University of British Columbia
Department of Electrical and Computer Engineering
Introduction to Robotics
MECH ELEC
Course Notes, updated December 2020

(with permission, modified by Prof Joseph Yan)

We will define a robot to be a programmable, active, computer-controlled mechanism capable of a variety of tasks. The mechanism is usually a serial kinematic linkage actuated by electromagnetic (stepper, DC servo, variable reluctance), hydraulic or pneumatic actuators.

The computer system consists of one or several microprocessors, that perform

- real-time motor control
- trajectory planning
- interaction with external sensors (vision, force-torque, proximity, etc).

Often, the computing architecture is partitioned into a programming system and a real-time system. Computing architectures will be briefly discussed at the end of the course.

Robots have their roots in the teleoperation systems used in the late 1940's to manipulate radioactive materials and in the computer numerically controlled (CNC) machines developed in the early 1950's. They are being used in unstructured environments, such as subsea and outerspace, and in predictable manufacturing environments. The hope has been that robots would provide significant autonomy for unstructured tasks and outstanding flexibility in manufacturing tasks. Unfortunately, neither has materialized to a significant extent. The AI capabilities to provide a machine with autonomy in performing a useful task are still far from what is needed, while the promised flexibility comes at signifcant cost in programming time. Research is being carried in both fields to improve autonomy and flexibility through easier programming. Both are characterized by the need for better interfaces to the human operator.

Aside from the old manufacturing applications, there are new and exciting applications of robotics in the areas of health care (medical robots that can assist with orthopaedic and endoscopic surgery), mining and constructions (large excavator machines are equipped with sensors and computer controls to make them behave like robots), scientific applications (extreme motion scaling), and virtual environments.

Following is an abridged history of Robotics:

- 1922 - "Robot" is introduced into the English vocabulary through the play R.U.R. (Rossum's Universal Robots), by Czech playwright Capek.
- 1947 - Electric teleoperator developed at Argonne National Labs in the USA to allow the manipulation of radioactive material from a safe distance.
- 1948 - GE develops Handy Man, a teleoperator with force feedback.
- 1953 - MIT demonstrates servo-controlled Computer Numerically Controlled (CNC) milling machine (storage on paper tape).
- 1954 - Devol applies for patent for a "programmable transfer device", the first programmable "robot".
- 1961 - Ernst MIT PhD thesis on a computer-operated mechanical hand.
- 1962 - AMF and Unimation develop robot products, essentially "pick-and-place" products.
- 1966 - Stanford AI group developes a robot with microphones, cameras and manipulators that could react to human input (speech, movement).
- 1970 - Unimate introduces 6-DOF robot, AMF "continuous path" robot
- 1972 - IBM develops 7565 (RS1) cartesian robot with gripper sensors.
- 1972 - Bolles and Paul demonstrate water pump assembly using vision and force feedback.
- 1973 - Will (IBM) uses robot with force and touch feedback for typewriter assembly.
- 1975 - GE introduces Man-Mate manipulator, "person amplifier" concept.
- 1977 - Nevin and Whitney invent Remote Compliance Center (RCC) device.
- 1974-1984 - Industrial robot market increases (ASEA, Cincinatti Milacron, FANUC).
- 1984 - Marc Raibert builds a One-Leg Hopper.

  `http://www.ai.mit.edu/projects/leglab/robots/3D_hopper/3D_hopper.html`

  This leads to many other interesting hopping/running/walking robots at his start-up, Boston Dynamics,, including Spot and Atlas.
- 1986-1992 - Robotics companies consolidate (GE, IBM, GM get out of the industrial robot market, Unimation sold to Staubli Automation, GM sells robotics interest to FANUC) industrial robots market flatens or drops.

- 1986- Multiple projects demonstrate various levels of driving autonomy: early example from Germany: https://www.youtube.com/watch?v=I39sxwYKlEE and recent one from Stanford https://www.youtube.com/watch?v=joIsgP9StAY
- 1987 - Scheinman introduces "RobotWorld" concept for robots with easily modifiable end-effectors for general assembly.
- 1987- Integrated Surgical Systems develops Robodoc for robot-assisted hip replacement
- 1998 - Computer Motion introduced the Zeus robot system for laparoscopic surgery. In 2001 they received FDA approval.
- 1998 - Intuitive Surgical Systems introduces da Vinci Surgical System for robot-assisted heart valve repair. The company has experienced tremendous growth since its technology was used for common procedures such as prostate surgery. It merged with Computer Motion in 2003.
- 1990 - "Haptic Interfaces", small robots that act as computer input-output devices that can produce force-feedback to the user are being developed. Microsoft, SensAble, Logitech, Haptic Technologies all sell products.
- 1995 - "Collaborative robots" or cobots are invented. These are passive systems that use non-holonomic motion to implement constraints that help people accomplish tasks.
- 1996 - Honda introduces first autonomous "humanoid" robot. Earlier prototypes later evolve into ASIMO(Advanced Step in Innovative MObility), introduced in 2000. ASIMO can walk, go up and down stairs, catch and kick a soccer ball.
- 1997- Mars rover Sojourner successfully explores planet surface for 3 months.1999Sony introduces Aibo (Artificial Intelligence roBOt) for entertainment robotics. Others (e.g., Necoro and My Real Baby) designed to appear as biological counterparts.
- 2003 - Kiva Systems is founded for warehouse automation. Bought by Amazon in 2012, it is now Amazon Robotics.
- 2004- DARPA Challenge to cross Mojave desert. In 2005, 5 vehicles meet the challenge.
- 2009-2019 ? self driving car efforts become commercial. Google (then Waymo), Tesla, Uber, Lyft, Ford, GM, etc all are funding large projects.
- 2010 - airborne drones become commonly available, various applications.

