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DIGITAL MACHINE AND ROBOTICS

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References

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Introduction

The definition for a robot is stated by Robot Institute of America as "A reprogrammable and multifunctional manipulator, devised for the transport of materials, parts, tools or specialized systems, with varied and programmed movements, with the aim of carrying out varied tasks". This definition is still far from perfect and needs additional principal properties such as versatility (having interchangeable geometry) and auto adaptability to environment (ability to redesign itself to varying environment).

These properties distinct modern robots from the automata machines those are built for mass production and from products of art of mechanics.

Robots are among the essential tools in today's Industry. They are the mechanical servants of human being, capable of performing several different tasks and operations better and safer than the human labor.There are commercial robots developed for different purposes from cleaning and inspection to serving human as a pet.

Advantages of Industrial Robots-

Automation using Robotic technology proved itself by increasing the productivity, safety, efficiency, quality, and consistency of products.

•Robotic devices works in hazardous environments, without needing workplace comfort such as lighting, air conditioning, noise protection etc.

•They work continuously for very long shifts of work periods without needing the work requirements of human labor.

•They can be designed more accurate than human.

•In extra-ordinary applications such as medical surgery robots, they can manage many surgery services which are impossible to be applied by a human.

•Robots can accomplish processing multiple tasks simultaneously.

Robotic Components

(1)- Manipulator or rover

Is the main mechanism that provides the ultimate function of the robot. It consists of a base, the links, the joints and other structural elements that complete a robot.

(2)- End-effectors

Is the device that is connected to the end of the last joint (hand) of a manipulator to handle objects, or performs required tasks by a direct contact. It can be a dexterous hand, a simple gripper, a magnetic clutch or a similar device that targets a direct contact to the processed material.

(3)- Actuators

Are the source of the force and movements of the manipulator joints. Stepper motors and hydraulic cylinders provide positional movement, while servo motor and pneumatic cylinders provide force for the movement of the manipulator joints, which requires feedback loop for the control of the end-effectors' position and orientation.

Types of Actuators

The motion of a robot is due to the action of the actuators moving each of the joints. There are three main types of actuators suitable in industrial applications named:

1. Electromagnetic actuators.

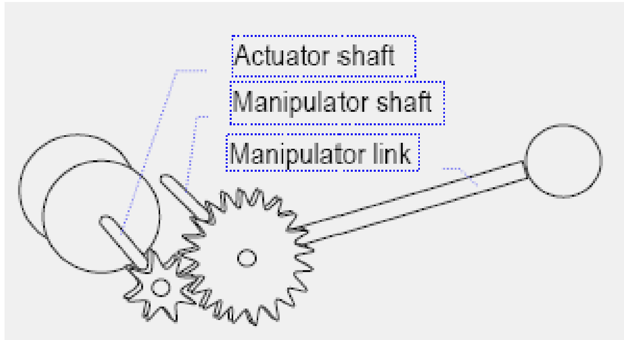
2. Hydraulic actuators.
3. Pneumatic actuators.

<u>Characteristics of Actuators</u>

1. The power to weight ratio of the actuators is the most important characteristic in the mechanical design of the robotic systems. The power to weight ratio of most electrical actuators are average, however, stepper motors that provide positional stiffness are generally heavier than dc-servomotors, which provide joint-torque. The power of the hydraulic systems is the highest, ranging from 50 to 5000 psi (pound per square inch, 14psi=1kg/cm^2).

2. The stiffness is the resistance of a material against elastic deformation. Compliance is the opposite concept, the tendency of deforming under a load. Pneumatic systems have very low stiffness due to the compressibility of gases. A typical hydraulic fluid has much lower elasticity, providing a higher stiffness in hydraulic actuators. This property makes a hydraulic actuator a directly position-determining device.

3. The torque supplied by an actuator mostly does not match to the desired torque required to move the joint. In such cases, a gear-train is necessary to match the joint torque to the actuator torque. A gear train with gear ratio N provides the reduction of speed *n* times, while increasing the torque with the same ratio.

