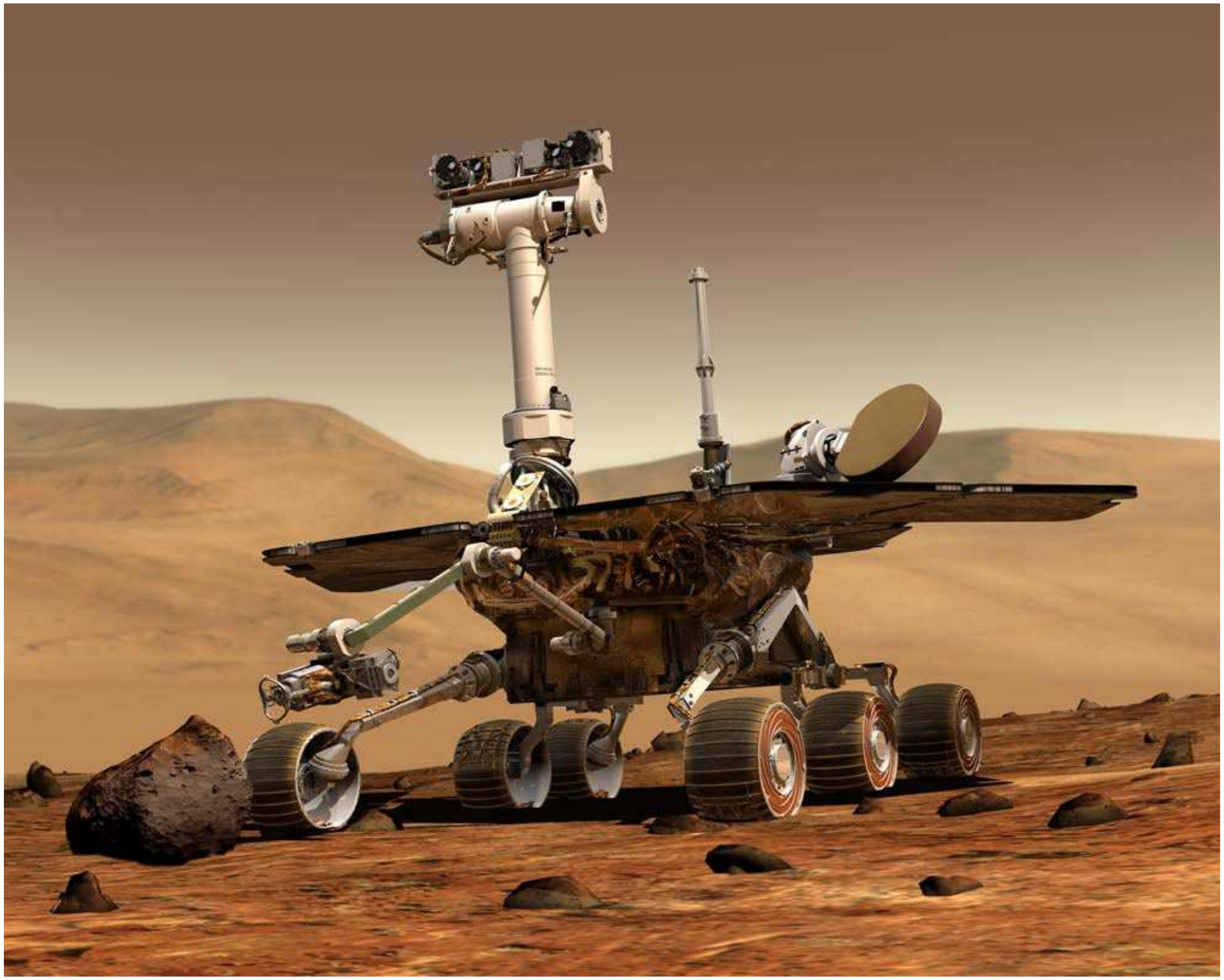
A typical industrial application: deburring

Workpiece (on end effector) must be moved relative to the tool according to desired motion profile (in this case a flat surface must be obtained) and with a prescribed force (which results in desired tolerances and surface finish).
See also Fig. 1.19 in SHV textbook.

