Motion planning for industrial manipulators is a challenging task when obstacles are present in the workspace so that collision-free paths must be found. However, not all paths are suitable for optimal task performance in terms of execution time or energetic cost. Trajectory generation schemes must therefore consider the system dynamics in order to find admissible solutions along a desired path subject to a cost function.
APPLICATION:

- ASSEMBLY
- COATING APPLICATIONS.
- CONVEYOR PALLET TRANSFER.
- DIE CASTING.
- FOUNDARY AND FORGING APPLICATIONS.
- INSPECTION Moulding.
- CASTING.
- MACHINE LOADING AND UNLOADING.
CLASSIFICATION: CLASSIFIED INTO SIX CATEGORIES

- ARM GEOMETRY (robot arm anatomy): RECTANGULAR; CYLINDRICAL; SPHERICAL; JOINTED-ARM (VERTICAL); JOINED-ARM (HORIZONTAL).

- DEGREES OF FREEDOM: ROBOT ARM; ROBOT WRIST.

- POWER SOURCES: ELECTRICAL; PNEUMATIC; HYDRAULIC; ANY COMBINATION.

- TYPE OF MOTION: SLEW MOTION; JOINT INTERPOLATION; STRAIGHT-LINE INTERPOLATION; CIRCULAR INTERPOLATION.

- PATH CONTROL: LIMITED SEQUENCE; POINT-TO-POINT; CONTINUOUS PATH; CONTROLLED PATH.

- INTELLIGENCE LEVEL: LOW-TECHNOLOGY (NONSERVO); HIGH-TECHNOLOGY (SERVO).
ARM GEOMETRY

- ROBOT MUST BE ABLE TO REACH A POINT IN SPACE WITHIN THREE AXES (X, Y, Z) BY MOVING FORWARD AND BACKWARD, TO THE LEFT AND RIGHT, AND UP AND DOWN.

- ROBOT MANIPULATOR MAY BE CLASSIFIED ACCORDING TO THE TYPE OF MOVEMENT NEEDED TO COMPLETE THE TASK.

RECTANGULAR-COORDINATED:

- HAS THREE LINEAR AXES OF MOTION.
- X REPRESENTS LEFT AND RIGHT MOTION
- Y DESCRIBES FORWARD AND BACKWARD MOTION.
- Z IS USED TO DEPICT UP-AND-DOWN MOTION.

THE WORK ENVELOPE OF A RECTANGULAR ROBOT IS A CUBE OR RECTANGLE, SO THAT ANY WORK PERFORMED BY ROBOT MUST ONLY INVOLVE MOTIONS INSIDE THE SPACE.
Figure 3.2.1 Rectangular or Cartesian-coordinated robot: (a) A rectangular coordinated arm moves in three linear axes. (b) The box-shaped work envelope within which a rectangular manipulator operates. (c) Overhead crane movements are similar to those of a rectangular-coordinated arm.
RECTANGULAR COORDINATES

ADVANTAGES:

- They can obtain large work envelope because travelling along the X-axis, the volume region can be increased easily.
- Their linear movement allows for simpler controls.
- They have high degree of mechanical rigidity, accuracy, and repeatability due to their structure.
- They can carry heavy loads because the weight-lifting capacity does not vary at different locations within the work envelope.

DISADVANTAGES:

- They make maintenance more difficult for some models with overhead drive mechanisms and control equipment.
- Access to the volume region by overhead crane or other material-handling equipment may be impaired by the robot-supporting structure.
- Their movement is limited to one direction at a time.
RECTANGULAR COORDINATES APPLICATION:

- PICK-AND-PLACE OPERATIONS.
- ADHESIVE APPLICATIONS (MOSTLY LONG AND STRAIGHT).
- ADVANCED MUNITION HANDLING.
- ASSEMBLY AND SUBASSEMBLY (MOSTLY STRAIGHT).
- AUTOMATED LOADING CNC LATHE AND MILLING OPERATIONS.
- NUCLEAR MATERIAL HANDLING.
- WELDING.
CYLINDRICAL-COORDINATED

