ENGINEERING ROBOTICS-

PROFESSIONAL ELECTIVE

INTRODUCTION

The field of robotics has its origins in science fiction. The term robot was derived from the English translation of a fantasy play written in Czechoslovakia around 1920. It took another 40 years before the modern technology of industrial robotics began. Today, Robots are highly automated mechanical manipulators controlled by computers.

Robotics:-

Robotics is an applied engineering science that has been referred to as a combination of machine tool technology and computer science. It includes machine design, production theory, micro electronics, computer programming & artificial intelligence.

OR

"Robotics" is defined as the science of designing and building Robots which are suitable for real life application in automated manufacturing and other non-manufacturing environments.

Industrial robot:-

The official definition of an industrial robot is provided by the robotics industries association (RIA). Industrial robot is defined as an automatic, freely programmed, servo-controlled, multi-purpose manipulator to handle various operations of an industry with variable programmed motions.

Need For using robotics in industries:-

Industrial robot plays a significant role in automated manufacturing to perform different kinds of applications.

1. Robots can be built as a performance capability superior to those of human beings. In terms of strength, size, speed, accuracy…etc.
2. Robots are better than humans to perform simple and repetitive tasks with better quality and consistency.
3. Robots do not have the limitations and negative attributes of human such as fatigue, need for rest, diversion of attention…..etc.
4. Robots are used in industries to save the time compared to human beings.
5. Robots can be applied in conditions or places which are hazardous to humans.

Specifications of robotics:-

1. Axis of motion
2. Work stations
3. Speed
4. Acceleration
5. Pay load capacity
6. Accuracy
7. Repeatability etc…

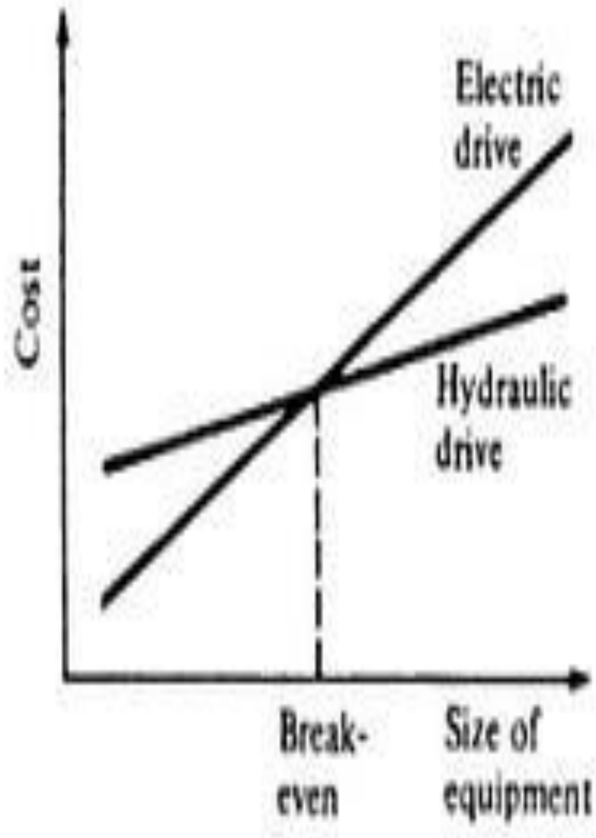
Overview of Robotics:-

"Robotics" is defined as the science of designing and building Robots which are suitable for real life application in automated manufacturing and other non-manufacturing environments. It has the following objectives,

1. To increase productivity
2. Reduce production life
3. Minimize labour requirement
4. Enhanced quality of the products
5. Minimize loss of man hours, on account of accidents.
6. Make reliable and high speed production.

Types of drive systems:-

1. Hydraulic drive
2. Electric drive
3. Pneumatic drive



Cost vs. size for electric drive and hydraulic drive.

1. Hydraulic drive:-

Hydraulic drive is **generally associated with larger robots**, such as the Unimate 2000 series. The usual advantages of the hydraulic drive system are that it **provides the robot with greater speed and strength**. The disadvantages of the hydraulic drive system are that it typically adds to the floor space required by the robot, and that a hydraulic system is inclined to leak on which is a nuisance. This type of system can also be called as non-air powered cylinders. In this system, **oil is used as a working fluid** instead of compressed air. Hydraulic system needs pump to generate the required pressure and flow rate. These systems are quite complex, costly and requires maintenance.

2. Electric drive:-

Electric drive systems do not generally provide as much speed or power as hydraulic systems. However, the **accuracy and repeatability of electric drive robots are usually better**. Consequently, **electric robots tend to be smaller**. Require less floor space, and their applications tend towards more precise work such as assembly.

In this System, **power is developed by an electric current**. It requires little maintenance and provides noise-less operation.

3. Pneumatic drive:-

Pneumatic drive is generally **reserved for smaller robots that possess fewer degrees of freedom** (two-to four-joint motions).

In this system, **air is used as a working fluid**, hence it is also called air-powered cylinders. Air is compressed in the cylinder and with the aid of pump the compressed air is used to generate the power with required amount of pressure and flow rates.

Applications of robots:-

Present Applications of Robots:-

(i) Material transfer applications

(ii) Machine loading and unloading

(iii) Processing operations like,

(a) Spot welding

(b) Continuous arc welding

(c) Spray coating

(d) Drilling, routing, machining operations

(e) Grinding, polishing debarring wire brushing

(g) Laser drilling and cutting etc.

(iv) Assembly tasks.

(v) Inspection, automation or test equipment.

Future Applications of Robots:-

The profile of the future robot based on the research activities will include the following,

(i) Intelligence

(ii) Sensor capabilities

(iii) Telepresence

(iv) Mechanical design

(v) Mobility and navigation (walking machines)

(vi) Universal gripper

(vii) Systems integration and networking

(viii) FMS (Flexible Manufacturing Systems)

(Ix) Hazardous and inaccessible non-manufacturing environments

(x) Underground coal mining

(xi) Fire fighting operations

(xii) Robots in space

(xiii) Security guards

(xiv) Garbage collection and waste disposal operations

(xv) Household robots

(xvi) Medical care and hospital duties etc.

Classification of Robots (or) Classification by co-ordinate system and control system:-

-> Co-ordinate systems:-

Industrial robots are available in a wide variety of sizes, shapes, and physical configurations. The vast majority of today's commercially available robots possess one of the basic configurations:

I. Polar configuration

2. Cylindrical configuration

3. Cartesian coordinate configurable

4. Jointed-arm configuration

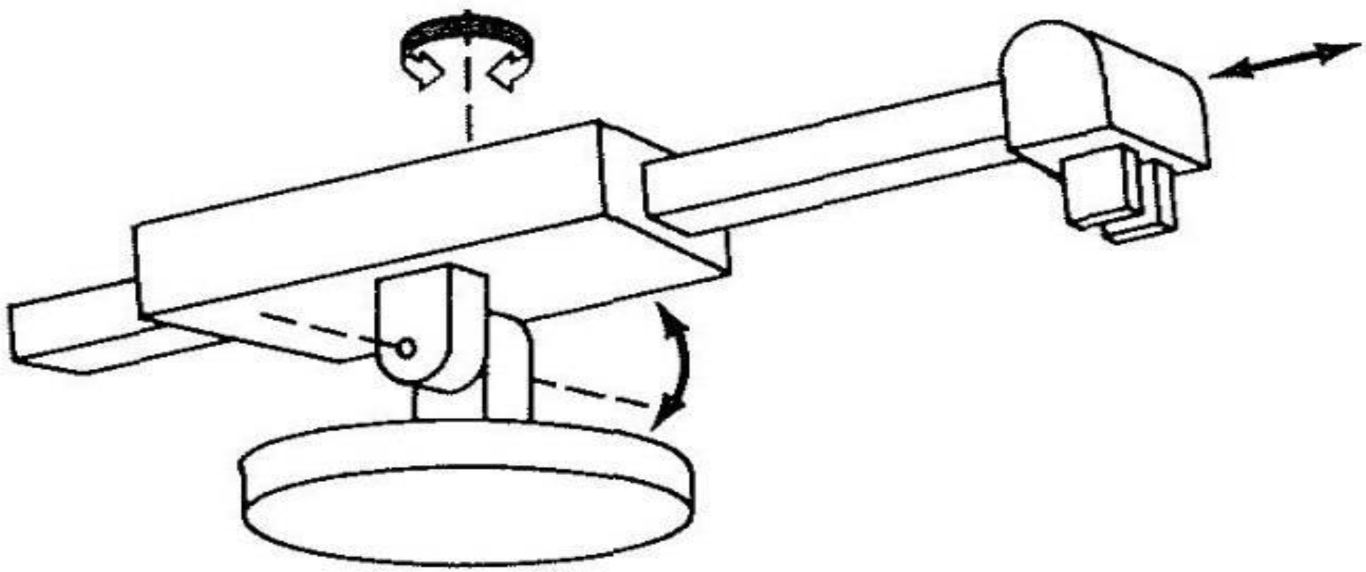
-> Control systems:-

With respect to robotics, the motion control system used to control the movement of the end-effector or tool.

1. Limited sequence robots (Non-servo)
2. Playback robots with point to point (servo)
3. Play back robots with continuous path control,
4. Intelligent robots.

CO-ORDINATE SYSTEMS

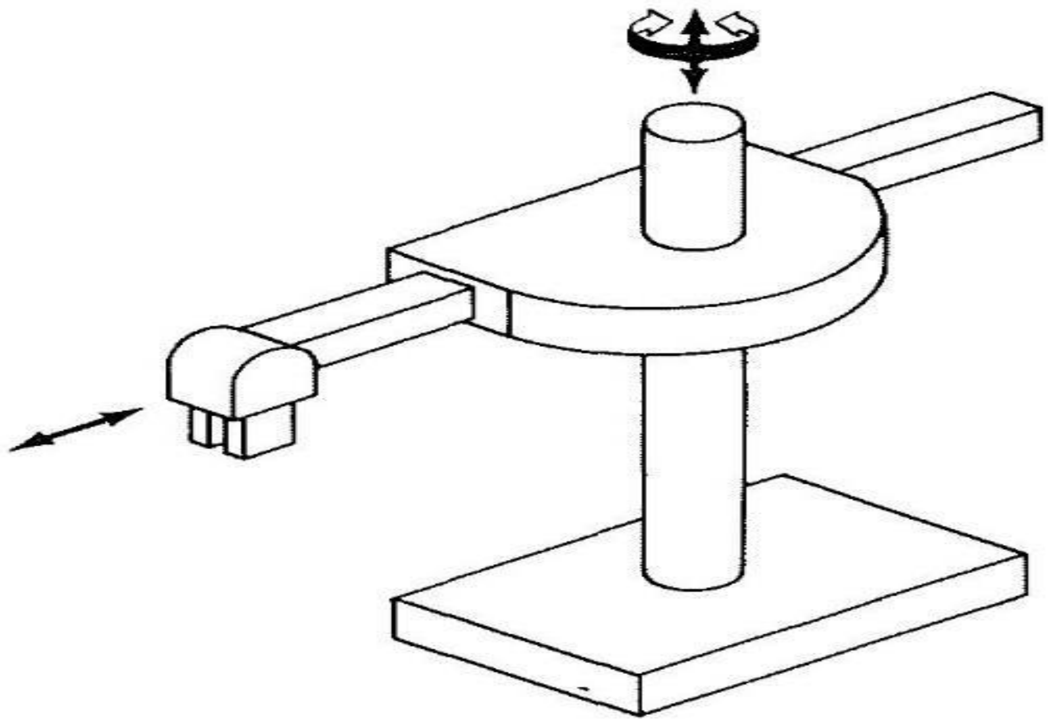
1. Polar configuration:-



Spherical

The polar configuration is pictured in part (a) of Fig. It uses a telescoping arm that can be raised or lowered about a horizontal pivot The pivot is mounted on a base. These various joints provide the robot with the capability to move its arm within a spherical space, and hence the name “spherical coordinate” robot is sometimes applied to this type. A number of commercial robots possess the polar configuration.

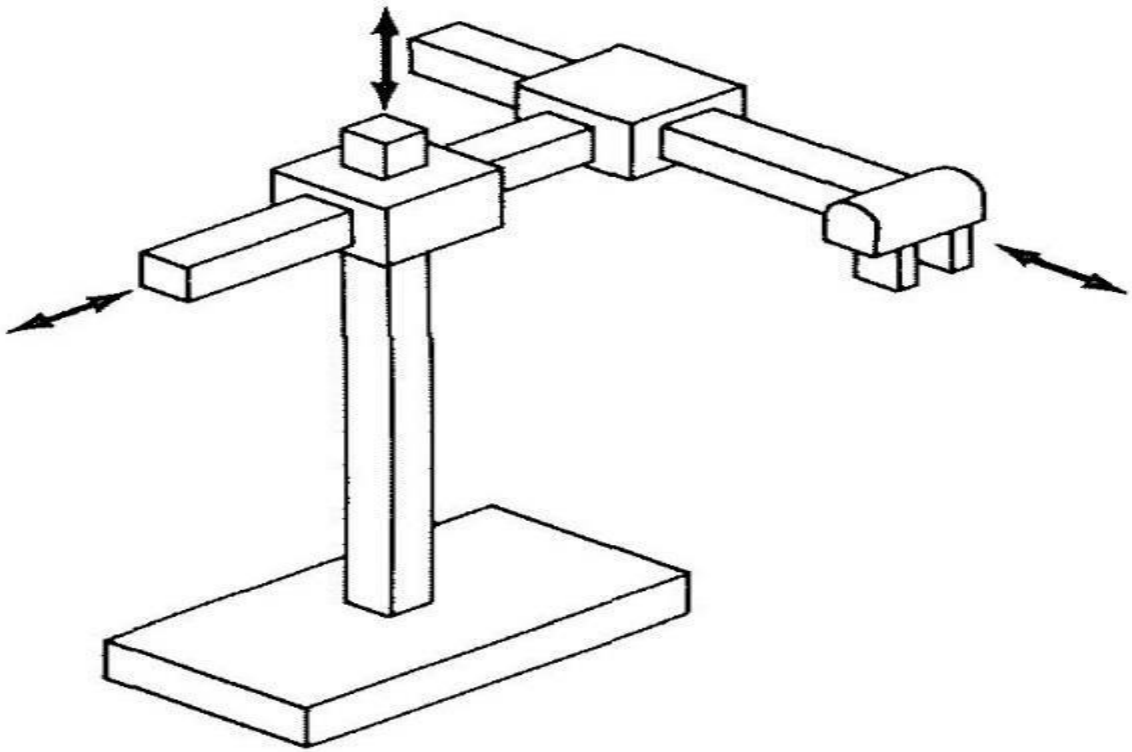
2. Cylindrical configuration:-



Cylindrical

The cylindrical configurable, as shown in fig, uses a vertical column and a slide that can be moved up or down along the column. The robot arm is attached to the slide so that it can he moved radially with respect to the column. By routing the column, the robot is capable of achieving a work space that approximates a cylinder.

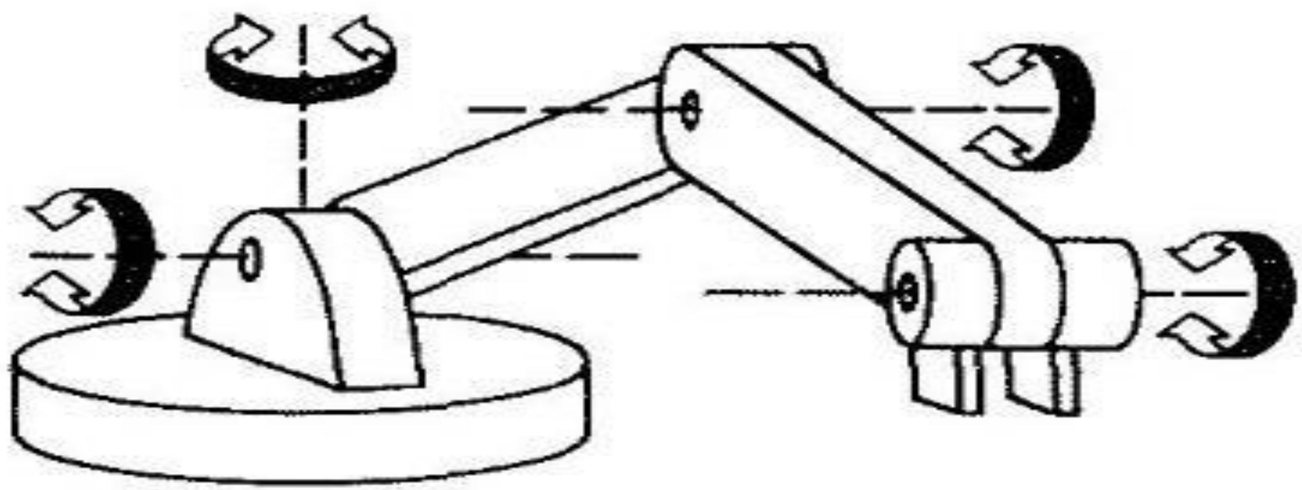
3. Cartesian coordinate configurable:-



Cartesian or *xyz*

The cartesian coordinate robot, illustrated in Fig, uses three perpendicular slides to construct the x, y, and z axes. Other names are sometimes applied to this configuration, including xyz robot and rectilinear robot. By moving the three slides relative to one another, the robot is capable of operating within a rectangular work envelope.

4. Jointed-arm configuration:-



Revolute

The jointed-arm robot is shown in Fig. Its configuration is similar to that of the human arm. It consists of two straight components. Corresponding to the human forearm and upper arm, mounted on a vertical pedestal. These components are connected by two rotary joints corresponding to the shoulder and elbow.

CONTROL SYSTEMS

1. Limited sequence robots (Non-servo):-

Limited sequence robots do not give servo controlled to inclined relative positions of the joints, instead they are controlled by setting limit switches & are mechanical stops. There is generally no feed back associated with a limited sequence robot to indicate that the desired position, has been achieved generally thin type of robots involves simple motion as pick & place operations.

2. Point to point motion:-

This type robots are capable of controlling velocity acceleration & path of motion, from the beginning to the end of the path. It uses complex control programs, PLC's (programmable logic controller's) computers to control the motion.

The point to point control motion robots are capable of performing motion cycle that consists of a series of desired point location. The robot is tough & recorded, unit.

3. Continuous path motion:-

These robots are capable of performing motion cycle in which the path followed by the robot in controlled. The robot move through a series of closely space point which describe the desired path.

Ex:- Spray painting, arc welding & complicate assembly operations.

4. Intelligent robots:-

These type of robots not only programmable motion cycle but also interact with it's environment. in a way that years intelligent. It can make logical decisions based on sensor data received from the operation.

There robots are usually programmed using an English like symbolic language not like a computer programming language.

Precision of movement (or) parameters of robot:-

The preceding discussion of response speed and stability is concerned with the dynamic performance of the robot. Another measure of performance is precision of the robot's movement. We will define precision as a function of three features:

1. Spatial resolution
2. Accuracy
3. Repeatability

These terms will be defined with the following assumptions.
(i) The definitions will apply at the robot's wrist end with no hand attached to the wrist.
(ii) The terms apply to the worst case conditions, the conditions under which the robot's precision will be at its wont. This generally means that the robot's arm is fully extended in the case of a jointed arm or polar configurable.
(iii) Third, our definitions will he developed in the context of a point-to-point robot.

1. Spatial resolution:-

The spatial resolution of a robot is the smallest increment of movement into which the robot can divide its work volume. Spatial resolution depends on two factors: the system's control resolution and the robot's mechanical inaccuracies. It is easiest to conceptualize these factors in terms of a robot with 1 degree of freedom.

The no. of increments $=2^{n}$

Where n = the number of bits in the control memory.

The control resolution = $Total\ moments\ range / The\ number\ of\ increments$

Example 2-1 Using our robot with 1 degree of freedom as an illustration, we will assume it has one sliding joint with a full range of 1.0 m (39.37 in.). The robot's control memory has a 12-bit storage capacity. The problem is to determine the control resolution for this axis of motion.

The number of control increments can be determined as follows:

$$\text{Number of increments} = 2^{12} = 4096$$

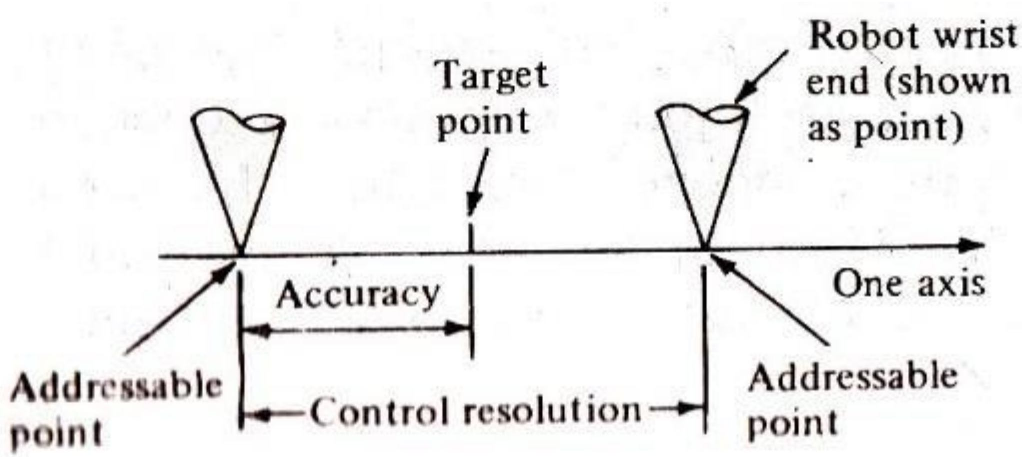
The total range of 1 m is divided into 4096 increments. Each position will be separated by

$$1\text{ m}/4096 = 0.000244\text{ m} \qquad \text{or} \qquad 0.244\text{ mm}$$

The control resolution is 0.244 mm (0.0096 in.).

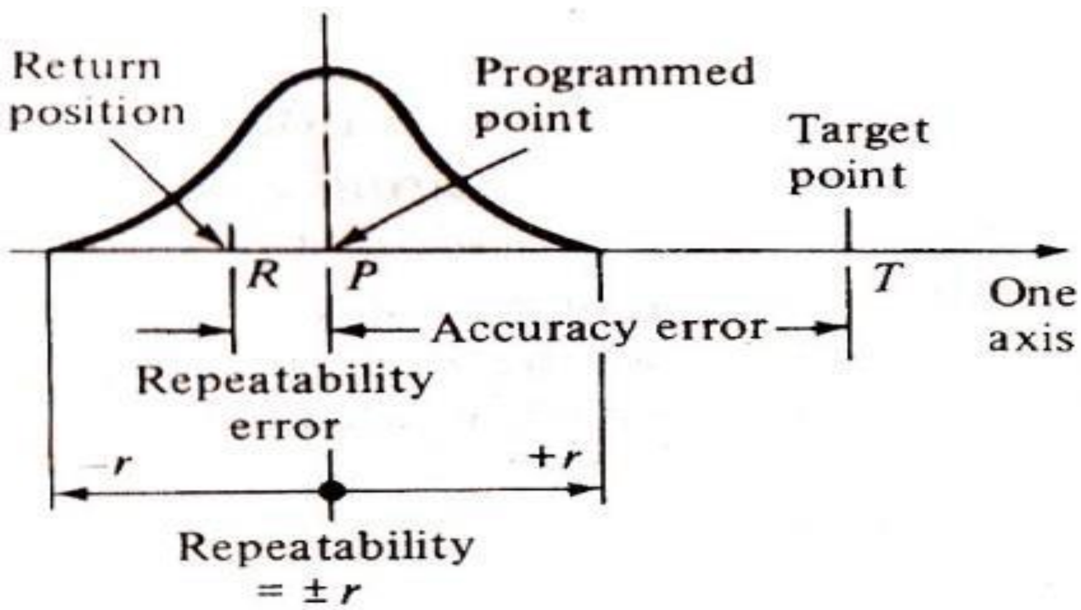
2. Accuracy:-

Accuracy refers to a robot's ability to position its wrist end at a desired target point within the work volume. The accuracy of a robot can be denned in terms of spatial resolution because the ability to achieve a given target point depends on how closely the robot can define the control increments for each of its joint motions.



3. Repeatability:-

Repeatability is concerned with the robot's ability to position its wrist or an end effector attached to its wrist at a point in space is known as repeatability. Repeatability and accuracy refer to two different aspects of the robot’s precision. Accuracy relates to the robot's capacity to be programmed to achieve a given target point. The actual programmed point will probably be different from the target point due to limitations of control resolution Repeatability refers to the robot’s ability to return to the programmed point when commanded to do so.



COMPONENTS OF INDUSTRIAL ROBOTICS

Main components of robot:-

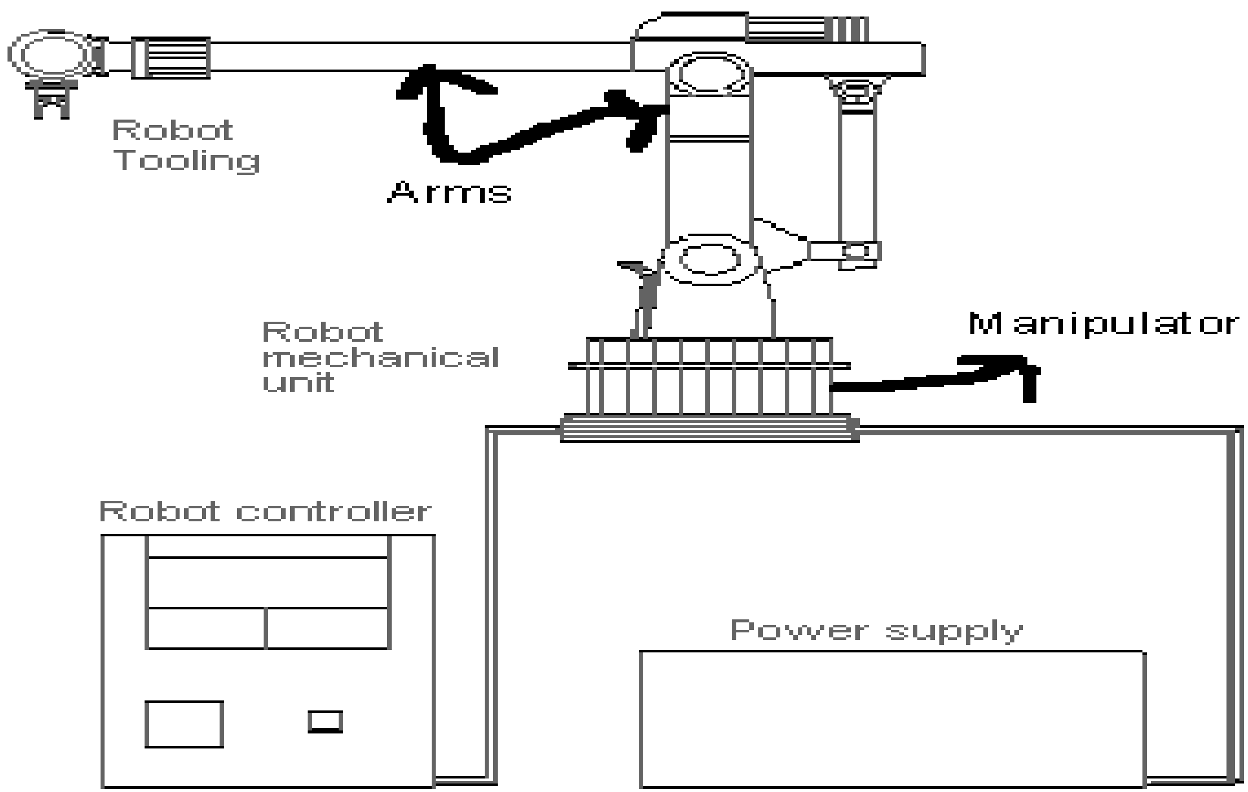
A typical stand-alone robot shown in fig below, comprises of the following basic components, namely.

1.Manipulator

2.Sensors devices

3.Robot Tooling

4.Robot controller unit (RCU)



1.Manipulator:

It consists of base, arm, & wrist similar to a human arm. It also includes power source either electric, hydraulic or pneumatic on receiving signals from robot controller this mechanical unit will be activated. The movement of manipulator can be in relation to it’s coordinate system. Which may be cartesian, cylindrical..etc.
Depending on the controller, movement may be point to point motion or continuous motion.
The manipulator is composed of 3 divisions,
i.The major linkages ii. The minor linkages (wrist components) iii. The end effectors (gripper or tool)

2. Sensors devices:
These elements in form the robot controller about the status of the manipulator. These sensors can be either analog or digital and combination. These are…
i. visual ii. Non – visual

3. Robot Tooling:

Robot tooling is nothing but hand or gripper of the robot also called as the “” end effector”. It is provided at the end of the arm. It is design depends on the nature of the work to be performed by the robot.

4. Robot controller unit (RCU):

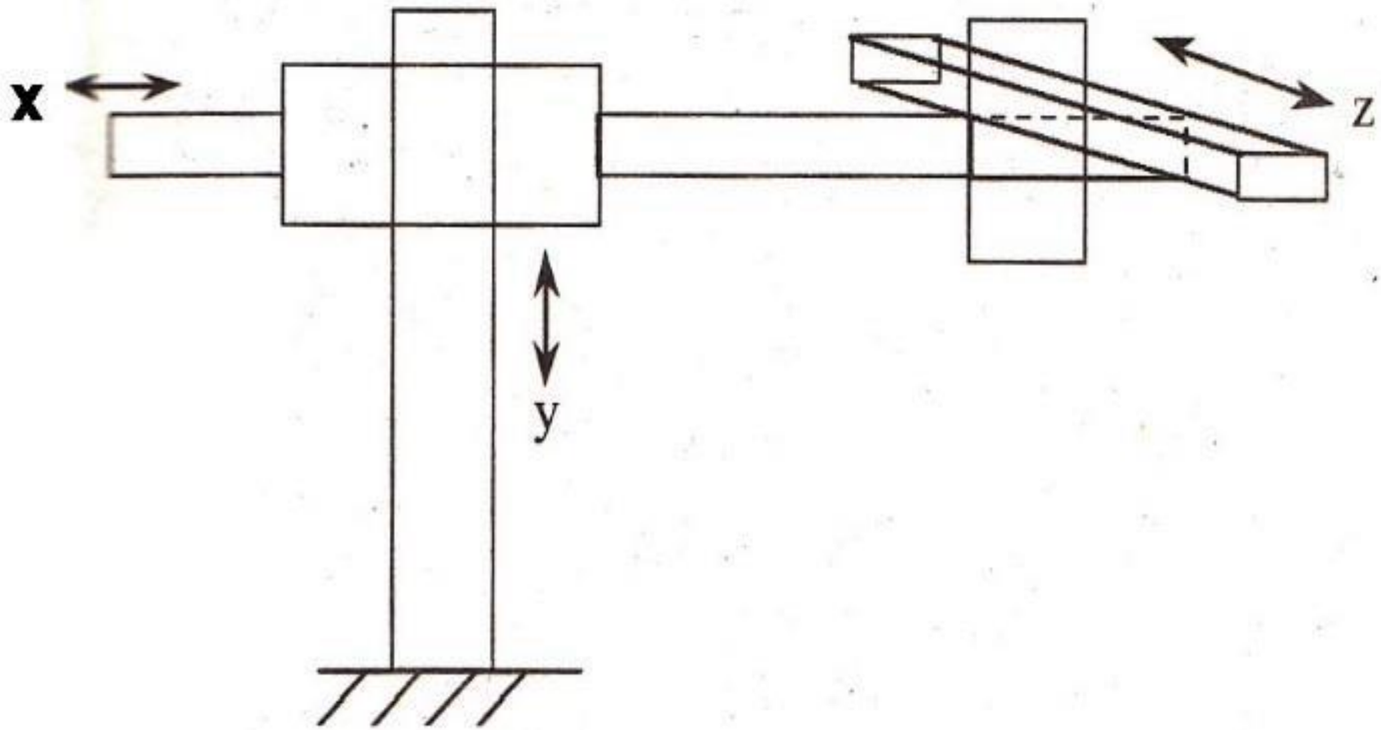
The instructions to the robot to perform the desired tasks are input through the key board of this unit. The controller converts the input programs to suitable signals which activate the manipulator to perform the desired tasks.