Robotics in medicine: surgery

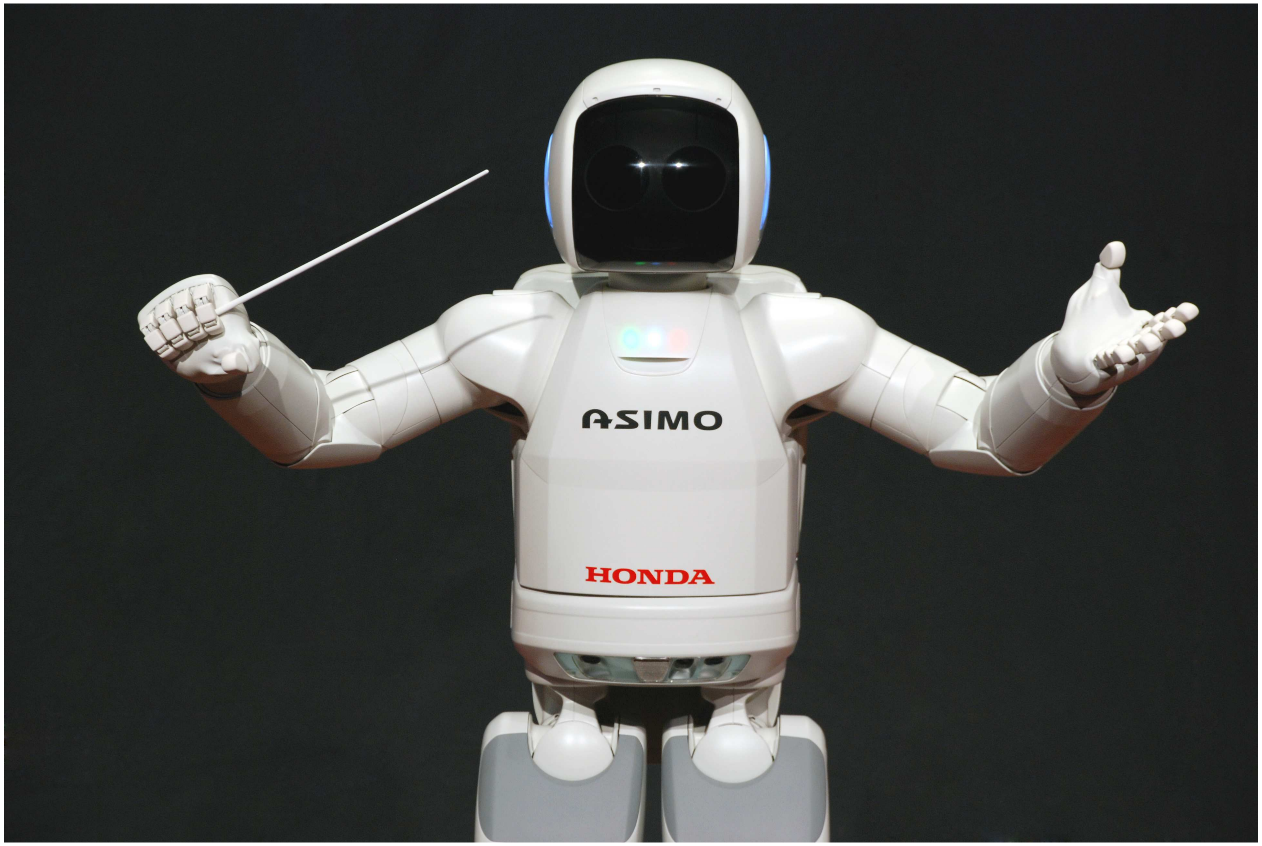
Robotic manipulators are used to obtain more degrees of freedom than the human wrist, without hand tremors and higher accuracy. 3D visual display is another advantage. Beating-heart surgery and tele-surgery is also possible.
See Bebek, Ö and Çavuşoğlu, M.C., Intelligent Control Algorithms for Robotic-Assisted Beating-Heart Surgery, IEEE Trans. Robotics, v23. N3, 2007, pp. 468-480.

Robotics in space exploration: Spirit and Opportunity



The vehicle itself is a mobile robot. In addition, the manipulator is fitted with several instruments (spectrometers, RAT (rock abrasion tool), microscope)

Household/Entertainment Robots



Humanoid robot with bipedal locomotion. Can recognize persons and facial expressions. Conducted the Detroit Symphony Orchestra in April 2008.