- Has two linear motions and one rotary motion.
- Robots can achieve variable motion.
- The first coordinate describes the angle theta of base rotation—about the up-down axis.
- The second coordinate corresponds to a radial or y—in-out motion at whatever angle the robot is positioned.
- The final coordinate again corresponds to the up-down z position.
- Rotational ability gives the advantage of moving rapidly to the point in z plane of rotation.
- Results in a larger work envelope than a rectangular robot manipulator.
- Suited for pick-and-place operations.
Figure 3.2.3  Cylindrical-coordinated robot: (a) A cylindrical-coordinated arm rotates about its base, moves in and out, and up and down. (b) The space between the two cylinders shown is the work envelope occupied by a cylindrical-coordinated manipulator. (c) The movements of a construction crane on top of a tall building are similar to those of a cylindrical-coordinated manipulator.
ADVANTAGE:

- THEIR VERTICAL STRUCTURE CONSERVES FLOOR SPACE.
- THEIR DEEP HORIZONTAL REACH IS USEFUL FOR FAR-REACHING OPERATIONS.
- THEIR CAPACITY IS CAPABLE OF CARRYING LARGE PAYLOADS.

DISADVANTAGE:

- THEIR OVERALL MECHANICAL RIGIDITY IS LOWER THAN THAT OF THE RECTILINEAR ROBOTS BECAUSE THEIR ROTARY AXIS MUST OVERCOME INERTIA.
- THEIR REPEATABILITY AND ACCURACY ARE ALSO LOWER IN THE DIRECTION OF ROTARY MOTION.
- THEIR CONFIGURATION REQUIRES A MORE SOPHISTICATED CONTROL SYSTEM THAN THE RECTANGULAR ROBOTS.
SPHERICALLY COORDINATED

- Has one linear motion and two rotary motions.
- The work volume is like a section of sphere.
- The first motion corresponds to a base rotation about a vertical axis.
- The second motion corresponds to an elbow rotation.
- The third motion corresponds to a radial (prismatic), or in-out, translation.
- A spherically coordinated robot provides a larger work envelope than the rectilinear or cylindrical robot.
- Design gives weight lifting capabilities.
- Advantages and disadvantages same as cylindrical-coordinated design.
Figure 3.2.5  Spherical- or polar-coordinated robot: (a) A polar- or spherical-coordinated manipulator rotates about its base and shoulder and moves linearly in and out. (b) The work envelope of a polar-coordinated manipulator is the space between the two hemispheres. (c) A ladder on a hook-and-ladder truck has movements similar to those of a polar-coordinated manipulator.
APPLICATIONS:

- DIE CASTING
- DIP COATING
- FORGING
- GLASS HANDLING
- HEAT TREATING
- INJECTION MOLDING
- MACHINE TOOL HANDLING
- MATERIAL TRANSFER
- PARTS CLEANING
- PRESS LOADING
- STACKING AND UNSTICKING.
DEGREES OF FREEDOM

- The degree of freedom or grip of a robotic system can be compared to the way in which the human body moves.

- For each degree of freedom a joint is required.

- The degrees of freedom located in the arm define the configuration.

- Three degrees of freedom located in the wrist give the end effector all the flexibility.
  - Pitch or bend: is the up-and-down movement of the wrist.
  - Yaw: is the right-and-left movement of the wrist.
  - Roll or swivel: is the rotation of the hand.

- The more the degrees of freedom, the greater is the complexity of motions encountered.
Figure 3.3.2 Six major degrees of freedom of a robotic system

1. Rotational traverse
2. Radial traverse
3. Vertical traverse
4. Pitch
5. Yaw
6. Roll
THE (4) POWER SOURCES USED IN CURRENT ROBOTS ARE:

- **ELECTRIC AND ELECTRO-MECHANICAL**: ALL ROBOTS USE ELECTRICITY AS THE PRIMARY SOURCE OF ENERGY.
  - Electricity turns the pumps that provide hydraulic and pneumatic pressure.
  - It also powers the robot controller and all the electronic components and peripheral devices.
  - In all electric robots, the drive actuators, as well as the controller, are electrically powered.
  - Because electric robots do not require a hydraulic power unit, they conserve floor space and decrease factory noise.
  - Affordable, small and simple
  - Direct-Current (DC) Motors: speed of the motor controlled by the input voltage
  - ServoMotors: position controlled (-180° ~ 180°)
PNEUMATIC: THESE ARE GENERALLY FOUND IN RELATIVELY LOW-COST MANIPULATORS WITH LOW LOAD CARRYING CAPACITY.

