Robotics and Automation

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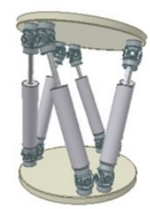
Chapter Two

Introduction To Robot Manipulators

Robotic Industrial Manipulators

- A robot manipulator is an electronically controlled mechanism, consisting of multiple segments, that performs tasks by interacting with its environment. They are also commonly referred to as robotic arms. Robot manipulators are extensively used in the industrial manufacturing sector.



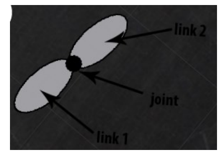



Kinematic Chain

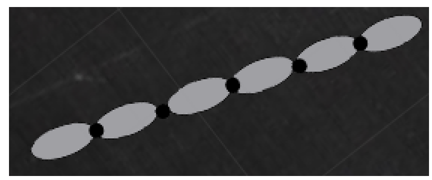
- Robotic Manipulators are composed of an assembly of links and joints. Links are defined as the rigid sections that make up the mechanism and joints are defined as the connection between two links. The device attached to the manipulator which interacts with its environment to perform tasks is called the end-effector.
- “Robotic manipulator is a set of links connected by joints to form a kinematic chain.”

Kinematic Chain

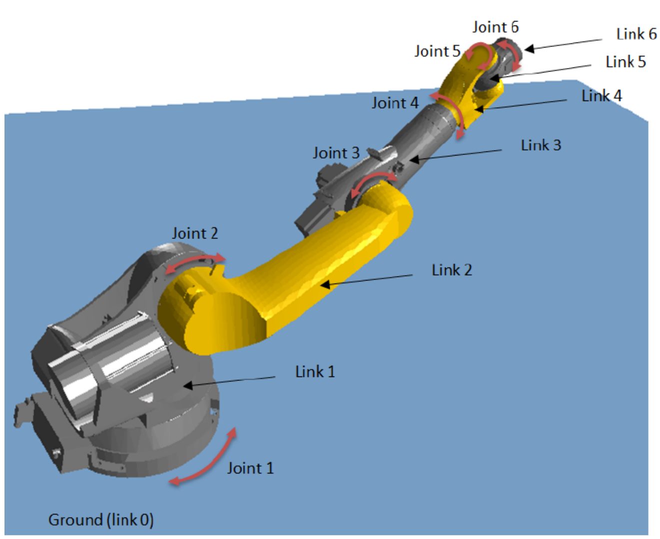
- Kinematic pair – two links connected by joint (mobile connection)



- Kinematic chain of manipulator is a combination of a couple of kinematic pairs



Kinematic Chain



Type of Joints

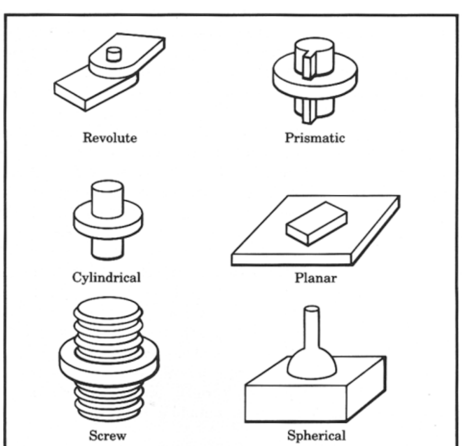
- Joints are typically **rotary (revolute)** or **linear (prismatic).**

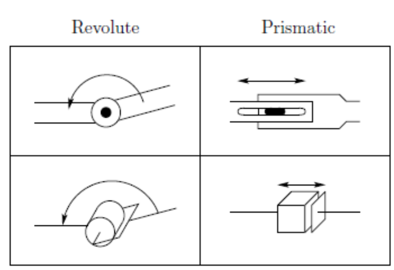
1- Revolute (R): A revolute joint is like a hinge and allows relative rotation between two links

2- Prismatic (P): A prismatic joint allows a linear relative motion between two links.

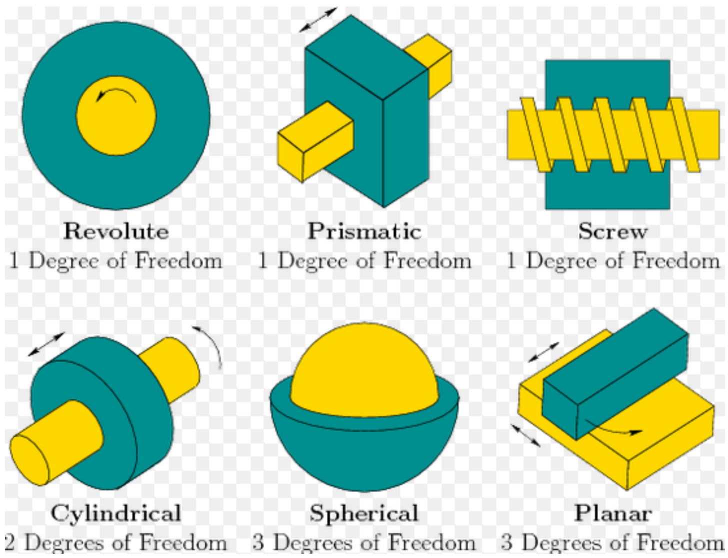
- Any other joint can represented by some combination of these two primary joints.
- Spherical joint can be seen as three revolute joints with zero link lengths.