`http://www.youtube.com/watch?v=qRUyVCfFh1U`

Fundamental Concepts

- Manipulators are formed by *links* connected by *joints*. A joint can be prismatic (links slide relative to each other) or revolute (links rotate relative to each other). We will make the fundamental assumption that each joint has only one *degree of freedom*. That is, we are ruling out ball/socket joints.
- The *configuration* of a manipulator is the complete specification of the positions of every one of its points. The set of all possible configurations is the *configuration space*.
- A manipulator has n *degrees of freedom* if exactly n parameters are required to completely speficy the configuration. A rigid, two-link planar manipulator has two degrees of freedom. If the links were flexible, more degrees of freedom would be needed to specify the configuration to an acceptable degree of accuracy.

Fundamental Concepts...

- A configuration provides only geometric information. The *state* of the manipulator is a set of variables which describe the changes in configuration in time in response to joint forces (control inputs) and external influences. The *state space* is the set of all possible states. It coincides with the notion of state space used in systems and control.

- The *workspace* of a manipulator is the set of all possible positions of the end effector (tool, gripper, etc.). It is determined by the geometry of the links and joints and the physical limits of the latter.

- The *dexterous workspace* is a subset of the workspace, defined by the set of reachable points in which the end effector can be freely oriented. Example: in a planar manipulator, points at a distance equal to the total link length cannot be reached with the wrist at an angle different than 0 degrees.

Classification of Manipulators

- Read SHV Section 1.2 for classification according to power source, geometry, method of control and application. We discuss two important classifications: *by method of control and by geometry.*

- Recalling basic controls courses, a control system can be either *open-loop* or *closed-loop*. In an open-loop control architecture, the input commands sent to the joints (motor voltages, hydraulic/pneumatic flows, etc) are determined in advance using a mathematical model, and are not a function of the actual motion of the manipulator. These robots are called *non-servo* manipulators.

- In a closed-loop or *feedback* control system, the input commmands sent to the joints are a function of the actual motion of the manipulator. This motion (possibly including force information) is obtained by a set of *sensors*. A computer is used to evaluate a function called the *control law*, which gives the values of inputs to be sent to the joints. The process takes place *online*, that is, commands are continuously being calculated and applied to the joints. These robots are called *servo* manipulators.

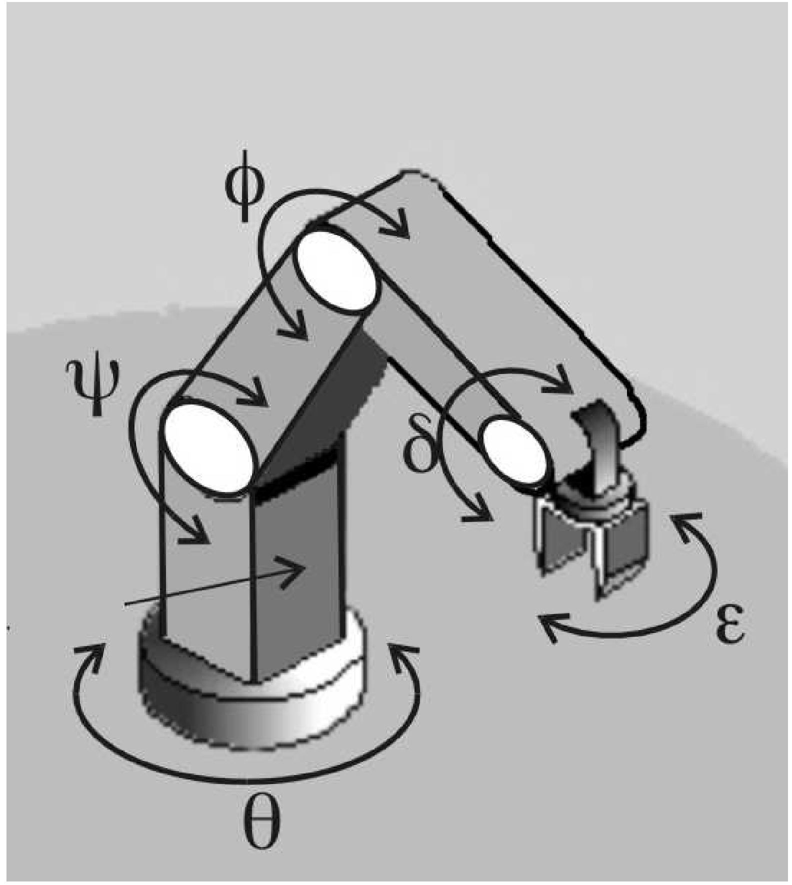
Classification of Manipulators...