Types of robot arms OR function line diagram representation of robot arms:-

The arms of the robot classified as following:

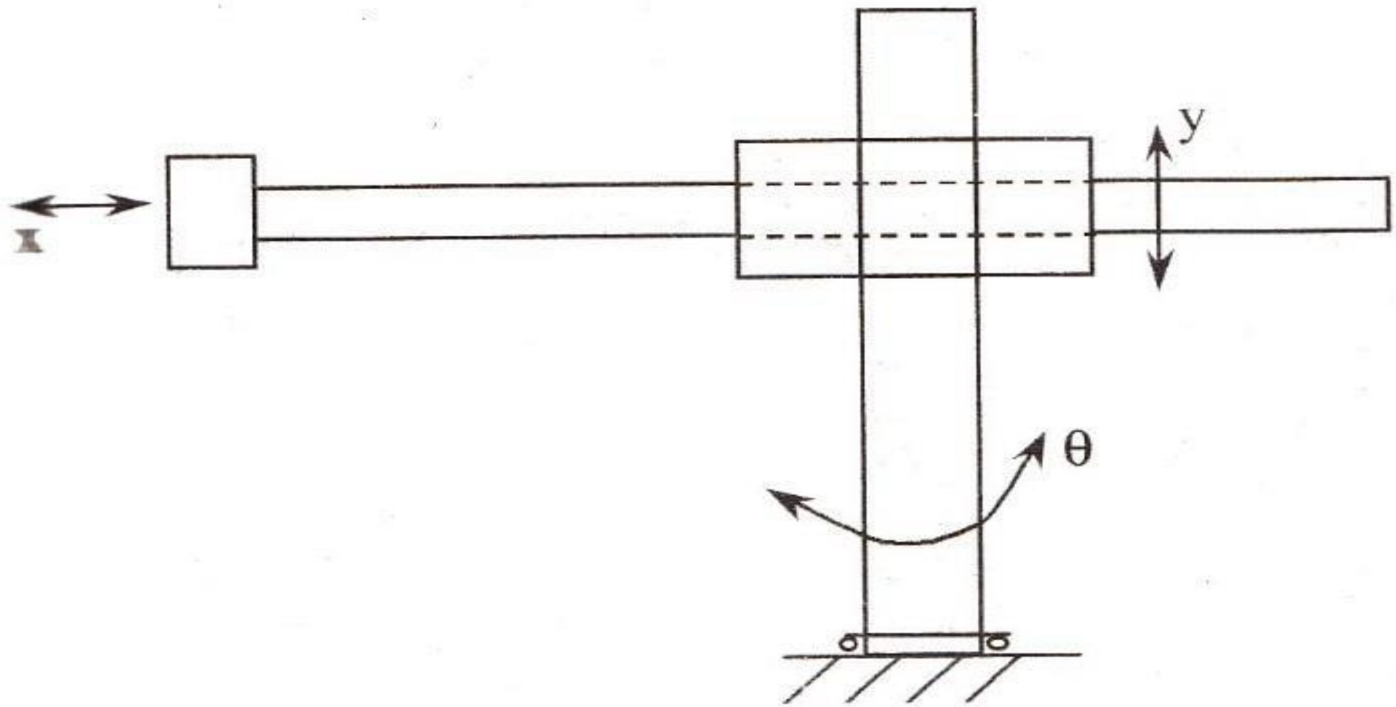
i. Cartesian robot
ii. Cylinder robot
iii. Polar robot
iv. Joint arm

i. cartesian robot:



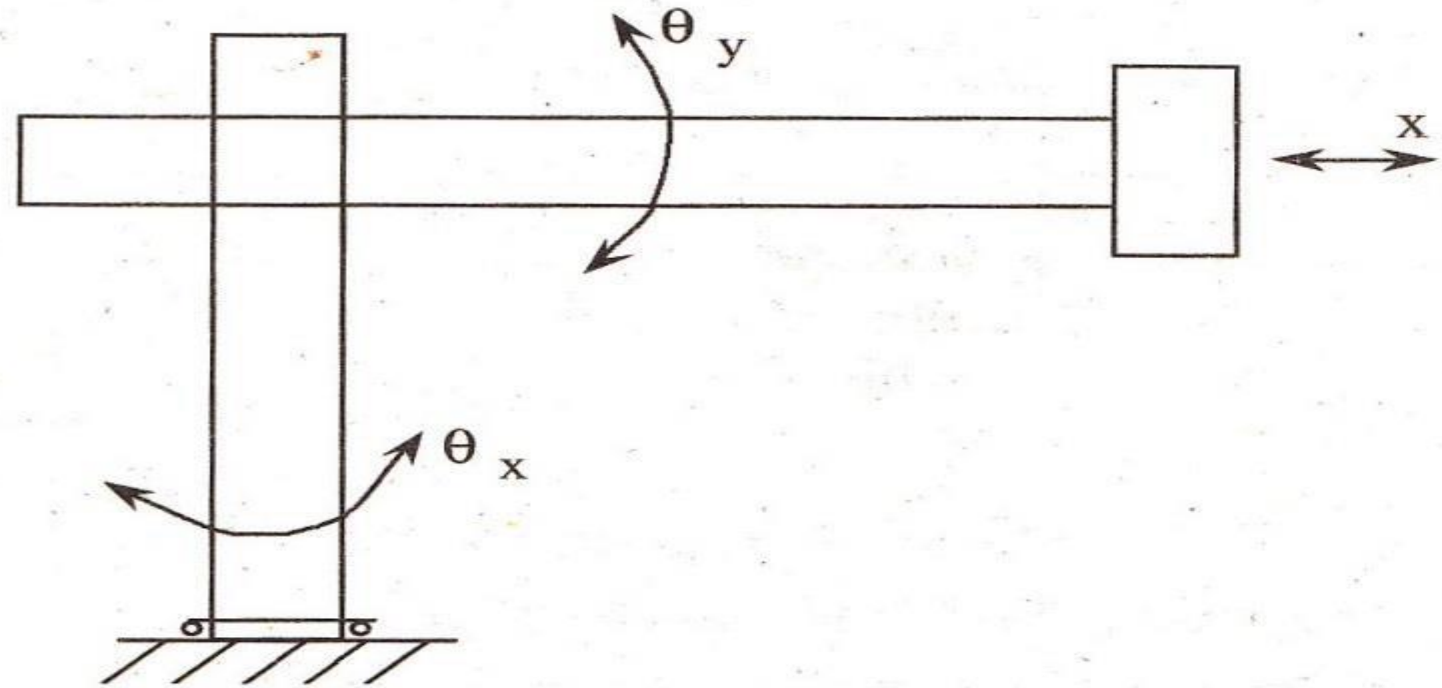
Cartesian robot has simplest configuration with prismatic joints. The work envelope of cartesian robot is cuboidal. It has large work volume but low density. It consists of 3 linear axes.

ii. Cylinder robot:



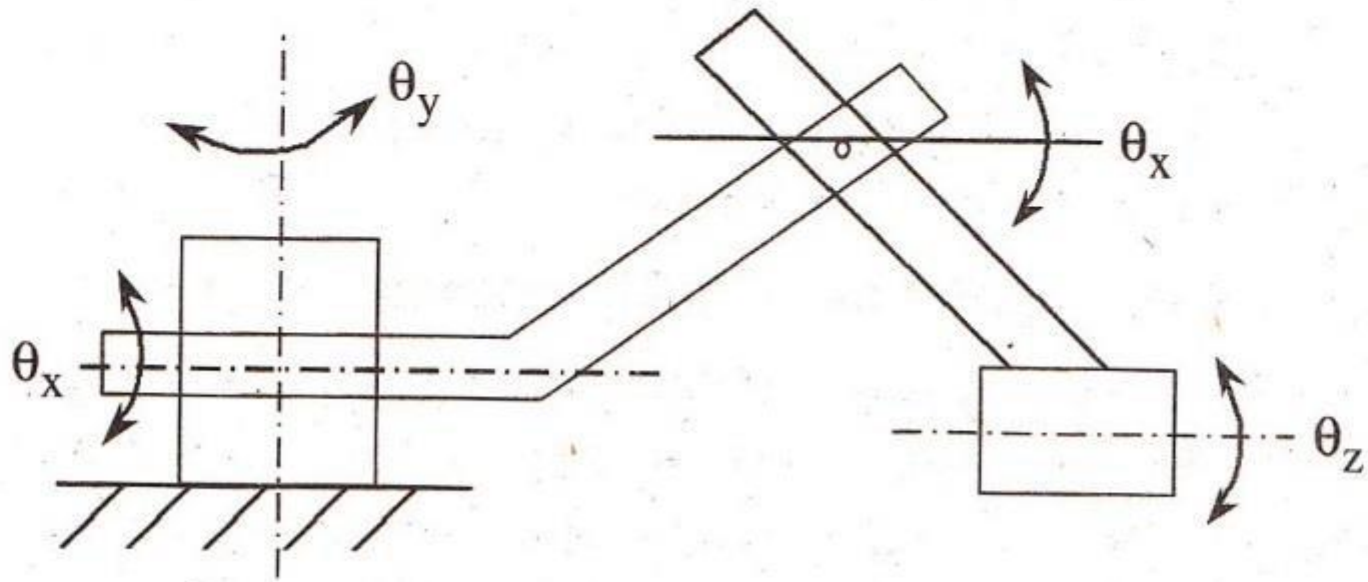
Cylinder robot makes use of two perpendicular prismatic joint and one revolute joint. The work envelope of cylinder robot approximates to a cylinder. It consists of two linear and one rotary axes.

iii. Polar robot:



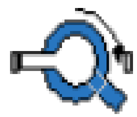
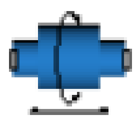
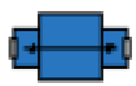
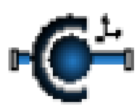
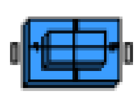
Polar robot consists of a rotating base, a telescopic link which can be raised or lowered about a horizontal revolute joint. It has a work envelope of a partial spherical shell. It consists of one linear and two rotary axes.

iv. Joint arm robot:



Joint arm robot also known as anthropomorphic robot. It functions similar to the human arm. It consists of two straight links. Similar to the human forearm and upper arm. These two links are mounted on rotary table and has a work envelope of spherical shape. It is the most dexterous one since all the joints are revolute joints. It consists of 3 rotary axes.

Table 1: Types 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 kinematics

Manipulator kinematics is the field of science that investigates the motion of manipulator links without regard to the forces that cause it. In that case the motion is determined with trajectory, i.e. positions, velocity, acceleration, jerk and other higher derivative components.

Control procedure of a robot includes several sequential steps to realize the program instruction and reference motion between a given starting and a destination positioning point (x_2, y_2, z_2) in a robot's working envelope. Generally these steps are as follows:

1. Detection of signals from position sensors located on the drive motor shaft and determination of rotation angles (e.g. α_a, β_a, γ_a) of manipulator links in the joint coordinate system.
2. Calculation of the real location of the manipulator gripper or the tool in the base or world Cartesian coordinate system x_a, y_a, z_a, i.e. solving the direct kinematics task of the manipulator using angles (α_a, β_a, γ_a) in joint coordinates.
3. Comparison of the real position with the given motion destination point location in the base or world coordinates; planning of motion trajectory between the start and destination points in a robot's working envelope space; determination of reference time diagrams for position, velocity, acceleration and jerk of manipulator gripper or tool, using linear or circular interpolation for trajectory generation.
4. Determination of motion time dependent reference coordinates in the Cartesian coordinate system (projections x_r, y_r, z_r).
5. Determination of motion time dependent joint reference coordinates (α_r, β_r, γ_r), i.e. solving the inverse kinematics tasks of the manipulator and transfer of the reference signals to manipulator joint drives.
6. Cyclic repeating of steps 1…5 and stopping the motion in the destination positioning point.

Direct kinematics of a manipulator

To solve a direct kinematics task of a manipulator, the position of the gripper or the tool centre point and gripper or tool orientation coordinates in the base or world coordinates are calculated if the joint angles measured by drive sensors are known in joint coordinates. In other words, the gripper or tool location is calculated according to the measured angles of manipulator joints (links).

Inverse kinematics of a manipulator

To solve an inverse kinematics task of a manipulator, the location of all manipulator joints (links) in joint coordinates is calculated if the gripper or tool reference position and orientation angles are calculated by the trajectory planner in the base or world Cartesian coordinates.

Methods for solving direct kinematics tasks

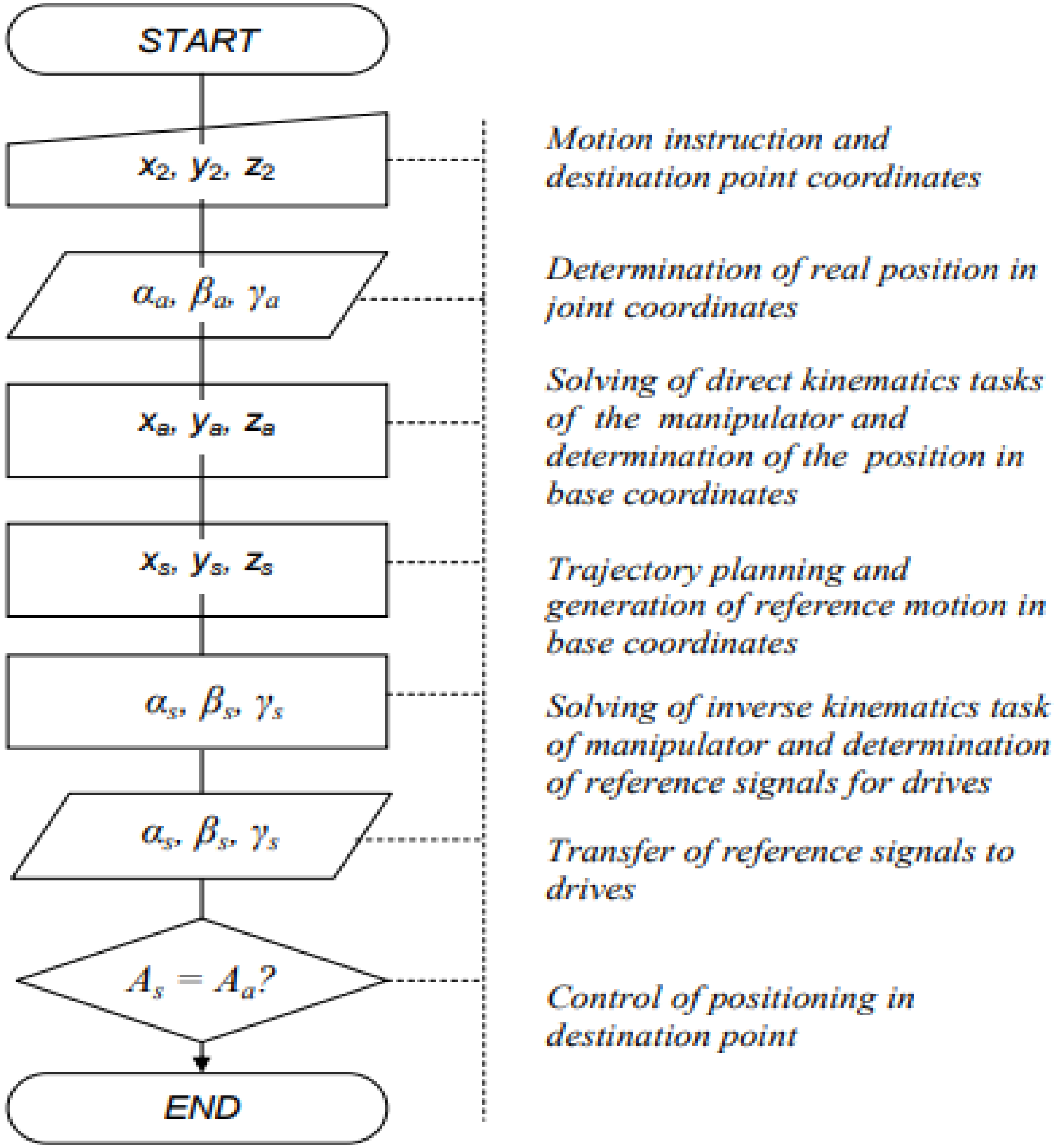
- Geometric method (using basic formulas of geometry and trigonometry)
- Matrix method (using transformation matrixes of coordinate systems)

Methods for solving of inverse kinematics tasks

- Definition of manipulator joints relative locations (pose) if multiple solutions exist.

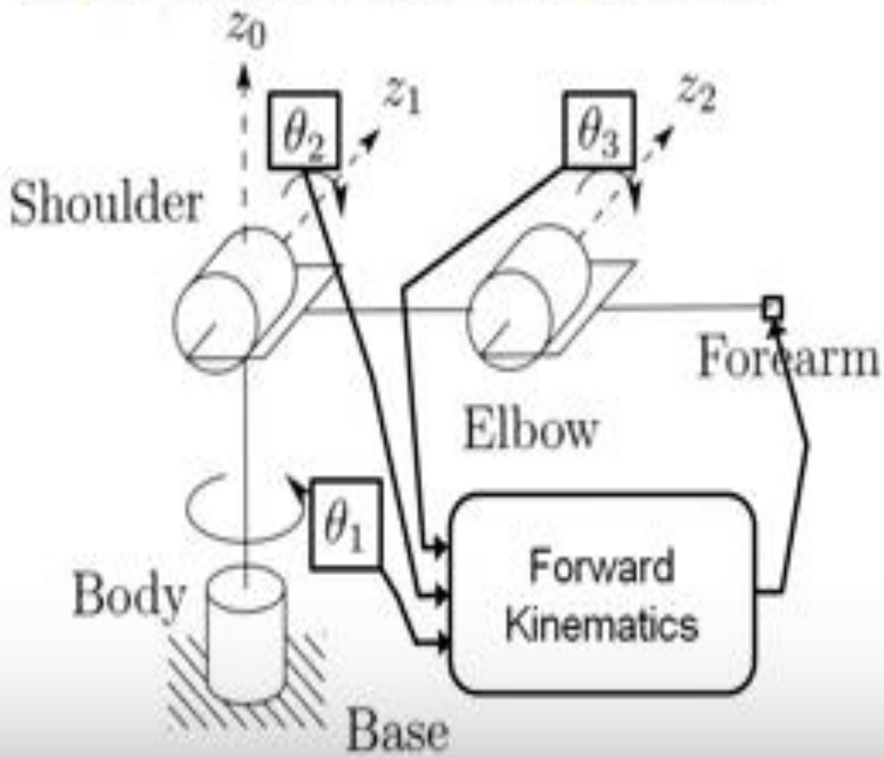
- Closed form solutions and iterative numerical solutions. Generally all systems with revolute and prismatic joints having a total of six degrees of freedom (DOF) as a single series chain are solvable.

The flow diagram for the trajectory and motion control of manipulator



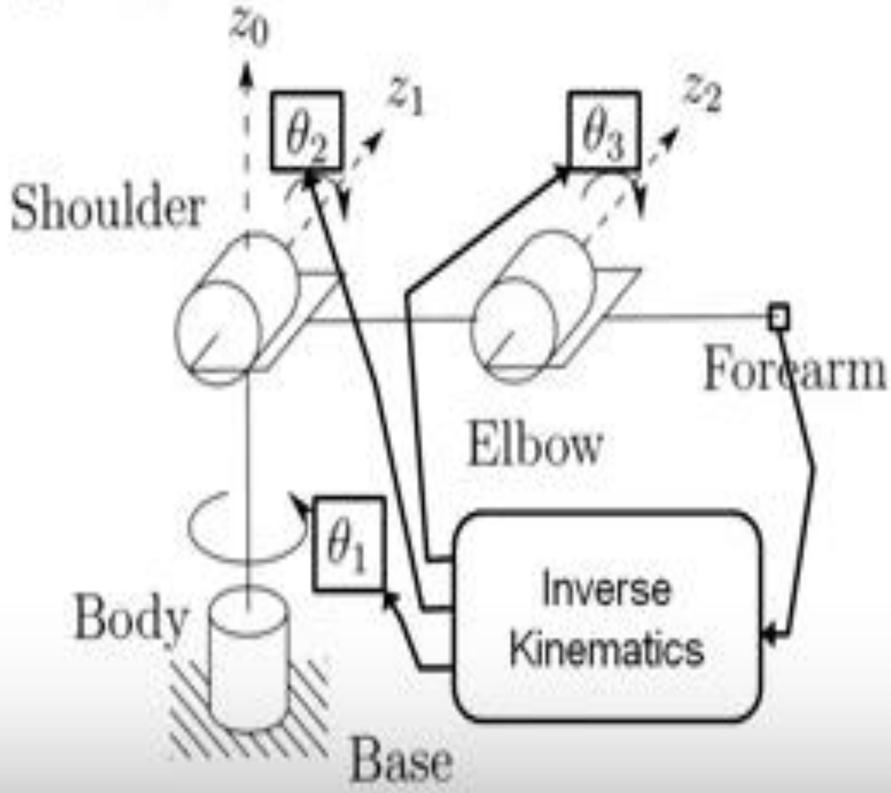
Forward Kinematics

- Finding the position and orientation of the tool point from the joint angles.



Inverse Kinematics

- Finding the joint angles to set a particular position and orientation of the tool point.



Coordinate systems (mostly based on ANSI R15-1)

Joint coordinate system: defined in each joint (θ_1, θ_2, ... θ_N). For rotational joint, it can be angles. The direct joint parameters can also be pulses or encoder counts.

World coordinate system: A Cartesian coordinate system (X, Y, Z, A, B, Z) with arbitrary location.

Base coordinate system: A Cartesian coordinate system (X_0, Y_0, Z_0, A_0, B_0, Z_0), with its origin at the base of the robot mounting plate. For robot with rotational first joint, the z-axis is vertical coincide with first joint (waist rotation). For robot with linear first joint, the origin is at the intersection of midpoint of travel of the fist axis and mounting surface. In addition,

X_0 : from origin to projection of center point of the work envelop.

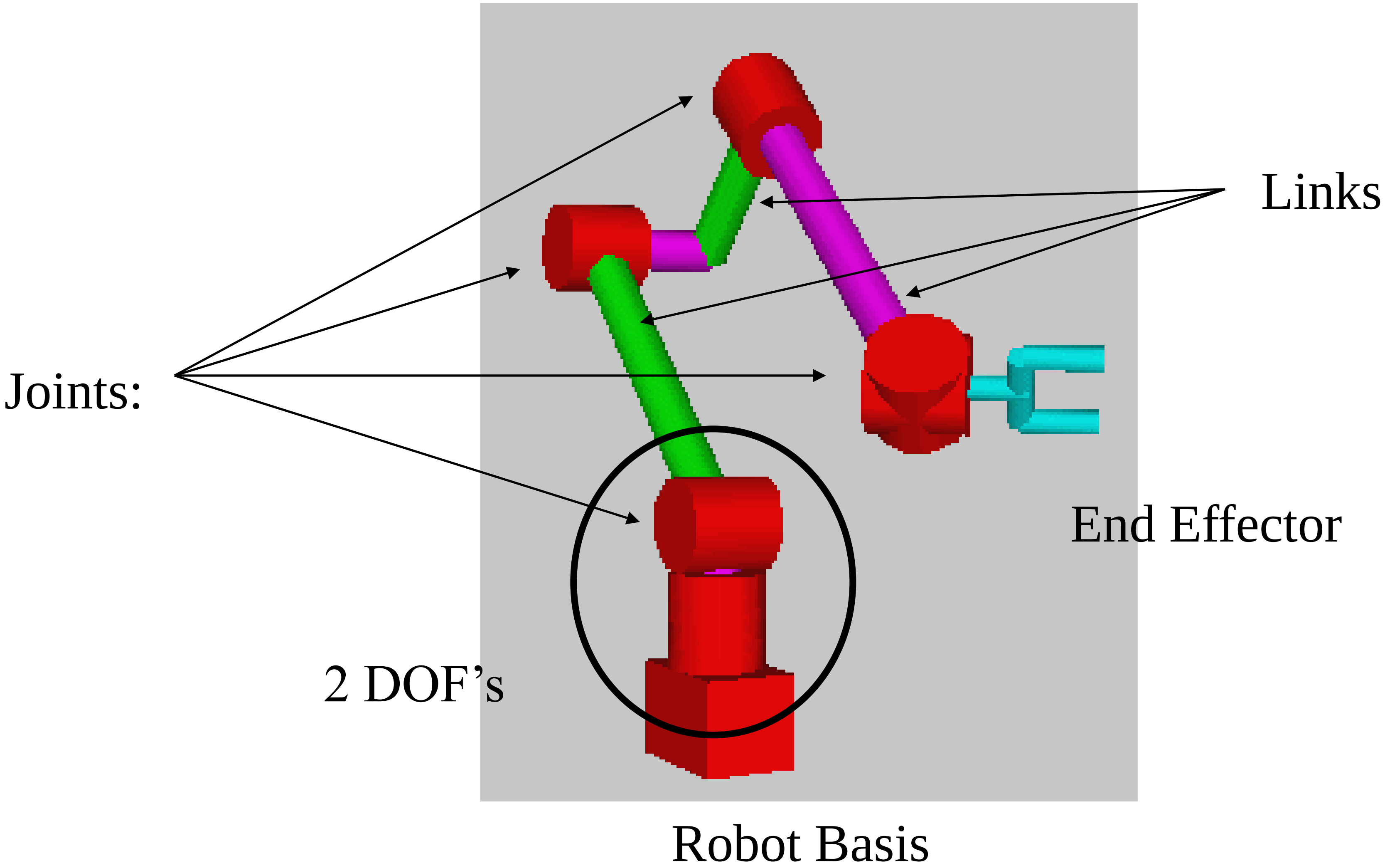
Z_0 : from origin away from base plate.

Tool interface coordinate system (X_t, Y_t, Z_t, A_t, B_t, Z_t): It is a Cartesian coordinate system defined at the tool mounting plate.

Z_t: Normal of the mounting plate or in the direction of the tool (gripper, nozzle)

X_t: normal to the surface of the gripper.

Links and Joints



Joint Variables

- General joint variable q_i
- Can be either revolute or prismatic (last example revolute only)
- $A_i = A_i(q_i)$ is the transformation matrix from frame $i - 1$ to i, derived from joint and link i.

Kinematic Chain

- The position and orientation of the end effector can be described by the transformation matrix:

$$H = T_n^0 = A_1(q_1)\cdots A_n(q_n) = \begin{bmatrix} R_n^0 & o_n^0 \\ 0 & 1 \end{bmatrix}$$

The challenge: complexity and uniformity

- Could calculate forward kinematics by inspection and reasoning
- Can be very complex!
- Need an approach which everyone can apply which simplifies things wherever possible

Denavit-Hartenberg Convention

- Each A matrix has 6 variables – 3 in the rotation matrix and 3 in the position vector.
- DH parameters collapse 6 variables to 4 **link parameters**, provided we follow a certain procedure for setting coordinate frames.
  - a_i is **link length** of link i
  - α_i is **link twist** of link i

  These don't change unless you reconfigure your robot

  - d_i is **link offset** of link i ← **prismatic variable**
  - θ_i is **joint angle** of joint i ← **revolute variable**

DENAVIT-HARTENBERG REPRESENTATION

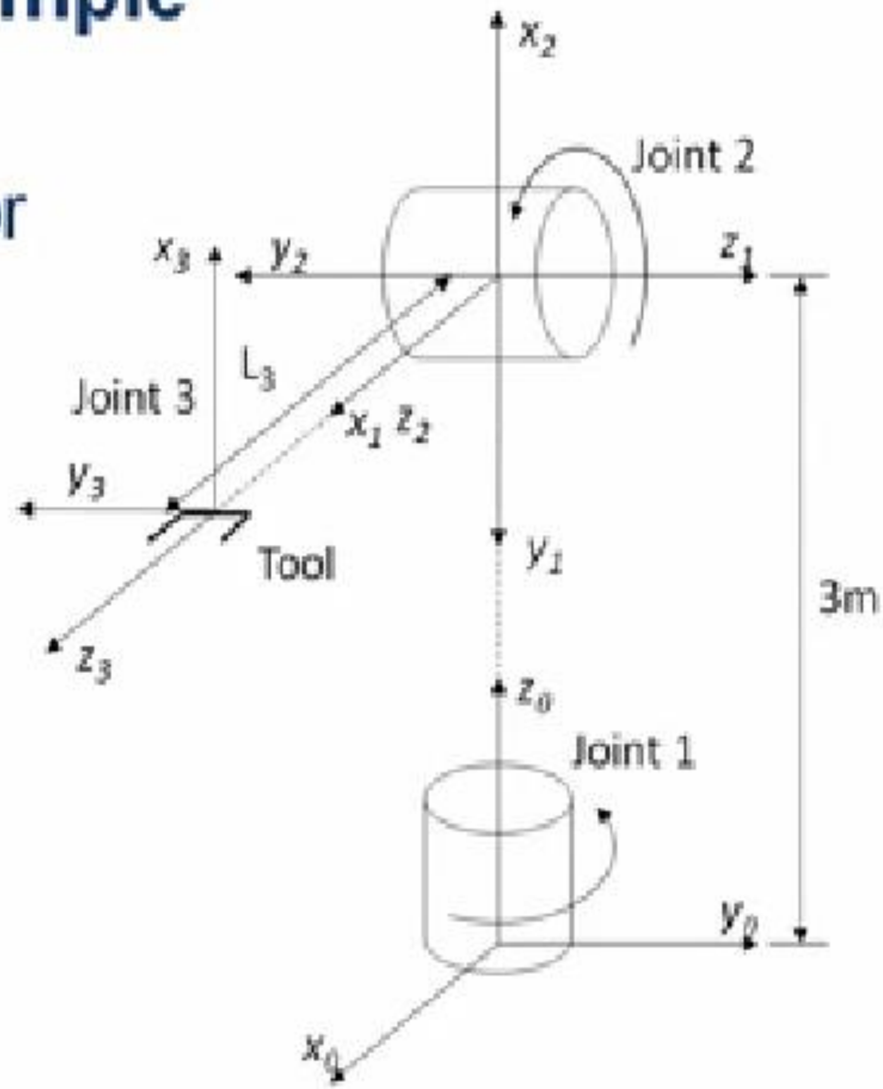
Symbol Terminologies :

- ⊙ $\boldsymbol{\theta}$: A rotation about the *z*-axis.
- ⊙ ***d*** : The distance on the *z*-axis.
- ⊙ ***a*** : The length of each common normal (Joint offset).
- ⊙ **α** : The angle between two successive *z*-axes (Joint twist)

Only θ and d are joint variables.

Example

- Find DH parameters for this robot. Identify the joint variables.



Steps in D-H convention

Step 1: Locate and label the joint axes $z_0, \dots, z_{n-1}$.

Step 2: Establish the base frame. Set the origin anywhere on the z_0-axis. The x_0 and y_0 axes are chosen conveniently to form a right-hand frame.

For $i = 1, \dots, n-1$, perform Steps 3 to 5.

Step 3: Locate the origin O_i where the common normal to z_i and z_{i-1} intersects z_i. If z_i intersects z_{i-1} locate O_i at this intersection. If z_i and z_{i-1} are parallel, locate O_i in any convenient position along z_i.

Step 4: Establish x_i along the common normal between z_{i-1} and z_i through O_i, or in the direction normal to the $z_{i-1} - z_i$ plane if z_{i-1} and z_i intersect.

Step 5: Establish y_i to complete a right-hand frame.

Step 6: Establish the end-effector frame $o_n x_n y_n z_n$. Assuming the n-th joint is revolute, set $z_n = \boldsymbol{a}$ along the direction z_{n-1}. Establish the origin O_n conveniently along z_n, preferably at the center of the gripper or at the tip of any tool that the manipulator may be carrying. Set $y_n = \boldsymbol{s}$ in the direction of the gripper closure and set $x_n = \boldsymbol{n}$ as $\boldsymbol{s} \times \boldsymbol{a}$. If the tool is not a simple gripper set x_n and y_n conveniently to form a right-hand frame.

Step 7: Create a table of link parameters a_i, d_i, α_i, θ_i.

$a_i =$ distance along x_i from O_i to the intersection of the x_i and z_{i-1} axes.

$d_i =$ distance along z_{i-1} from O_{i-1} to the intersection of the x_i and z_{i-1} axes. d_i is variable if joint i is prismatic.

$\alpha_i =$ the angle between z_{i-1} and z_i measured about x_i (see Figure 3.3).

$\theta_i =$ the angle between x_{i-1} and x_i measured about z_{i-1} (see Figure 3.3). θ_i is variable if joint i is revolute.

Step 8: Form the homogeneous transformation matrices A_i by substituting the above parameters into (3.10).

Step 9: Form $T_n^0 = A_1 \cdots A_n$. This then gives the position and orientation of the tool frame expressed in base coordinates.

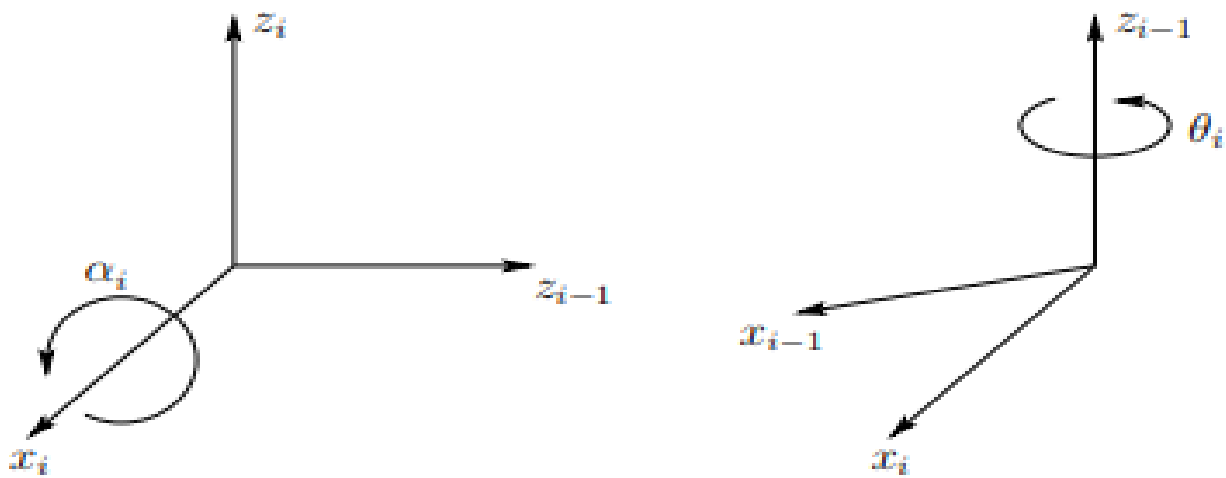


Figure 3.3: Positive sense for α_i and θ_i.

DENAVIT-HARTENBERG REPRESENTATION

Procedures for assigning a local reference frame to each joint:

1. * All joints are represented by a *z*-axis.
   - (right-hand rule for rotational joint, linear movement for prismatic joint)

2. The common normal is one line mutually perpendicular to any two skew lines.

3. Parallel *z*-axes joints make a infinite number of common normal.

4. Intersecting *z*-axes of two successive joints make no common normal between them(Length is 0.).

•DENAVIT-HARTENBERG REPRESENTATION

The necessary motions to transform **from one reference frame** to the next.

(I) Rotate about the z_n-axis an able of θ_{n+1}. (Coplanar)

(II) Translate along z_n-axis a distance of d_{n+1} to make x_n and x_{n+1} colinear.

(III) Translate along the x_n-axis a distance of a_{n+1} to bring the origins of x_{n+1} together.

(IV) Rotate z_n-axis about x_{n+1} axis an angle of α_{n+1} to align z_n-axis with z_{n+1}-axis.

In this convention, each homogeneous transformation Ai is represented as a product of four basic transformations

DH Matrix

Should look familiar!

$$A_i = \mathrm{Rot}_{z,\theta_i}\mathrm{Trans}_{z,d_i}\mathrm{Trans}_{x,a_i}\mathrm{Rot}_{x,\alpha_i}$$

$$= \begin{bmatrix} c_{\theta_i} & -s_{\theta_i} & 0 & 0 \\ s_{\theta_i} & c_{\theta_i} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{\alpha_i} & -s_{\alpha_i} & 0 \\ 0 & s_{\alpha_i} & c_{\alpha_i} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{\theta_i} & -s_{\theta_i}c_{\alpha_i} & s_{\theta_i}s_{\alpha_i} & a_i c_{\theta_i} \\ s_{\theta_i} & c_{\theta_i}c_{\alpha_i} & -c_{\theta_i}s_{\alpha_i} & a_i s_{\theta_i} \\ 0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rules for Assigning Frames

Rule 1: z_{i-1} is axis of actuation of joint i.

Axis of revolution of revolute joint

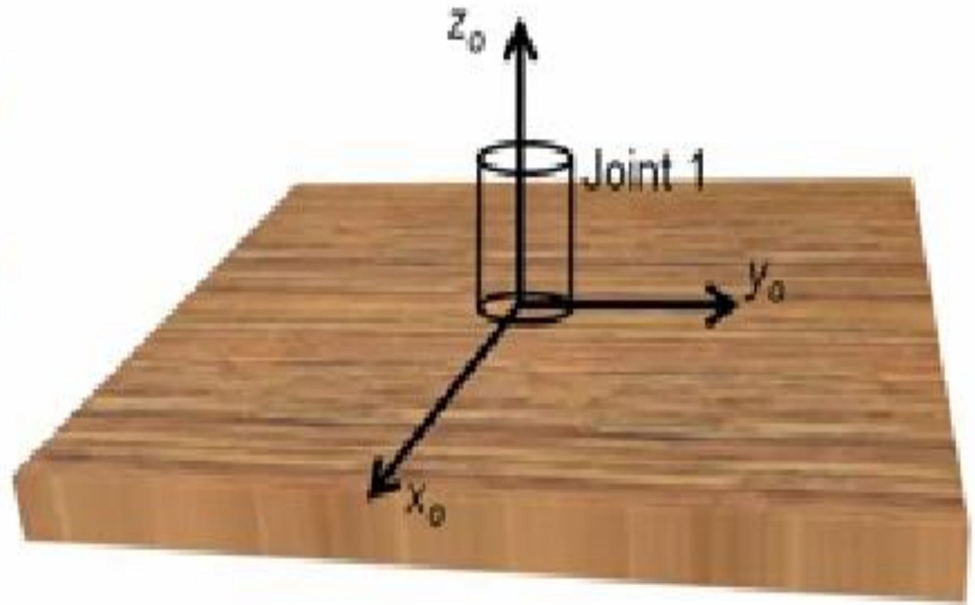
Axis of translation of prismatic joint

Rule 2: Axis x_i is set so it is perpendicular to and intersects z_{i-1}.