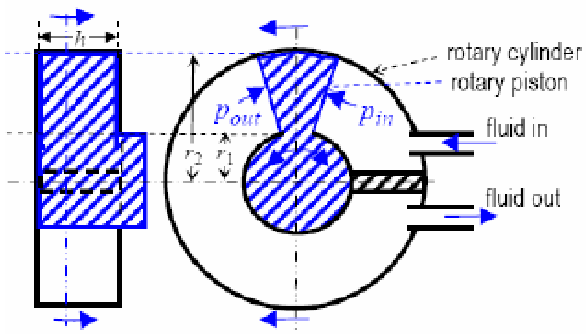


Gear Train

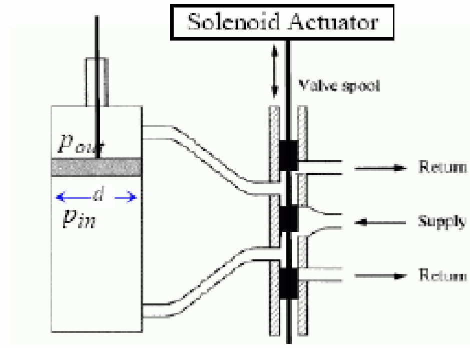
<u>Hydraulic Actuators</u>

Hydraulic actuators are mostly cylinder type, industrial rotary types are also available. Hydraulic systems provide the highest power/weight ratio and largest forces at low speeds for both rotary and linear joints. They are suitable for microprocessor and electronic controls through electromagnetic valves. First robots used in car manufacturing for mounting heavy parts are hydraulic robots with over 100 kg payloads lifting almost to 1.5m. However, due to high maintenance cost of their power unit and the leakage problems they are not used any more. Today's auto manufacturers mostly prefer electric servos over hydraulic. But in heavy industry, where the hydraulic units are a must due to other reasons, the hydraulic robots keep their popularity.

The force F, delivered by a linear hydraulic cylinder is proportional to effective area A of the piston times the working pressure ($p=p_{in}-p_{out}$) on the piston; $F=p*A$



Rotary hydraulic cylinder



Hydraulic servo valve

In heavy industry robotic application, pressures up to 100 kg /cm^2 and up to 50 cm^2 piston areas are possible, giving up to 5000 kg of force (50000 Newton). In rotary cylinders, the total output torque is obtained by the integral of the force on torque arm.

$$T = \int_A p dA = \int_{r_1}^{r_2} phdr = \tfrac{1}{2} ph(r_2^2 - r_1^2)$$

Where p is the fluid pressure, h is the width of the cylinder; r_1 and r_2 are the inner and outer radius of the rotary cylinder as shown in the Figure. The flow rate of the oil determines exactly the speed of the motion, or amount of fluid in cylinder Q determines the actuator position q, i.e.

$$Q = \frac{\pi d^2}{4} q \quad \text{For linear cylinders}$$

where d is the piston diameter.

Thus, a servo control unit usually measures the delivered fluid to determine the joint displacement. The following parts make up a typical electronic hydraulic servo control unit.

- Hydraulic linear or rotary cylinders to provide ram or shaft torque.
- Electromagnetic Servo valves to control motion,
- A hydraulic high pressure pump running by a diesel engine or electric motor.

• Returned fluid and pressurized fluid reservoirs,

• Cooling system fans and radiators to remove the dissipated heat.

Advantages of Hydraulic actuator:

1. Large lift capacity.
2. High power to weight ratio.
3. Moderate speeds.
4. Oil is incompressible, lead to stiff structure.
5. Very good servo control can be achieved.
6. Self lubricating and self cooling.
7. Operate in stalled condition with no damage.
8. Fast response.
9. Smooth operation at low speed.

Disadvantages:

1. Hydraulic systems are expensive.
2. Maintenance problems with seals causing leakage.
3. Not suitable for high speed cycling.
4. Need for remote power source which uses floor space.
5. Need for a return line.

Pneumatic actuators

Pneumatic cylinder construction makes extensive use of aluminum and other nonferrous alloys to reduce weight and the corrosive effects of air. Aluminum cylinders also transfer heat efficiently.