- The sophistication of the control algorithm determines whether a servo robot can operate as a *point-to-point* or as a *continuous path* device. In the former, the manipulator can achieve any desired fixed position and orientation, but there is no control of the trajectory followed between each position. This would be sufficient, for example, for a drilling robot used in the auto industry.
- A continuous path robot can achieve precise tracking of a reference trajectory, including velocity and acceleration profile following. As an example, welding robots can produce complicated 3D welding seams.

Common Kinematic Arrangements

- The types of the first three joints (prismatic or revolute) starting from the base, are used to generate a classification of manipulators according to kinematic (mechanical) configuration. The wrist is described separately.
- Three joints of two possible kinds (R and P) yield 8 possible arrangements, however only 4 combinations are frequently used, with the RRP found in two varieties: **articulated (RRR), spherical (RRP), SCARA (RRP), cylindrical (RPP)** and **Cartesian (PPP)**.
- These combinations correspond to open kinematic chains (end effector is not joined to another link), also called *serial* robots. We restrict our study to these. *Parallel* manipulators use a closed kinematic chain (see Fig. 1.18) and require more advanced study.

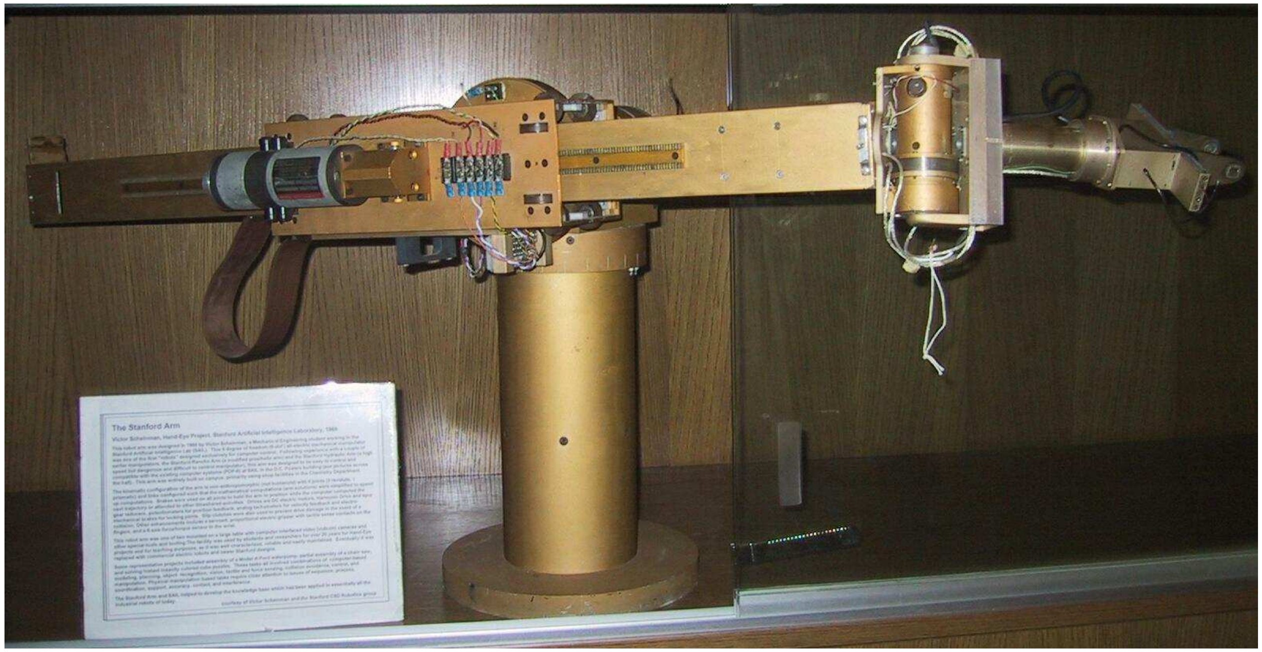
Articulated Manipulator (RRR)



See also Figs. 1.9, 1.10 (workspace) in SHV.