- 2019 Boston Dynamics launches Spot, a walking/running robot (e.g. Boston Dynamics - https://www.youtube.com/watch?v=yLtdzJ6mVMk)

In this set of notes, we will be concerned primarily with manipulators.

By a *manipulator* we will usually refer to an open kinematic chain of *links* connected in series by *revolute* or *prismatic* joints. Although strictly speaking, any motion platform can be referred to as a manipulator, e.g., a Stewart platform, as shown schematically in Figure 1, in this course we will deal primarily with serial manipulators.

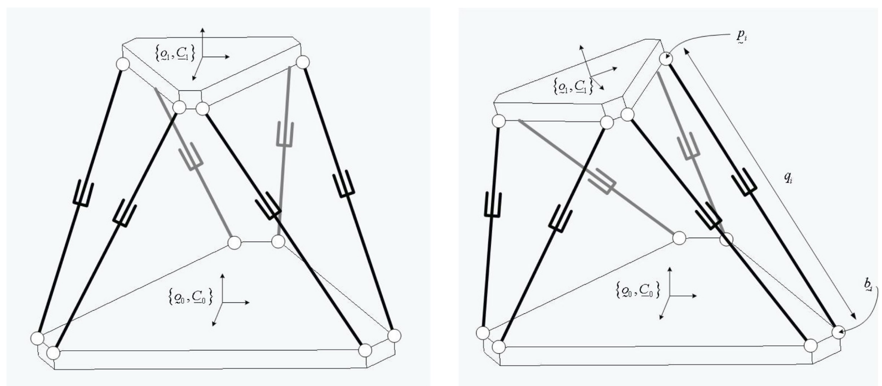
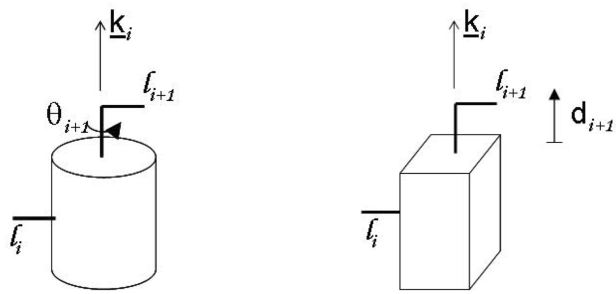


Figure 1: 6-DOF parallel manipulator, Gough-Stewart or Stewart Platform.

A revolute joint allows a single rotation of link l_{i+1} with respect to l_i about an axis $\underline{k}_i$. Revolute joints will be represented by cylinders connected to links as shown in Figure 2(a). The rotation takes place about the link entering the base of the cylinder.

A prismatic joint allows a single translation of link l_{i+1} with respect to l_i along an axis $\underline{k}_i$. Prismatic joints will be represented by rectangular boxes connected to links as shown in Figure 2(b). The translation takes place about the link entering the smaller face of the box.



(a) (b)

Figure 2: Schematic representations of the (a) revolute joint and (b) prismatic joint

The number of *degrees-of-freedom* of a serial manipulator is equal to its number of joints. In order to position and orient a body arbitrarily in space, a manipulator should have at least 6 degrees of freedom (DOF). If the manipulator has more than 6 degrees of freedom, the manipulator is called redundant. In some applications, fewer than 6 degrees of freedom suffice. If the robot carries a symmetrical tool, 5 degrees of freedom suffice. For “planar” assembly tasks, such as placing components on a circuit board, 4 degrees of freedom suffice.

The proximal link of a robot is called the base or mechanical ground. The distal link of a robot is called the end-effector. The distal link of a robot is usually equipped with a gripper, providing a seventh degree of freedom that can be used to pick up parts or tools.

The *reachable workspace* of a manipulator is the set of achievable end-effector positions, irrespectively of the end-effector orientation at that position. The *dextrous workspace* of a manipulator is the set of achievable end-effector positions with arbitrary orientation of the end-effector.