Rule 3: Derive y_i from x_i and z_i.

Rule 1: Base Frame

- z_0 is the axis of actuation of joint 1.
- x_0 and y_0 are set as convenient, provided they make right handed set.
  - Usually set to a useful reference such as orientation of work cell or table.

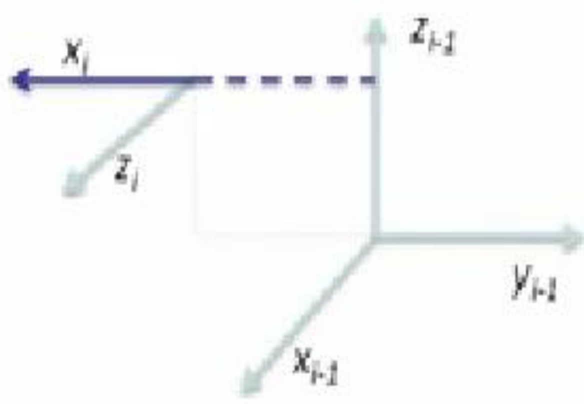


Rule 1: Tool Frame

- **Where rules allow**
  - z_n is the **approach** direction of the tool
  - y_n is the **slide** direction of the gripper
  - x_n is the **normal** direction to other axes

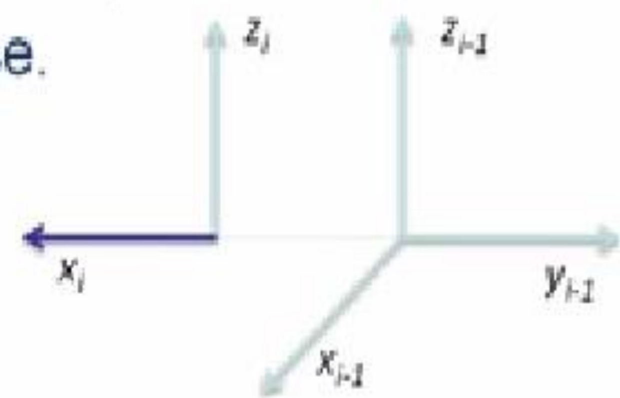
Rule 2: Case 1

- **z_{i-1} and z_i are not coplanar**
  - There is only one line possible for x_i, which is the shortest line from z_{i-1} to z_i.
  - o_i is at intersection of x_i and z_i.



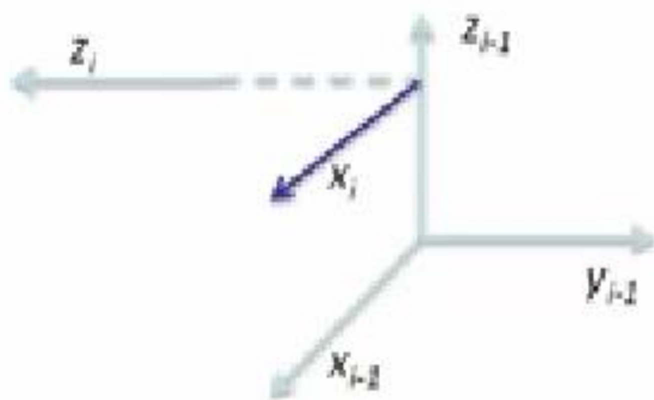
Rule 2: Case 2

- **z_{i-1} and z_i are parallel**
  - There are an infinite number of possibilities for x_i from z_{i-1} to z_i.
  - Usually easiest to choose an x_i that passes through o_{i-1} (so that $d_i = 0$).
  - o_i is at intersection of x_i and z_i.
  - $\alpha_i = 0$ always for this case.



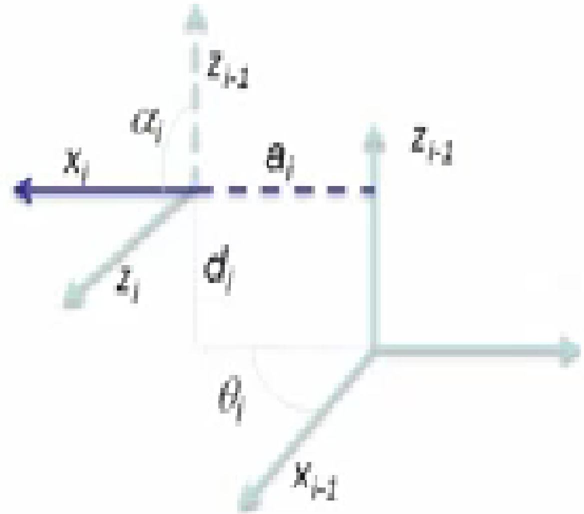
Rule 2: Case 3

- **z_{i-1} intersects z_i**
  - x_i is normal to the plane of z_{i-1} and z_i.
  - Positive direction of x_i is arbitrary.
  - o_i naturally sits at intersection of z_{i-1} and z_i but can be anywhere on z_i.
  - a_i = 0 always for this case.



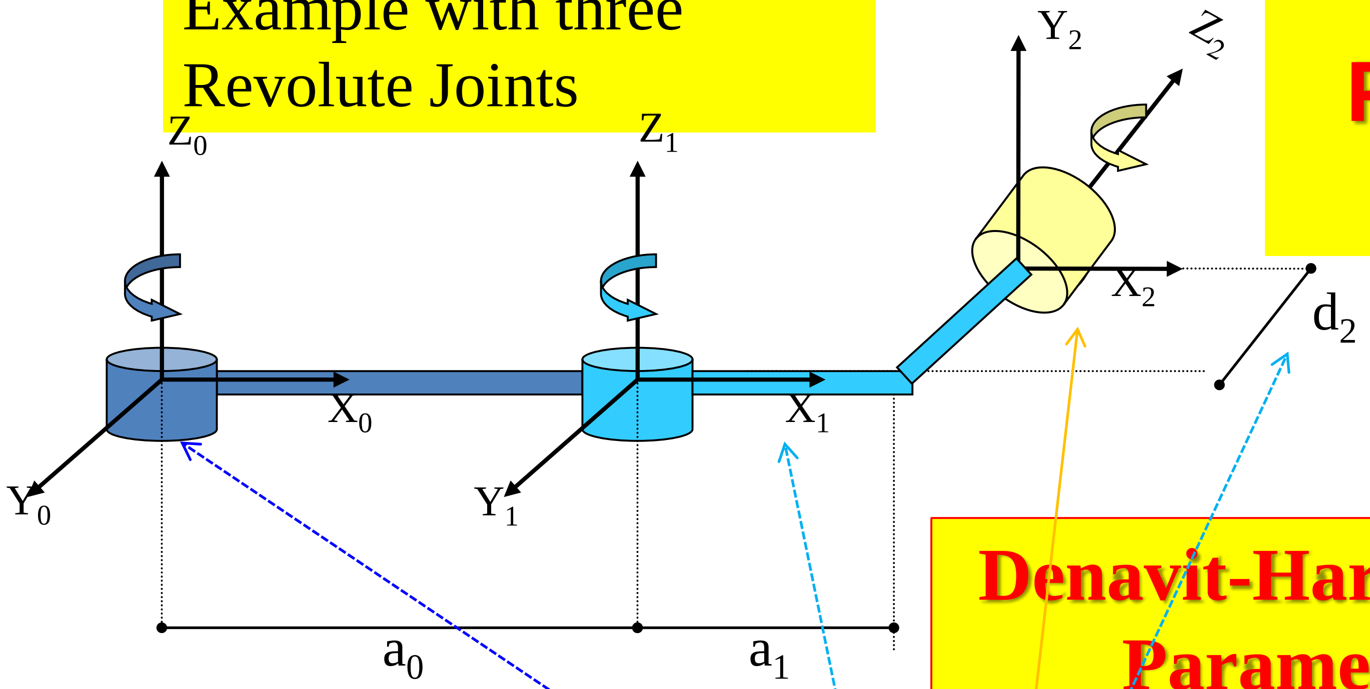
Finding DH parameters

- a_i is distance from z_{i-1} to z_i measured along x_i.
- angle α_i is angle from z_{i-1} to z_i measured about x_i.
- d_i is distance from x_{i-1} to x_i measured along z_{i-1}.
- angle θ_i is from x_{i-1} to x_i measured about z_{i-1}.



The DH Parameter Table

Example with three Revolute Joints



Notice that the table has two uses:

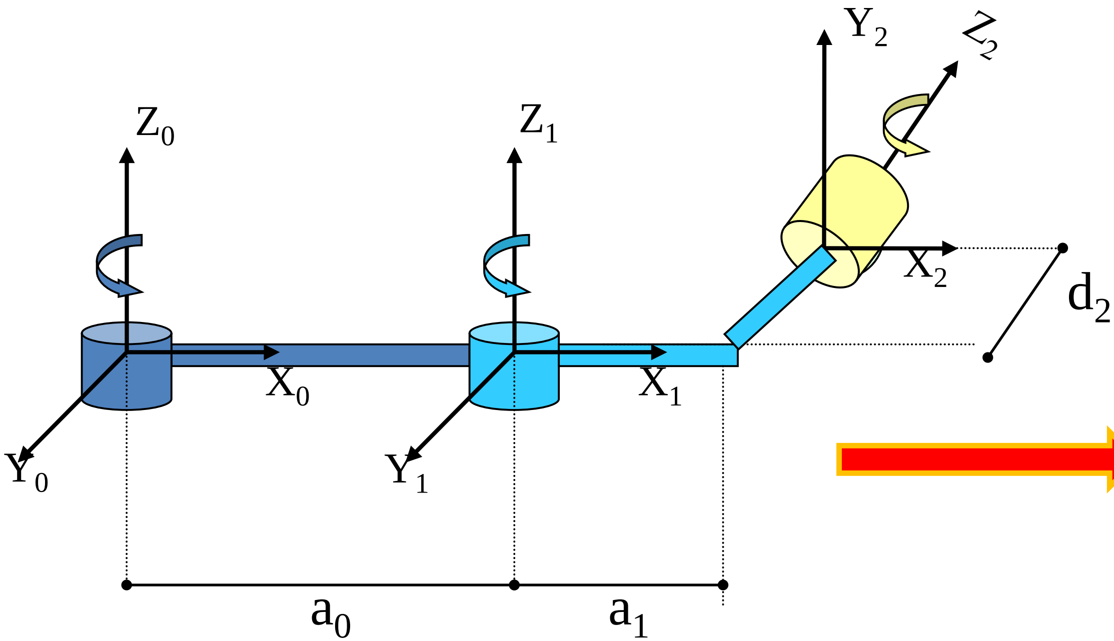
1) To describe the robot with its variables and parameters.

2) To describe some state of the robot by having a numerical values for the variables.

Denavit-Hartenberg Link Parameter Table

i	$\alpha_{(i-1)}$	$a_{(i-1)}$	d_i	θ_i
0	0	0	0	θ_0
1	0	a_0	0	θ_1
2	-90	a_1	d_2	θ_2

We calculate with respect to previous Θ



i	$\alpha_{(i-1)}$	$a_{(i-1)}$	d_i	θ_i
0	0	0	0	θ_0
1	0	a_0	0	θ_1
2	-90	a_1	d_2	θ_2

The same table as last slide

$$\mathbf{V}^{X_0 Y_0 Z_0} = \mathbf{T}\begin{bmatrix} \mathbf{V}^{X_2} \\ \mathbf{V}^{Y_2} \\ \mathbf{V}^{Z_2} \\ \mathbf{1} \end{bmatrix}$$

World coordinates

tool coordinates

$$\mathbf{T} = ({}_{0}\mathbf{T})({}^{0}_{1}\mathbf{T})({}^{1}_{2}\mathbf{T})$$

Note: T is the D-H matrix with *(i-1)* = 0 and *i* = 1.

These matrices T are calculated in next slide

The same table as last slide

i	$\alpha_{(i-1)}$	$a_{(i-1)}$	d_i	θ_i
0	0	0	0	θ_0
1	0	a_0	0	θ_1
2	-90	a_1	d_2	θ_2

$$ {}_0\mathbf{T} = \begin{bmatrix} \cos\theta_0 & -\sin\theta_0 & 0 & 0 \\ \sin\theta_0 & \cos\theta_0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

This is just a rotation around the Z_0 axis

$$ {}^0_1\mathbf{T} = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & a_0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

This is a translation by a_0 followed by a rotation around the Z_1 axis

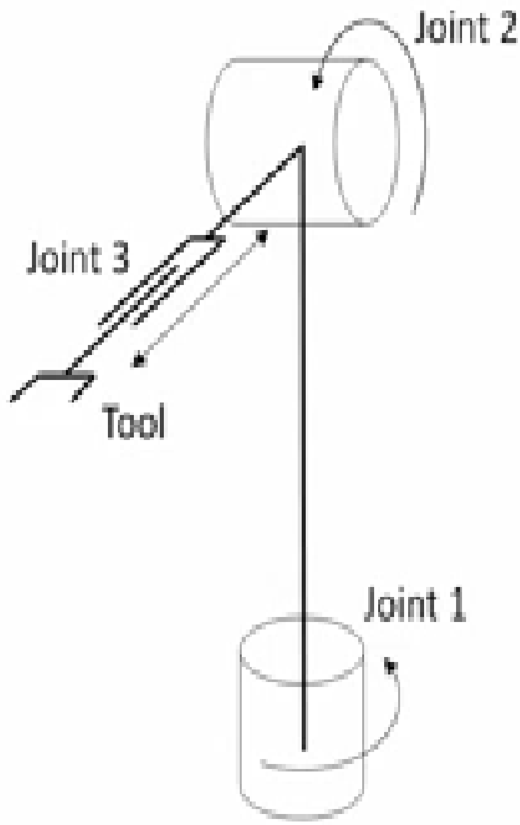
$$ {}^1_2\mathbf{T} = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & a_1 \\ 0 & 0 & 1 & d_2 \\ -\sin\theta_2 & -\cos\theta_2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

This is a translation by a_1 and then d_2 followed by a rotation around the X_2 and Z_2 axis

$$ \mathbf{T} = ({}_0\mathbf{T})({}^0_1\mathbf{T})({}^1_2\mathbf{T}) $$

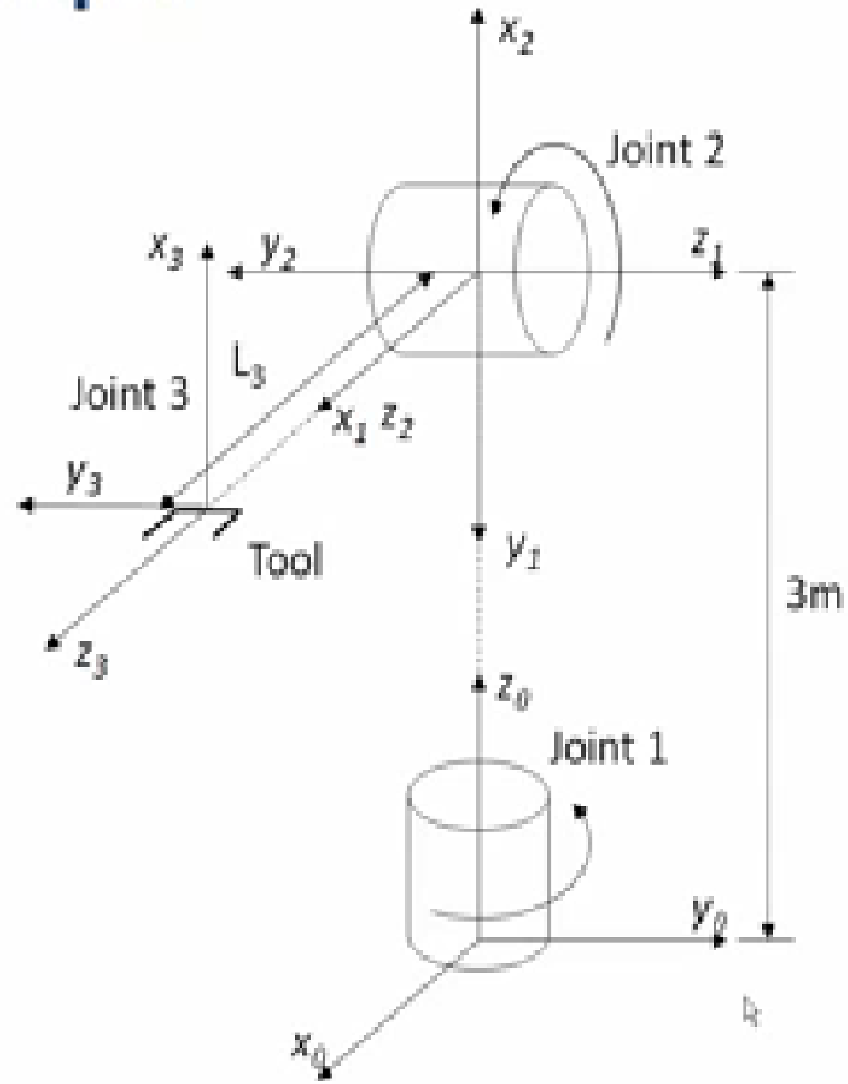
Example

- Assign coordinate frames so that we can find DH parameters for this robot.



Example

- $a_1 = 0$, $\alpha_1 = -90°$,
  $d_1 = 3m$, $\boldsymbol{q_1 = \theta_1 = 0°}$
- $a_2 = 0$, $\alpha_2 = -90°$,
  $d_2 = 0$, $\boldsymbol{q_2 = \theta_2 = -90°}$
- $a_3 = 0$, $\alpha_3 = 0°$,
  $\boldsymbol{q_3 = d_3 = L_3}$, $\theta_3 = 0°$
- Find the A matrices.



Example

- $a_1 = 0,\ \alpha_1 = -90°,$
  $d_1 = 3\text{m},\ q_1 = \theta_1 = 0°$
- $a_2 = 0,\ \alpha_2 = -90°,$
  $d_2 = 0,\ q_2 = \theta_2 = -90°$
- $a_3 = 0,\ \alpha_3 = 0°,$
  $q_3 = d_3 = L_3,\ \theta_3 = 0°$

$$\Rightarrow \begin{bmatrix} c_{\theta_i} & -s_{\theta_i}c_{\alpha_i} & s_{\theta_i}s_{\alpha_i} & a_i c_{\theta_i} \\ s_{\theta_i} & c_{\theta_i}c_{\alpha_i} & -c_{\theta_i}s_{\alpha_i} & a_i s_{\theta_i} \\ 0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_1 = \begin{bmatrix} c_1 & 0 & -s_1 & 0 \\ s_1 & 0 & c_1 & 0 \\ 0 & -1 & 0 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix};\ A_2 = \begin{bmatrix} c_2 & 0 & -s_2 & 0 \\ s_2 & 0 & c_2 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Example

$$T_3^0 = A_1 A_2 A_3$$

First: $T_2^0 = A_1 A_2$

$$A_1 = \begin{bmatrix} c_1 & 0 & -s_1 & 0 \\ s_1 & 0 & c_1 & 0 \\ 0 & -1 & 0 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix}; A_2 = \begin{bmatrix} c_2 & 0 & -s_2 & 0 \\ s_2 & 0 & c_2 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- $a_1 = 0$, $\alpha_1 = -90°$, $d_1 = 3\text{m}$, $q_1 = \theta_1 = 0°$
- $a_2 = 0$, $\alpha_2 = -90°$, $d_2 = 0$, $q_2 = \theta_2 = -90°$
- $a_3 = 0$, $\alpha_3 = 0°$, $q_3 = d_3 = L_3$, $\theta_3 = 0°$

$$T_2^0 = \begin{bmatrix} c_1 c_2 & s_1 & -c_1 s_2 & 0 \\ s_1 c_2 & -c_1 & -s_1 s_2 & 0 \\ -s_2 & 0 & -c_2 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Example

$$T_3^0 = T_2^0 A_3$$

$$= \begin{bmatrix} c_1c_2 & s_1 & -c_1s_2 & 0 \\ s_1c_2 & -c_1 & -s_1s_2 & 0 \\ -s_2 & 0 & -c_2 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_1c_2 & s_1 & -c_1s_2 & -L_3c_1s_2 \\ s_1c_2 & -c_1 & -s_1s_2 & -L_3s_1s_2 \\ -s_2 & 0 & -c_2 & 3-L_3c_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- $a_1 = 0$, $\alpha_1 = -90°$, $d_1 = 3\text{m}$, $q_1 = \theta_1 = 0°$
- $a_2 = 0$, $\alpha_2 = -90°$, $d_2 = 0$, $q_2 = \theta_2 = -90°$
- $a_3 = 0$, $\alpha_3 = 0°$, $q_3 = d_3 = L_3$, $\theta_3 = 0°$

Example

$$T_3^0 = \begin{bmatrix} c_1c_2 & s_1 & -c_1s_2 & -L_3c_1s_2 \\ s_1c_2 & -c_1 & -s_1s_2 & -L_3s_1s_2 \\ -s_2 & 0 & -c_2 & 3-L_3c_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & 0 & 1 & L_3 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

- $a_1 = 0$, $\alpha_1 = -90°$, $d_1 = 3\text{m}$, $q_1 = \theta_1 = 0°$
- $a_2 = 0$, $\alpha_2 = -90°$, $d_2 = 0$, $q_2 = \theta_2 = -90°$
- $a_3 = 0$, $\alpha_3 = 0°$, $q_3 = d_3 = L_3$, $\theta_3 = 0°$

Inverse Kinematics

- There are no good universal algorithms for producing the inverse kinematics of a serial link manipulator.
- We will take an approach based on geometrical interpretation.
- Simplify by decoupling the position and rotation expressions from the transformation matrix.

Decoupling Position and Rotation

- Recall that the transformation has the form

$$H = \begin{bmatrix} R & d \\ 0 & 1 \end{bmatrix}$$

- For many robots the orientation is set by a wrist at the end of the manipulator.
- Position is therefore set by the first three joints.
- **We will only consider the position problem.**

Geometric Approach

- Relies on having only orthogonal twists, and many zero length parameters.
- Project robot on to xy planes to find simple geometrical relationships.
- Do **not** use acos(), asin() or atan() as they produce poor results.
- Always use atan2(x,y) to find angles from positions.

MANIPULATOR DYNAMICS

In Dynamics of **Manipulators** we study forces applied to manipulators. To perform a particular task the manipulator is accelerated from rest to start moving, then the end-effector may be required to be moved with a constant velocity and then decelerated to bring it to rest at the desired point. Such motion requires variation of torques at the joints by actuators in accordance to the desired trajectory.
Our task in Dynamics of Manipulators is to find the torque to be generated by the torque actuators at the manipulator joints. The **functions** of the **torque variation** depend upon the **trajectory** to be followed by the manipulator, **masses of links**, **friction in link joints** and **force applied** by or payload at the end-effector.

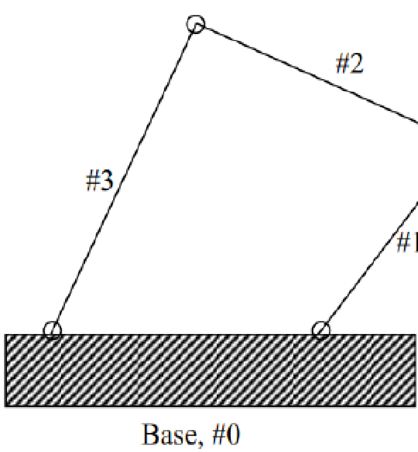
Dynamic analysis of manipulator has two types of problems to be solved:

•The trajectory with variation of position, velocity and acceleration is given and torques required at manipulator joints to move along the desired trajectory are to be found.
•Torques variations are given and the motion of manipulator has to be found. It may involve finding position, velocity and also acceleration.

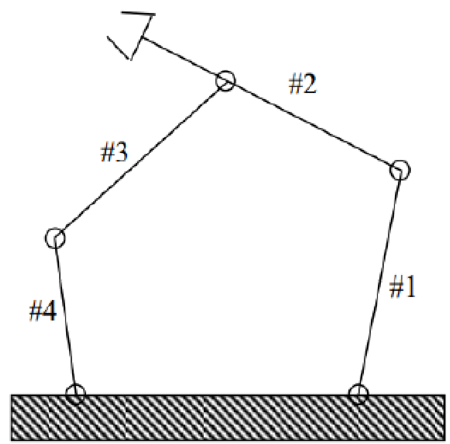
Closed and Open Chain

- Simple Kinematic Chain: When each and every link is coupled to at most two other links
  - Closed: If each and every link coupled to two other links → Mechanism
  - Open: If it contains only two links (end ones) that are connected to only one link → Manipulator

Closed-chain

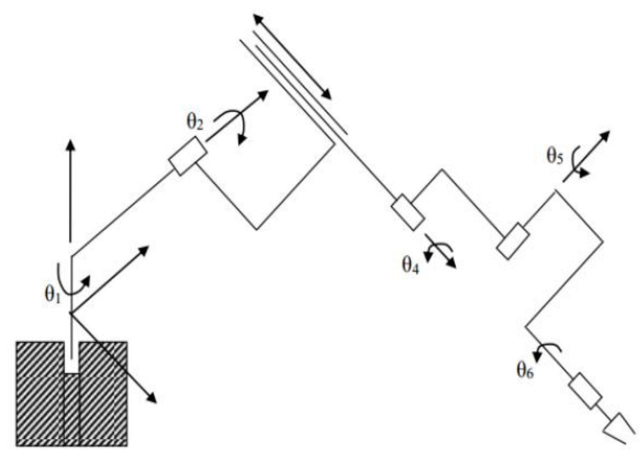


A four-bar mechanism



A five-bar mechanism

Open-chain



A robot manipulator

DEGREES OF FREEDOM

GRUBLER'S RULE

Degrees of freedom/mobility of a mechanism: It is the number of inputs (number of independent coordinates) required to describe the configuration or position of all the links of the mechanism, with respect to the fixed link at any given instant.

Grubler's equation: Number of degrees of freedom of a mechanism is given by:

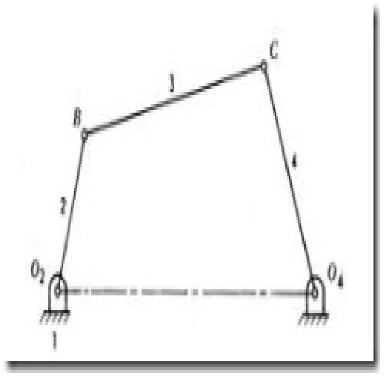
$$F = 3(n-1) - 2j$$

F = Degrees of freedom

n = Number of links

j= number of joints

(i)

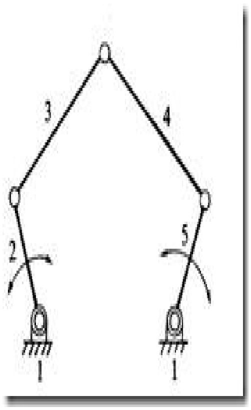


$$F = 3(n-1) - 2j$$

F = 3(4-1)-2(4) = 1

I.e., one input to any one link will result in definite motion of all the links.

(ii)



F = 3(5-1)-2(5) = 2

I.e., two inputs to any two links are required to yield definite motions in all the links.

Differential Transformation of Manipulators

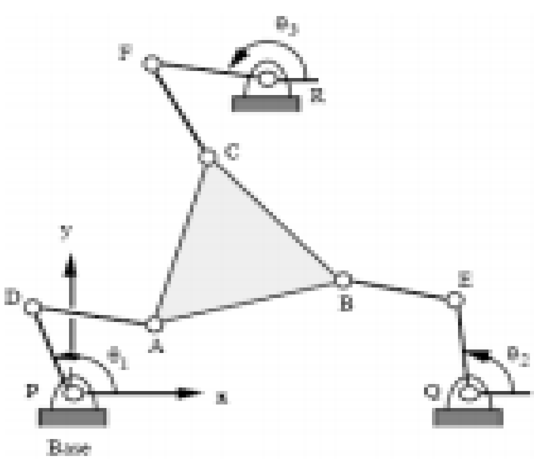
•**Parallel manipulators** are mechanisms where all the links are connected to the ground and the moving platform at the same time.

•They possess high rigidity, load capacity, precision, structural stiffness, velocity and acceleration since the end-effector is linked to the movable plate in several points.

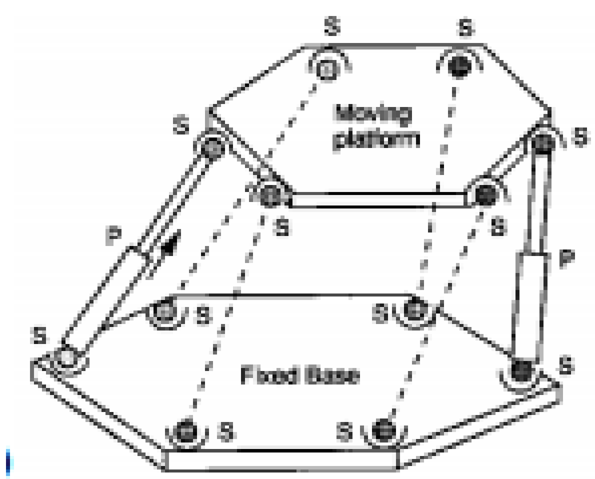
•Parallel manipulators can be classified into two fundamental categories, namely spatial and planar manipulators.

•The first category composes of the spatial parallel manipulators that can translate and rotate in the three dimensional space.

•The planar parallel manipulators which composes of second category, translate along the x and y-axes, and rotate around the z-axis, only.



Planar parallel robot manipulator



Spatial parallel robot manipulator

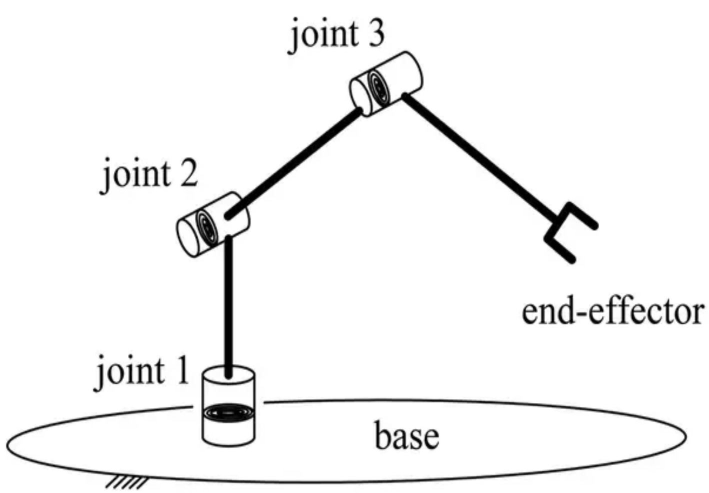
•In a **serial manipulator**, several linkages are serially connected like a chain to give a desired motion to the end-effector.

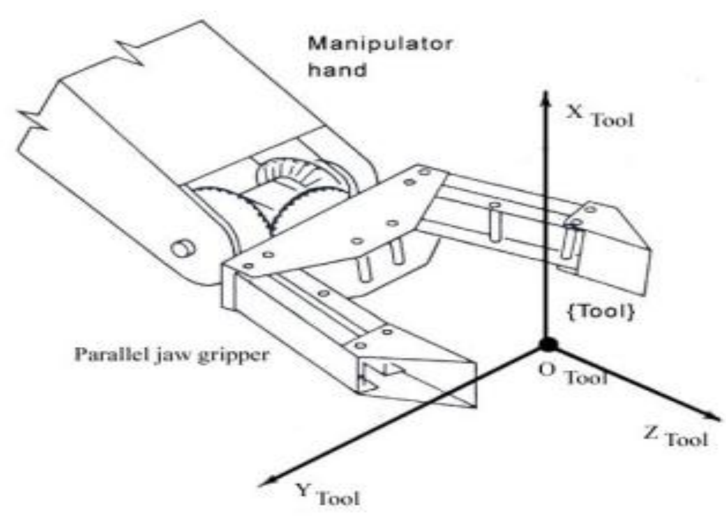
•A serial manipulator consists of a fixed base, a series of links connected by joints, and ending at a free end carrying the tool or the end-effector.

•In contrast to parallel manipulators, there are no closed loops.

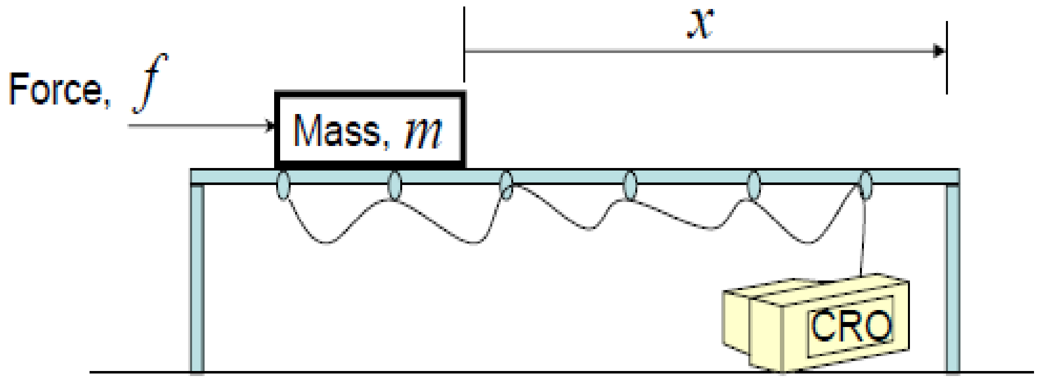
•By actuating the joints, one can position and orient the end-effector in a plane or in three-dimensional (3D) space to perform desired tasks with the end-effector.

• **Serial manipulators** are the most common industrial robots. They are designed as a series of links connected by motor-actuated joints that extend from a base to an end-effector.