PUMA (Programmable Universal Manipulator for Assembly) robots are RRR. **We have a PUMA robot in the lab.**

Spherical Manipulator (RRP) non-SCARA

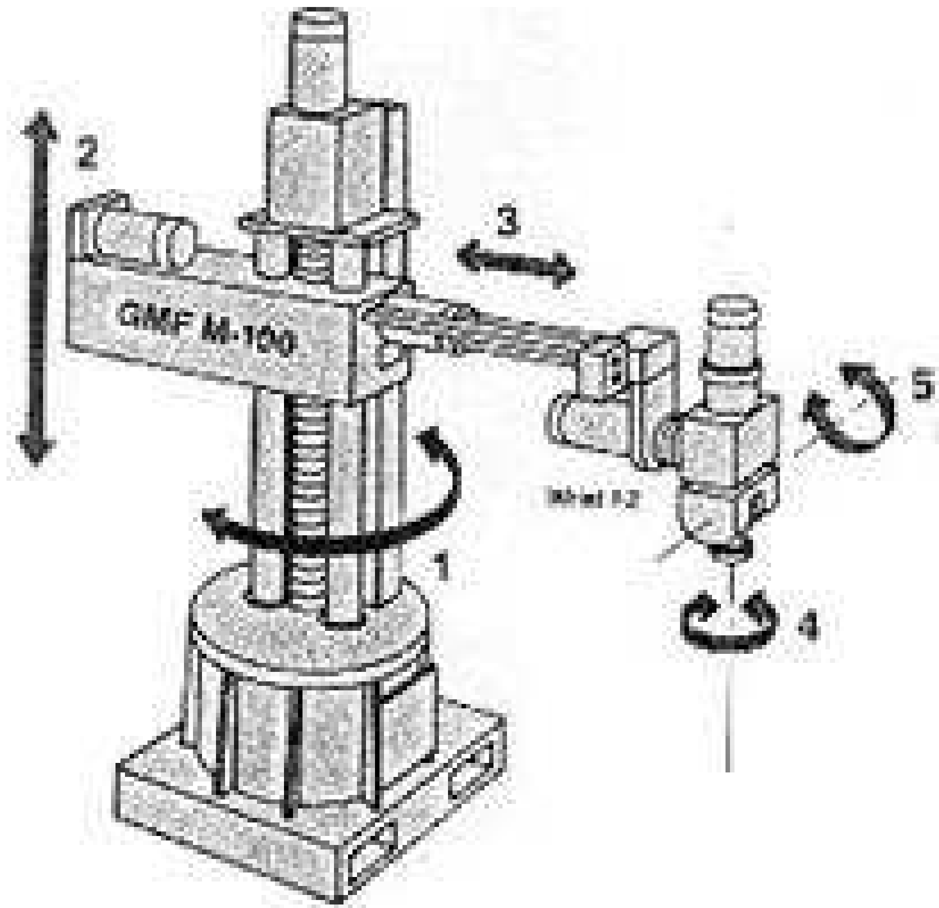


Known as Stanford Arm (historical reasons). See also Fig. 1.12 in SHV.

Spherical Manipulator (RRP) SCARA

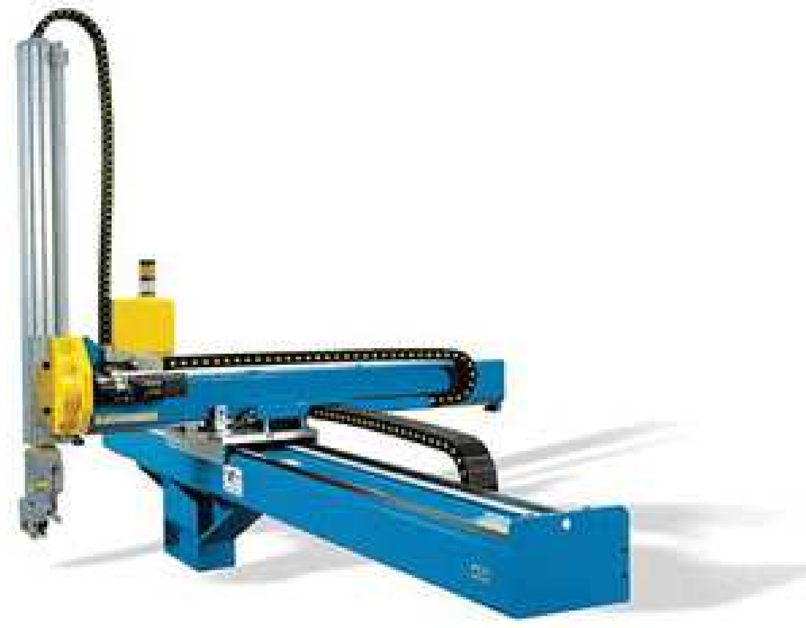
SCARA: Selective Compliant Articulated Robot for Assembly. See also Fig. 1.13 in SHV.