Advantages of pneumatic actuators:

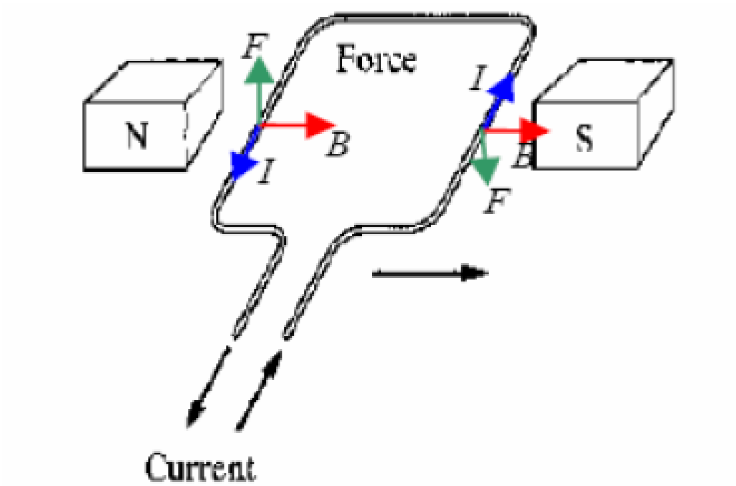
1. Relatively in expensive.
2. High speed.
3. No return line required.

Disadvantages:

1. Compressibility of air limits control and accuracy aspects.
2. Noise pollution from exhausts.
3. Leakage of air can be of concern.
4. Difficulties with control of speeds.

Electromagnetic actuators:

Electromagnetic actuators are mostly solenoid or relay, The basic law beneath the electric motors is the force **F** generated on a current conducting wire in a magnetic field **B**, i.e., $\mathbf{F} = \mathbf{I} \times \mathbf{B}$, where **I** is the vector of current along the wire. A wire rotating in the magnetic field produces a voltage. Similarly, a motion of the current carrying wire in a magnetic field against this torque generates an induced voltage V at the terminals of the wire. A DC motor uses this principle by switching the current with a commentator to keep the current always in the highest region of the magnetic field. An AC motor uses stationary wires (stator), while generating an induced voltage in the rotating coils (rotor) to obtain a rotating magnetic field.



A current passing through a wire in a magnetic field produces a force.

$F=B*I=1/2(N.I)^2(\mu A/x^2)$

Where:

N=number of turns of wire in the coil.

μ=permeability ($4\pi*10^{-7}$) H/m in air.

A=planger cross- section area in (cm^2).

X=air gap (cm).

Example: find the initial force capability for a solenoid that has an 800 turn coil. The planger is a square with 2 cm sides. The initial air gap is 1cm and 2A initial current.

Solution:

$F=1/2(N.I)^2(\mu A/x^2)$

$=0.5*(800*2)^2(4\pi*10^{-7})*2*2/1$

$=6.434$ N.

(4)- Sensors

Are the devices those can convert information about the state of the robotic system to electrical signal in the format that can be used by the robot controller. By this means, they provide communication of robot to its environment. Robotic systems may contain internal sensor devices such as shaft encoders connected at the manipulator joints, and force-torque sensors at the wrist joint. They can also contain external sensor devices such as vision systems to detect the end-effectors location, proximity sensors at several locations to detect the state of materials and devices in the work environment.

•Human senses: sight, sound, touch, taste, and smell provide us vital information to function and survive

•Robot sensors: measure robot configuration/condition and its environment and send such information to robot controller as electronic signals (e.g., arm position, presence of toxic gas)

•Robots often need information that is beyond 5 human senses (e.g., ability to: see in the dark, detect tiny amounts of invisible radiation, measure movement that is too small or fast for the human eye to see)

1. **Vision Sensor**: e.g., to pick bins, perform inspection, etc. Part-Picking: Robot can handle work pieces that are randomly piled by using 3-D vision sensor. Since alignment operation, a special parts feeder, and an alignment palette are not required, an automatic system can be constructed at low cost.
2. **Strain Gage and FSRs:** A strain gage is a directional wound wire that changes resistance due to change of wire length and cross section. Usually four strain gage resistors in bridge configuration provide one reliable ratio metric measurement of the mechanical deformation. A force sensing resistor (FSR) is available by Interlink Electronics. The resistance of the polymer thick-film device changes from 500K to 1K while the applied force is changing from 0.010 to 10 kg (0.1 to 100N).