Dynamics



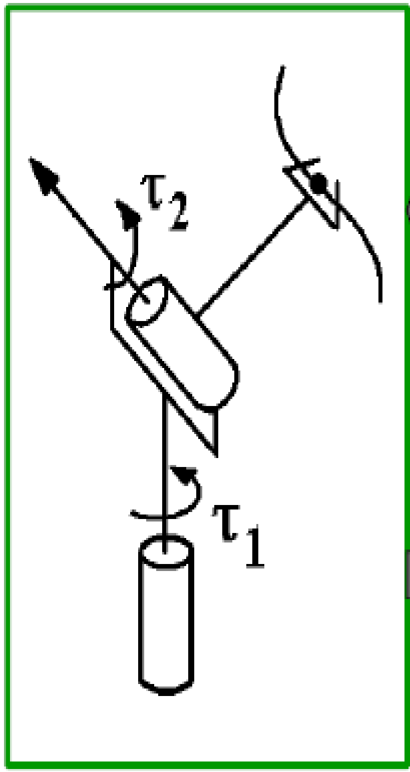
Newton's 2nd law: $f = m\ddot{x}$ → Modelling

Given m , $\ddot{x}$; Find f → Inverse dynamics

Given m , f ; Find $\ddot{x} = \dfrac{f}{m}$ → Forward dynamics

$\dot{x} = \int \ddot{x}\,dt$; $x = \int \dot{x}\,dt$ → Integrations

Inverse vs. Forward Dynamics

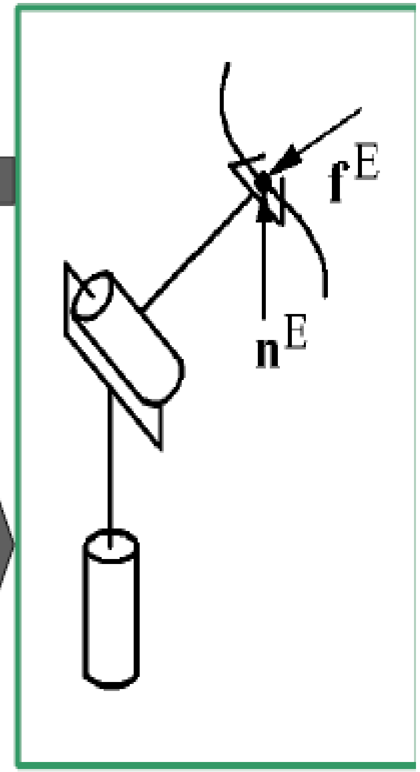


Inverse Dynamics

Find joint torques/forces for given joint motions and end-effector moment/force

Forward Dynamics

Find end-effector motion for known joint torques/forces



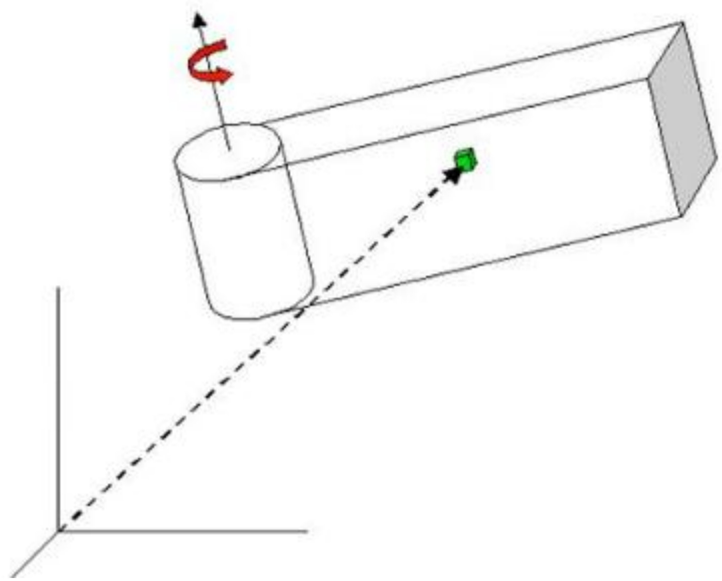
Dynamic Modeling

- For manipulator arms:
  - Relate forces/torques at joints to the motion of manipulator + load
    - External forces usually only considered at the end-effector
    - Gravity (lift arms) is a major consideration

    - Need to derive the equations of motion
      - Relate forces/torque to motion
    - Must consider distribution of mass
    - Need to model external forces

Manipulator Link Mass

- Consider link as a system of particles
  - Each particle has mass, dm
  - Position of each particle can be expressed using forward kinematics



Jacobian Matrix - Formulation

What is a Jacobian of a robot system?

A Jacobian defines the dynamic relationship between two different representations of a system. It is a m x n matrix.

For example, if we have a 2-link robotic arm, there are two obvious ways to describe its current position:

1) the end-effector position and orientation (which we will denote **x**), and

2) as the set of joint angles (which we will denote **q**).

The Jacobian for this system relates how movement of the elements of **q** causes movement of the elements of **x**.

Jacobian as a **transformation matrix for velocity**.

Formally, a Jacobian is a set of partial differential equations:

$$\mathbf{J} = \frac{\partial \mathbf{x}}{\partial \mathbf{q}}.$$

With a bit of manipulation we can get a neat result:

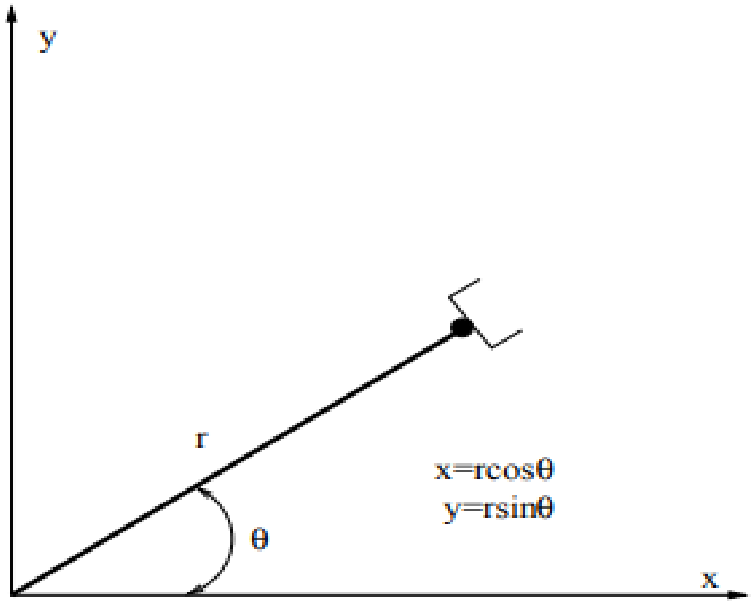
$$\mathbf{J} = \frac{\partial \mathbf{x}}{\partial t}\frac{\partial t}{\partial \mathbf{q}} \rightarrow \frac{\partial \mathbf{x}}{\partial \mathbf{t}} = \mathbf{J}\frac{\partial \mathbf{q}}{\partial t},$$

or

$$\dot{\mathrm{x}} = \mathrm{J}\,\dot{\mathrm{q}},$$

where $\dot{\mathrm{x}}$ and $\dot{\mathrm{q}}$ represent the time derivatives of x and q. This tells us that the end-effector velocity is equal to the Jacobian, J, multiplied by the joint angle velocity.

Jacobian - Serial Manipulator



2-DOF Polar, planar manipulator. The endpoint has coordinates $(rCos\theta\ ,\ rSin\theta)$.

Joint 1 is a revolute joint and joint 2 is a prismatic joint, with an endpoint of $(rCos\theta\ ,\ rSin\theta)$. Let us find the rate of change of x and y, i.e. their velocities, using the chain rule to differentiate x and y with respect to time t

$$z = F(x, y) \quad dz = \frac{\partial F}{\partial x}dx + \frac{\partial F}{\partial y}dy \quad \frac{dz}{dt} = \frac{\partial F}{\partial x}\frac{dx}{dt} + \frac{\partial F}{\partial y}\frac{dy}{dt}$$

Jacobian Matrix

$$\frac{dx}{dt} = \frac{\partial(r\ cos\theta)}{\partial r}\frac{dr}{dt} + \frac{\partial(r\ cos\theta)}{\partial \theta}\frac{d\theta}{dt} \quad ==> \quad \dot{x} = cos\theta\dot{r} - r\,sin\theta\dot{\theta}$$

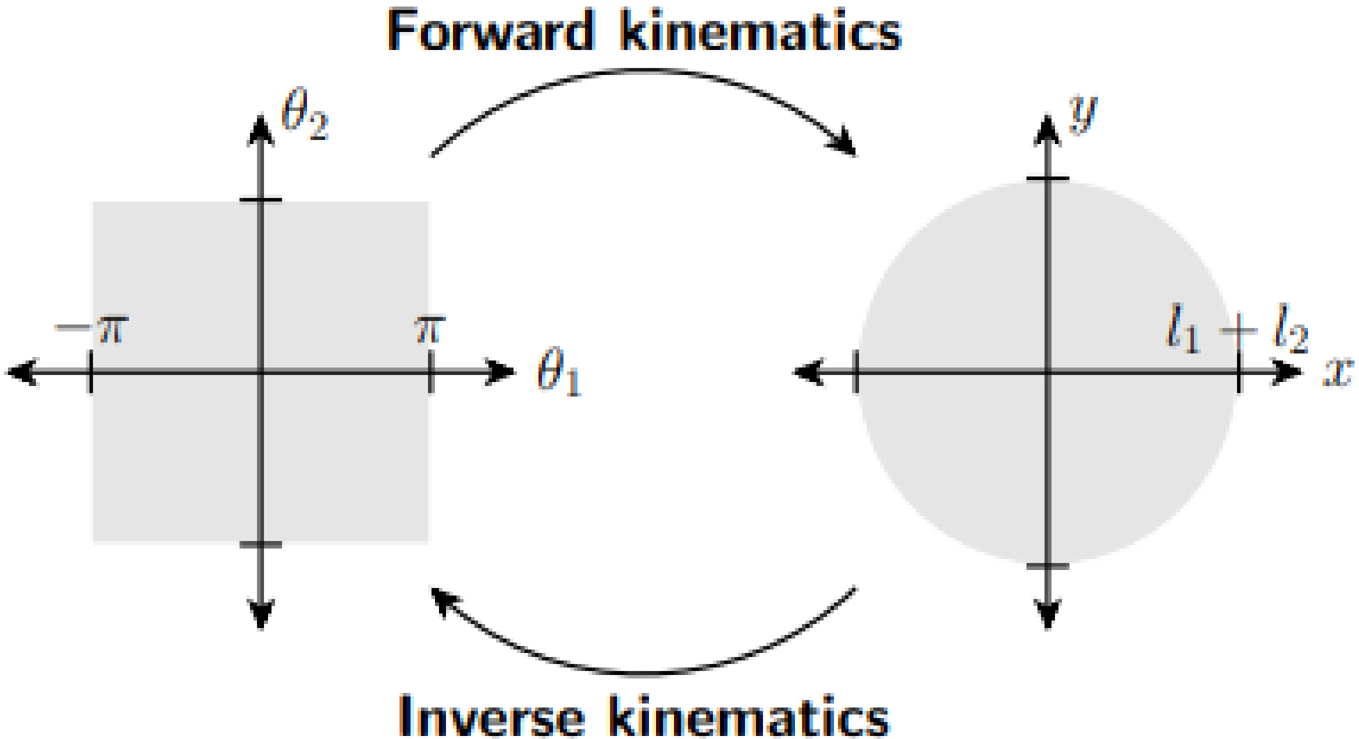
$$\frac{dy}{dt} = \frac{\partial(r\ sin\theta)}{\partial r}\frac{dr}{dt} + \frac{\partial(r\ sin\theta)}{\partial \theta}\frac{d\theta}{dt} \quad ==> \quad \dot{y} = sin\theta\dot{r} + r\ cos\theta\dot{\theta}$$

$$\begin{bmatrix} \frac{dx}{dt} \\ \frac{dy}{dt} \end{bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial \theta} & \frac{\partial x}{\partial r} \\ \frac{\partial y}{\partial \theta} & \frac{\partial y}{\partial r} \end{bmatrix} \begin{bmatrix} \frac{d\theta}{dt} \\ \frac{dr}{dt} \end{bmatrix}$$

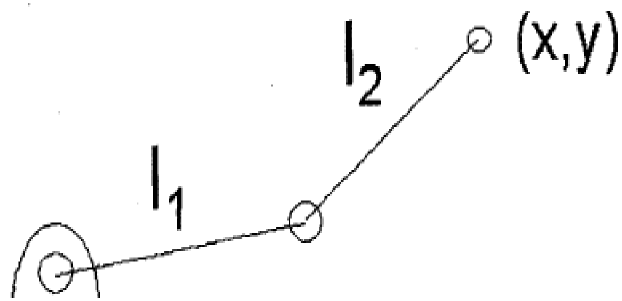
$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} -r\ sin\ \theta & cos\ \theta \\ r\ cos\ \theta & sin\ \theta \end{bmatrix} \begin{bmatrix} \dot{\theta} \\ \dot{r} \end{bmatrix}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = J \begin{bmatrix} \dot{\theta} \\ \dot{r} \end{bmatrix} \ where\ \ J = \begin{bmatrix} -r\ sin\ \theta & cos\ \theta \\ r\ cos\ \theta & sin\ \theta \end{bmatrix}$$

Kinematics of two-link robot



RR Manipulator



A 2 link example

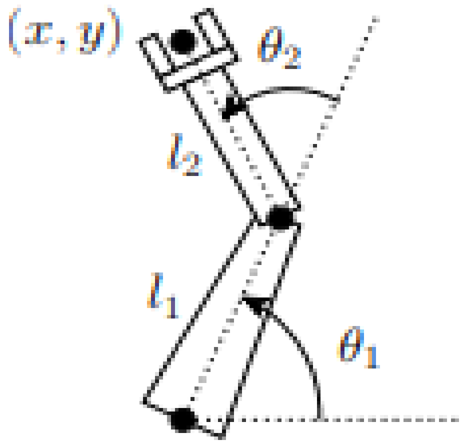
The Jacobian is an m x n matrix. Take **a two link planar manipulator** in the plane with revolute joints and axis of rotation perpendicular to the plane of the paper. Let us first derive the positional part of a Jacobian. First from the forward kinematics we derive the description of the position and orientation of the end-effector in Cartesian space with respect to the joint coordinates.

θ_1 *and* θ_2 *– joint angles of robot* (configuration space, joint space)

l_1, l_2 *– length of links 1 an 2 respectively* (robot parameters)

x, y - position of end effector (task space)

Forward kinematics of two-link robot



- Position of "elbow" x_0, y_0

$$
\begin{aligned}
x_0 &= \ell_1 \cos(\theta_1) \\
y_0 &= \ell_1 \sin(\theta_1)
\end{aligned}
$$

- So, position of end effector x, y

$$
\begin{aligned}
x &= \ell_1 \cos(\theta_1) + \ell_2 \cos(\theta_1 + \theta_2) \\
y &= \ell_1 \sin(\theta_1) + \ell_2 \sin(\theta_1 + \theta_2)
\end{aligned}
$$

- For simplicity, we'll write this as

$$
\begin{aligned}
x &= \ell_1 c_1 + \ell_2 c_{12} \\
y &= \ell_1 s_1 + \ell_2 s_{12}
\end{aligned}
$$

- *Jacobian* matrix contains derivatives of robot end effector with respect to joint angles

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} l_1c_1 + l_2c_{12} \\ l_1s_1 + l_2s_{12} \end{bmatrix}$$

The instantaneous motion of the position vector (x, y) is

$$\begin{aligned} \delta x &= -(l_1s_1 + l_2s_{12})\delta\theta_1 - l_2s_{12}\delta\theta_2 \\ \delta y &= (l_1c_1 + l_2c_{12})\delta\theta_1 + l_2c_{12}\delta\theta_2 \end{aligned}$$

If we group the coefficients in front of $\delta\theta_1$ and $\delta\theta_2$ we obtain a matrix equation which can be written as

$$\delta x = \begin{bmatrix} \delta x \\ \delta y \end{bmatrix} = \begin{bmatrix} -y & -l_2s_{12} \\ x & l_2c_{12} \end{bmatrix} \begin{pmatrix} \delta\theta_1 \\ \delta\theta_2 \end{pmatrix}$$

The $2x2$ matrix in the above equation is the Jacobian, $J(\mathbf{q})$.

$$\delta\mathbf{x} = J(\mathbf{q})\delta\mathbf{q}$$

Now if we consider the differentiation *w.r.t.* time, we can write the relationship between $\dot{\mathbf{x}}$ and $\dot{\mathbf{q}}$.

$$\dot{\mathbf{x}} = J(\mathbf{q})\dot{\mathbf{q}}$$

Trajectory Planning

INTRODUCTION

- Path and trajectory planning means the way that a robot is moved from one location to another in a controlled manner.

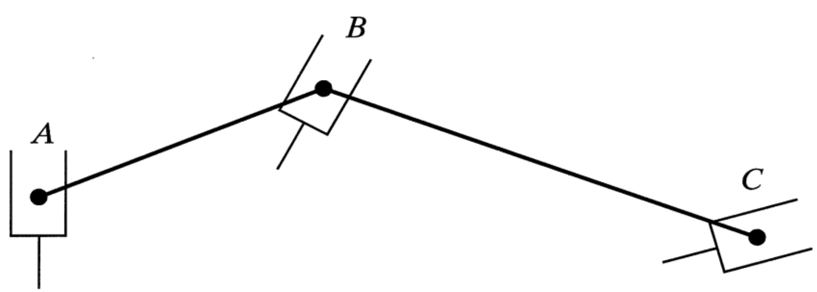
- The sequence of movements for a controlled movement between motion segment, in straight-line motion or in sequential motions.

- It requires the use of both kinematics and dynamics of robots.

Path: an ordered locus of points in the space (either joint or operational), which the manipulator should follow. Path is a pure geometric description of motion.

Trajectory: a path on which timing law is specified, e.g., velocities and accelerations in its each point.

The **path planning** is the planning of the whole way from point A to point C, including stopping in defined path points. The path includes several continuous motion trajectories that need the **trajectory planning**. If a path cannot be previously planned because of limited previous information, the motion task is named as path finding.



Robot Motion Planning

Path planning (global):

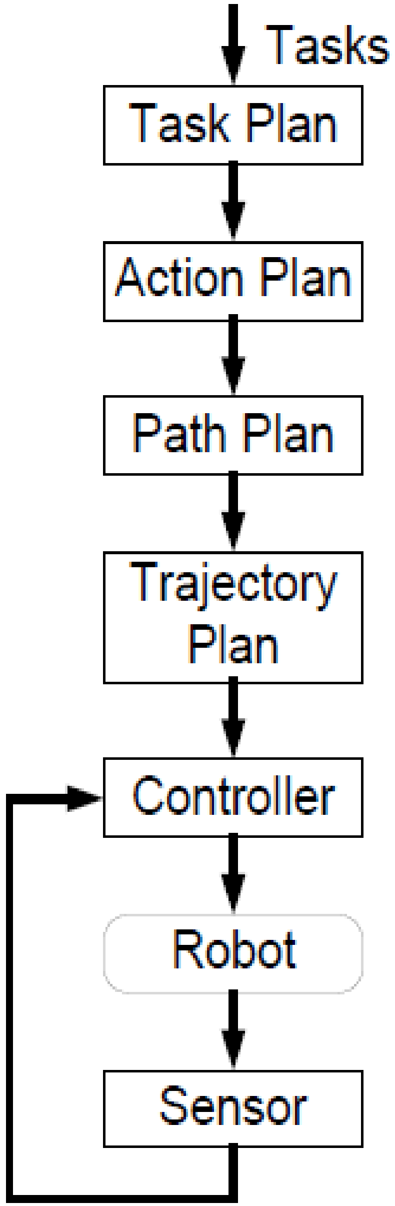
•Geometric path.

•Issues: obstacle avoidance, shortest path.

Trajectory generating (local):

•"Interpolate" or "approximate" the desired path by a class of polynomial functions and

•generate a sequence of time-based "control set points" for the control of manipulator from the initial configuration to its destination.



Path planning strategies are:

− path constrained (signed path) off-line or on-line path planning with collision avoidance

− position controlled motion with on-line obstacle identification and collision avoidance (without path constraints, i.e. path signs)

− path constrained off-line path planning or on-line pass through the signed path (collisions are possible)

− position controlled motion without obstacle identification (collisions are possible)

The main path planning tasks for a robot are as follows:

- grasping and releasing objects
- moving from place to place
- following previously specified paths
- following moving objects
- working with other manipulators
- exerting forces (i.e. pushing, pulling and holding)
- exerting torques
- collecting data
- using tools

TYPES OF MOTION

- A robot manipulator can make four types of motion in traveling from one point to another in the workplace:
  - Slew motion
  - Joint-interpolated motion
  - Straight-line interpolation motion
  - Circular interpolation motion

SLEW MOTION

- Slew motions represent the **simplest type of motion**.

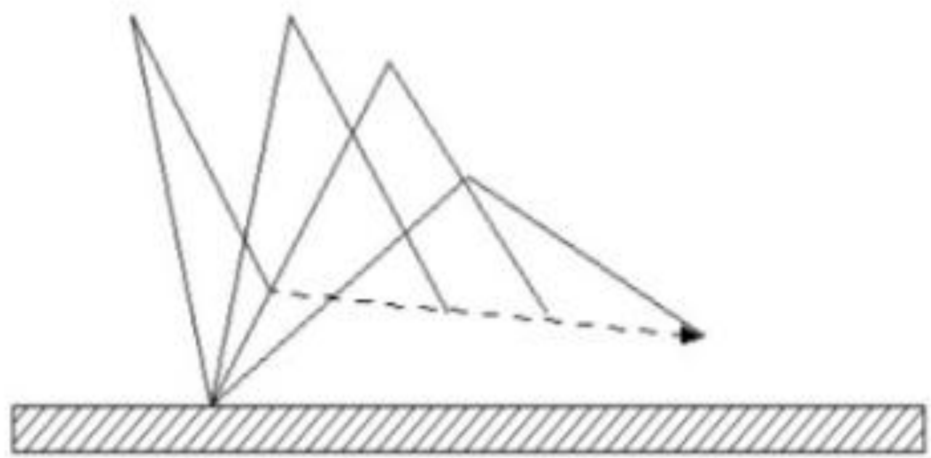
- The robot is commanded to travel from one point to another where **each axis** of the manipulator **travels at a default speed** from its initial position to the required final destination.

JOINT-INTERPOLATED MOTION

- **Joint-interpolated motion** requires the robot controller to calculate the time it will take **each joint to reach** its destination at the **commanded speed**.
- Then it **selects the maximum time** among these values and uses it as the time for the other axes.
- The advantage of joint-interpolated motion compared to slew motion is that the joints are driven at **lower velocities**, and therefore the **maintenance problems are much less** for the robot.

STRAIGHT-LINE INTERPOLATION MOTION

- Straight-line interpolation motion requires the end of the end effector to travel along a straight path determined in rectangular coordinates.
- This type of motion is the most demanding for a controller to execute, except for a rectangular-coordinated robot.
- Straight-line interpolation is very useful in applications such as arc welding, inserting pins into holes, or laying material along a straight path.



CIRCULAR INTERPOLATION MOTION

- Circular interpolation motion requires the robot controller to define the points of a circle in the workplace based on a minimum of three specified positions.
- The movements that are made by the robot actually consist of short straight-line segments.
- Circular interpolation is more readily available using a programming language rather than manual or teach pendant techniques.

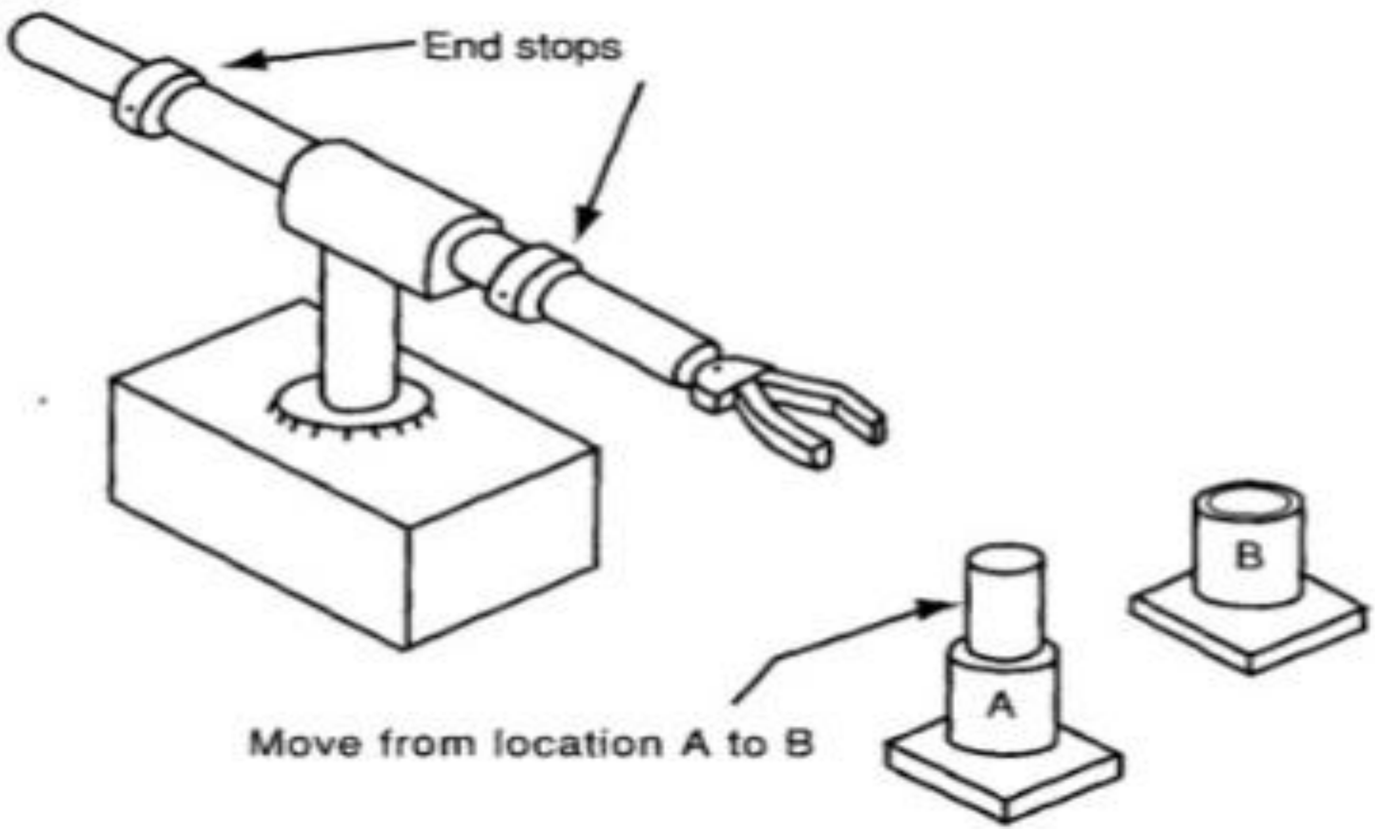
PATH CONTROL

- There are four type of path control:
  - **Limited-sequence**
  - **Point-to-point**
  - **Controlled path**
  - **Continuous path**

LIMITED SEQUENCE

- This type of robots does not use servo-control to indicate relative positions of the joints.
- Instead, they are controlled by setting limit switches and/or mechanical stops together with a sequencer to coordinate and time the actuation of the joints.
- With this method of control, the individual joints can only be moved to their limits of travel.
- This has the effect of severely limiting the number of distinct points that can be specified in a program for these robots.
- Therefore, their control system is intended for simple motion cycles, such as pick-and-place applications where each axis is normally limited to two end points.
- However, some pick-and-place robots also include one or two intermediate stops; therefore, they can be called stop-to-stop or sometimes bang-bang.

LIMITED SEQUENCE

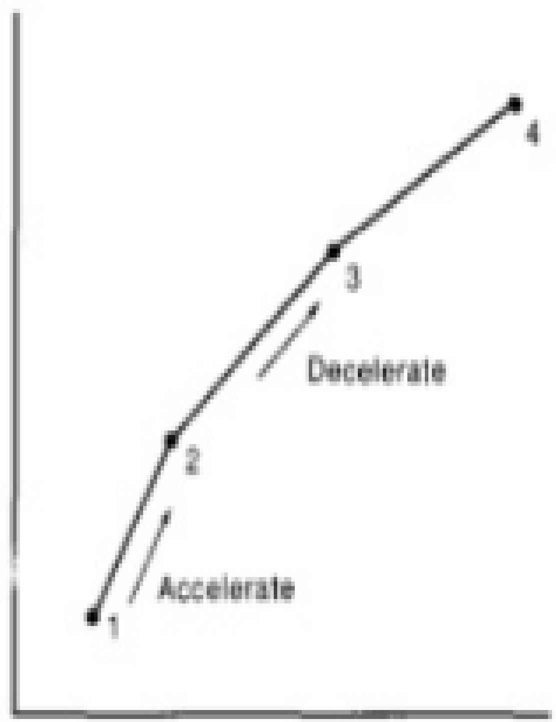


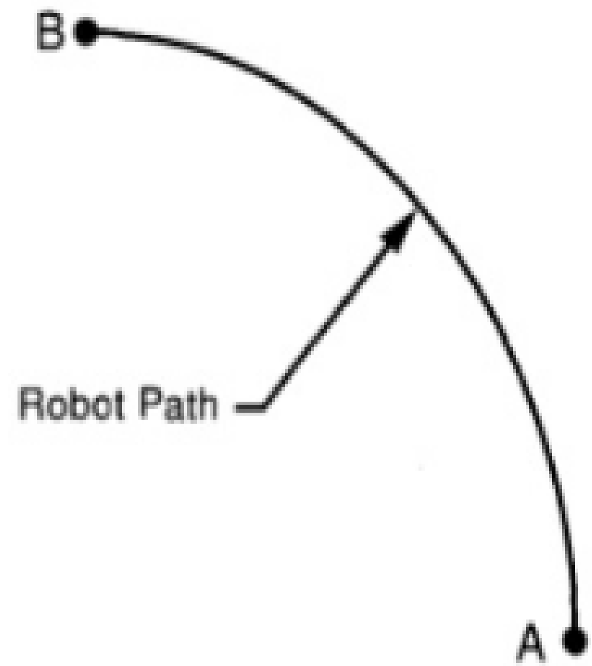
POINT-POINT SEQUENCE

- Point-to-point robots driven by servos are often controlled by potentiometers set to stop the robot arm at a specified point.
- They can be programmed (taught) to move *from* a point within the work envelope *to* another point within the work envelope.
- This versatility greatly expands their potential applications.
- Application: machine loading and unloading applications as well as more-complex applications, such as spot welding (resistance welding), assembly, grinding, inspection, palletizing, and depalletizing.
- Point-to-point motion involves the movement of the robotic system through a number of discrete points.

POINT-POINT SEQUENCE

- Although the point-to-point robot can move to any point within its work envelope, it does not necessarily move in a straight line between two points.





CONTROLLED PATH

- Controlled path is a specialized control method that is part of the general category of a point-to-point robot but with more-precise control.
- The controlled path robot ensures that the robot will describe the right segment between two taught points.

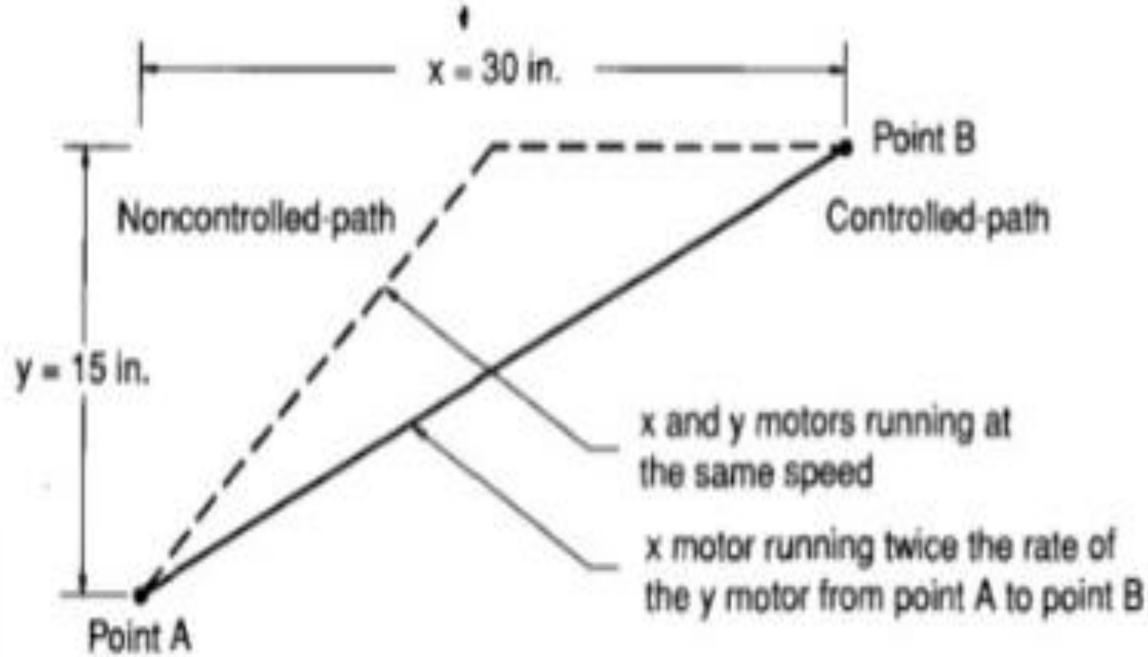
- Controlled-path is a calculated method and is desired when the manipulator must move in a perfect path motion.

- Controlled-path robots can generate straight lines, circles, interpolated curves, and other paths with high accuracy.

- Paths can be specified in geometric or algebraic terms in some of these robots.

CONTROLLED PATH

- The difference between the execution of a point-to-point controlled-path and a point-to-point noncontrolled-path program is illustrated in Figure below



CONTINUOUS PATH

- Continuous-path motion is an extension of the point-to-point method.
- The difference is that continuous path involves the utilization of more points and its path can be an arc, a circle, or a straight line.
- A continuous-path program can have several thousand points.
- Continuous-path motion is more concerned with control of the path movement than with end-point positioning.
- Programming of the path of motion is accomplished by an operator physically moving the end effector of the robot through its path of motion.

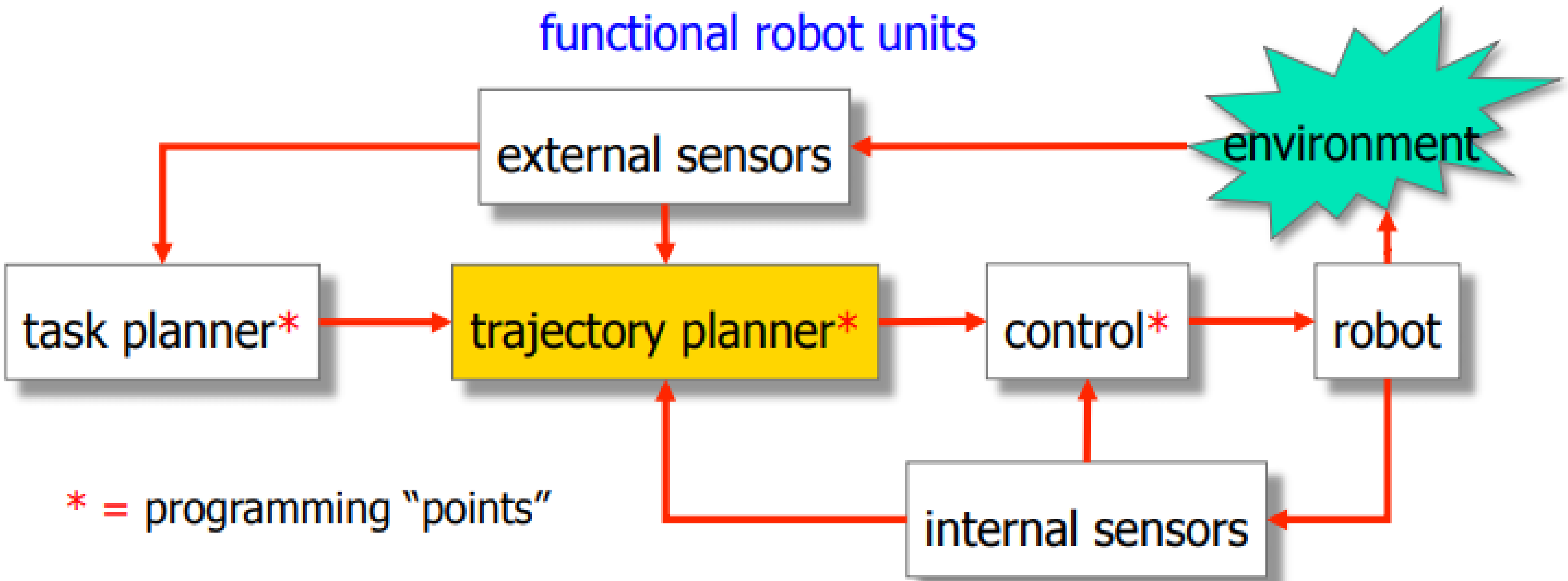
CONTINUOUS PATH

- The continuous-path robot is programmed differently than the point-to-point robot and the controlled-path robot.