Cylindrical Manipulator (RPP)



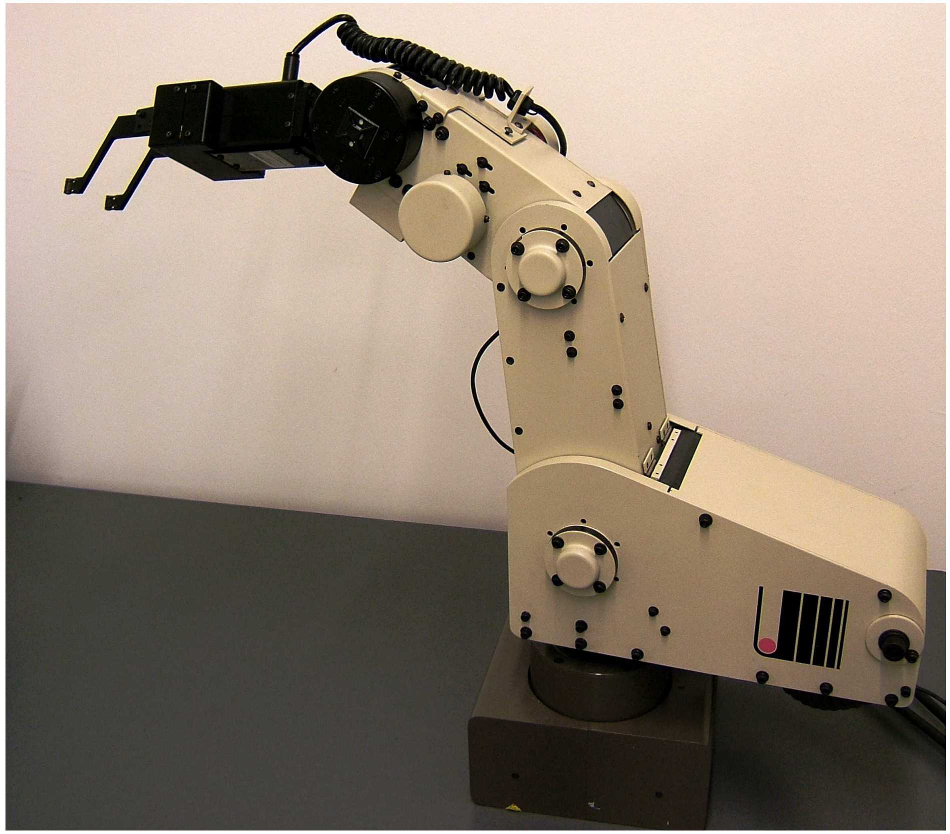
See also Fig. 1.15 in SHV.

Cartesian Manipulator (PPP)