Type of Joints

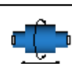
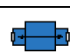
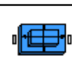




Type of Joints



Type of Joints

Name of joint	Representation	Description
Revolute		Allows relative rotation about one axis.
Cylindrical		Allows relative rotation and translation about one axis.
Prismatic		Allows relative translation about one axis.
Spherical		Allows three degrees of rotational freedom about the center of the joint. Also known as a ball-and-socket joint.
Planar		Allows relative translation on a plane and relative rotation about an axis perpendicular to the plane.

Manipulator Workspace and Degree of Freedom (DOF)

- The number of **degrees of freedom** that a manipulator possesses is the number of independent position variables that would have to be specified in order to locate all parts of the mechanism.
- In other words, the number of degrees of freedom is equal to the total number of independent displacements or aspects of motion.
- This is a general term used for any mechanism. For example, a four-bar linkage has only one degree of freedom (even though there are three moving members).

Manipulator Workspace and Degree of Freedom (DOF)

- In the case of typical **industrial robots**, because a manipulator is usually an **open kinematic chain**, and because **each joint position is usually defined with a single variable**, **<u>the number of joints equals the number of degrees of freedom</u>**.
- Typically, a manipulator should possess at least six independent DOF, three for positioning and three for orientation, to move the end-effector to an arbitrary position and orientation in three dimensional space.

Manipulator Workspace and Degree of Freedom (DOF)

- With fewer than six DOF, the arm cannot reach every point in its workspace with arbitrary orientation. However, The difficulty of controlling a manipulator increases rapidly with increasing the number of links.
- Certain applications such as reaching around or behind (avoid) obstacles require more than six DOF. A manipulator having more than six links is referred to as a kinematically redundant manipulator.

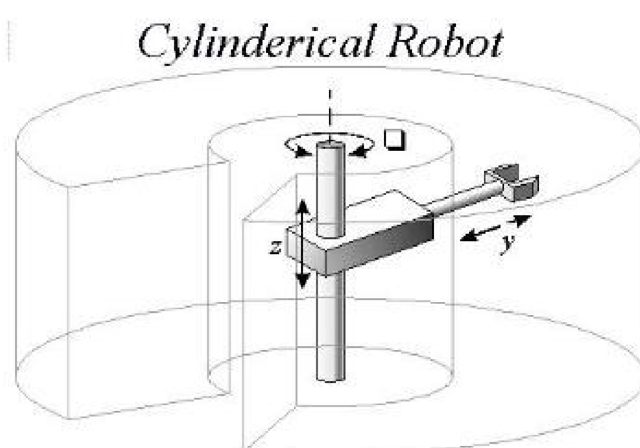
Manipulator Workspace and Degree of Freedom (DOF)

- **Workspace:** The workspace of a manipulator is the total volume swept out by the end-effector as the manipulator executes all possible motions.
- It can be determined analytically or experimentally
- The workspace is constrained by the geometry of the manipulator as well as mechanical constraints on the joints. For example, a revolute joint may be limited to less than a full 360^0 of motion.

Manipulator Workspace and Degree of Freedom (DOF)

- The workspace is often broken down into a **reachable workspace** and a **dextrous workspace**.
- **The reachable workspace** is the entire set of points reachable by the manipulator, whereas the **dextrous workspace** consists of those points that the manipulator can reach with an arbitrary orientation of the end effector.
- Obviously, dexterous workspace is a subset of the reachable workspace.

Manipulator Workspace and Degree of Freedom (DOF)



Robot Manipulator Classifications

- Robot manipulators can be classified by several criteria, such as their **power source** or **way in which the joints are actuated**, their **geometry** or **kinematic structure**, their intended **application area**, or their **method of control**.
- Such classification is useful primarily in order to determine which robot is right for a given task. For example, an hydraulic robot would not be suitable for food handling or clean room applications.

Robot Manipulator Classifications

- **According to power source, the robot manipulators are:**

1- Electrically powered: Robots driven by DC- or AC-servo motors are increasingly popular since they are cheap, clean and quiet.

2- Hydraulically powered: Hydraulic actuators are unrivalled in their speed response and torque, and usually used to lift heavy loads. However, the hydraulic robots tend to leak hydraulic fluid, require much more peripheral equipment and maintenance, and they are noisy.

3- pneumatically powered: Pneumatic robots are inexpensive and simple, but cannot be controlled precisely. As a result, pneumatic robots are limited in their range of applications and popularity.