3. **Force Sensor:** Resistive, piezoelectric, capacitive and magnetic force sensors mostly convert the force to a small displacement by an elastic

deformation of sensor substrate, and detect the electrical or optical effect of this deformation. Piezoelectric ceramic material develops a charge on material surface proportional to its deformation. Three pairs of strain gages may give torque and force readings in three dimension

4. **Velocity and Acceleration Sensors :** A tachogenerator is a small voltage generator with a permanent magnet that generates a voltage proportional to its rotor velocity. However, in robotics the joint speed is simply calculated from the derivative of the joint displacement. In an accelerometer, the compounds f the force exerted by a mass on three axes are measured by six silicon strain o gages. Again, the accelerometers are rarely used in applications since the calculation of the acceleration is possible using the rate of change of displacement.

5. **Infrared and Light Sensors :** Infrared sensors are an assembly of infrared light source and an infrared sensitive diode or transistor, which produces proportional electrical signals to the light intensity. An infrared LED serves as an inexpensive infrared light source, and an infrared phototransistor reads the intensity of the transferred or reflected light. They are also used for data transmission between electrically isolated digital circuits against high voltages.

An array of LED's provides multiple readings with a single photo transistor by means of time multiplexing, which also solves the phototransistor dependent parameter differences in the analog readings. Whenever possible, the sensor system is built to work on digital signals; either light exists or does not exist. Optical focusing and moving mirrors may provide very precise sweeping of the search area in very short time periods, for optical range finding and proximity detection purposes. Optical sensing is widely used in shaft encoders and in proximity switches, since they have no wearing parts at all.

6. Proximity Sensors

A proximity sensor is a device which provides an electric signal (switch status, voltage, current, resistive change etc.) when the sensor is in a distance range to a specified target.

- A micro switch with a long flexible lever arm can be used as proximity sensor by mechanical contact.
- In magnetic proximity sensors, the magnetic field of a permanent magnet turns a reed relay on or off when the magnet is close enough to the reed-relay.
- In inductive proximity sensors, the distance to a magnetic material is detected by an unbalance in magnetic fields of an induction coil setup.
- In optical proximity sensors, the intensity of the reflected or obstructed infrared beam indicates the distance to the reflecting or obstructing material.
- In ultrasonic proximity sensors, echo or transmission of an ultrasound wave indicates the existence of an object.

Other types of proximity sensors are used in special constraints of environment such as noise, electrical disturbance, full darkness requirements, etc. There are capacitive, Eddy current, and Laser proximity sensors and range finders available for the industrial use.

(5)- Control of industrial robots

Can be studied in various hierarchical levels

•Top level of control is the organization level, which accepts and interprets input commands and related feedback from the system, defines the task to be executed, then segments the task into subtasks in the appropriate order of execution.

•The medium level is a coordination level, in which the instructions (subtasks) are processed together with feedbacks from the process in order to generate the lowest level commands (including desired trajectories) which should be followed by the manipulator.

•The lowest level of control is the hardware control level of manipulator, and involves execution of desired motion. Hardware control level needs a model of the manipulator motion, and a performance criterion or cost function for the design of the joint controllers.

(a)- Controller

•Provide necessary intelligence to control the manipulator/mobile robot.

•Process the sensory information and compute the control commands for the actuators to carry out specified tasks.

Controller is a device that collects signals from the position sensors. It processes them and generates the actuator signals to move the manipulator joints in harmony, so that the manipulator tracks the pre-programmed motion. The controller provides the hardware control level of the manipulator.

(b)- Processor is generally a dedicated computer system built of many microprocessors or microcontrollers to accomplish the higher level control action.

The processor contains the storage medium to keep the programs. It provides the joint positions to the controller for a smooth movement of the manipulator along the programmed trajectories.

(c)- Software of robotic systems can be grouped in three main levels.

• The **operating system** operates the computer.

• The **coordination level programs** keep the manipulator in the trajectory.

•The **organization level programs** provide switching between the coordination level programs depending on the feedback collected by the sensors in the robot environment. This level provides the intelligence of the robotic system, which means to act properly on the changing environmental conditions.

<u>Robot Technical Specifications</u>

Followings are the significant characteristics of a typical industrial robot.

1. The workspace is the geometrical space defined by all possible end-point positions of a robot mechanism. The shape of the workspace depends on the link and joint types and joint displacement limitations. The accuracy and repeatability of a robot is valid only in the workspace described by the manufacturer.