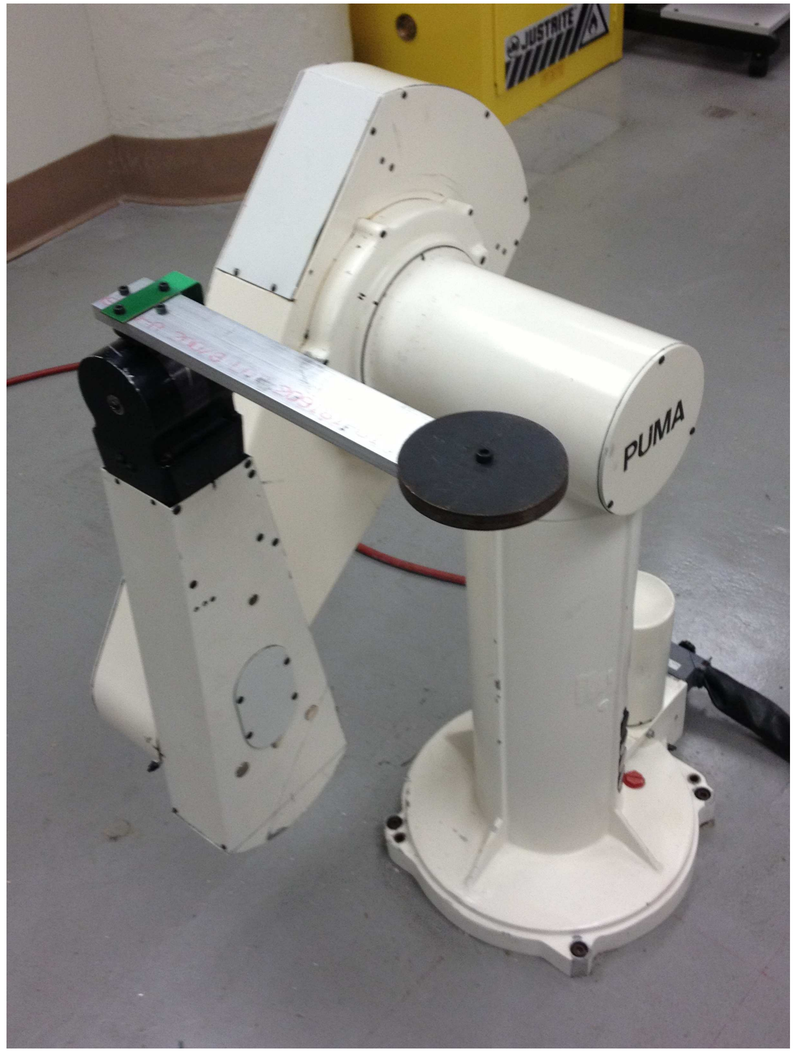
See also Fig. 1.16 in SHV.

Mitsubishi RM-501 MoveMaster



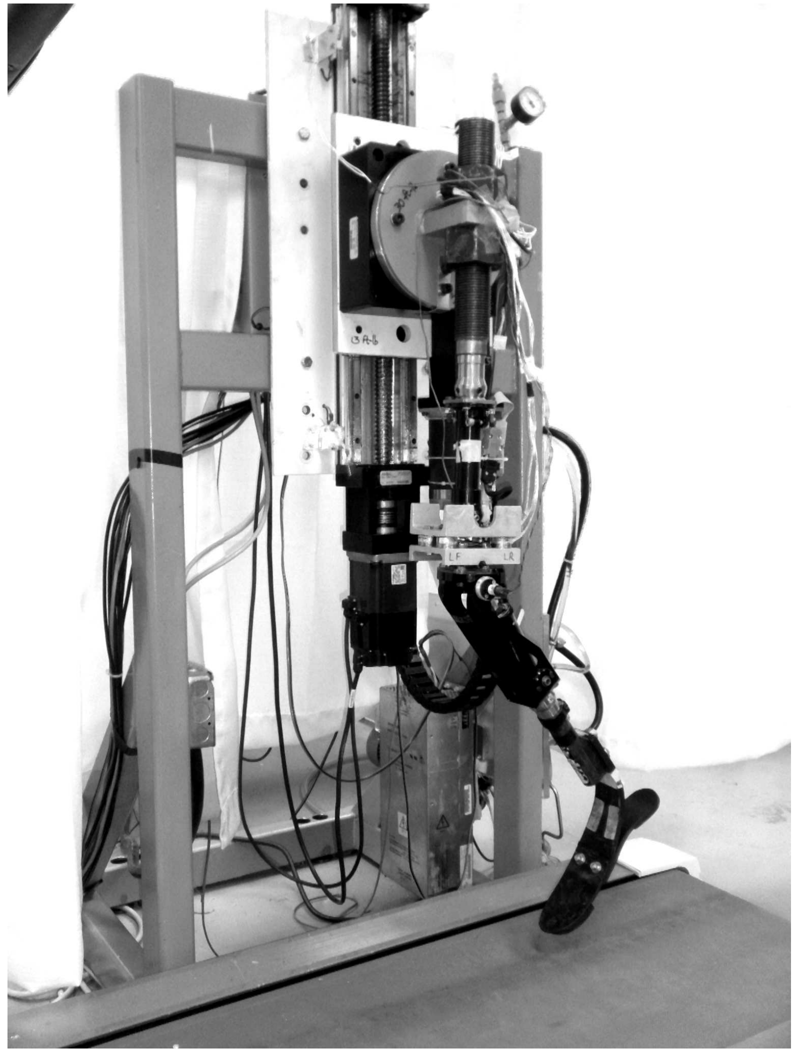
We have a similar robot in the lab. How many DOF does it have and to which one of the 5 kinds does it belong?