Robot Manipulator Classifications

- **Robot manipulators are classified by control methods into:**

1- **Non-servo robots:** The earliest robots were non-servo robots. These robots are essentially open-loop devices whose movement is limited to predetermined mechanical stops, and they are useful primarily for materials transfer.

2- **Servo robots:** Servo robots use closed-loop computer control to determine their motion and are thus capable of being truly multifunctional, reprogrammable devices. Servo controlled robots are further classified according to the method that the controller uses to guide the end-effector. The simplest type of robot in this class is the point-to-point robot.

Robot Manipulator Classifications

Servo robots:

- **A point-to-point** robot can be taught a discrete set of points but there is no control on the path of the end-effector in between taught points. Such robots are usually taught a series of points with a teach pendant (handheld device). The points are then stored and played back. Point-to point robots are severely limited in their range of applications.
- **In continuous path robots,** on the other hand, the entire path of the end-effector can be controlled. For example, the robot end-effector can be taught to follow a straight line between two points or even to follow a contour such as a welding seam. In addition, the velocity and/or acceleration of the end-effector can often be controlled.

Robot Manipulator Classifications

- **Robot manipulators are classified by the Kinematic structure into:**

1- Serial manipulators: links and joints are connected to form open kinematic chain

2- Parallel manipulators: links and joints are connected to form closed kinematic chain

3- Hybrid manipulators: Combining serial and parallel manipulators.

Robot Manipulator Classifications

- Serial manipulators

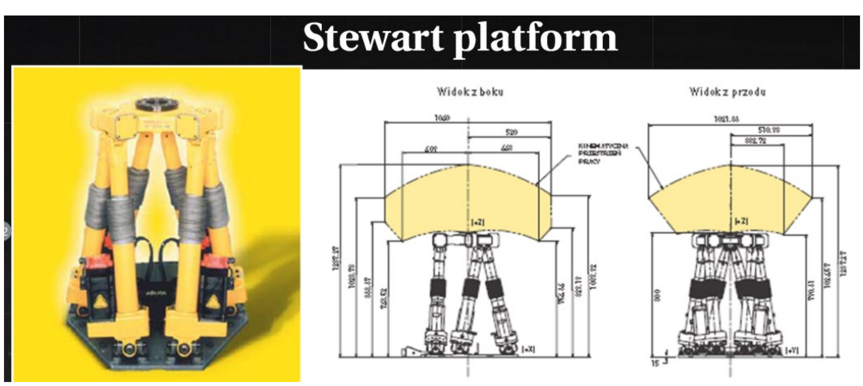
Robot Manipulator Classifications

- Parallel manipulators

Tripod robot consists of three parallel arms

Robot Manipulator Classifications

- Hybrid manipulators



Serial Manipulators

- Most industrial serial manipulators at the present time have **six or fewer degrees-of-freedom**. These manipulators are usually classified kinematically on the basis of the **first three joints of the arm**, with the wrist being described separately. The majority of these manipulators fall into one of five geometric types:

1- Articulate (RRR)

2- Spherical (RRP)

3- SCARA (RRP)

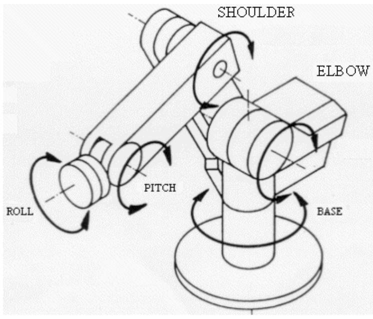
4- Cylindrical (RPP)

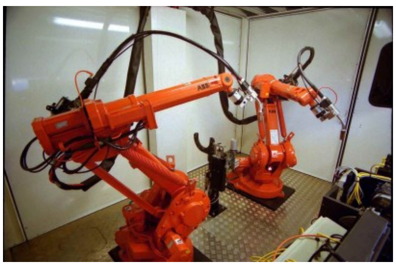
5- Cartesian (PPP)

Articulated Manipulators (RRR)

- The articulated manipulator is an industrial robot with rotary joints and is also called a **revolute**, or **anthropomorphic** manipulator.
- Articulated robots can range from simple two-jointed structures to systems with 10 or more interacting joints.
- Three revolute joints; the axes of second and third R joints are parallel, whereas the axis of first R joint is vertical.
- Relatively large movement freedom in a compact space.

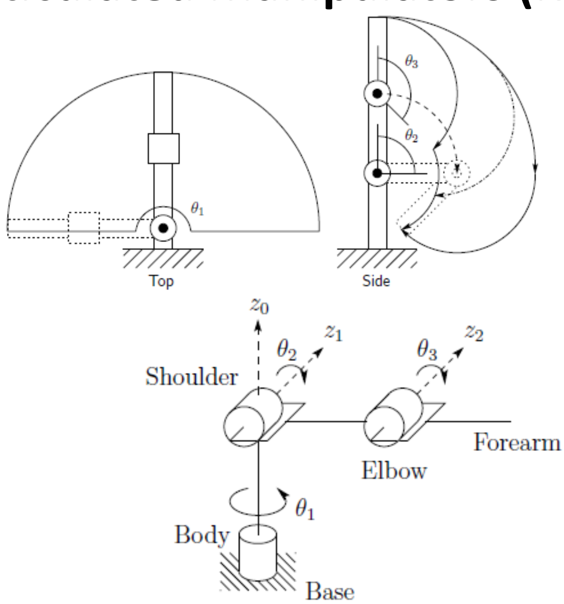
Articulated Manipulators (RRR)





The Motoman SK16 manipulator.