- Rather than leading the robot to the point desired by pushing buttons on a teach pendant, the manipulator of a continuous-path robot is programmed by grabbing hold of the robot's arm and actually leading the arm through the path that we wish the robot to remember.

- The robot remembers not only the exact path through which the programmer moves the manipulator but also the speed at which the programmer moves the manipulator.

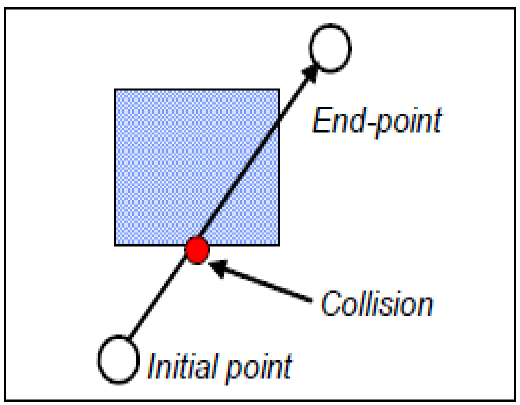
Trajectory planner interfaces



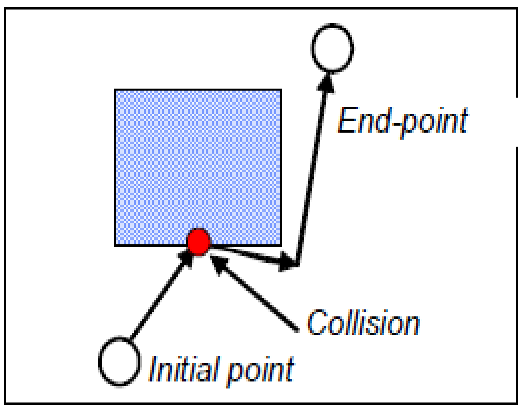
Collision detection and collision avoidance

Collision detection is the most important factor of Path Planning. Without automatic collision avoidance, the robotic work cell must be engineered to be collision free, or sub-optimal paths must be chosen by a human programmer.

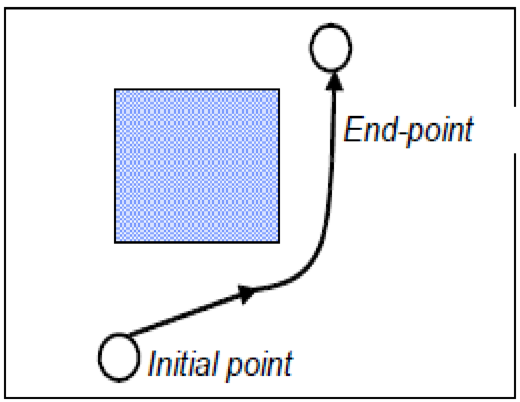
Local collision detection is important when moving through an unknown or uncertain environment. These allow for feedback to the planner, for halting paths which contain collisions. Global Collision Avoidance may be done for planning paths which should avoid objects by a certain margin of safety.



No collision avoidance



Local collision avoidance



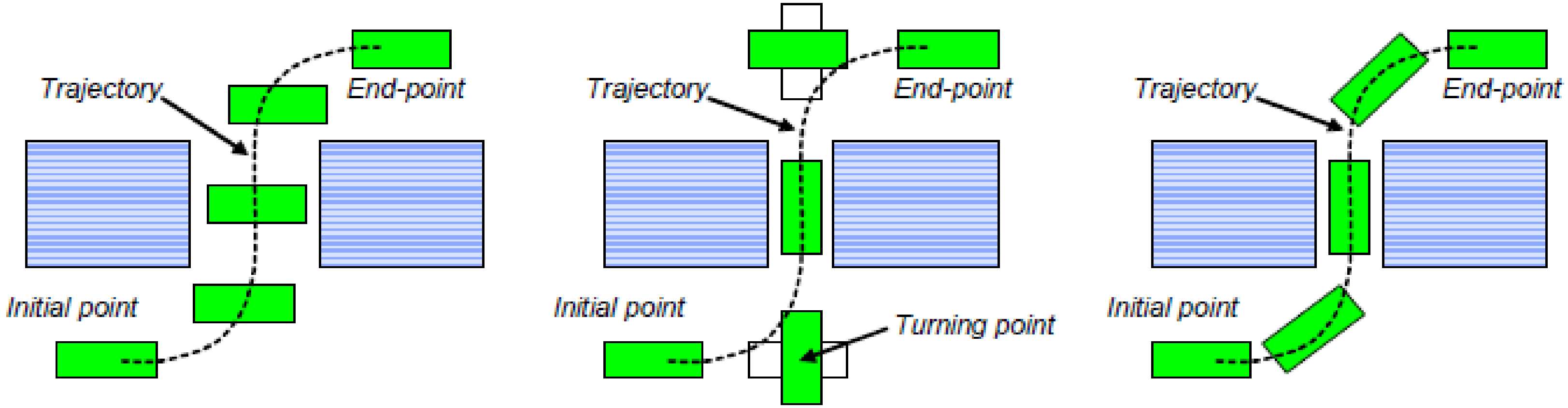
Global collision avoidance

Motion of obstacles

Motion of obstacles can cause significant path planning problems. Motion occurs in the form of rotation and translation. In most cases an obstacle in the environment may be categorized into motion categories:

- static (un-moving),
- deterministic (has predictable occurrence and positions), and
- random (Freely moving, with no regular occurrence).

All of these are of interest because most parts fixed in a workcell are static, workpieces from feeders and conveyors are deterministic, and human intruders are random. Random obstacle motion usually occurs so quickly that path planning may only be able to escape the path of the obstacle, not compensate it. In the case of random moving obstacles a robot must have sensors for the detection of obstacles to avoid collisions.



Parallel motion Turning in definite points Continuous turning

Problems of robot motion if turning is needed to avoid collision

The aim of the trajectory generation:

•To generate inputs to the motion control system which ensures that the planned trajectory is executed.

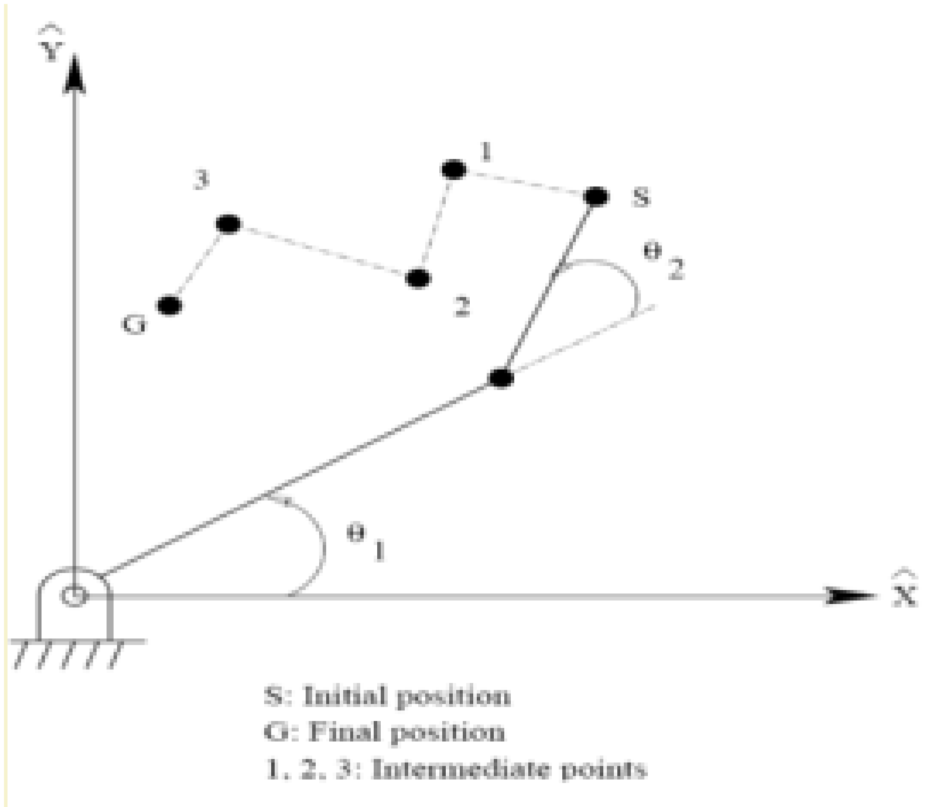
•The user or the upper-level planner describes the desired trajectory by some parameters, usually: Initial and final point (point-to-point control).

•Finite sequence of points along the path (motion through sequence of points).

•Trajectory planning/generation can be performed either in the joint space or operational space.

TRAJECTORY PLANNING

To determine time history of position, velocity and acceleration of end-effector of a manipulator, while moving from an initial position to a final position through some intermediate/via points.



TRAJECTORY PLANNING

Points	Cartesian scheme	Joint-space scheme
S	(X_S, Y_S)	$(\theta_1^{S}, \theta_2^{S})$
1	(X_1, Y_1)	$(\theta_1^{1}, \theta_2^{1})$
2	(X_2, Y_2)	$(\theta_1^{2}, \theta_2^{2})$
3	(X_3, Y_3)	$(\theta_1^{3}, \theta_2^{3})$
G	(X_G, Y_G)	$(\theta_1^{G}, \theta_2^{G})$

Joint-space description:

•The description of the motion to be made by the robot by its joint values.

•The motion between the two points is unpredictable.

Various Trajectory Functions

•Cubic polynomial

•Fifth-order polynomial

•Linear trajectory function

Operational space description:

•In many cases operational space = Cartesian space.

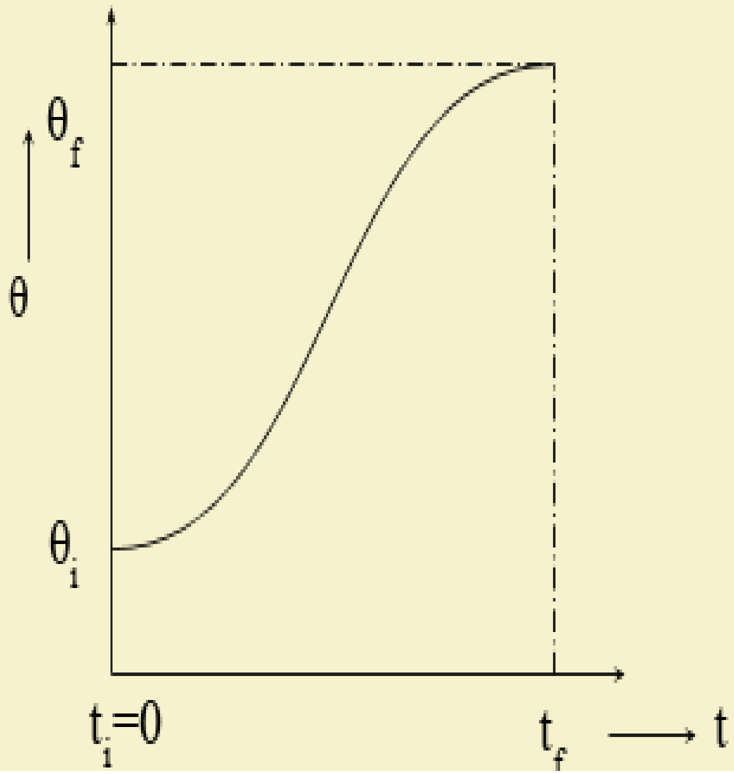
•The motion between the two points is known at all times and controllable.

•It is easy to visualize the trajectory, but it is difficult to ensure that singularity does not occur.

POLYNOMIAL TRAJECTORY FUNCTION

CASE:1

Initial and final values of joint angle are known, and angular velocities at the beginning and end of the cycle are kept equal to zero.



At $t = t_i = 0$; $\theta = \theta_i$, $\dot{\theta} = 0$

At $t = t_f$; $\theta = \theta_f$, $\dot{\theta} = 0$

Let us consider **cubic polynomial**

$$\theta(t) = C_0 + C_1 t + C_2 t^2 + C_3 t^3$$

where C_0, C_1, C_2, C_3 are the coefficients.

Differentiate $\theta(t)$ with respect to time to get angular velocity

$$\dot{\theta}(t) = C_1 + 2C_2 t + 3C_3 t^2$$

Apply the initial conditions to angular displacement and velocity equations. We get,

$$C_0 = \theta_i$$

$$C_1 = 0$$

$$C_0 + C_1 t_f + C_2 t_f^2 + C_3 t_f^3 = \theta_f$$

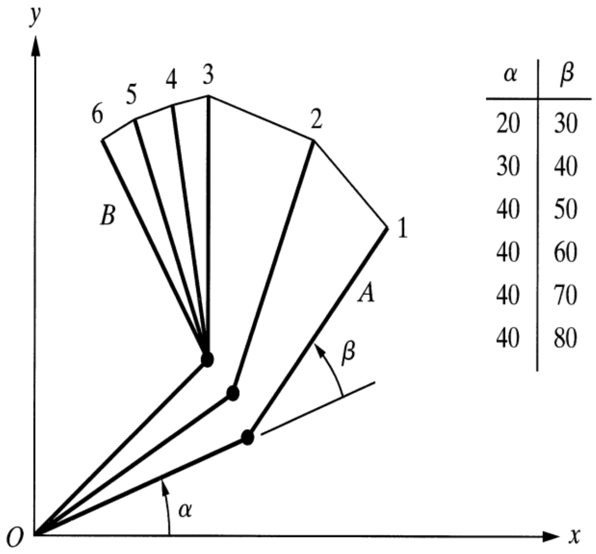
$$C_1 + 2C_2 t_f + 3C_3 t_f^2 = 0$$

Solving above equations, We get

$$\theta(t) = \theta_i + \frac{3(\theta_f - \theta_i)}{t_f^2} t^2 - \frac{2(\theta_f - \theta_i)}{t_f^3} t^3$$

BASICS OF TRAJECTORY PLANNING

- Let's consider a simple 2 degree of freedom robot.
- We desire to move the robot from Point A to Point B.
- Let's assume that both joints of the robot can move at the maximum rate of 10 degree/sec.
- Let's assume that both joints of the robot can move at the maximum rate of 10 degree/sec.



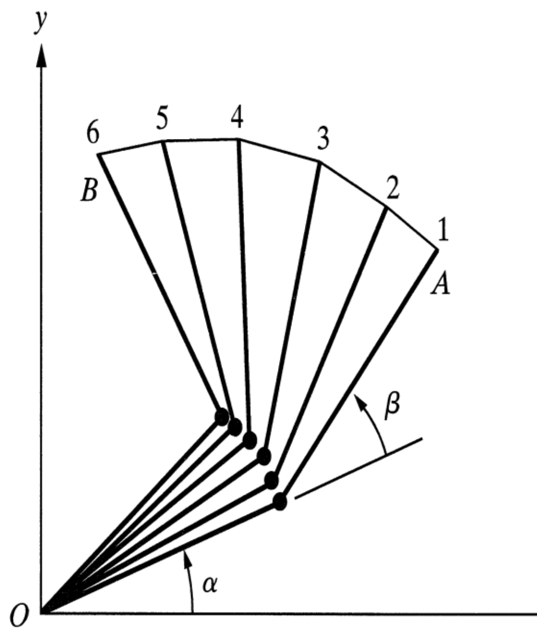
α	β
20	30
30	40
40	50
40	60
40	70
40	80

Joint-space nonnormalized movements of a robot with two degrees of freedom.

- **Move the robot from A to B, to run both joints at their maximum angular velocities.**
- **After 2 [sec], the lower link will have finished its motion, while the upper link continues for another 3 [sec].**
- **The path is irregular and the distances traveled by the robot's end are not uniform.**

BASICS OF TRAJECTORY PLANNING

- Let's assume that the motions of both joints are normalized by a common factor such that the joint with smaller motion will move proportionally slower and the both joints will start and stop their motion simultaneously.



α	β
20	30
24	40
28	50
32	60
36	70
40	80

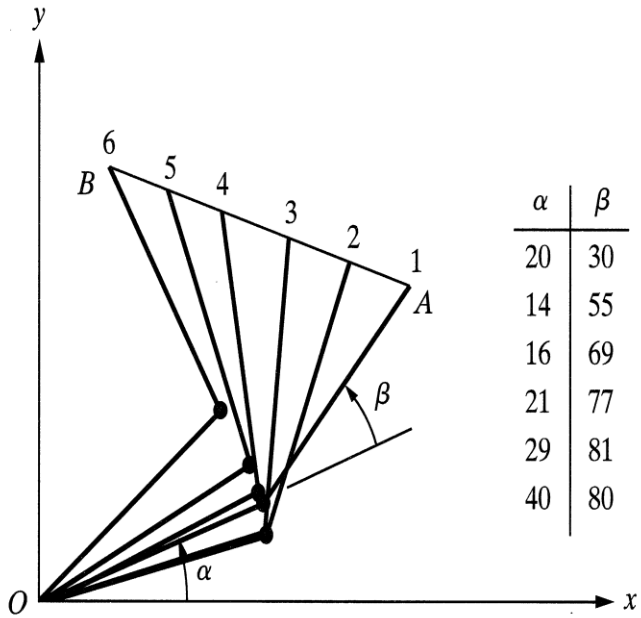
Joint-space, normalized movements of a robot with two degrees of freedom.

- **Both joints move at different speeds, but move continuously together.**
- **The resulting trajectory will be different.**

BASICS OF TRAJECTORY PLANNING

- Let's assume that the robot's hand follow a known path between point A to B with straight line.

- The simplest solution would be to draw a line between points A and B, so called interpolation.



α	β
20	30
14	55
16	69
21	77
29	81
40	80

Cartesian-space movements of a two-degree-of-freedom robot.

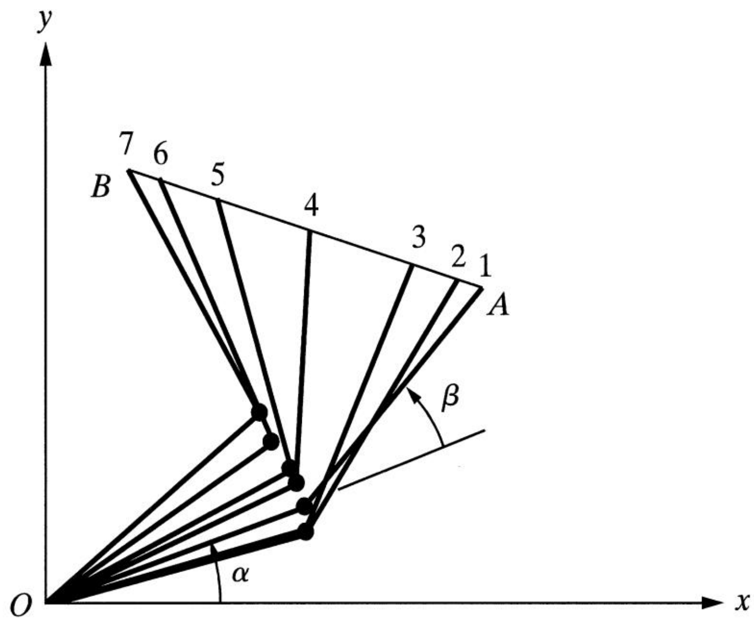
- **Divide the line into five segments and solve for necessary angles α and β at each point.**

- **The joint angles are not uniformly changing.**

BASICS OF TRAJECTORY PLANNING

- Let's assume that the robot's hand follow a known path between point A to B with straight line.

- The simplest solution would be to draw a line between points A and B, so called interpolation.



Trajectory planning with an acceleration-deceleration regiment.

- **It is assumed that the robot's actuators are strong enough to provide large forces necessary to accelerate and decelerate the joints as needed.**

- **Divide the segments differently.**
  - **The arm move at smaller segments as we speed up at the beginning.**
  - Go at a constant cruising rate.
  - Decelerate with smaller segments as approaching point B.

Joint-Space Scheme

- To fit a smooth (continuous) curve through ($\theta 1S$, $\theta 11$, $\theta 12$, $\theta 13$, $\theta 1G$)

- First and second order derivatives must be continuous.

Various Trajectory Functions

- Cubic polynomial

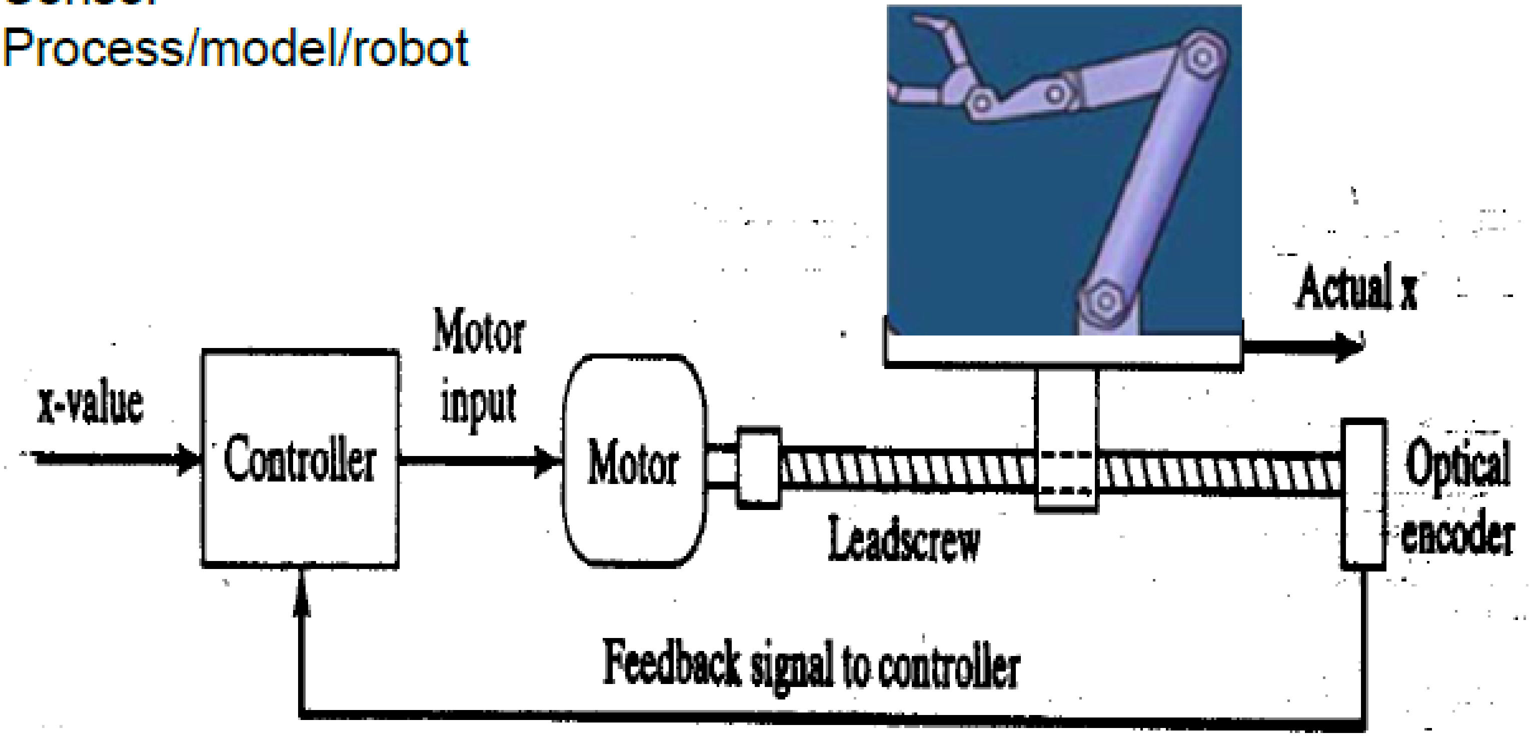
- Fifth-order polynomial

- Linear trajectory function

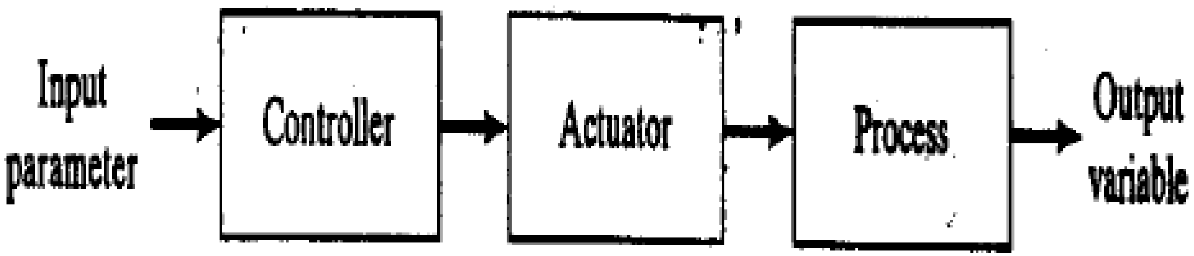
ROBOTICS - ACTUATORS AND SENSORS

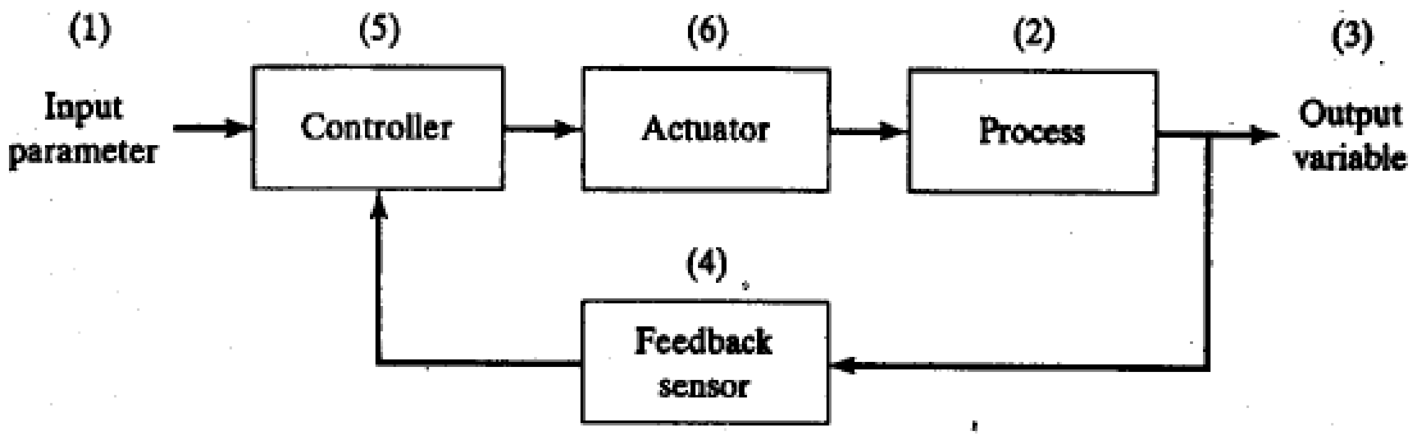
Sub-systems in robot control

- Controller
- Actuator
- Sensor
- Process/model/robot



Open loop and closed loop





INTRODUCTION

ACTUATORS:

- Actuation is the process of conversion of energy to mechanical form. A device that accomplishes this conversion is called actuator.
- Actuator plays a very important role while implementing control. The controller provides command signal to the actuator for actuation.
- The control codes aims at "deriving the actuator when an event has occurred"

ACTUATORS FOR ROBOTS:

1. Actuators are used in order to produce mechanical movement in robots.

2. Actuators are the muscles of robots. There are many types of actuators available depending on the load involved. The term load is associated with many factors including force, torque, speed of operation, accuracy, precision and power consumption.

Actuators

- *Electrical* : stepper motors, DC servo motors
- *Pneumatic* : air pressure
- *Hydraulic* : fluid pressure (oil pressure).
- *Advanced actuators* : ultrasonic motors, artificial muscles, molecular motors.

1. Electromechanical actuators convert electrical energy into mechanical energy. Magnetism is the basis of their principle of operation. They are DC, AC and stepper motors.

2. DC motors require a direct current or voltage source as the input signals.

3. AC motors require an alternating current or voltage source

1. Stepper motors have capability of achieving precision angular rotation in both directions and are commonly employed to accommodate digital control technology.

2. Hydraulic and pneumatic actuators are under fluid power actuators. Fluid power refers to energy that is transmitted via a fluid under pressure. When a pressure is applied to a confined chamber containing a piston, the piston will exert a force causing a motion.

3. Materials which undergo some sort of transformations through physical interaction, are referred to as active materials. Piezoelectric (voltage-load), shape-memory alloys (react to heat), magnetostrictive are examples of these materials.

CHARACTERISTICS OF ACTUATING SYSTEMS

1. Weight, Power-to-weight Ratio, Operating pressure

1) Stepper motors are generally heavier than servomotors for the same power.

2) The high the voltage of electric motors, the better power-to-weight ratio.

3) Pneumatic systems delivers the lowest power-to-weight ratio .

4) Hydraulic systems have the highest power-to-weight ratio . In these systems, the weight is actually composed of two portions. One is the hydraulic actuators, and the other is the hydraulic power unit (pump, cylinders, rams, reservoirs, filter, and electric motor). If the power unit must also move with the robot, the total power-to-weight ratio will be much less.

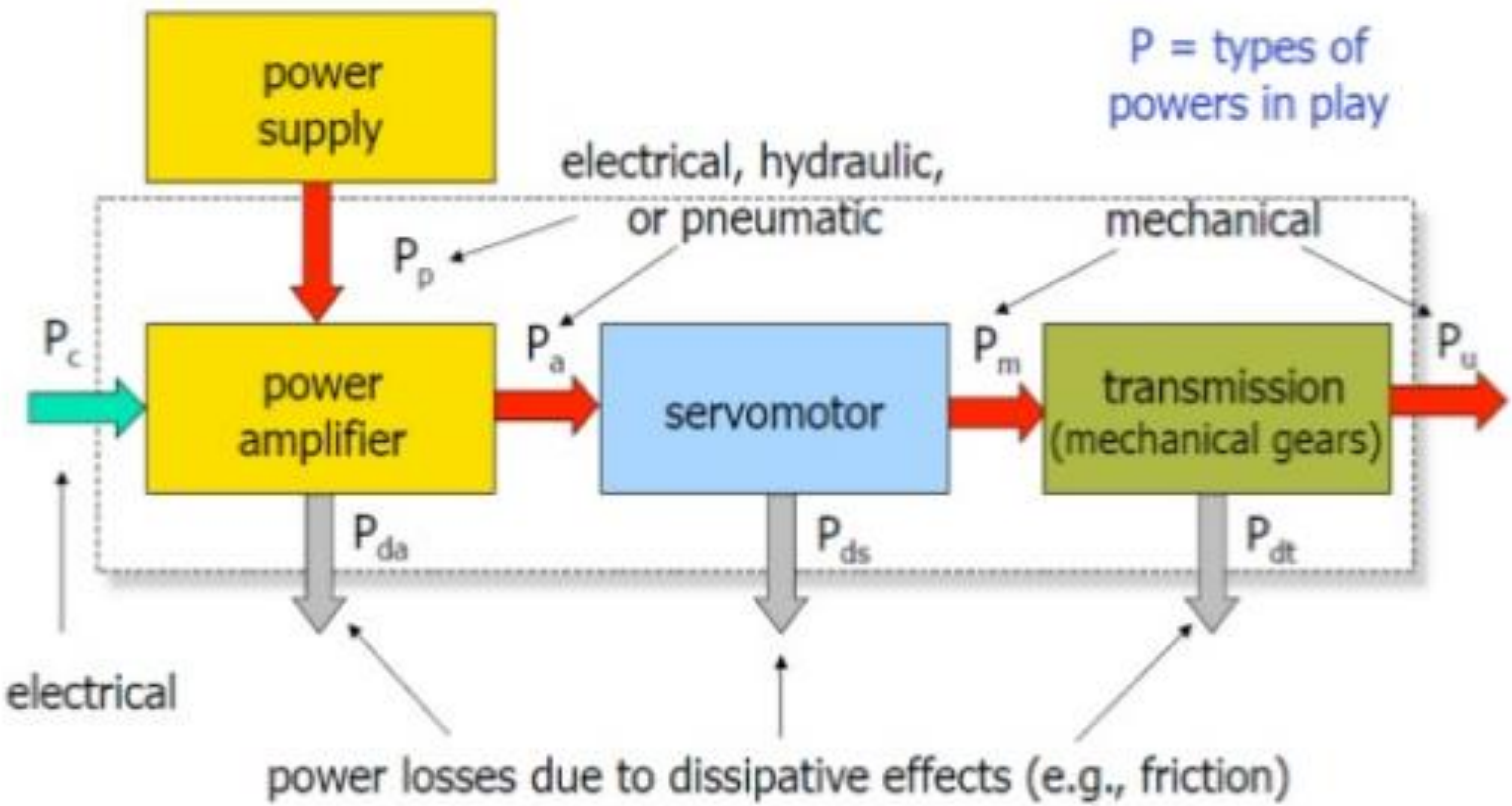
2. Stiffness versus compliance

1) Stiffness is the resistance of a material against deformation. The stiffer the system, the larger the load that is needed to deform it. Conversely, the more compliant the system the easier it deforms under the load.
2) Stiffness is directly related to the modulus of elasticity of the material. Hydraulic systems are very stiff and non-compliant while pneumatic systems are easily compressed and thus are compliant.
3) Stiff systems have a more rapid response to changing loads and pressures and are more accurate.
4) Although stiffness causes a more responsive and more accurate systems, it also creates a danger if all things are not always perfect.