PUMA 560



We have this robot in the lab. How many DOF does it have and to which one of the 5 kinds does it belong?

CSU Hip Simulating Robot



This robot was designed and built at CSU. How many DOF does it have and to which one of the 5 kinds does it belong?

Basic Problems in Motion Control of Robots

- **Forward Kinematics**: Determine the position and orientation of the end effector given the values (pointwise in time) of the joint variables.
- **Inverse Kinematics**: Determine a solution for the joint variables that result in a desired position and orientation (pointwise in time) of the end effector.
- **Velocity Kinematics**: Similar to the forward and inverse kinematics problems, with the added requirement of following a path with prescribed velocity profile. Of particular importance is the study of *singularities*, which are points where the manipulator effectively loses one or more degrees of freedom due to rank deficiency in the Jacobian matrix.
- **Path Planning and Trajectory Generation:** This is the problem of how best to command the manipulator between specified points in the presence of obstacles and other constraints.

Basic Problems in Motion Control of Robots

- **Decoupled Control**: Also called Independent Joint Control, applies ideas from classical control to achieve trajectory tracking and disturbance rejection. The assumption is that each joint can be treated as a SISO system, without dynamic coupling between links.
- **Dynamics**: Methods to derive mathematical models suitable for subsequent controls-oriented studies. Properties of the model are also studied.
- **Multivariable (MIMO) Control**: Dynamic coupling between links cannot be neglected due high inertias / high accelerations. Nonlinear control techniques are available to handle this case.
- **Force Control**: Motion control with the added requirement of maintaining a prescribed force (or at least maintaining the force within bounds) between tool and workpiece.

Basic Problems in Motion Control of Robots

- **Impedance Control**: Achieving a specified dynamic relationship between external forces applied to the manipulator and the resulting deviations from a nominal trajectory.
- **Robust Control:** Designing fixed-gain controllers capable of maintaining stability and performance even with model errors.
- **Adaptive Control:** Designing controllers whose gains are continuously adjusted to counter uncertain or changing model parameters.
- **State Estimation:** Obtaining estimates for variables of interest from direct measurements of other variables and model information.

Basic Problems in Motion Control of Robots

- **Parameter Estimation**: Obtaining estimates for unknown system parameters from observations of input/output data.
- **Machine Vision**: A study of camera systems and how they are used to determine the position and velocity of the robot, along with the location of workpieces and obstacles. Visual servoing implies using the output from the cameras as feedback sensors to be used in the control algorithm.
- **Kinematic Calibration:** (Automatic) correction to the kinematic relationships to account for parts wear, drifts, thermal effects, etc.
- **Cooperative Controls:** The study of strategies (motion planning, control algorithms) to distribute common tasks among groups of robots.

MCE/EEC 647/747: course overview

- This is an introductory course directed at ME and EE students, with a focus on dynamics and control.
- We go over forward, inverse and velocity kinematics as a brief overview. These topics are indispensable. MCE652: Robotics and Machine Vision focuses on these topics.
- We briefly cover decoupled control as a refresher of classical control ideas.
- Dynamics will be studied with a focus on obtaining the model of any given manipulator configuration. We also focus on the properties of the model: linear parameterization, passivity, etc.
- We introduce/review Lyapunov stability theory and related concepts applicable to nonlinear dynamical systems.
- We study the standard MIMO nonlinear control techniques for robotic manipulators, including robust and adaptive approaches. An overview of force control techniques will be offered.
- New topics for Spring 15: inverse kinematics by decoupling, manipulability, impedance control, task space modeling and control, as time permits.

What Robots Can't Do

- `http://www.youtube.com/watch?v=gsOaQGF7kiQ`
- `http://www.youtube.com/watch?v=hC-Wg5jHkmg`