2. Payload is the maximum load to be carried by the robot while satisfying all technical specifications. Mostly, a robot can hold four to tenfold of its payload if in that application the specified accuracy and speed is not important. Typical payload to weight ratio of the industrial robots is in the range of 1/5 to1/10.

3. Reach is the farthest distance a robot can expand its arm in the workspace. A painting robot which does not require high accuracy may have longer reach than the assembly robots. A typical assembly robot may have reach in the range from 0.40 to 0.80 meters.

4. Precision (validity) is the accuracy of the manipulator end-point position. Accuracy of a manipulator is limited both by the flexible bending of the manipulator mechanism, and also by the accuracy of the position feedback encoders, actuators and controller.

5. Repeatability (variability) error is the maximum deviation of position between the trials to move the endpoint of the robot to the same point repeatedly. For example, if we make 100 trials to move to a point and the tip moves maximum 1mm away from that point, the repeatability error of the robot for that point is 1mm. Most industrial robots have repeatability around 0.05 mm.

Robot Programming

A typical industrial robot is mostly programmed in one of the following four modes:

1. Physical Setup Mode is typical programming method for very simple pick-and-place manipulators, where programmable logic controllers (PLC's), proximity and limit switches, event switches, and timers are used to perform cyclic operation of the manipulator for a desired task.

2. Walking Through Mode is an elaborated teach mode. The operator teaches the manipulator which way to move by forcing the manipulator to move in the desired way. This is the most common programming method for playback robots. It is conveniently used for painting and assembly robots.

3. Lead Through or Teach Mode is for continuous path playback robots and a typical programming mode of a manipulator with positional control capability. Manipulator is moved to the desired positions by the aid of a teach pendant (a control keypad), and the desired positions are stored into program memory in the desired sequence. After teaching is accomplished, controller is set to playback mode, in which the controller moves the manipulator point to point to the desired positions.

4. Software Mode is off-line program writing mode using a text editor or graphical interface. Programming in software mode requires knowledge on operating system and robot languages. Sensor information is easily included to the programming, and the task definitions can be extracted using the data of the processed objects from the computer-aided-design (CAD) database. It is the most sophisticated, and the most versatile way of programming a robot. Most industrial robots have more than one programming modes, and, the most convenient programming mode depends to the task to be programmed.

Robot Programming Languages

Robot language is the specific high level programming language of a robot system. Each manufacturer designs a robot language for a family of robot model. These languages are at different levels of sophistication depending on the type of applications. Many of them are based on common programming languages such as COBOL, Basic, C, and FORTRAN. Other application specific languages are either interpreter based, or compiled to the assembler or common high level languages.

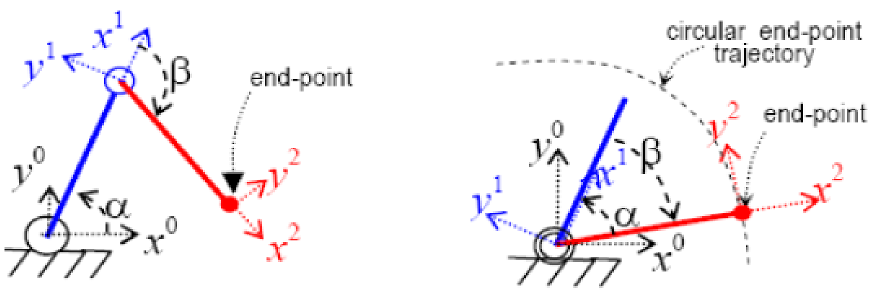
1. **Interpreter languages** are easy to trace and debug since each command can be interpreted step by step, but they are slow because each line is executed sequentially and independently. Many industrial robots use their own interpreter languages.