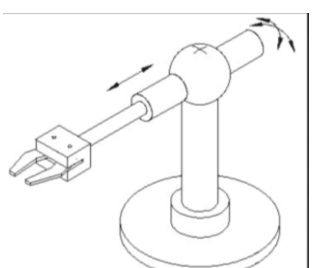
Articulated Manipulators (RRR)

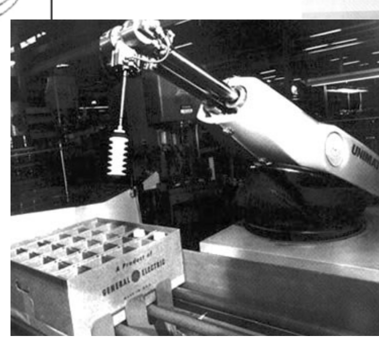


Spherical (RRP) Manipulator

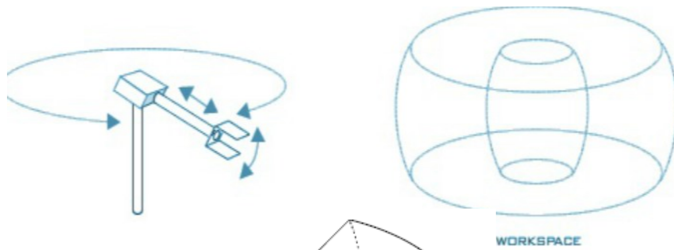
- If the third R joint in the articulate manipulator is replaced with a prismatic joint, then the result is the spherical manipulator. (i.e. It is a robot with two rotary joints and one prismatic joint).
- The spherical manipulator, also called polar manipulator, has three mutually perpendicular axes (has z_0, z_1, z_2 mutually perpendicular).
- The joint variables are the spherical coordinates of the end-effector with respect to the base.
- Spherical manipulators have lost practicality in the workplace due to 6 axes articulated manipulators.

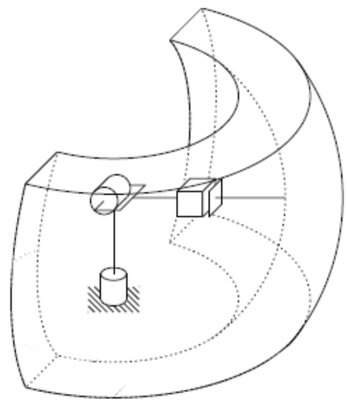
Spherical (RRP) Manipulator





Spherical (RRP) Manipulator



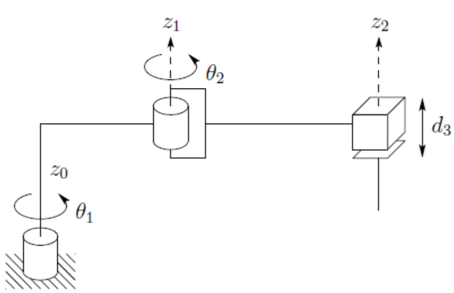


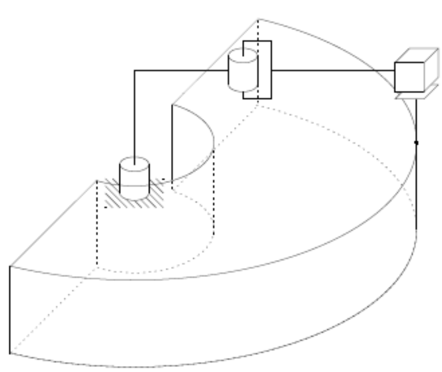
SCARA Manipulator (RRP)

- SCARA is the short for **Selective Compliant Articulated Robot for Assembly.**
- It is RRP but the axes are parallel (parallel z_0, z_1, z_2).
- Specially designed for assembly operations.
- The SCARA construction allow for precise work and quick assembly or packaging.