The dextrous workspace of a manipulator is much smaller than the reachable workspace. In some instances, in order to define meaningful workspaces, the range of orientations can be limited to define a *semi-dextrous* workspace, e.g. 45° rotation about an arbitrary axis at any position within the semi-dextrous workspace.

A number of manipulator kinematic structures have been used to construct robots. Classified according to the type of *arm* used, one can distinguish the following common arms shown in Figure 3:

Cartesian, usually of the *gantry* type, or similar to classical positioning tables. For such robots, the dynamics, path planning and control are relatively simple, and the workspace is easy to define and visualize. These robots are large. Gantry type robots are difficult to align.

Cylindrical, usually smaller than spherical manipulators are used in pick and place tasks with the parts arranged in a cylindrical pattern. Telescoping motion of the arm keeps the wrist orientation unchanged. There are penumatic pick-and-place robots of this type that use adjustable mechanical stops (only simple digital computer control).

Spherical, usually large, sturdy robots that can have heavy payloads. All the motors of spherical manipulators are in the base. They do not have a particulary good dextrous workspace because of interference with the arm.

SCARA (Selective Compliant Articulated Robot for Assembly), mainly used for planar operations, popular for board assembly and test.

Articulated (also *elbow* or *anthropomorphic*). These robots have a large workspace for the length of the arm. Care must be taken in placing them to avoid running into singularities while performing a task. Often, these are constructed using a parallelogram linkage, to avoid carrying a large forearm motor. The wrist base is oriented by the motion of the arm, so full 6 DOF motion coordination is necessary in order to place the end-effector at a given position and orientation.

There are plenty of others structures, including parallel robots.

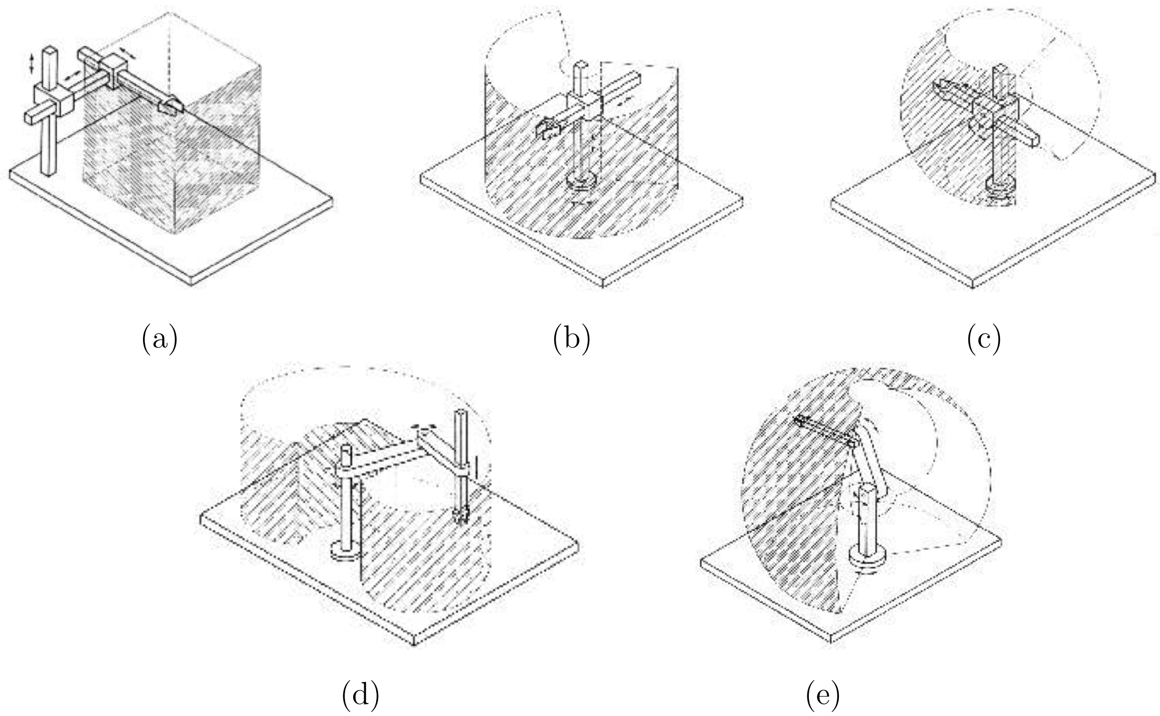


Figure 3: Examples of common manipulator configurations: (a) Cartesian, (b) Cylindrical, (c) Spherical, (d) SCARA and (e) Articulated.

Common Control Methods:

- mechanical stops
- point to point
- continuous path

Common Performance Specifications:

- repeatability
- accuracy
- resolution
- payload

Other (important but neglected) specifications may include:

- stiffness

- bandwidth (disturbance rejection)
- cleanliness

This course will be mainly concerned with direct (forward) and inverse kinematics, manipulator dynamics and control approaches.