2. **Compiler based languages** are compiled to machine language (object code) before their execution. These programs are much faster and efficient, but debugging of these languages requires more effort since the program cannot be executed in single-step mode. Some languages have both a compiler for efficient usage, and an interpreter for debug mode. It is possible to test a program in single-step mode, and then execute it at much faster speeds.
3. **Machine Language** level is the lowest possible programming level of programmable robots. It is the primitive programming language of the processor. All programs are either compiled to machine language, or interpreted by an interpreter that runs in machine language. Programs directly written at machine level may be very efficient and fast, but debugging and programming is extremely difficult.
4. **Point-to-Point** level languages (i.e. Cincinnati "Milacron") are very primitive, simple to program easy to use interpreter languages. The points to be followed are simply listed sequentially mostly in task-frame. It generally lacks structuring and modularity (very weak in branching, and conditional statements).
5. **Primitive Motion** Level languages are interpreter based languages equipped with programming modularity. They have commands for sensory data processing and branching, which makes the language suitable for simple intelligent applications.
6. **Structured Programming** Level languages are compiler based powerful languages which allow sophisticated programming. However, they are more difficult to learn.

7. **Task Oriented Languages** are the top level of the robotic programming which has not yet been implemented by any manufacturer. Instead of programming a robot task in detail with each and every step necessary to complete the task, the user will only specify which task to do, and the controller (or interpreter) will create all other necessary steps of the task. IBM in 1980's proposed it, but never accomplished a fully working system. It is still an open research area to develop a task oriented language.

Degrees of Freedom:-

An n-link kinematics system is made of a chain of links connected to each other by the joints. The system is an open-chain, each joint can move freely independent from all other joints. For the simplicity of the analysis we assume the first joint is moving in the base coordinate frame, the second joint is moving in the coordinate frame of the first link, and so on, the end-point is a fixed position in the nth coordinate frame. Then, two joints may either contribute to the movement of the end-point in two different directions, or, if the joint movements are dependant to each other, then, the end-point may move only in a single direction. The joints those contribute to the movement of the end effectors in a new and independent direction are called independent joints. The total number of the independent joints determines the degrees of freedom (DOF) of that kinematics system.



For example, in a planar space (in the paper plane), a kinematics system made of two rotational joints is shown in the Figure. In this case, the joint angular positions α and β contribute to the movement of the end-point in both x0 and y0 directions freely, and thus they are independent joints. If the two joints were exactly on the same point of the plane, then the two joints would not result in independent movements of the end-point in two different dimensions. The end point would move along a fixed circular trajectory proportional to $\alpha \_ \beta$. In our planar example, the position and orientation of a frame is expressed in the base frame by three variables (dimension along axes x0, y0 and the angular orientation with respect to the x0 axis).

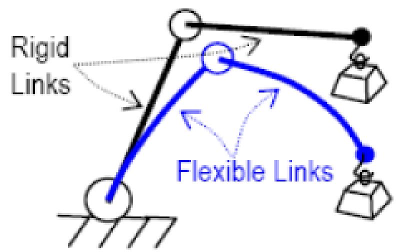
Thus, we cannot have a planar kinematics system with four or over four degrees of freedom. Similarly, in a three dimensional world, an end-point frame is expressed in the base frame by its position along x-y-z axis, and angular rotation with respect to **z** (roll), y (pitch) and x axes (yaw), total by six DOF. Thus, in 3-D world, a kinematics system cannot have higher than 6 DOF even if it has over 6 joints. In some cases, a joint is not designed to be stable along the range of movement, but it stays stable only at the end points of the joint range. For example, in some pneumatic joints, the link moves from one end to the other end but cannot stay somewhere at the mid. These kind of joints are considered only to be half independent, and contributes only 1/2 to DOF of the system.

Many industrial robots were designed to have only four or five degrees of freedom to reduce the cost and increase the reliability and stability of the manipulators. On the other side, there are also many robot manipulators particularly designed for the working environments with many obstacles in workplace with extra one or two joints instead of exactly six.

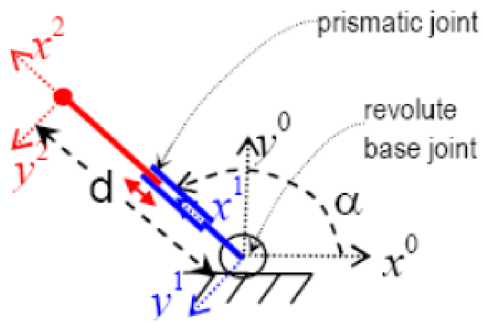
These kinds of kinematics systems are called redundant kinematics systems. The redundancy of extra joints provides flexibility to approach to the desired position and orientation in various configurations of the joint angles creating opportunity of obstacle avoidance in the path planning.