SCARA Manipulator (RRP)

SCARA Manipulator (RRP)



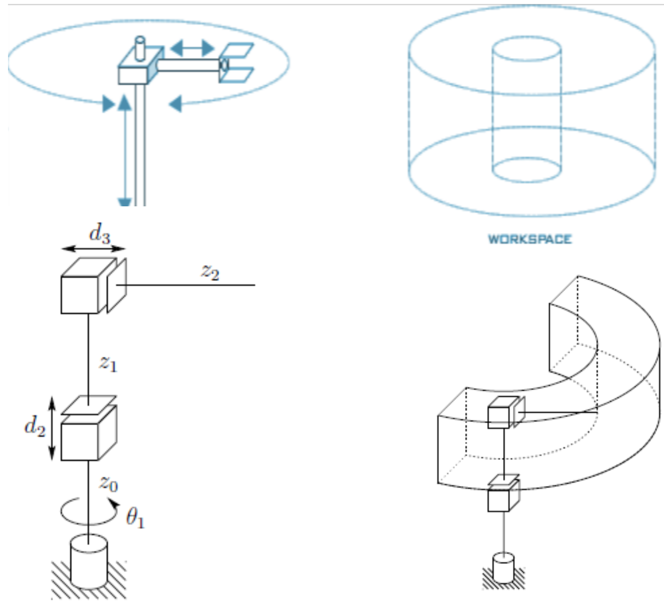


Cylindrical Manipulator (RPP)

- The first joint is revolute and produces a rotation about the base, whereas the second and third joints are prismatic.
- The joint variables are the cylindrical coordinates of the end-effector with respect to the base.
- Its Rigid structure, allows large payloads and good repeatability.

Cylindrical Manipulator (RPP)

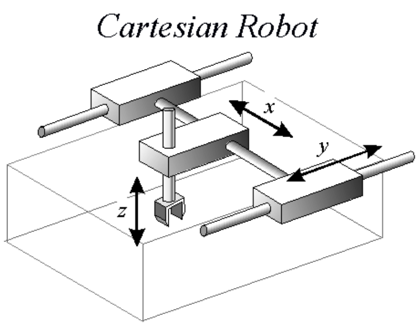
Cylindrical Manipulator (RPP)



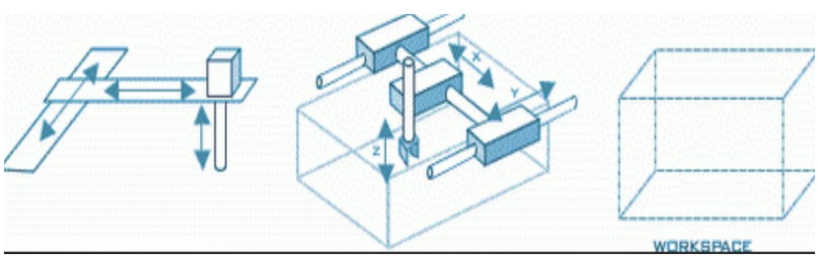
Cartesian Manipulator (PPP)

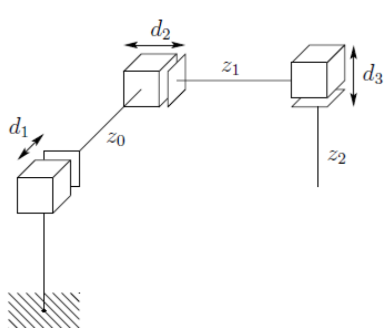
- Also called rectangular, rectilinear, gantry.
- Robot has the ability to move its gripper to any position within the cube or cuboid workspace.
- The first three joints are prismatic.
- The joint variables are the Cartesian coordinates of the end-effector with respect to the base.
- the kinematic description of this manipulator is the simplest of all configurations
- Useful for transfer of materials, and table-top assembly.

Cartesian Manipulator (PPP)



Cartesian Manipulator (PPP)





Manipulators Primary Vendors

- Kuka (Germany)
- Fanuc (Japan)
- ABB (Sweden, US)
- Panasonic (Japan)
- Sankyo (Japan)
- Mitsubishi (Japan)
- Adept (US)
- Seiko (Japan)
- Motoman (Japan)

Typical Costs: $20,000 - $80,000

Application

- Welding
- Painting
- Surface finishing
- Aerospace and automotive industries
- Assembly operations
- Inspection of parts
- Underwater and space exploration
- Hazardous waste remediation

Basic Assumptions and Terminology

- A robot manipulator with *n joints* will have *(n + 1)* links. Each joint connects two links.
- We number joints from *1* to *n*, and links from *0* to *n*. So that joint *i* connects links *(i – 1)* and *i*.
- The location of joint *i* is fixed with respect to the link *(i–1)*.
- When joint *i* is actuated, the link *i* moves. Hence the link *(i-1)* is fixed. In addition, link 0 is fixed.