Factors to be considered while choosing the drive system for robots

a) Accuracy
b) Repeatability
c) Degree of freedom
d) Mobility
e) Coordinate systems
f) Gravitational and acceleration force
g) Backlash, friction and thermal effects
h) Weight
i) Power-to-weight ratio
j) Operating pressure

Actuation systems

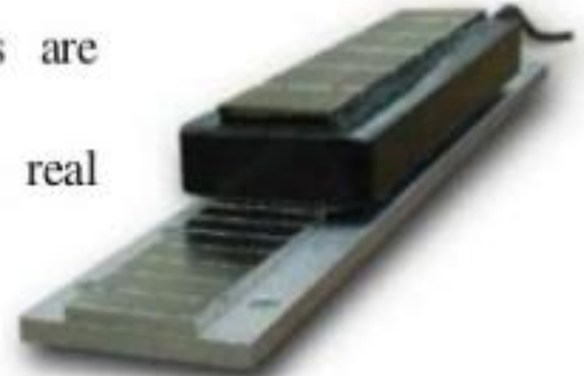


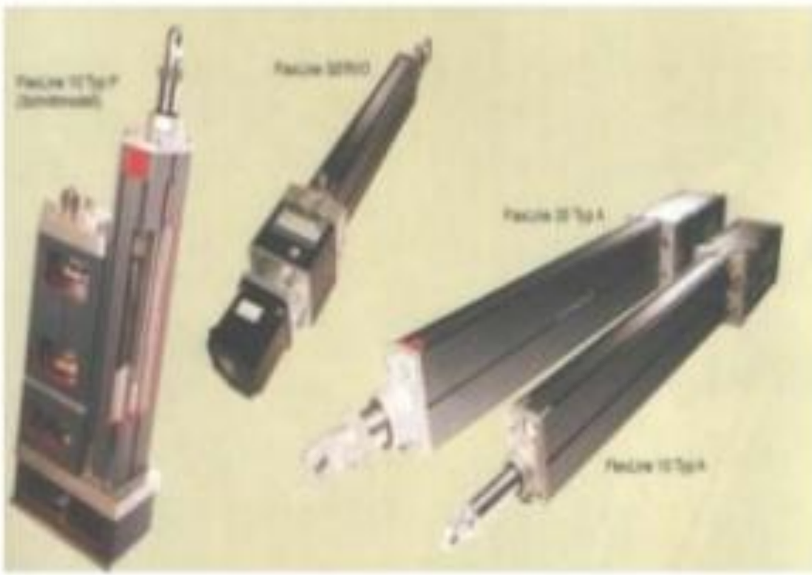
ELECTRICAL ACTUATORS

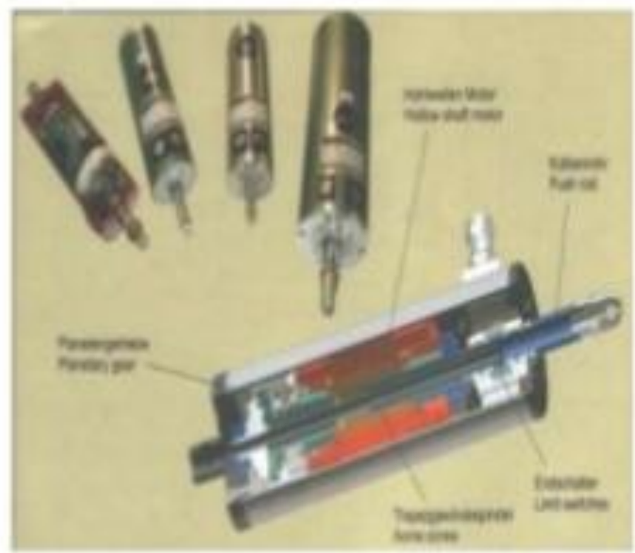
1) Easy to control
2) From W to MW
3) Normally high velocities 1000 - 10000 rpm
4) Several types
5) Accurate servo control
6) Ideal torque for driving
7) Excellent efficiency
8) Autonomous power system

ELECTRICAL ACTUATORS

1. Mainly rotating but also linear ones are available
2. Linear movement with gear or with real linear motor







ELECTRICAL ACTUATOR TYPES

1. Servo Motor
2. DC-motors
3. Brushless DC-motors
4. Asynchronous motors
5. Synchronous motors
6. Reluctance motors
7. Stepper Motor

SERVO SYSTEM

1. Servo is mechanism based on feedback control.
2. The controlled quantity is mechanical.

Properties of Servo Motor

1. High maximum torque/force allows high (de)acceleration
2. High zero speed torque/force
3. High bandwidth provides accurate and fast control
4. Works in all four quadrants
5. Robustness

What is a Servo Motor?

•A servomotor is a rotary actuator or **linear** actuator that allows for precise control of angular or **linear** position, velocity and acceleration.

•It consists of a suitable motor coupled to a sensor for position feedback.

•If you want to rotate and object at some specific angles or distance, then you use servo motor.

•It is just made up of simple motor which run through **servo mechanism**.

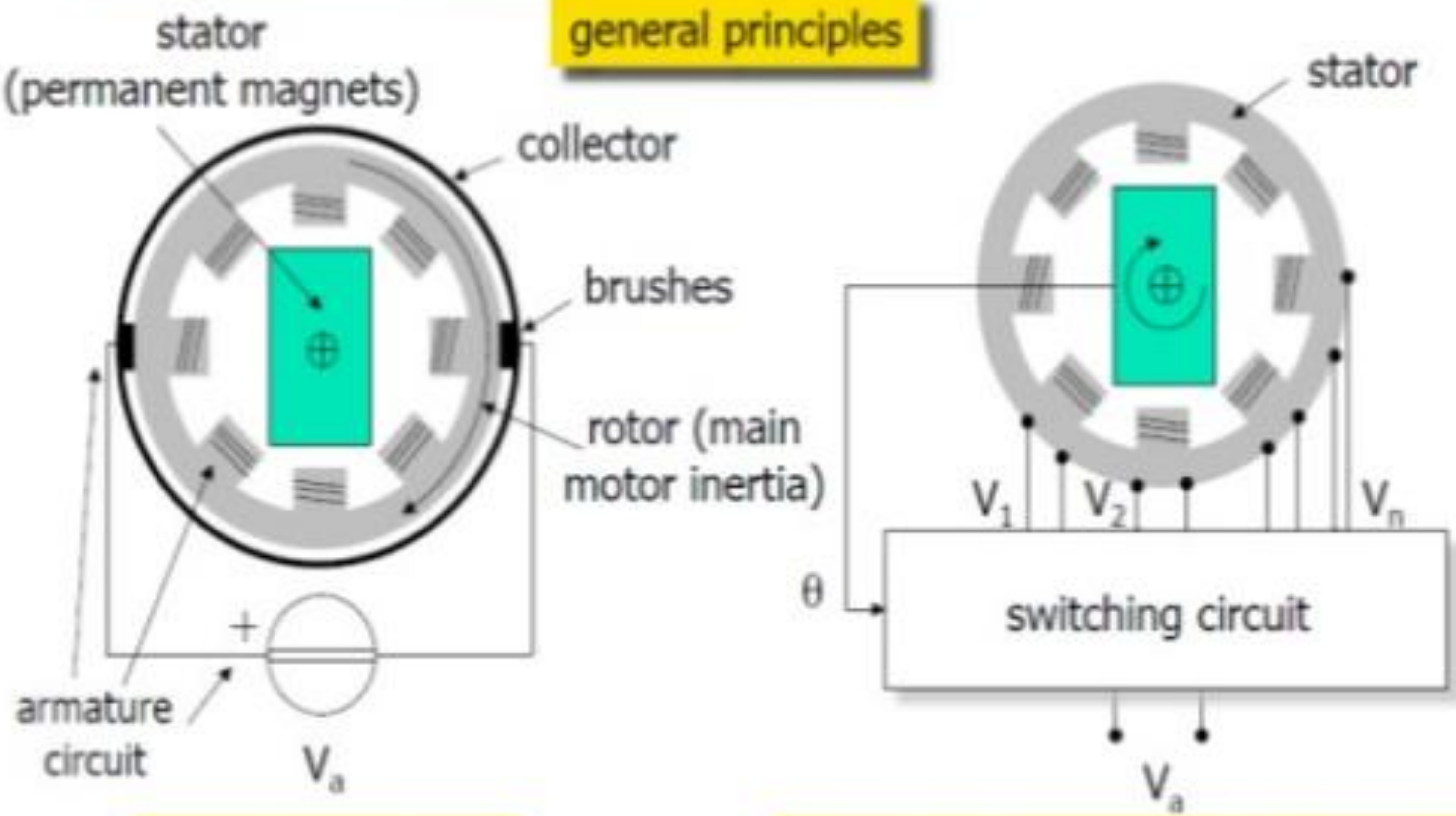
•If motor is used is DC powered then it is called DC servo motor, and if it is AC powered motor then it is called AC servo motor.

•The position of a servo motor is decided by electrical pulse and its circuitry is placed beside the motor.

•We can get a very high torque servo motor in a small and light weight packages. Due to these features they are being used in many applications like toy car, RC helicopters and planes, Robotics, Machine etc.

Electrical servomotors for robots

general principles



direct current (DC)

with electronic switches (brushless)

TYPES OF SERVO MOTORS

- AC servo motor

- Dc servo motor

- Continuous rotation servo motor

- Linear servo motor

Construction of Servo Motor

Servo motor is Dc motor which consist of following parts:

•Stator winding
•Rotor winding
•Bearing
•Shaft
•Encoder

✓The servo motor consists of a stator and rotor winding.

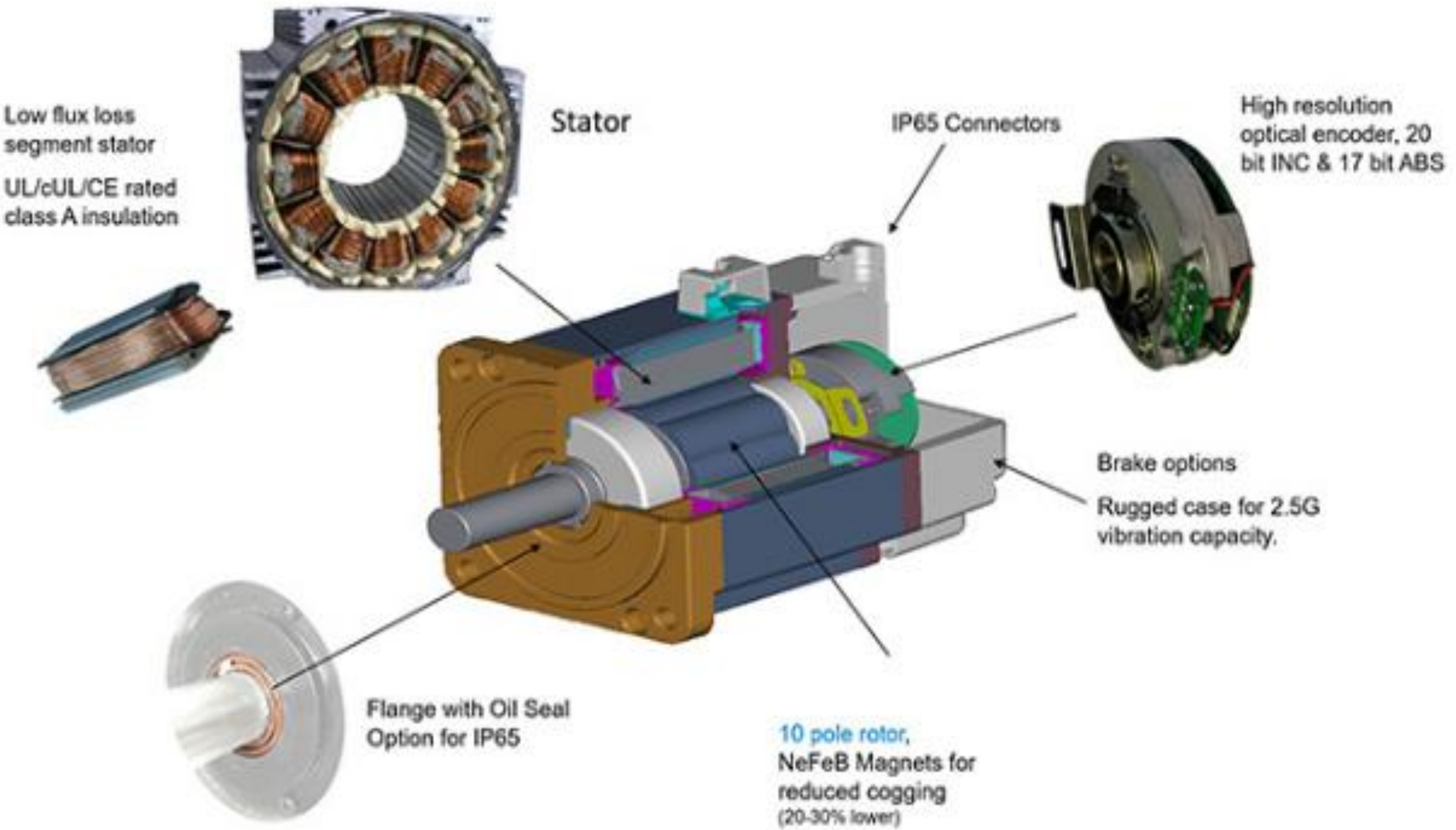
✓The stator winding is wound on stationary part of the motor and this winding is also called field winding of the motor, this winding could the permanent magnets.

✓The rotor winding is wound on the rotating part of the motor and this winding is also called the armature winding of the motor.

✓The motor consists of two bearing on front and back side for the free movement of shaft.

✓Shaft is basically the iron rod on which the armature winding is coupled. The encoder has the approximate sensor for telling the rotational speed and revolution per minute of the motor. The construction of servo motor is shown in figure.

Servo Motor Construction




Stator
From the position of the rotor, a rotating magnetic field is created to efficiently generate torque.
Winding
Current flows in the winding to create a rotating magnetic field.
Bearing
Ball Bearing
Shaft
This part transmits the motor output power. The load is driven through the transfer mechanism (such as the coupling).
Rotor
A high-function rare earth or other permanent magnet is positioned externally to the shaft.
Encoder
The optical encoder always watches the number of rotations and the position of the shaft.
Encoder Cable
Motor Cable

Electrical servomotors

- advantages
  - power supply available everywhere
  - low cost
  - large variety of products
  - high power conversion efficiency
  - easy maintenance
  - no pollution in working environment
- disadvantages
  - overheating in static conditions (in the presence of gravity)
    - use of emergency brakes
  - need special protection in flammable environments

STEPPER MOTORS

1. A sequence of (3 or more) poles is activated in turn, moving the stator in small "steps".
2. Very low speed / high angular precision is possible without reduction gearing by using many rotor teeth.
3. Can also perform a "microstep" by activating both coils at once.

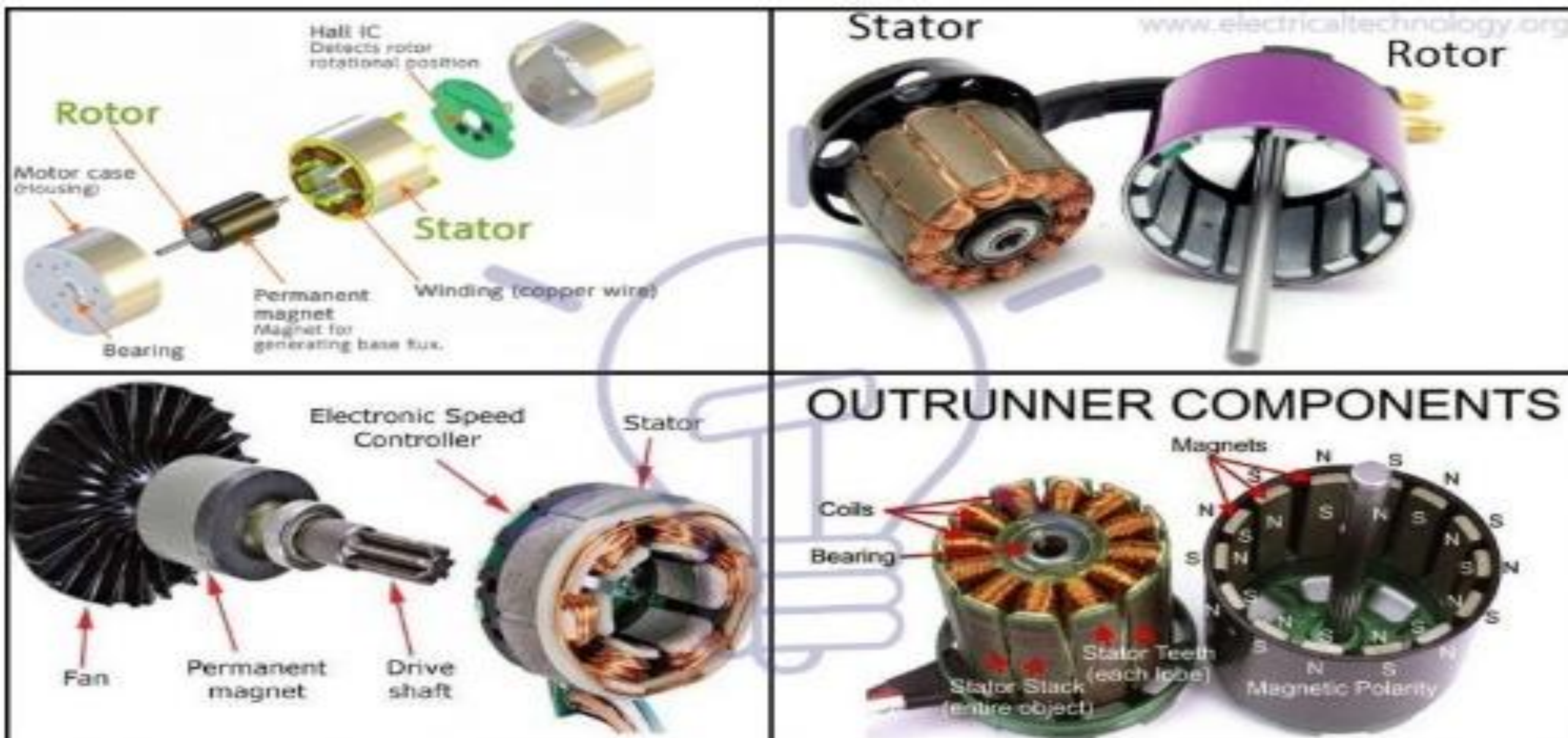
Stepper Motor

STEPPER MOTOR

1. A Stepper motor is a digital actuator where input is in the form of programmed energization of stator winding and output is in the form of discrete angular position.
2. Rotation of rotor occurs because of magnetic interaction between rotor pole and poles of sequentially energized stator winding.

What is Brushless DC motor?

Unlike conventional brushed type DC motor, wherein the brushes make the mechanical contact with commutator on the rotor so as to form an electric path between a DC electric source and rotor armature windings, BLDC motor employs electrical commutation with permanent magnet rotor and a stator with a sequence of coils. In this motor, permanent magnet (or field poles) rotates and current carrying conductors are fixed.



Construction of BLDC Motor

What is a Stepper Motor?

•It is a brushless electromechanical device which converts the train of electric pulses applied at their excitation windings into precisely defined step-by-step mechanical shaft rotation.

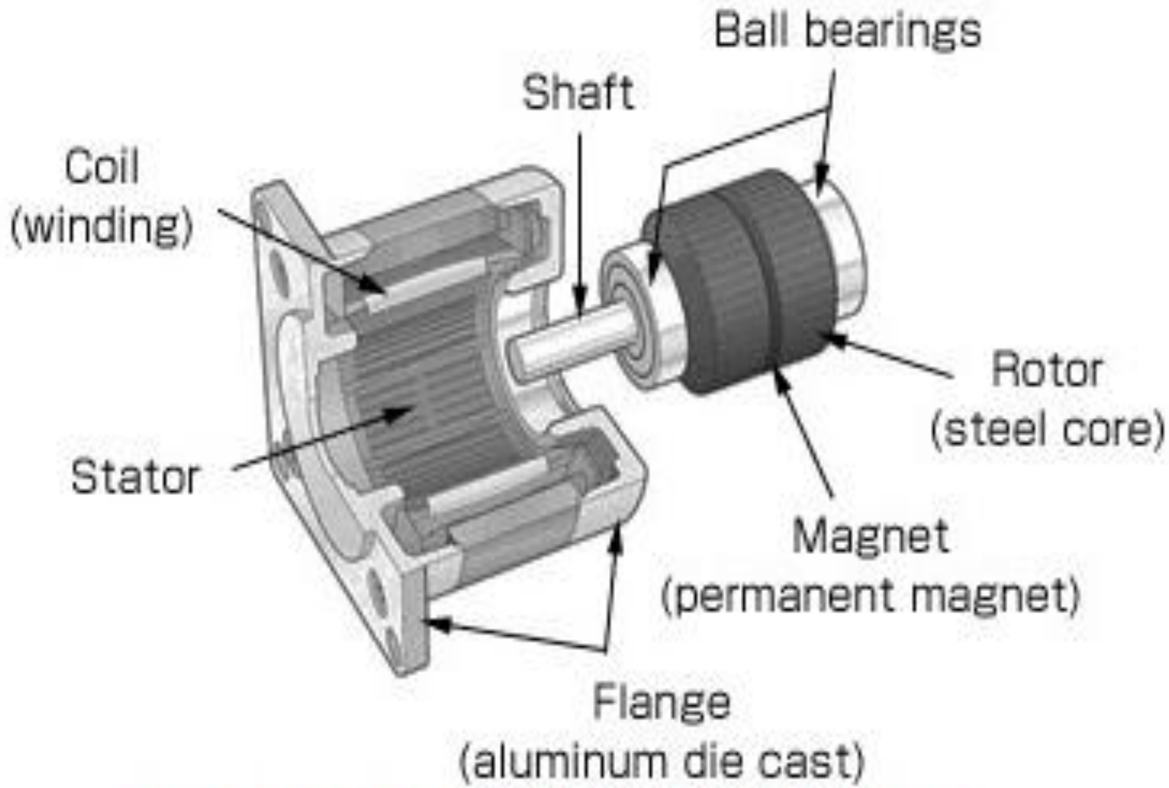
•The shaft of the motor rotates through a fixed angle for each discrete pulse. This rotation can be linear or angular. It gets one step movement for a single pulse input.

•When a train of pulses is applied, it gets turned through a certain angle.

•The angle through which the stepper motor shaft turns for each pulse is referred as the step angle, which is generally expressed in degrees.

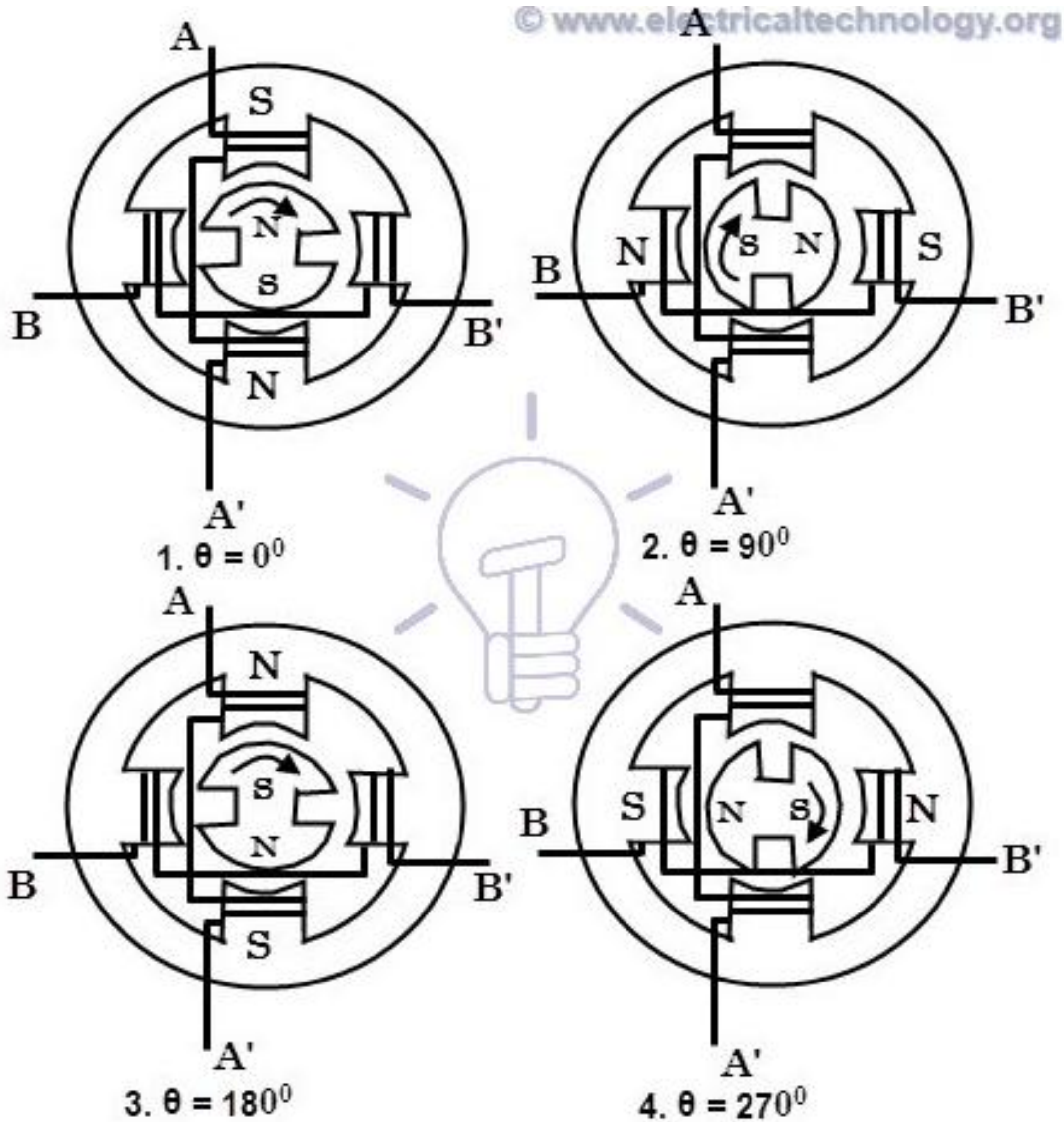
•Unlike other motors it operates on a programmed discrete control pulses that are applied to the stator windings via an electronic drive.

•The rotation occurs due to the magnetic interaction between poles of sequentially energized stator winding and poles of the rotor.



Construction of Stepper Motor

Working of Permanent Magnet Stepper Motor



Step angle =

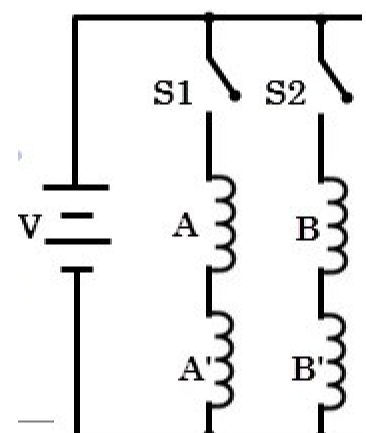
360/Nr x phase

i.e.360/2 x 2 = 90^0

Nr – Number of poles

of rotor.

Phase – 2 or 3



STEPPER MOTOR SELECTION

1. Permanent Magnet / Variable Reluctance
2. Unipolar vs. Bipolar
3. Number of Stacks
4. Number of Phases
5. Degrees Per Step
6. Microstepping
7. Pull-In/Pull-Out Torque
8. Detent Torque

Advantages and Disadvantages of Electrical actuators

Advantages:

1. High power conversion efficiency
2. No pollution of working environment
3. They are easily maintained and repaired
4. Light weight
5. The drive system is well suited for electronic control

Disadvantages:

1. Poor dynamic response
2. Conventional gear driven create backlash
3. A larger and heavier motor must be used which must be costly.

HYDRAULIC ACTUATORS

A hydraulic system generally consists of the following parts:

1. Hydraulic linear or rotary cylinders and rams to provide the force or torque needed to move the joints and are controlled by servo valve or manual valve.
2. A hydraulic pump to provide high pressure fluid to the system
3. Electric motor to operate the hydraulic pump.
4. Cooling system to get rid of heat (cooling fans, radiators, and cooled air).
5. Reservoir to keep fluid supply available to the system.
6. Servo valve which is a very sensitive valve that controls the amount and the rate of the fluid to the cylinders. The servo valve is generally driven by a hydraulic servomotor.
7. Sensors to control the motion of the cylinders (position, velocity, magnetic, touch,..)
8. Connecting hoses to transport the pressurized fluid.
9. Safety check valves, holding valves.

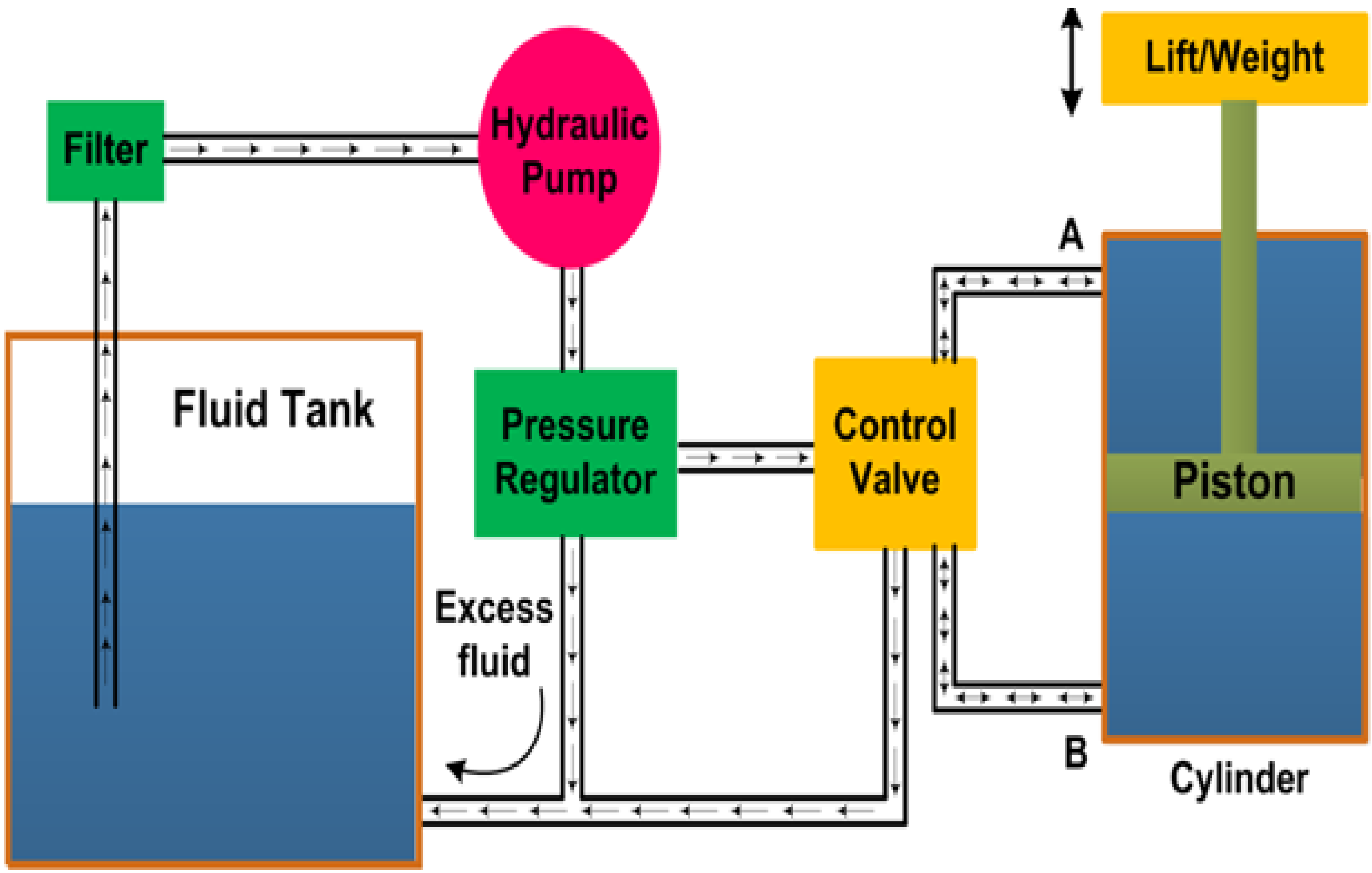


Figure Schematic of hydraulic system

Construction and Working Principle:

- The output shaft transfers the motion or force however all other parts help to control the system.
- The storage/fluid tank is a reservoir for the liquid used as a transmission media.
- The liquid used is generally high density incompressible oil.
- It is filtered to remove dust or any other unwanted particles and then pumped by the hydraulic pump.
- The capacity of pump depends on the hydraulic system design.
- These pumps generally deliver constant volume in each revolution of the pump shaft.
- The pressure regulator is used regulate the pressure of the fluid and also redirects the excess fluid back to the storage tank
- The pressure generated by the hydraulic pump is distributed to the cylinder through pressure regulator and control valves according to the requirement, which is proportional to the amount of load needed to be supported by them.

- The movement of piston is controlled by changing liquid flow from port A and port B.
- The cylinder movement is controlled by using control valve which directs the fluid flow.
- The fluid pressure line is connected to the port B to raise the piston and it is connected to port A to lower down the piston.
- The valve can also stop the fluid flow in any of the port.
- The leak proof piping is also important due to safety, environmental hazards and economical aspects.
- Some accessories such as flow control system, travel limit control, electric motor starter and overload protection may also be used in the hydraulic systems

Advantages and Disadvantages of hydraulic drive

Advantages:

- Precision motion control over a wide range of speeds and loads
- Robust
- Greater Strength

Disadvantages:

- Expensive
- High maintenance
- Not energy efficient
- Noisy
- Not suited for clean-air environment

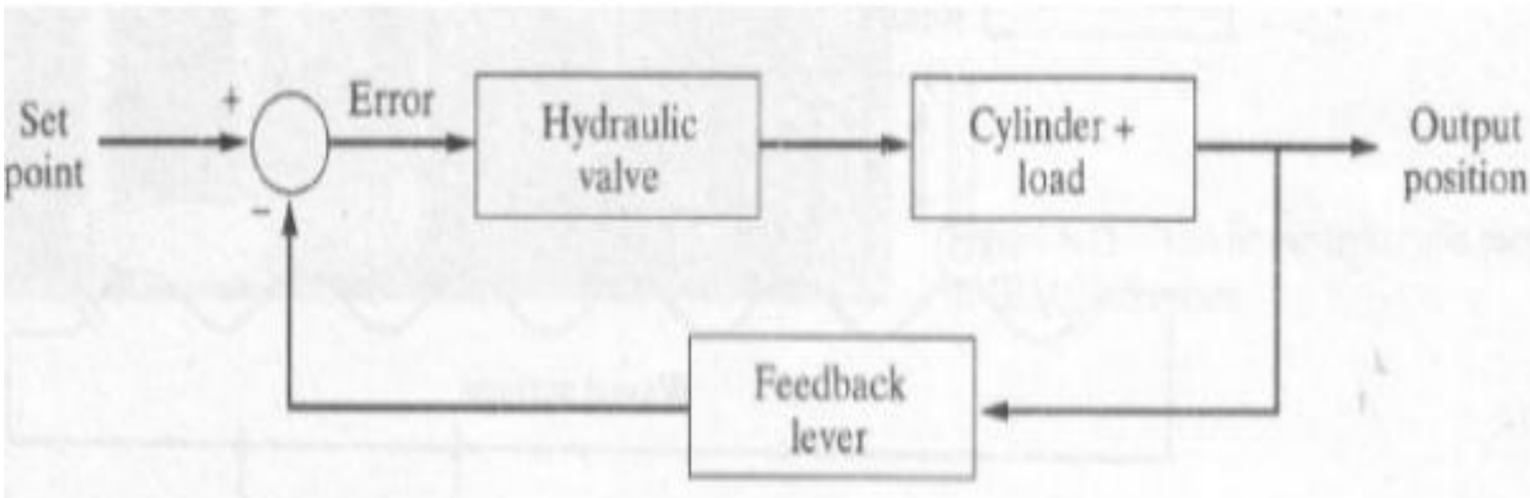


Figure shows the schematic of the, block diagram for the feedback loop.