Manipulator Joints, Links, and Coordinate Systems:-

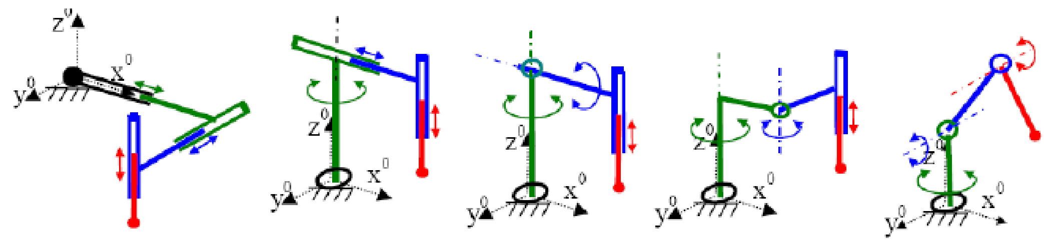
A typical industrial robot manipulator has an open-chain kinematics with multiple rigid links moving in a base coordinate frame through the displacement of the joints. The displacement of each joint provides either the movement of the end-point in different dimensions, or helps to have choices of configurations for the same end-point position and orientation.



A joint provides movement of two contiguous links with respect to each others coordinate frames.
A prismatic joint provides a translational movement of the link with respect to the previous link, without any rotational effect.



A revolute joint provides purely rotation around **z**-axis of the coordinate-frame of the previous link with the joint displacement. In the Figure you see a revolute and a prismatic joint on a planar kinematics system. α Represents the revolute displacement of the base-joint, and d is the displacement joint.
We simply abbreviate this kinematics configuration by RP, where the first letter stands for the base joint type, the second and further letters denote the other joint-types counting from base to tip.
There are several other types of joints theoretically possible in kinematics such as sliding, spherical, helical (screw), elliptic, and parabolic movements.



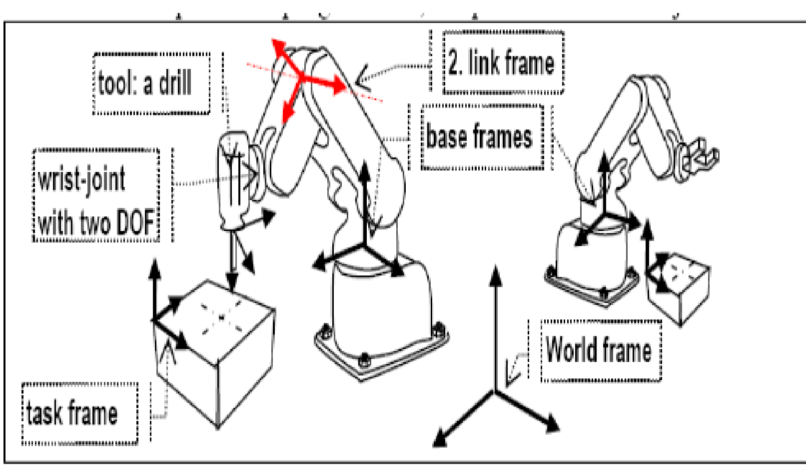
a) Cartesian (or gantry) b) Cylindrical c) Spherical d) SCARA e) Articulated

Reference Frames:-

In general, the analysis of displacement and motion of a body with respect to the other bodies requires assignment of reference coordinate frames to each of the moving bodies.

- The task to be performed is first specified in the **task reference frame**, which is a coordinate frame attached to the processed body.
- If there are multiples of processed bodies in the work place, an **absolute world reference frame** is useful for the coordination of the task reference frames.
- **A manipulator base reference frame** specifies the location of the robot manipulator.
- **A link reference frame** is assigned to each link to specify the location of the links.
- **A tool reference frame** is assigned to the tool in use which moves together with the hand of the robot arm. Tool reference frame is needed to describe the approach and depart of the tool to the object under operation.

Mostly, the task is expressed in the task reference frame using Cartesian coordinates. Rarely, cylindrical or other coordinate systems may be more convenient than Cartesian. In all cases, while the manipulator is programmed, the paths are stored in joint coordinates.



Typical reference coordinate frames in a robot work place