Basic Assumptions and Terminology

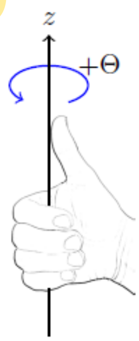
- With the i^{th} joint, we associate **joint variable q_i**:

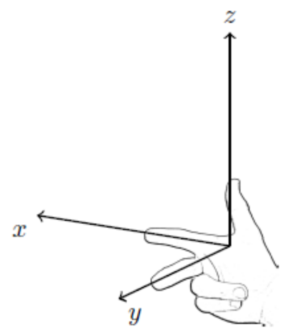
$$q_i = \begin{cases} \theta_i & \text{if joint } i \text{ is revolute} \\ d_i & \text{if joint } i \text{ is prismatic} \end{cases}$$

- **Joint space (joint vector)** is a set of all joint variables in the manipulator.
- For each link we attach rigidly the coordinate frame $(o_i\, x_i\, y_i\, z_i)$ for the link *i*. **(Using right hand rule).**
- When joint i is actuated, the link *i* and its frame experience a motion.
- The frame $(o_0\, x_0\, y_0\, z_0)$ attached to the base is referred to as **inertia frame (base frame)**

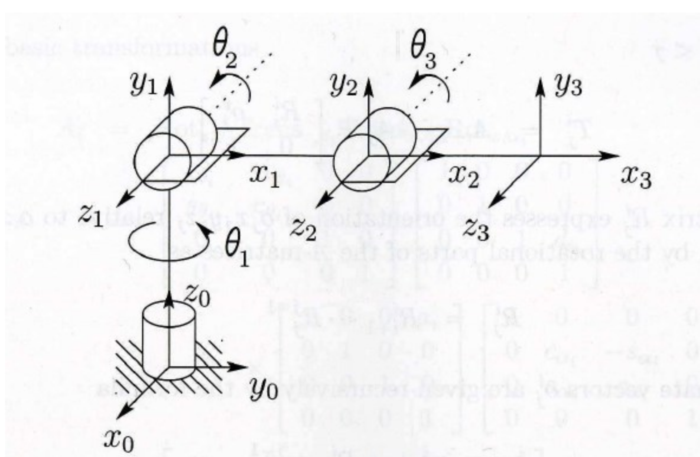
Basic Assumptions and Terminology

To describing locations and orientations in three dimensions the right handed coordinate system is used. In addition, the right hand rule is used to determine the direction of positive rotation around an axis.





Basic Assumptions and Terminology



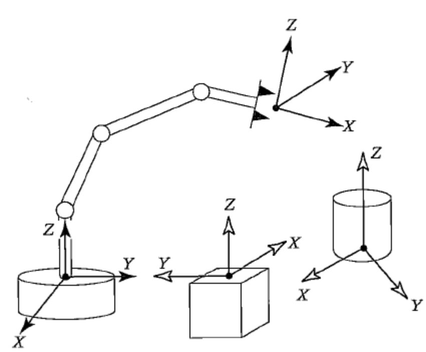
Coordinate frames attached to elbow manipulator

Basic Assumptions and Terminology

- In the study of robotics, we are constantly concerned with the location of objects in three-dimensional space. These objects are the links of the manipulator, the parts and tools with which it deals, and other objects in the manipulator's environment. These objects are described by just two attributes: **position and orientation.**
- In order to describe the position and orientation of a body in space, we will always attach a coordinate system, **or frame**, rigidly to the object. We then proceed to describe the position and orientation of this frame with respect to some reference coordinate system.

Basic Assumptions and Terminology

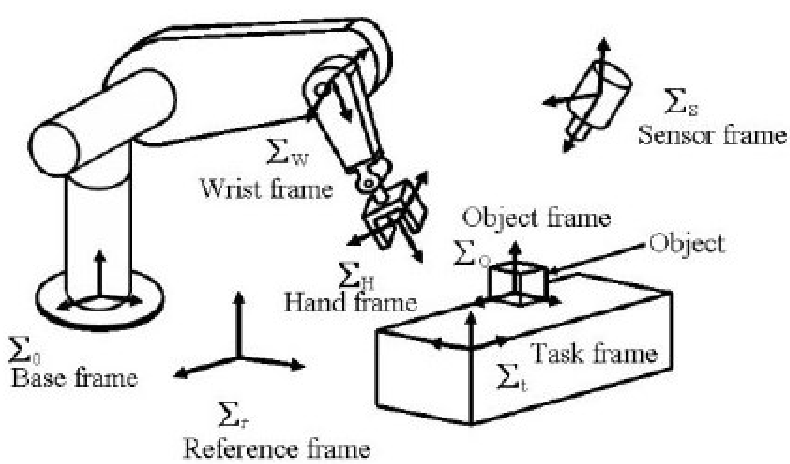
- Any frame can serve as a reference system within which to express the position and orientation of a body, so we often think of ***transforming*** or changing the description of these attributes of a body from one frame to another.



Basic Assumptions and Terminology

- The motion of robot manipulators are analyzed using a reference frame, which includes a base frame that is attached to the nonmoving base of manipulator, an end-effector frame that is attached to the end-effector of manipulator, sensor frames that are attached, for example, to the force sensor and vision sensor, an object frame that is attached to the body of the object, and a work frame that is attached to the work cell.

Basic Assumptions and Terminology



Overview

- **Kinematics** : study of the geometric description of motion (position, speed and acceleration) regardless of the causing force or torque.
- **Dynamics**: study the forces required to cause motion.
- The study of the **kinematics of manipulators** refers to all the geometrical and time-based properties of the motion (position, velocity, and acceleration).