Pneumatic Actuators

A **pneumatic** control valve actuator converts energy (typically in the form of compressed air) into mechanical motion. The motion can be rotary or linear, depending on the type of actuator.

Method of operation:

•Compressed air from the compressor is stored in an air tank and then fed through a pipeline system to the necessary areas of the system.

•A pneumatic actuator (for example, an air cylinder) converts the energy from this compressed air into motion.

•The motion can be rotary or linear, depending on the type of actuator.

TYPES OF PNEUMATICS ACTUATORS

Pneumatic cylinders can be used to get linear, rotary and oscillatory motion. There are three types of pneumatic actuator: they are

i) Linear Actuator or Pneumatic cylinders

ii) Rotary Actuator or Air motors

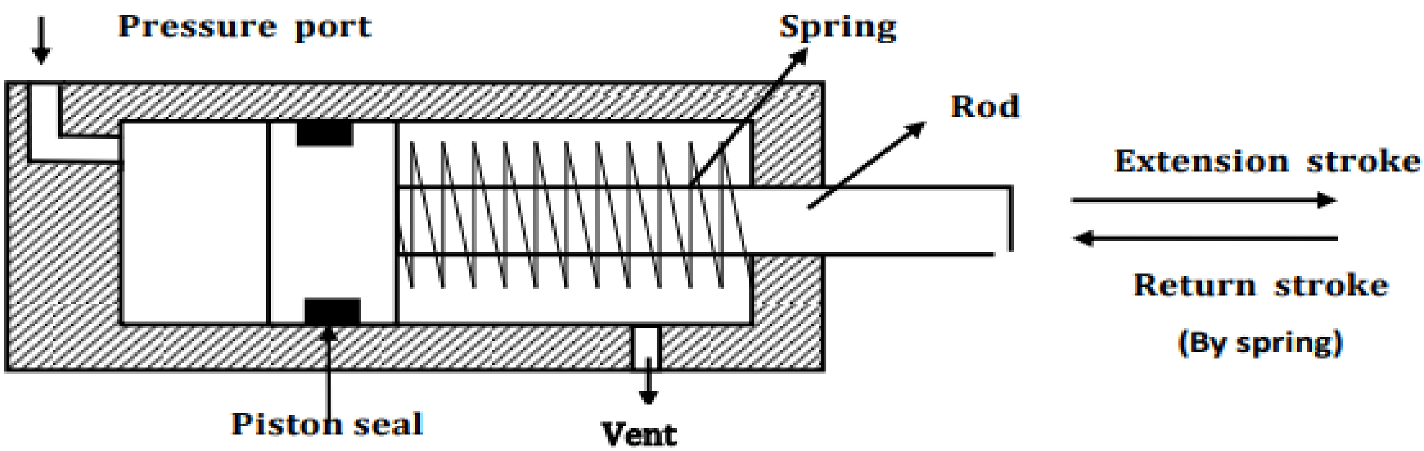
iii) Limited angle Actuators

Pneumatic cylinders are devices for converting the air pressure into linear mechanical force and motion. The pneumatic cylinders are basically used for single purpose application such as clamping, stamping, transferring, branching, allocating, ejecting, metering, tilting, bending, turning and many other applications.

Single acting cylinder has one working port. Forward motion of the piston is obtained by supplying compressed air to working port. Return motion of piston is obtained by spring placed on the rod side of the cylinder. Schematic diagram of single acting cylinder is shown in Figure

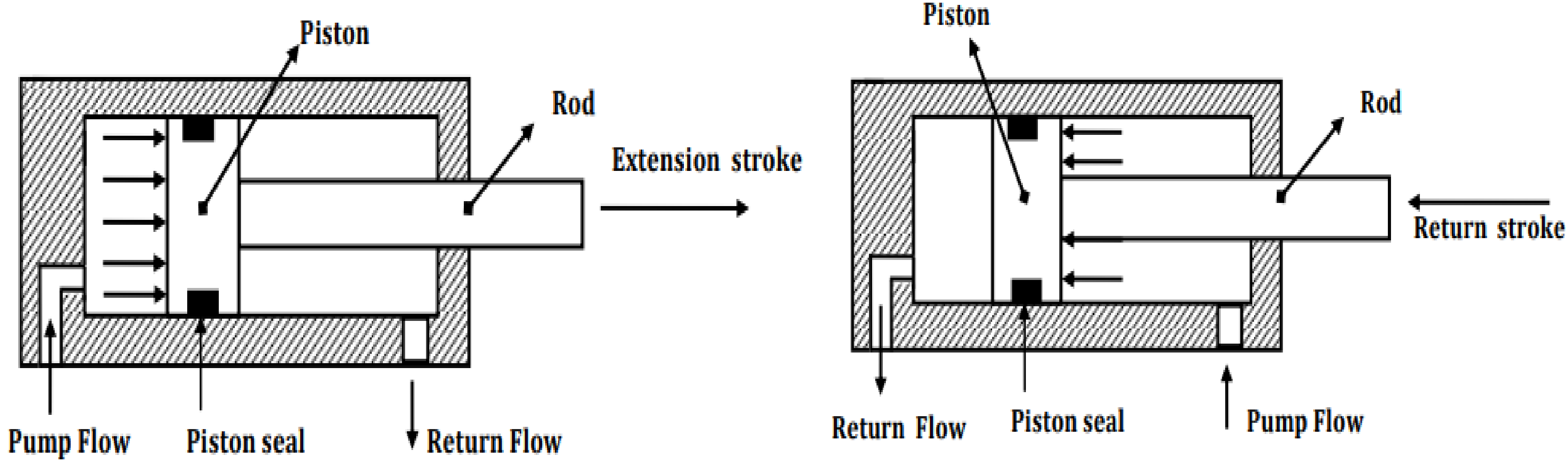
Single acting cylinders are used where force is required to be exerted only in one direction. Such as clamping, feeding, sorting, locking, ejecting, braking etc.,

Single acting cylinder is usually available in short stroke lengths [maximum length up to 80 mm] due to the natural length of the spring. Single Acting Cylinder exert force only in one direction. Single acting cylinders require only about half the air volume consumed by a double acting cylinder for one operating cycle.



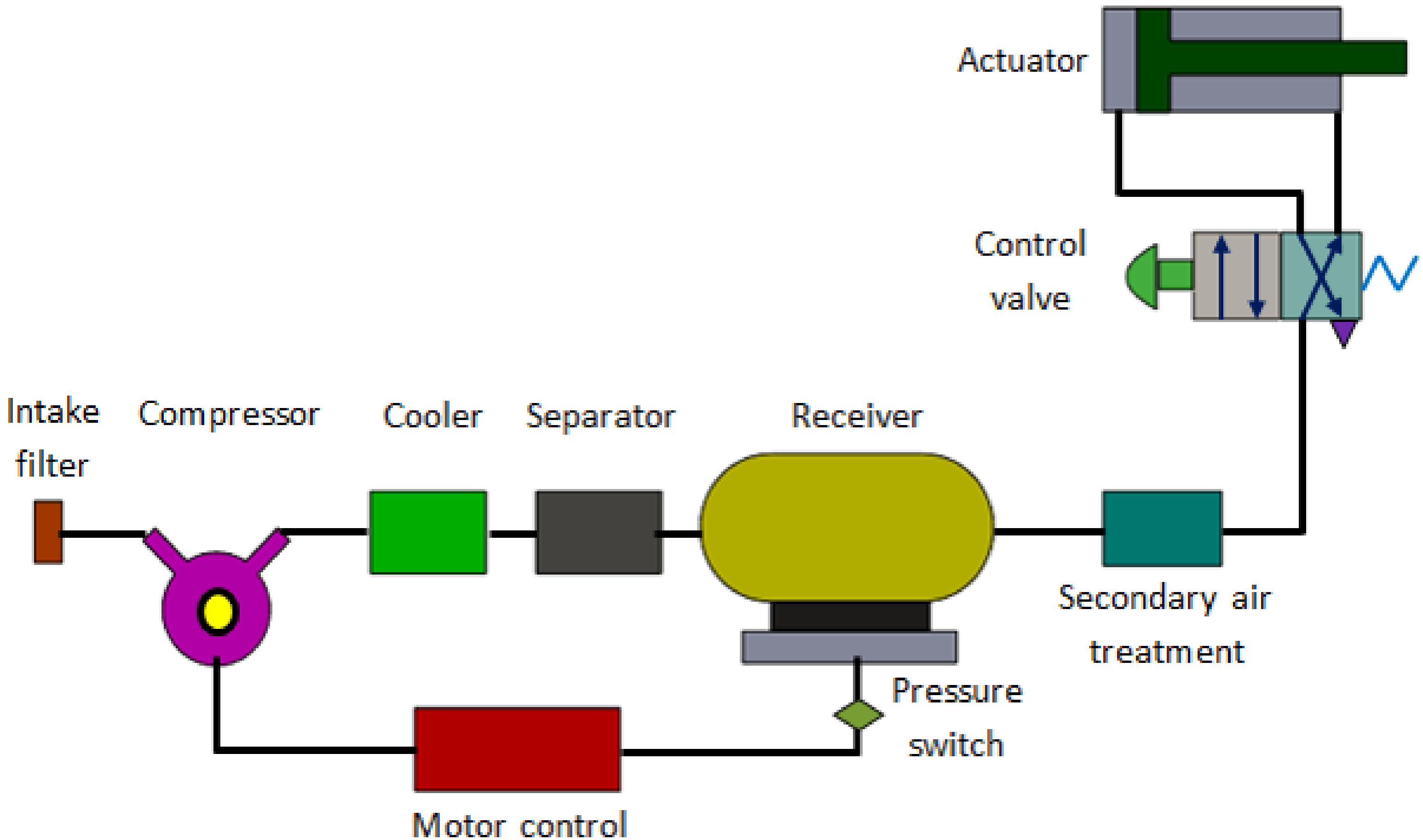
Construction features of single acting cylinder

The construction features of double acting cylinder are shown in Figure The construction of double acting cylinder is similar to that of a single cylinder. However, there is no return spring. In double acting cylinder, air pressure can be applied to either side (supply and exhaust) of the piston, thereby providing a pneumatic force in both directions. The double acting cylinders are mostly commonly used in the application where larger stroke length is required.



Double acting cylinder

Basic Components of Pneumatic System



a. **Air filters:** These are used to filter out the contaminants from the air.

b. **Compressor:** Compressed air is generated by using air compressors. Air compressors are either diesel or electrically operated. Based on the requirement of compressed air, suitable capacity compressors may be used.

c. **Air cooler:** During compression operation, air temperature increases. Therefore coolers are used to reduce the temperature of the compressed air.

d. **Dryer:** The water vapor or moisture in the air is separated from the air by using a dryer.

e. **Control Valves:** Control valves are used to regulate, control and monitor for control of direction flow, pressure etc.

f. **Air Actuator:** Air cylinders and motors are used to obtain the required movements of mechanical elements of pneumatic system.

g. **Electric Motor:** Transforms electrical energy into mechanical energy. It is used to drive the compressor.

h. **Receiver tank :** The compressed air coming from the compressor is stored in the air receiver.

Advantages

1) Higher actuation speed than an electric actuator.

2) Actuation speed can be adjusted as desired using a controller.

3) Can be used as an emergency shutoff or release valve. (Single acting type; spring return type)

4) Can be used for valves that require frequent opening / closing.

5) Simple configuration makes it easy to maintain.

Disadvantages

1) Additional cost for dust/moisture removing dryer or dust filter is required because instrument air is used.

2) Response speed becomes slower (due to the compression of air) where the actuator is significantly distant from the supply air source.

3) A larger size actuator is required to obtain high output power.

4) Actuation is affected by fluctuation in air pressure and flow rate.

OTHER TYPES OF ACTUATORS.

1. Piezoelectric
2. Magnetic
3. Ultrasound
4. Shape Memory Alloys

Advanced actuators: small, low power consumption, micro motion

- Ultrasonic motors : micro robots, cameras, micro motion devices ..
- Artificial muscles : prosthetic, bio applications..
- Molecular motors : bio applications

Ultrasonic motors

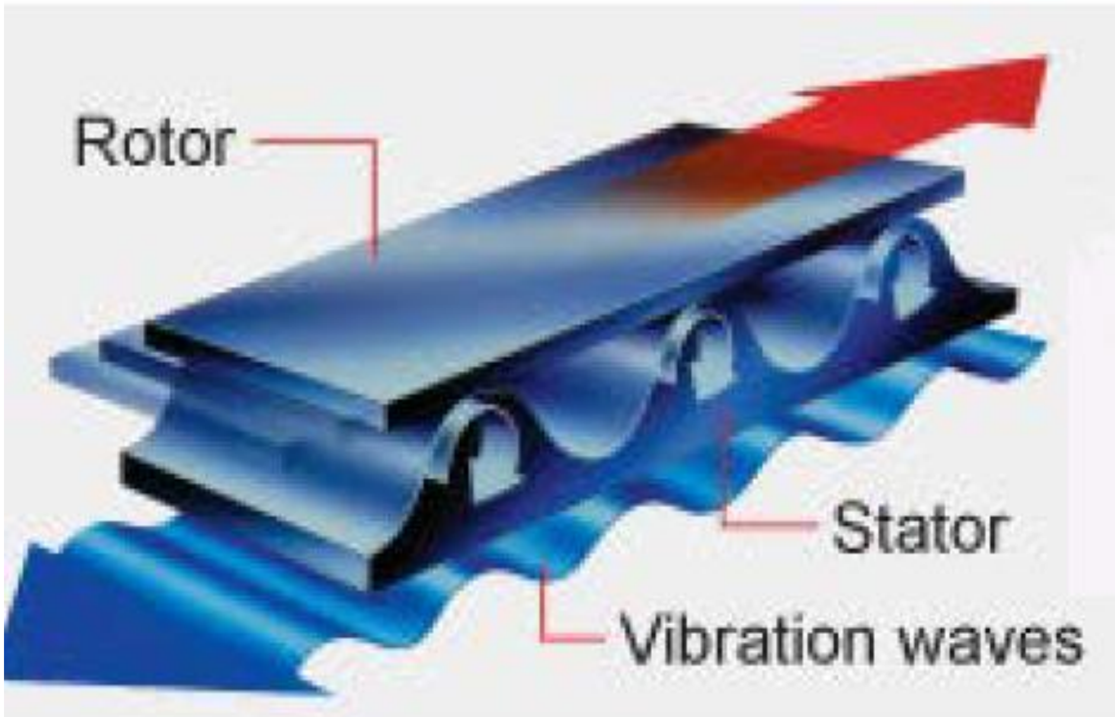
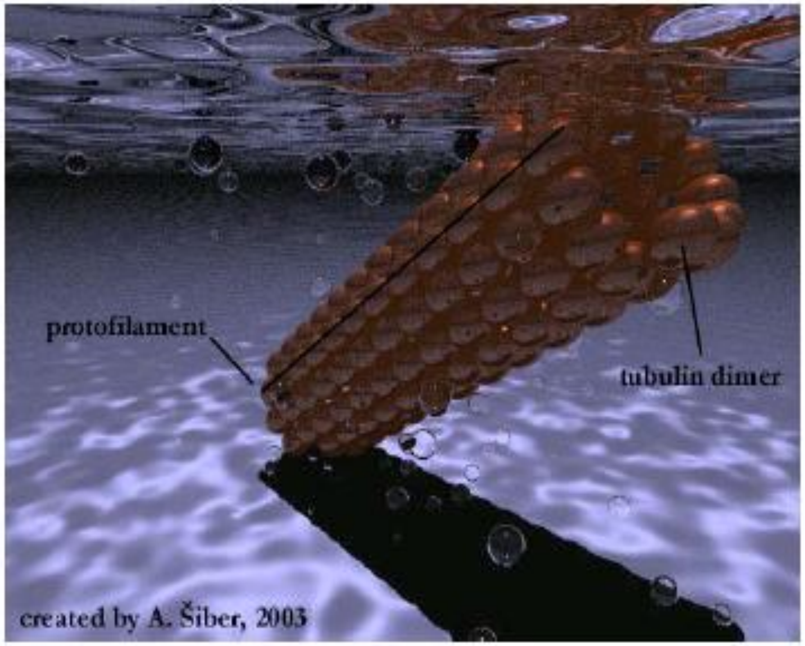


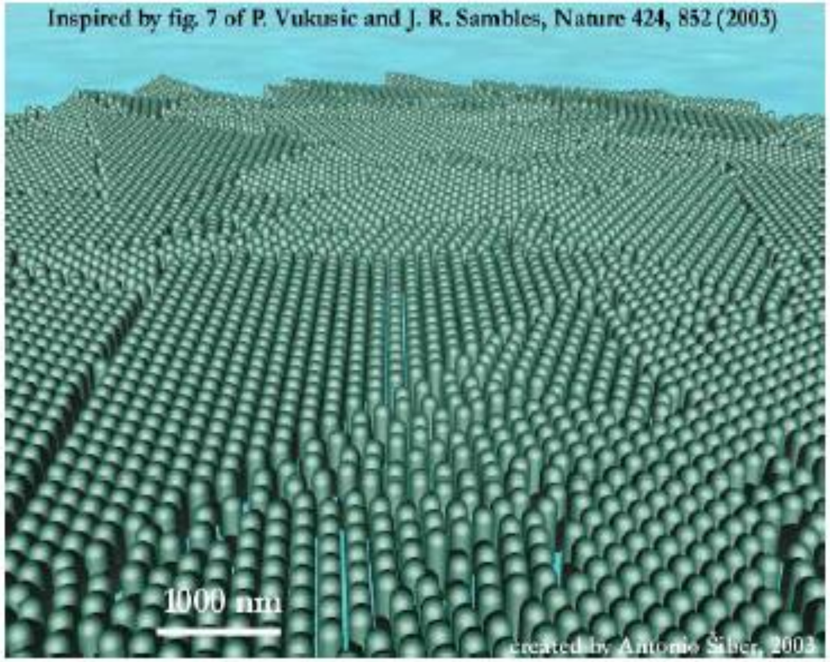
Fig. Motion due to dry friction and vibration.

Fig. Ring motors used in cameras.

Molecular motors

Protein-based molecular motors harness the chemical free energy released by the hydrolysis of ATP in order to perform mechanical work.





Introduction

- **Robotic sensing** is a branch of robotics science intended to give robots sensing capabilities, so that robots are more human-like.
- Robotic sensing mainly gives robots the ability to see, touch, hear and move and uses algorithms that require environmental feedback.
- The use of sensors in robots has taken them into the next level of creativity. Most importantly, the sensors have increased the performance of robots to a large extent. It also allows the robots to perform several functions like a human being.

General Classification of Sensors

- **Internal sensors:** required for basic working of the system (e.g. position, velocity,).

- **External sensors:** interaction with the environment (vision, force, ...).

There are a number of ways in which sensing devices may be classified:

•By their type of operation - analog or digital.

•Whether the quantity is sensed directly or indirectly.

•By the medium by which they operate - optical, electrical etc.

•By their application.

Sensors used for closed loop position control: Internal sensors

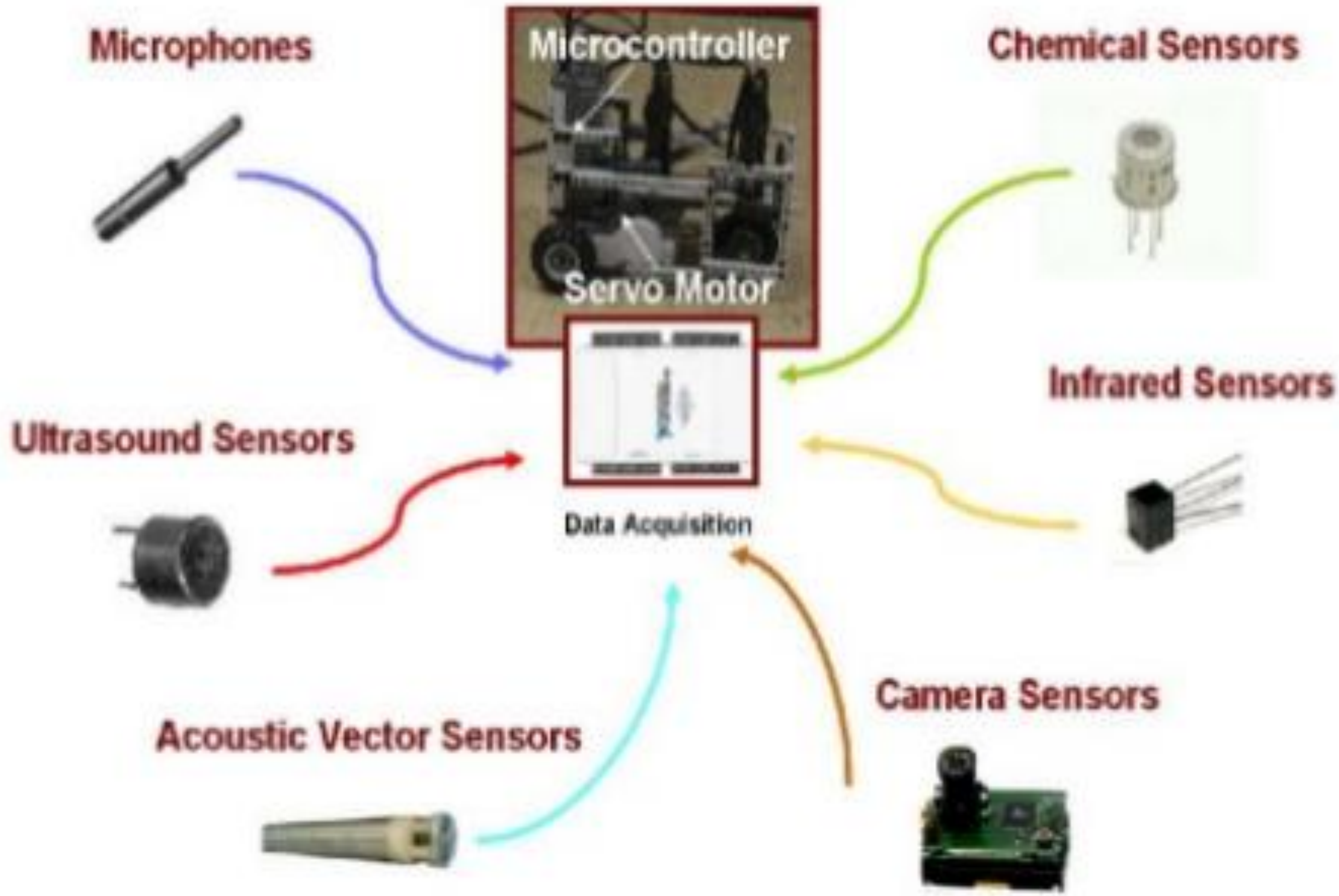
- Position
- Velocity
- Acceleration

e.g. potentiometers, encoders, LVDT, Tachometers, Accelerometers

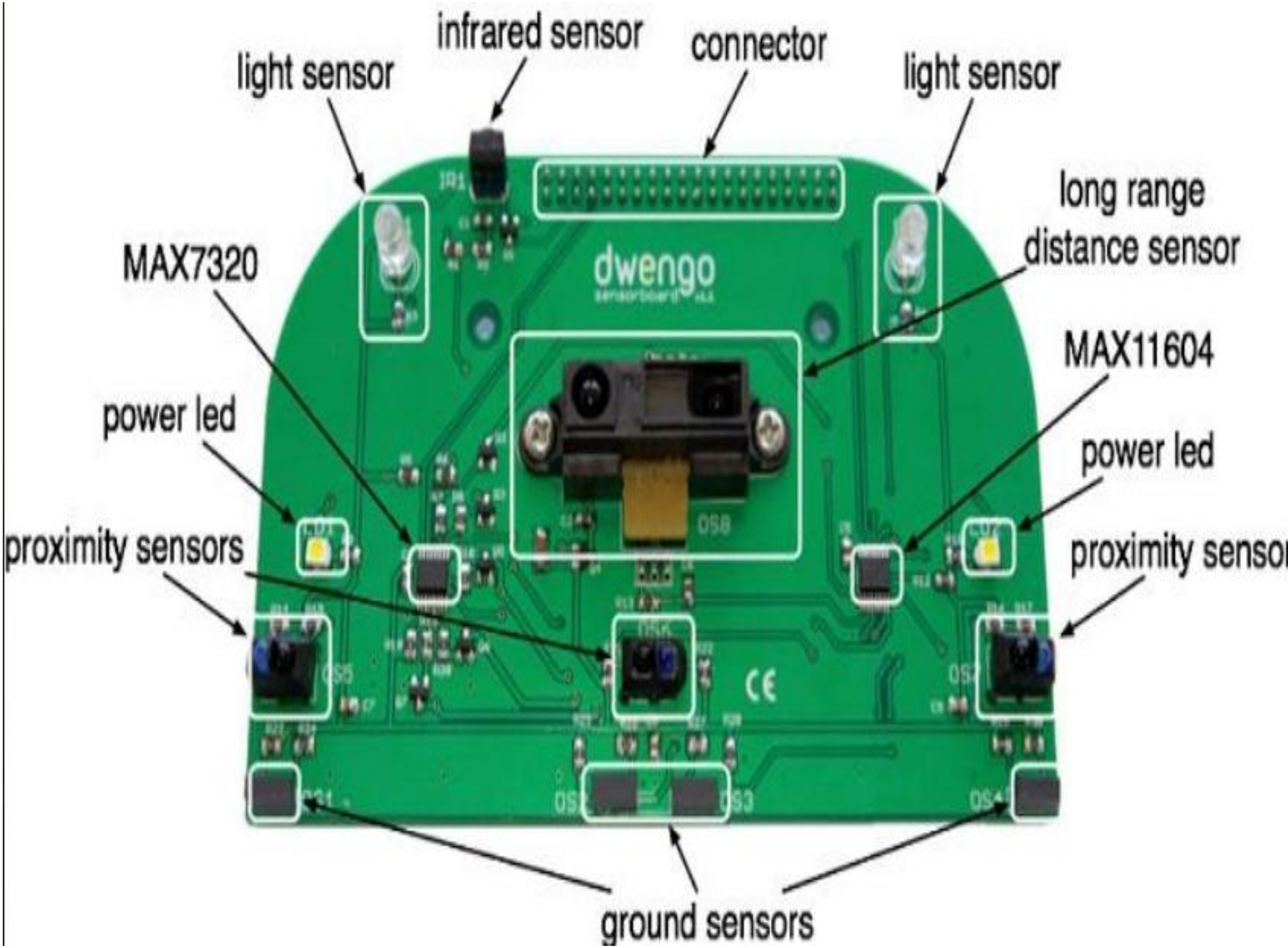
Sensors for interaction with the environment: External sensors

- Touch
- Force
- Pressure
- Slip
- Proximity
- Vision

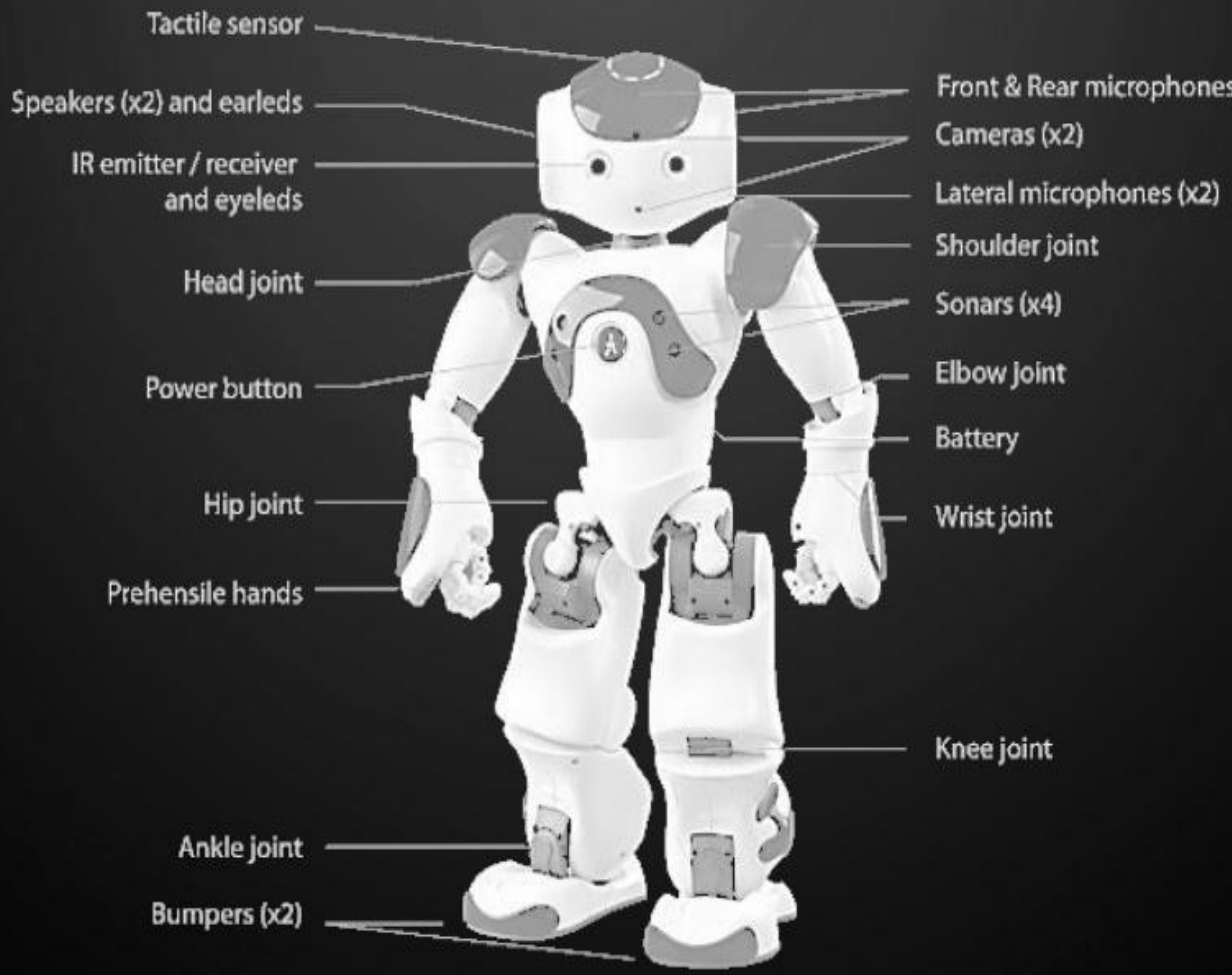
e.g. on/off switches, ultrasonic, force sensor, hall effect, inductive sensor, piezo sensor

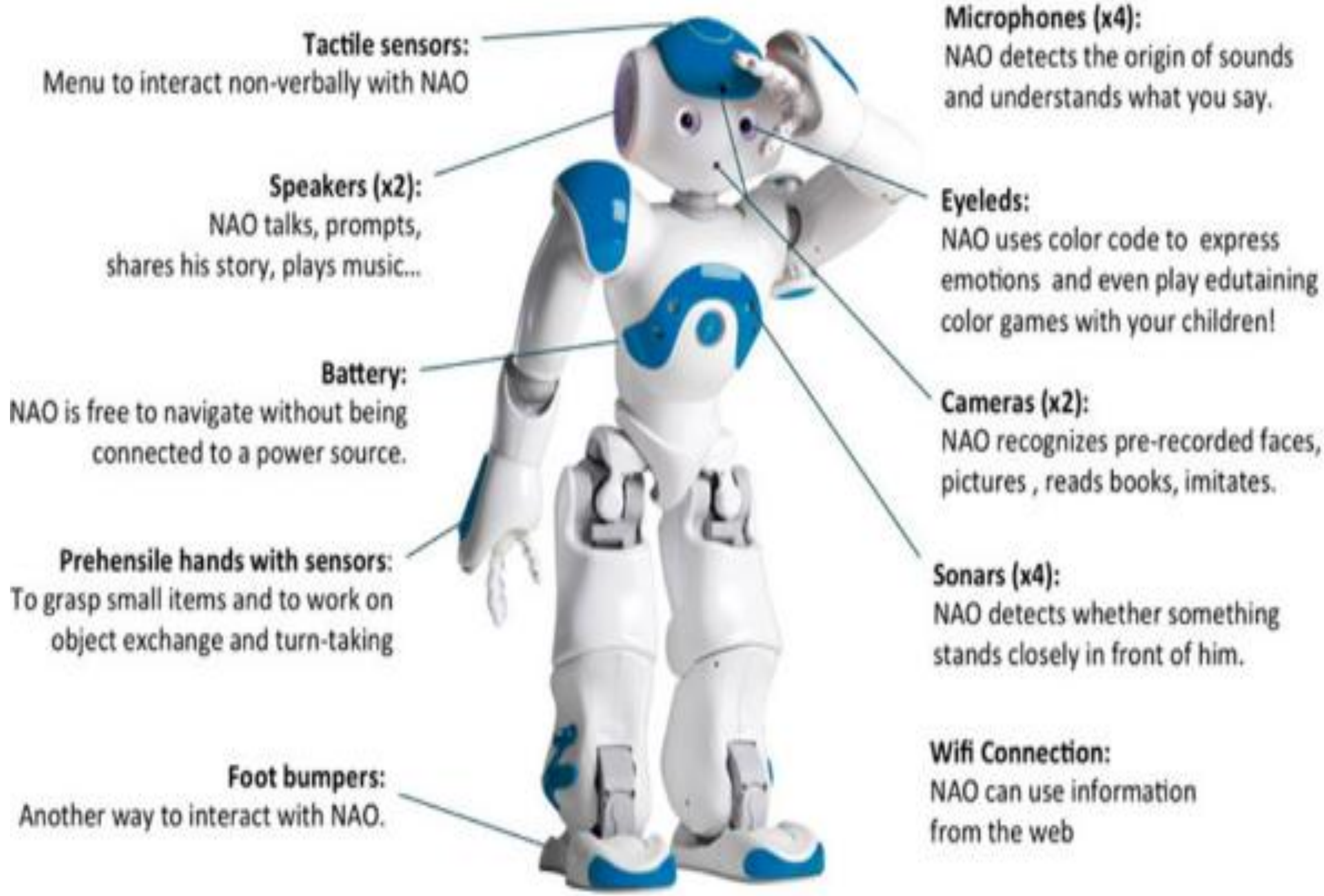


SENSORS USED IN ROBOT SENSING


infrared sensor
connector
light sensor
light sensor
long range
distance sensor
MAX7320
dwengo
MAX11604
power led
power led
proximity sensors
proximity sensor
ground sensors

Advanced sensor model technologies for robotics




Tactile sensors:
Menu to interact non-verbally with NAO
Speakers (x2):
NAO talks, prompts,
shares his story, plays music...
Battery:
NAO is free to navigate without being
connected to a power source.
Prehensile hands with sensors:
To grasp small items and to work on
object exchange and turn-taking
Foot bumpers:
Another way to interact with NAO.
Microphones (x4):
NAO detects the origin of sounds
and understands what you say.
Eyeleds:
NAO uses color code to express
emotions and even play edutaining
color games with your children!
Cameras (x2):
NAO recognizes pre-recorded faces,
pictures , reads books, imitates.
Sonars (x4):
NAO detects whether something
stands closely in front of him.
Wifi Connection:
NAO can use information
from the web

Sensor Type	Description
Tactile sensors	Used to determine whether contact is made between sensor and another object. Two types: touch sensors which indicate when contact is made and force sensors which indicate the magnitude of the force with the object.
Proximity sensors	Used to determine how close an object is to the sensor. Also called a range sensor.
Optical sensors	Photocells and other photometric devices that are used to detect the presence or absence of objects. Often used in conjunction to proximity sensors.