Overview

- **Spatial Description**: Robotic manipulation implies that parts and tools will be moving around in space by the manipulator mechanism. This naturally leads to the need of representing positions and orientations of the parts, tools, and the mechanism it self.
  - ✓ Position and Orientation Description.
  - ✓ Transformation between Frames.

Overview

- **Forward Kinematics**: A very basic problem in the study of mechanical manipulation is called forward kinematics. This is the static geometrical problem of computing the position and orientation of the end-effector of the manipulator. Specifically, given a set of joint angles (joint variables), the forward kinematic problem is to compute the position and orientation of the tool frame relative to the base frame. Sometimes, we think of this as changing the representation of manipulator position from a joint space description into a Cartesian space (task space) description.

Overview

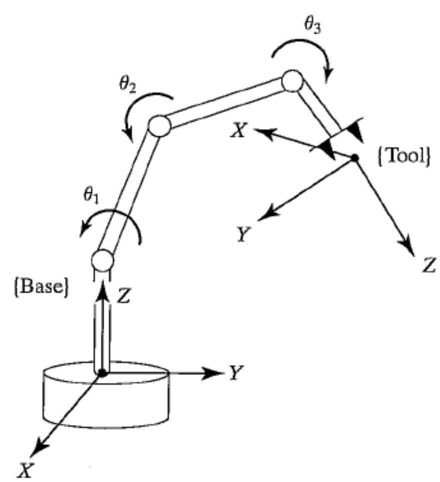


FIGURE 1.6: Kinematic equations describe the tool frame relative to the base frame as a function of the joint variables.

Overview

Inverse Kinematics:

- Given the position and orientation of the end-effector of the manipulator, calculate all possible sets of joint angles that could be used to attain this given position and orientation. This is a fundamental problem in the practical use of manipulators.
- This is a rather complicated geometrical problem that is routinely solved thousands of times daily in human and other biological systems.
- In robotics, a computer control algorithm is used to perform this calculation. In some ways, solution of this problem is the most important element in a manipulator system.

Overview

Inverse Kinematics:

- It is a mapping of "locations" in 3-D Cartesian space to "locations" in the robot's internal joint space.
- Some early robots lacked this algorithm. They were simply moved (sometimes by hand) to desired locations, which were then recorded as a set of joint values (i.e. as a location in joint space) for later playback.

Overview

Inverse Kinematics:

- The inverse kinematics problem is not as simple as the forward kinematics one. Because the kinematic equations are nonlinear, their solution is not always easy (or even possible) in a closed form. Also, questions about the existence of a solution and about multiple solutions arise.
- Study of these issues gives one an appreciation for what the human mind and nervous system are accomplishing when we, seemingly without conscious thought, move and manipulate objects with our arms and hands.

Overview

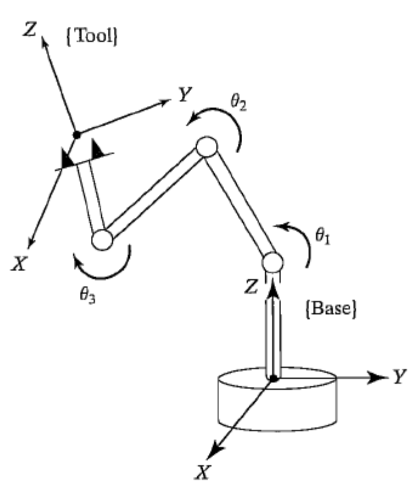


FIGURE 1.7: For a given position and orientation of the tool frame, values for the joint variables can be calculated via the inverse kinematics.

Overview

- **Velocity Kinematics:** In order to drive the end effector to follow a contour at constant velocity, or at any prescribed velocity, we must know the relationship between the velocity of the tool and the joint velocities.
- **The Jacobian:** it specifies a mapping from velocities in joint space to velocities in Cartesian space. (i.e. How the joint velocities are related to the end-effector velocity and resulting force.)

Overview

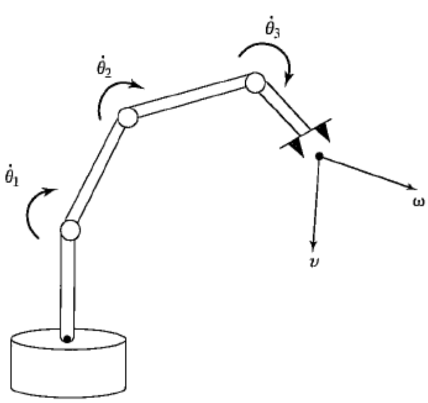
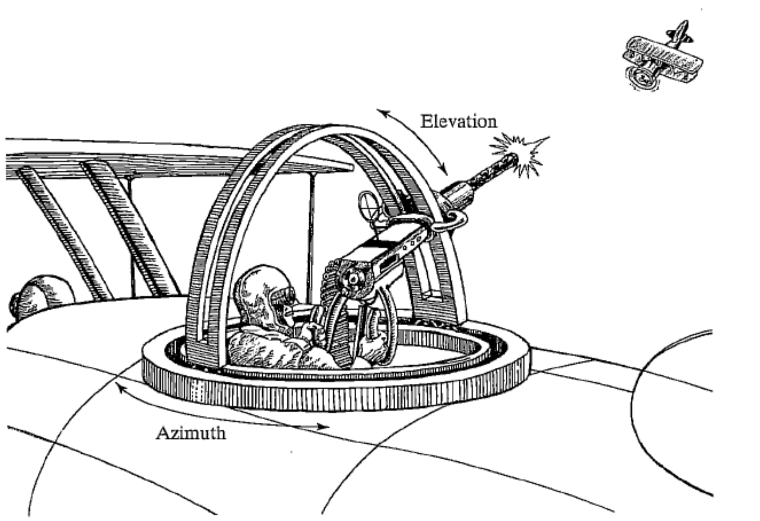


FIGURE 1.8: The geometrical relationship between joint rates and velocity of the end-effector can be described in a matrix called the Jacobian.

Overview

- **Kinematic Singularity:** is a point within the robot workspace where the robot's Jacobian matrix losses rank. (i.e. At certain points, called singularities, the Jacobian mapping is not invertible).
- **Force control:** Manipulators do not always move through space; sometimes they are also required to touch a workpiece or work surface and apply a static force. In this case the problem arises: Given a desired contact force and moment, what set of joint torques is required to generate them? Once again, the Jacobian matrix of the manipulator arises quite naturally in the solution of this problem.

Overview



Overview

Manipulator Dynamics:

- In order to accelerate a manipulator from rest, slide at a constant end effector velocity, and finally decelerate to a stop, a complex set of torque functions must be applied by the joint actuators.
- The exact form of the required functions of actuator torque depend on the spatial and temporal attributes of the path taken by the end-effector and on the mass properties of the links and payload, friction in the joints, and so on.
- One method of controlling a manipulator to follow a desired path involves calculating these actuator torque functions by using the dynamic equations of motion of the manipulator (Lagrange Equations).

Overview

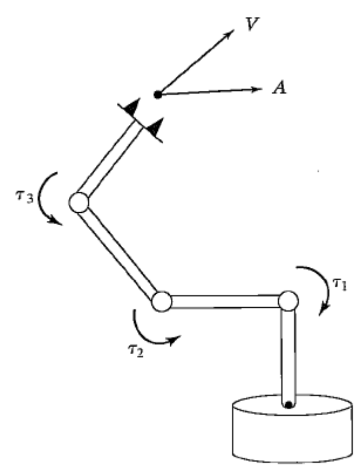


FIGURE 1.10: The relationship between the torques applied by the actuators and the resulting motion of the manipulator is embodied in the dynamic equations of motion.

Overview

- **Path planning and Trajectory Generation**: The robot control problem is typically decomposed into three tasks: path planning, trajectory generation, and trajectory tracking. The path planning problem is to determine a path in task space to move the robot to a goal position while avoiding collisions with objects in its workspace. These paths are encode position information without timing considerations, i.e. without considering velocities and accelerations along the planned paths. The trajectory generation problem is to generate reference trajectories that determine the time history of the manipulator along a given path or between initial and final configurations.

Overview

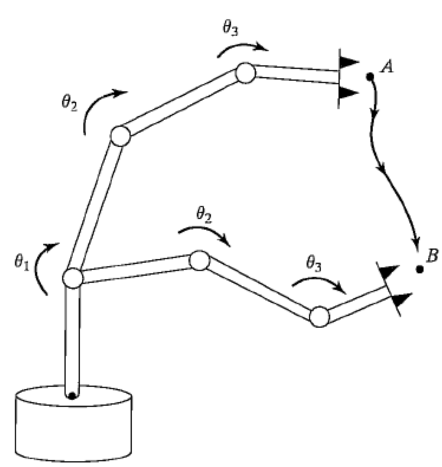


FIGURE 1.11: In order to move the end-effector through space from point A to point B, we must compute a trajectory for each joint to follow.

Overview

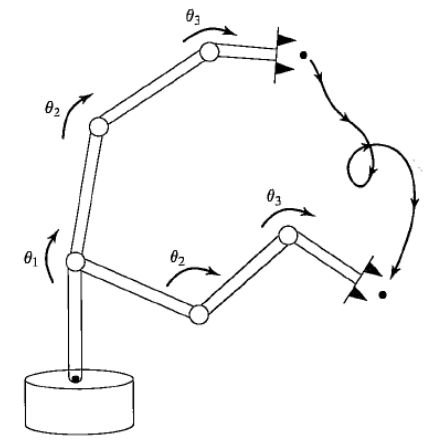


FIGURE 1.13: In order to cause the manipulator to follow the desired trajectory, a position-control system must be implemented. Such a system uses feedback from joint sensors to keep the manipulator on course.