Sensor Type	Description
Machine vision	Used in robotics for inspection, parts identification, guidance and other uses.
Miscellaneous category	temperature, fluid pressure, fluid flow, electrical voltage, current and other physical properties.

Proximity Sensing

Proximity sensing normally means detecting:

a. Presence or absence of an object.
b. The size or simple shape of an object.

Proximity sensors can be further classified as contact or non - contact, and as analog or digital in operation. The choice of sensor is determined by the physical, environmental and control conditions. They include the following:

Mechanical - Any suitable mechanical / electrical switch may be adopted but because a certain amount of force is required to operate a mechanical switch it is common to use microswitches.

Pneumatic - These proximity sensors operate by breaking or disturbing an air flow. The Pneumatic proximity sensor is an example of a contact type sensor.

Optical - In the simplest form, optical proximity sensors operate by breaking a light beam which falls onto a light sensitive device such as a photocell. These are examples of non contact sensors. Care must be exercised with the lighting environment of these sensors for example optical sensors can be blinded by flashes from arc welding processes, airborne dust and smoke clouds may impede light transmission etc.

Electrical -
Electrical proximity sensors may be contact or non - contact. Simple contact Sensors operate by making the sensor and the component complete an electrical circuit. Non – contact electrical proximity sensors rely on the electrical principles of either induction for Detecting metals or capacitance for detecting non metals as well.

Range Sensing -
Range sensing detects how near or far a component is from the sensing position, although they can also be used as proximity sensors. Distance or range sensors use non - contact analog techniques. Short range sensing, between a few millimetres and a few hundred millimetres is carried out using electrical capacitance, inductance and magnetic technique. Longer range sensing is carried out using transmitted energy waves of various types.
Eg. radio waves, sound waves and lasers.

Force Sensing

There are six types of forces (as shown below) that may require sensing. In each case the application of the force may be static (Stationary) or dynamic t Moving). Force is a vector quantity in that it must be specified in both magnitude and direction. Force sensors are therefore analog an operation and sensitive to the direction in which they act.

•Tensile Force
•Compressive Force
•Shear force
•Torsional Force
•Bending Force
•Frictional Force

A number of techniques exist for sensing force, some direct and some indirect.

Tensile Forces: -Can be determined by Strain Gauges, these show a change in their electrical resistance when their length is increased. These gauges measure change in electrical resistance which can be translated into force and are therefore indirect devices.

Compressive Forces: -
Can be determined by devices known as Load Cells, these operate by detecting either a change in dimension of the cell under compressive load or by detecting an increase in the pressure within the cell under load or by exhibiting a change in electrical resistance under a compressive load.

Torsional and Bending Forces: -
Can be regarded as a combination of tensile and compressive forces so a combination of the above technique are employed.

Frictional Forces: -
These relate to situations where movement is to be restrained, so friction force is Detected indirectly using a combination of force and movement sensors.

Tactile Sensing

- Tactile sensing means sensing through touch.
- The simplest types of tactile sensors use an array of simple touch sensors arranged in rows and columns.
- These are commonly called matrix sensors.
- Each individual sensor is activated when brought into contact with the object.
- By detecting which sensors are active (digital) or the magnitude of the output signal (analog) an imprint of the component can be determined. The imprint is then compared to previously stored imprint information to determine the size or shape of the component.
- Mechanical, optical and electrical tactile sensors are available.

Vision

- **Method:** The visual sensing system can be based on anything from the traditional camera, sonar, and laser to the new technology radio frequency identification (RFID), which transmits radio signals to a tag on an object that emits back an identification code. All four methods aim for three procedures—sensation, estimation, and matching.
- **Image processing:** Image quality is important in applications that require excellent robotic vision. Robots can gather more accurate information from the resulting improved image.
- **Usage:** Visual sensors help robots to identify the surrounding and take appropriate action. Robots analyze the image of the immediate environment imported from the visual sensor. The result is compared to the ideal intermediate or end image, so that appropriate movement can be determined to reach the intermediate or final goal.

2) Touch

- **Signal Processing:** Touch sensory signals can be generated by the robot's own movements. It is important to identify only the external tactile signals for accurate operations. Recent solution applies an adaptive filter to the robot's logic. It enables the robot to predict the resulting sensor signals of its internal motions, screening these false signals out. The new method improves contact detection and reduces false interpretation.
- **Usage :** Touch patterns enable robots to interpret human emotions in interactive applications. Four measurable features—force, contact time, repetition, and contact area change—can effectively categorize touch patterns through the temporal decision tree classifier to account for the time delay and associate them to human emotions with up to 83% accuracy.

3) Hearing

- **Signal processing:** Accurate audio sensor requires low internal noise contribution. Traditionally, audio sensors combine acoustical arrays and microphones to reduce internal noise level. Recent solutions combine also piezoelectric devices. These passive devices use the piezoelectric effect to transform force to voltage, so that the vibration that is causing the internal noise could be eliminated. On average, internal noise up to about 7dB can be reduced.
- Robots may interpret strayed noise as speech instructions. Current voice activity detection (VAD) system uses the complex spectrum circle centroid (CSCC) method and a maximum signal-to-noise ratio (SNR) beamformer.
- **Usage**
  Robots can perceive our emotion through the way we talk. Acoustic and linguistic features are generally used to characterize emotions.

SENSORS USED IN ROBOTICS

- **a) Proximity Sensor:** This type of sensor is capable of pointing out the availability of a component. Generally, the proximity sensor will be placed in the robot moving part such as end effector. This sensor will be turned ON at a specified distance, which will be measured by means of feet or millimeters. It is also used to find the presence of a human being in the work volume so that the accidents can be reduced.
- **Infrared (IR) Transceivers**: An IR LED transmits a beam of IR light and if it finds an obstacle, the light is simply reflected back which is captured by an IR receiver. Few IR transceivers can also be used for distance measurement.
- **Ultrasonic Sensor**: These sensors generate high frequency sound waves; the received echo suggests an object interruption. Ultrasonic Sensors can also be used for distance measurement.
- **Photoresistor**: Photoresistor is a light sensor; but, it can still be used as a proximity sensor. When an object comes in close proximity to the sensor, the amount of light changes which in turn changes the resistance of the Photoresistor. This change can be detected and processed.

b) Range Sensor

- Range Sensor is implemented in the end effector of a robot to calculate the distance between the sensor and a work part. The values for the distance can be given by the workers on visual data. It can evaluate the size of images and analysis of common objects. The range is measured using the Sonar receivers & transmitters or two TV cameras.

c) Tactile Sensors

- A sensing device that specifies the contact between an object, and sensor is considered as the **Tactile Sensor.** Tactile sensors are often in everyday objects such as elevator buttons and lamps which dim or brighten by touching the base. There are also innumerable applications for tactile sensors of which most people are never aware.
- This sensor can be sorted into two key types namely:

a)Touch Sensor, and

b) Force Sensor.

TACTILE SENSORS

- Tactile sensing includes any form of sensing which requires physical touching between the sensor and the object to be sense.

- The need for touch or tactile sensors occurs in many robotic applications, from picking oranges to loading machines. Probably the most important application currently is the general problem of locating, identifying, and organizing parts that need to be assembled.

- **Tactile sensor system includes the capability to detect such things as:**
  1. **Presence**
  2. **Part shape, location, orientation, contour examination**
  3. **Contact are pressure and pressure distribution**
  4. **Force magnitude, location, and direction**
  5. **Surface inspection : texture monitoring, joint checking, damage detection**
  6. **Object classification : recognition, discrimination**
  7. **Grasping : verification, error compensation (slip, position ,orientation)**
  8. **Assembly monitoring**

a)Touch Sensor

- The **touch sensor** has got the ability to sense and detect the touching of a sensor and object. Some of the commonly used simple devices as touch sensors are micro – switches, limit switches, etc. If the end effector gets some contact with any solid part, then this sensor will be handy one to stop the movement of the robot. In addition, it can be used as an inspection device, which has a probe to measure the size of a component.

Touch Sensor

The **force sensor** is included for calculating the forces of several functions like the machine loading & unloading, material handling, and so on that are performed by a robot. This sensor will also be a better one in the assembly process for checking the problems. There are several techniques used in this sensor like Joint Sensing, Robot – Wrist Force Sensing, and Tactile Array Sensing.

d) Light Sensor

- A Light sensor is used to detect light and create a voltage difference. The two main light sensors generally used in robots are Photoresistor and Photovoltaic cells. Other kinds of light sensors like Phototubes, Phototransistors, CCD's etc. are rarely used.
- Photoresistor is a type of resistor whose resistance varies with change in light intensity; more light leads to less resistance and less light leads to more resistance. These inexpensive sensors can be easily implemented in most light dependant robots.
- Photovoltaic cells convert solar radiation into electrical energy. This is especially helpful if you are planning to build a solar robot. Although photovoltaic cell is considered as an energy source, an intelligent implementation combined with transistors and capacitors can convert this into a sensor.

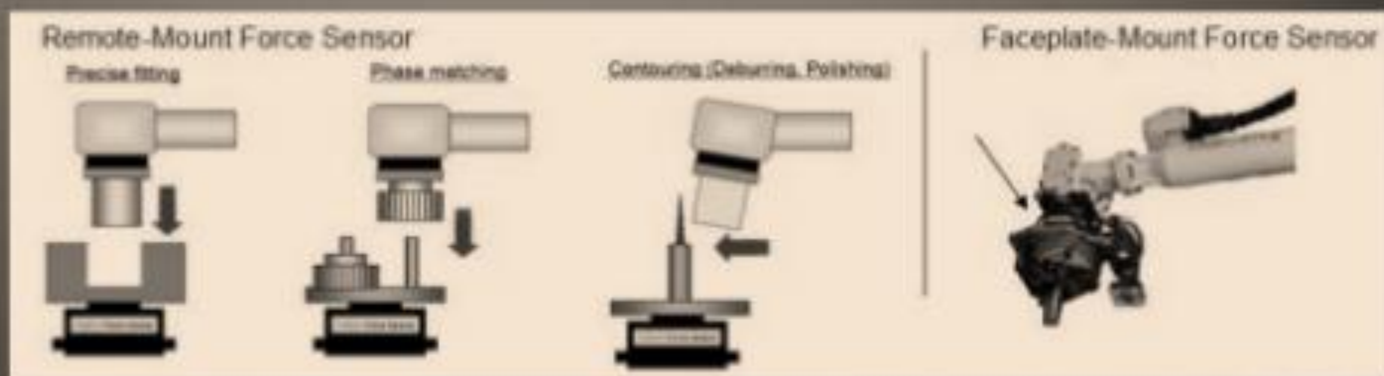
Temperature Sensor

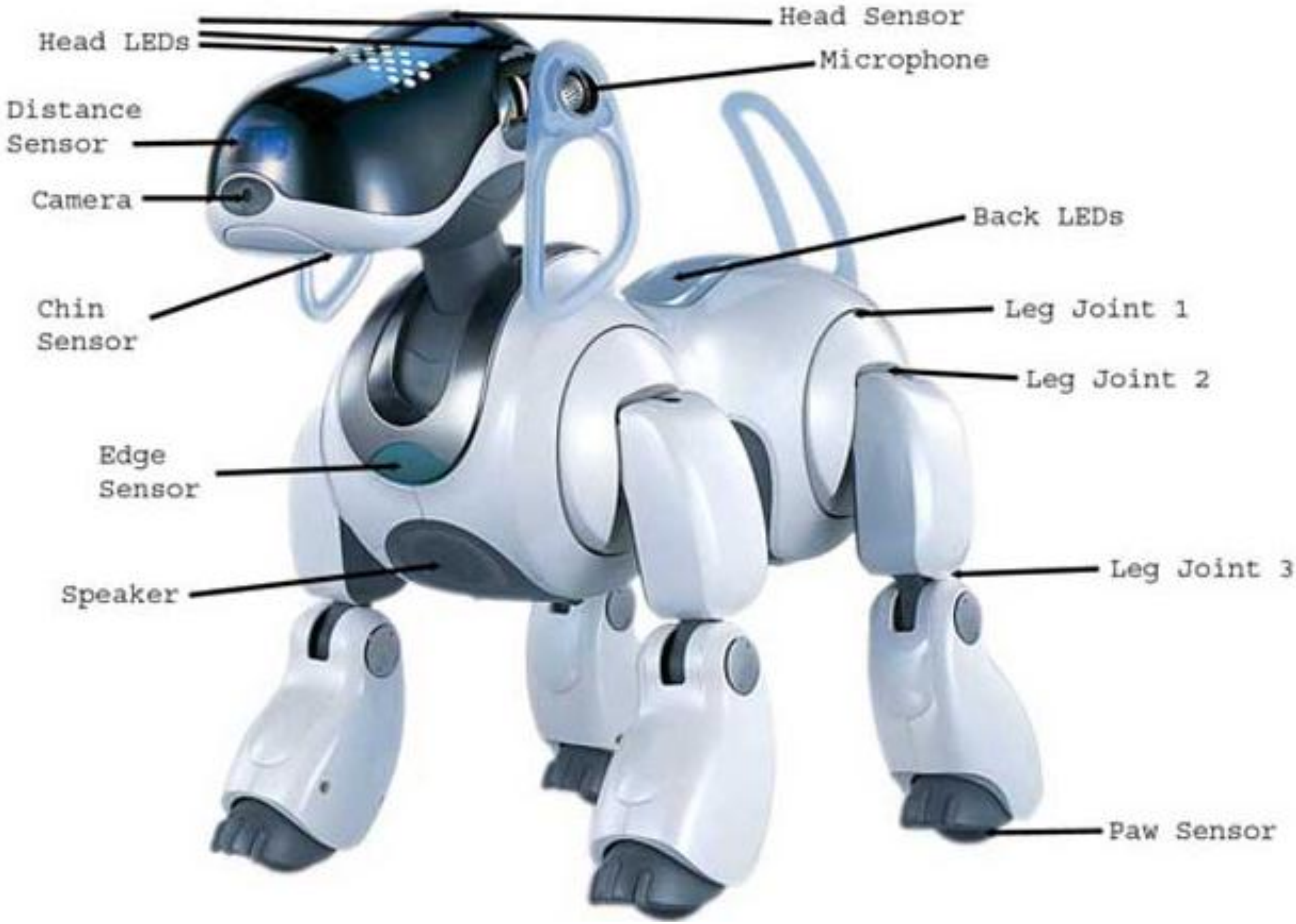
- Tiny temperature sensor ICs provide voltage difference for a change in temperature.
- NTC Thermistor can be assembled in housing in a variety of configurations for temperature sensing, measurement, detection, indicator, monitoring and control.
- Thermistor temperature sensor probe assemblies can conveniently attach to or be an integral part of any system to monitor or control temperature.
- The primary factors which determine the optimum configuration of a thermistor assembly are the operating environment; mounting & time.

- Applications for temperature sensing include air temperature sensors, surface temperature sensors and immersion temperature sensors. Housings for air temperature sensors are often simple, inexpensive devices such as molded plastic shells, deep- drawn brass or aluminum cylinders, or even stainless steel tubes.

SENSORS

- Sensors provide awareness of the environment by sensing things.Sensors are the core of robots.It is the system that alerts the robots..
- Sensing can be in different forms like-
  - Light
  - Sound
  - Heat
  - Chemicals
  - Force
  - Object proximity
  - Physical orientation/position
  - Magnetic & Electric Fields
  - Resistance

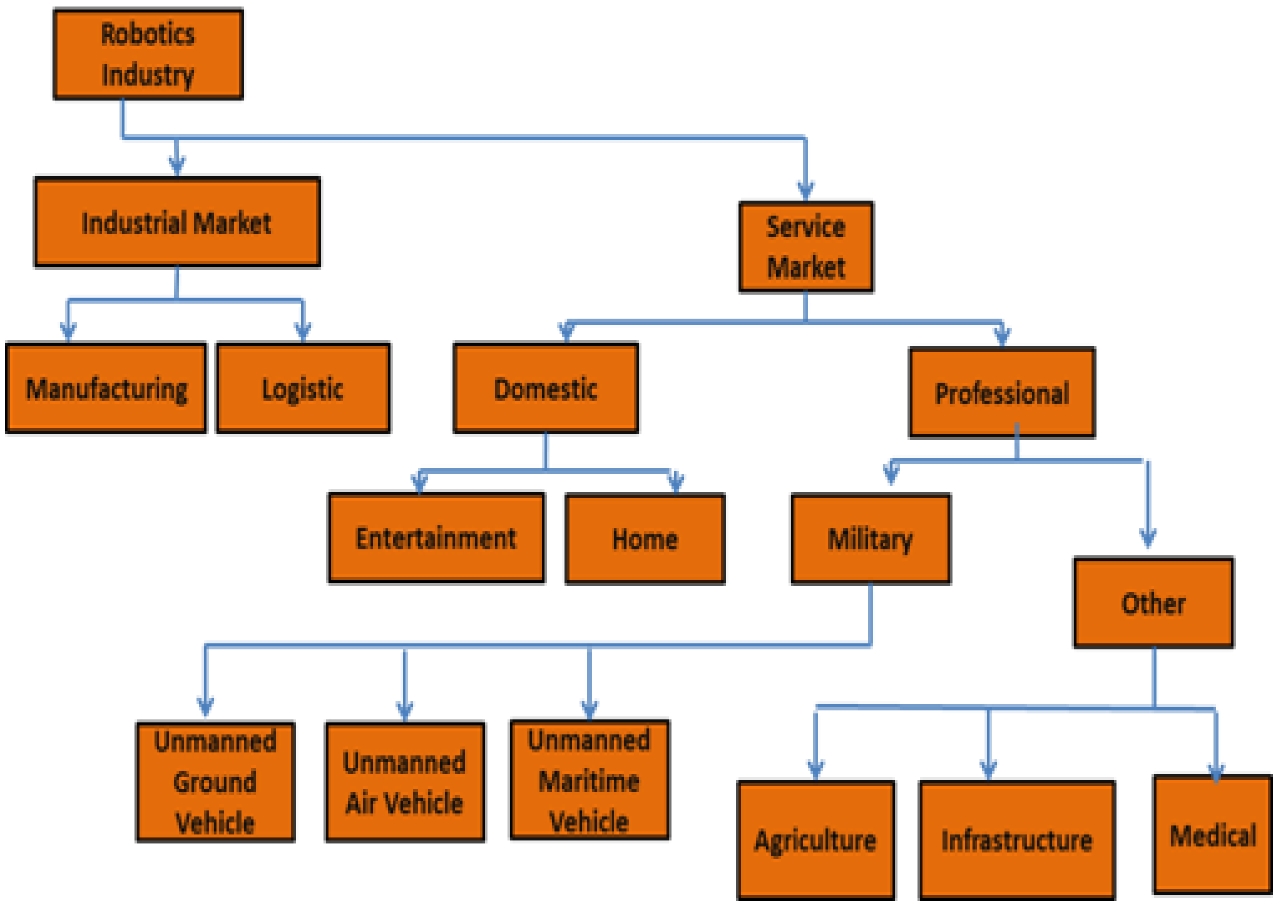


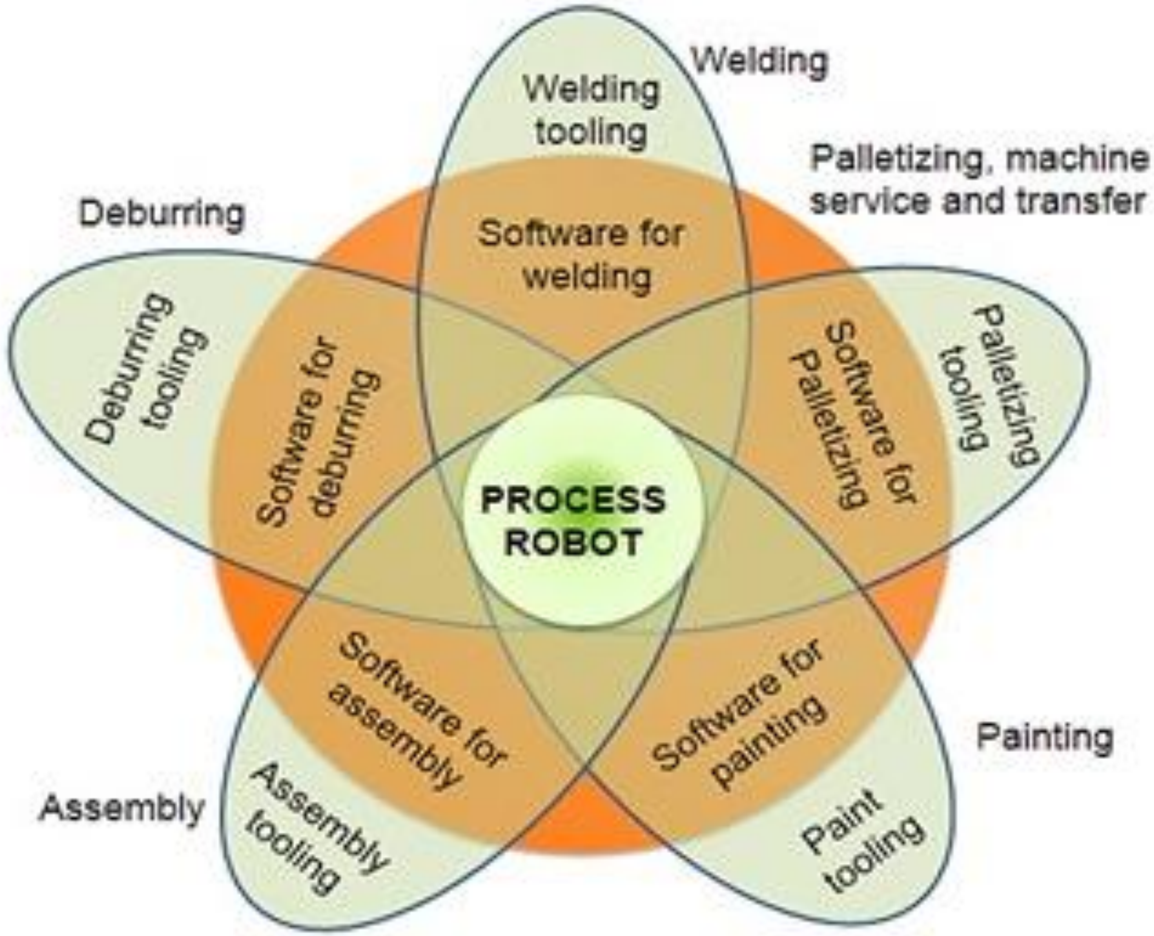


Head LEDs
Distance Sensor
Camera
Chin Sensor
Edge Sensor
Speaker
Head Sensor
Microphone
Back LEDs
Leg Joint 1
Leg Joint 2
Leg Joint 3
Paw Sensor

ROBOT APPLICATIONS

Modern Robotics is a branch of engineering technologies that involves the conception, design, manufacturing, and operation of intelligent systems. This field overlaps with electronics, computer science, artificial intelligence , electrics, mechanics, micro/nanotechnology, biology, medicine, etc.





Applications of robots in industry and manufacturing

Industrial Robotics- Manufacturing

- ✓ Perception for operation
- ✓ Human-like-dexterous manipulation
- ✓ Adaptive and configurability assembly
- ✓ Robots working with humans
- ✓ Autonomous navigation
- ✓ Rapid deployment of assembly lines
- ✓ Green manufacturing
- ✓ Model-based integration and design supply chains
- ✓ Interoperability and component technologies
- ✓ Nano Technology

- ✓ Architecture & Representation
- ✓ Control and planning
- ✓ Format Methods
- ✓ Learning and Adaption
- ✓ Modeling, Simulation, And Analysis
- ✓ Novel Mechanism
- ✓ Perception Robust Sensors
- ✓ Human Robot Interaction
- ✓ Social Interactive Robots

- ✓ Mining
- ✓ Processing
- ✓ Discrete part manufacturing
- ✓ Assembly
- ✓ Logistics (transport & distribution)

Applications of robots in industry and manufacturing

Situation	**Description**
Hazardous work environment for humans	In situations where the work environment is unsafe, unhealthy, uncomfortable, or otherwise unpleasant for humans, robot application may be considered.
Repetitive work cycle	If the sequence of elements in the work cycle is the same, and the elements consist of relatively simple motions, robots usually perform the work with greater consistency and repeatability than humans.
Difficult handling for humans	If the task requires the use of heavy or difficult-to-handle parts or tools for humans, robots may be able to perform the operation more efficiently.
Multi-shift operation	A robot can replace two or three workers at a time in second or third shifts, thus they can provide a faster financial payback.
Infrequent changeovers	Robots' use is justified for long production runs where there are infrequent changeovers, as opposed to batch or job shop production where changeovers are more frequent.
Part position and orientation are established in the work cell	Robots generally don't have vision capabilities, which means parts must be precisely placed and oriented for successful robotic operations.

Robots are mainly used in three types of applications:

- Material handling;
- Processing operations;
- Assembly and inspection.

In material handling, robots move parts between various locations by means of a gripper type end-effector. Material handling activity can be sub divided into material transfer and machine loading and/or unloading.

In processing operations, the robot performs some processing activities such as grinding, milling, etc. on the work-part. The end-effector is equipped with the specialized tool required for the respective process. The tool is moved relative to the surface of the work-part.

Material handling applications

Application	Description
Material transfer	• Main purpose is to pick up parts at one location and place them at a new location. Part re-orientation may be accomplished during the transfer. The most basic application is a pick-and-place procedure, by a low-technology robot (often pneumatic), using only up to 4 joints. • More complex is palletizing, where robots retrieve objects from one location, and deposit them on a pallet in a specific area of the pallet, thus the deposit location is slightly different for each object transferred. The robot must be able to compute the correct deposit location via powered lead-through method, or by dimensional analysis. • Other applications of material transfer include de-palletizing, stacking, and insertion operations.

Machine loading and/or unloading	• Primary aim is to transfer parts into or out-of a production machine.
	• There are three classes to consider:
	  ○ machine loading—where the robot loads the machine
	  ○ machine unloading—where the robot unloads the machine
	  ○ machine loading and unloading—where the robot performs both actions
	• Used in die casting, plastic molding, metal machining operations, forging, press-working, and heat treating operations.

Robotic process operations

Process	Description
Spot Welding	Metal joining process in which two sheet metal parts are fused together at localized points of contact by the deployment of two electrodes that squeeze the metal together and apply an electric current. The electrodes constitute the spot welding gun, which is the end effector tool of the welding robot.
Arc Welding	Metal joining process that utilizes a continuous rather than contact welding point process, in the same way as above. Again the end effector is the electrodes used to achieve the welding arc. The robot must use continuous path control, and a jointed arm robot consisting of six joints is frequently used.
Spray Coating	Spray coating directs a spray gun at the object to be coated. Paint or some other fluid flows through the nozzle of the spray gun, which is the end effector, and is dispersed and applied over the surface of the object. Again the robot must use continuous path control, and is typically programmed using manual lead-through. Jointed arm robots seem to be the most common anatomy for this application.
Other applications	Other applications include: drilling, routing, and other machining processes; grinding, wire brushing, and similar operations; waterjet cutting; and laser cutting.

Assembly

- The assembly system is a combination of a robot, a transfer device and part feeders.
- One approach in designing assembly systems is that the assembled object is moving on a straight line indexing or rotary indexing table and in each station a robot is adding one part to the assembled object.
- This configuration requires many simple robots along the assembly line, each performing a particular operation.
- The advantage of this system is the small cycle time per product.

Inspection

- The robots perform loading and unloading tasks to support an inspection or testing machine.
- This case is really machine loading and unloading, where the machine is an inspection machine. The robot picks parts that enter the cell, loads and unloads them to carry out the inspection process.
- In some cases, the inspection may result in parts sortation that must be accomplished by the robot.
- The robot manipulates an inspection device, such as a mechanical probe, to test the product. This case is similar to a processing operation in which the end effector attached to the robot wrist is the inspection probe.

Other Applications of Robots

Domestic or household robots – Robots which are used at home. This sort of robots consists of numerous different gears for example- robotic pool cleaners, robotic sweepers, robotic vacuum cleaners, robotic sewer cleaners and other robots that can perform different household tasks. Also, a number of scrutiny and tele-presence robots can also be considered as domestic robots if brought into play in that sort of environment.

Medical robots – Robots employed in medicine and medicinal institutes. First & foremost surgical treatment robots. Also, a number of robotic directed automobiles and perhaps lifting supporters.

Service robots – Robots that cannot be classed into any other types by practice. These could be various data collecting robots, robots prepared to exhibit technologies, robots employed for research, etc.

Other Applications of Robots

Military robots – Robots brought into play in military & armed forces. This sort of robots consist of bomb discarding robots, various shipping robots, exploration drones. Often robots at the start produced for military and armed forces purposes can be employed in law enforcement, exploration and salvage and other associated fields.

Entertainment robots – These types of robots are employed for entertainment. This is an extremely wide-ranging category. It begins with model robots such as robosapien or the running photo frames and concludes with real heavy weights like articulated robot arms employed as movement simulators.

Space robots – I would like to distinct out robots employed in space as a split apart type. This type of robots would consist of the robots employed on Canadarm that was brought into play in space Shuttles, the International Space Station, together with Mars explorers and other robots employed in space exploration & other activities.

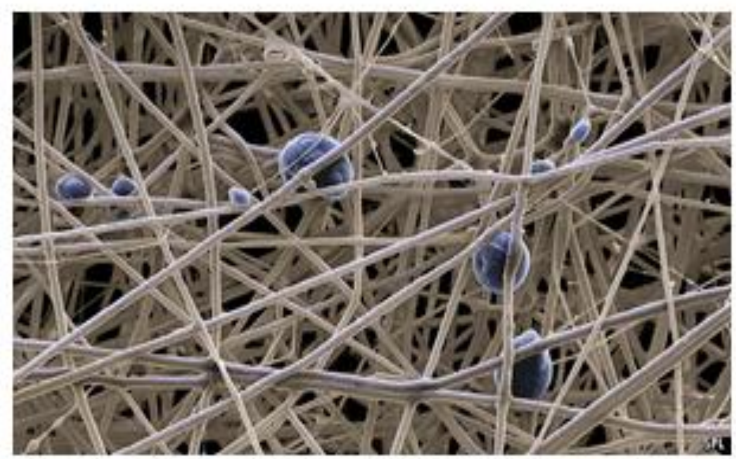
Robot Applications in Industry

Intrinsically Safe Robots Working with Humans: The Democratization of Robots

Humanlike Dexterous Manipulation

Cloud" Robotics and Automation for Manufacturing

Humans and robots in the workplace



Nano manufacturing

Robot Applications in Healthcare

Capture human state and behavior

In-clinic and in-home servicing specific tasks

Snake-like robotic for endoscopic surgical procedures

ugment human mobility and capability

Human machine interaction

Learning and Adaptation

Minimally invasive surgical robot- Da Vinci

- Robotics technologies are being developed toward promoting aging in place, delaying the onset of dementia, and providing companionship to mitigate isolation and depression.

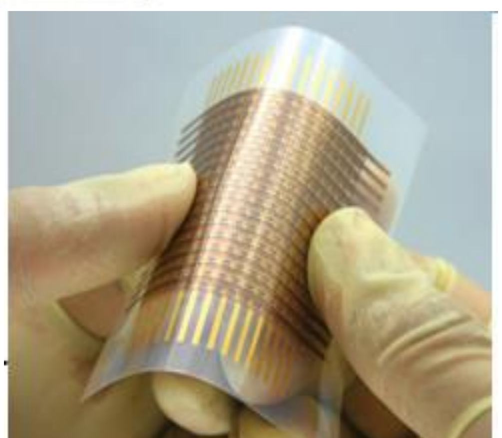
- Robots are also being used for surgery, rehabilitation and in intelligent prostheses to help people recover lost function.

Service Robotics

- Service robotics is defined as those robotic systems that assist people in their daily lives at work, in their houses, for leisure, and as part of assistance to the handicapped and elderly, etc.

  - Healthcare & Quality of Life
  - Energy & Environment
  - Manufacturing & Logistics
  - Automotive & Transportation
  - Homeland Security & Infrastructure Protection
  - Entertainment & Education

- **Scientific and Technical Challenges**
  - **Mobility:** *autonomously driving cars, 3D navigation..*
  - **Manipulation:** *Grasping, tactile sensing,...*
  - **Planning:** *situational awareness, obstacle avoidance*
  - **Sensing and Perception:** *skin-like tactile sensor...*



Key Challenges

Quality of Life: There is need for revolutionary transportation mobility solution

ATRS™ Robotic Wheelchair System

Key Challenges

Agriculture: There is a need to address farmers' constant struggle to keep costs

Autonomous Tractor

Key Challenges

Infrastructure: There is a need to automate the inspection and maintenance of our nation's bridges, highways, pipelines

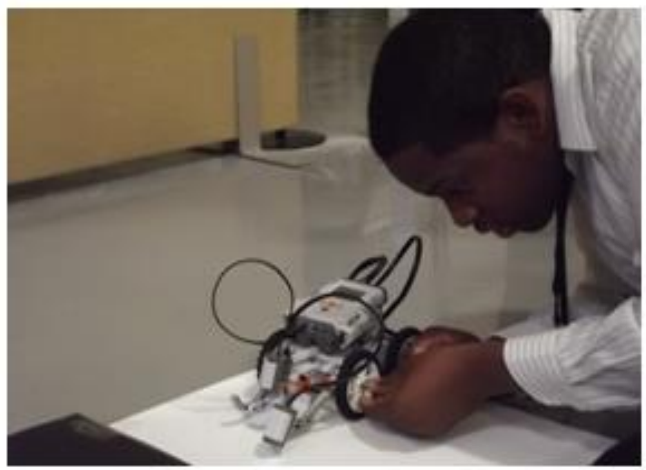
Responder™ Pipeline Robot

Key Challenges

Transportation: There is a need for intelligent highways to autonomous public transportation systems

Key Challenges

Education: There is a need to provides students with a tactile and integrated means to investigate basic concepts in math, physics, computer science and other STEM disciplines



Encouragement by sense of accomplishment: a student is building and programming a ground robot

Key Challenges

Homeland Security and Defense: There is a need for viability of search and rescue efforts, surveillance, explosives countermeasures, fire detection

The Bear, from Vecna Robotics,

Key Challenges

Mining: There is a need to reduce the costly downtime of underground and surface mining.

Autonomous Haul Truck