- PNEUMATIC DRIVES HAVE BEEN USED FOR MANY YEARS FOR POWERING SIMPLE STOP-TO-STOP MOTIONS.
- IT IS INHERENTLY LIGHTWEIGHT, PARTICULARLY WHEN OPERATING PRESSURES ARE MODERATE.
HYDRAULIC ACTUATORS PROVIDE A LARGE AMOUNT OF POWER FOR A GIVEN ACTUATOR.

THE HIGH POWER-TO-WEIGHT RATIO MAKES THE HYDRAULIC ACTUATOR AN ATTRACTIVE CHOICE FOR MOVING MODERATE TO HIGH LOADS AT REASONABLE SPEEDS AND MODERATE NOISE LEVEL.

HYDRAULIC MOTORS USUALLY PROVIDE A MORE EFFICIENT WAY OF ENERGY TO ACHIEVE A BETTER PERFORMANCE, BUT THEY ARE EXPENSIVE AND GENERALLY LESS ACCURATE.
Joint Space Trajectories

• For a robot to operate efficiently it must be able to move from point to point in space.
• A trajectory is a time history of position, velocity and acceleration for each joint.
• Trajectories are computed at run time and updated at a certain rate - the Path Update Rate.
Joint Space Trajectory Planning

Consider a robot with only one link.

• Kinematics gives one configuration for B.

• Choice of two trajectories to get there.

• May wish to specify a via point - maybe to avoid an obstacle.
Joint Space Schemes.

We need to describe path shapes in terms of functions of joint angles. $\theta(t)$

Lots of choices for continuous functions
**Manipulator path control** is controlling the path followed by the arm traveling from one point to another in the workspace.

*Interpolation Definition:* is a means of determining the value of an unknown data point based on the values of known surrounding data points.
A ROBOT MANIPULATOR CAN MAKE FOUR TYPES OF MOTION IN TRAVELLING FROM ONE POINT TO ANOTHER IN THE WORKPLACE:

- **SLEW MOTION**: SIMPLEST TYPE OF MOTION. ROBOT IS COMMANDED TO TRAVEL FROM ONE POINT TO ANOTHER AT DEFAULT SPEED. Performs without any calculations so it often leads to unanticipated results and wear on the robot joints.

- **JOINT-INTERPOLATED MOTION**: REQUIRES THE ROBOT CONTROLLER TO CALCULATE THE TIME IT WILL TAKE EACH JOINT TO REACH ITS DESTINATION AT THE COMMANDED SPEED. Calculates (using controller) the amount of time it will take each joint to reach its destination at the commanded speed. It then selects the maximum time among these and uses this value as the time for each axis. This means that a separate velocity is calculated for each axis. An advantage is that the robot joints move at a calculated speed, causes less stress on the joints and path can be repeated because it is predictable. All joints move at the same time.
Joint Interpolated Motion is the dominant type of joint motion when moving the robot in forward kinematics. Typically, the robot is commanded to move from the current configuration to a new set of joint values. Obviously, there are numerous ways the robot controller could choose to make the change. For example, the robot controller could choose to move joint one to its new value, then joint 2, etc., until all the joints have been moved to their new values, but this would take more time than necessary. For this reason, joint interpolated motion is the algorithm of choice.
The joint interpolated algorithm

1. examines each joint for the changes in joint angles,
2. estimates the time to accomplish each joint change at the current speed setting, given the speed allowables for each joint,
3. determines the joint which will take the longest time to accomplish the joint change,
4. then slows
TYPES OF MOTION - CONT-

- **STRAIGHT-LINE INTERPOLATION MOTION:** Requires the end of the end effector to travel along a straight path determined in rectangular XY coordinates.
  - Useful in applications such as arc welding, inserting pins into holes, or laying material along a straight path.
  - Most demanding for the controller because the transformations must be computed.

- **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.
  - Circular interpolation produces a linear approximation of the circle and is more readily available using a programming language rather than manual or teach pendant techniques.
PATH CONTROL

COMMERCIALY AVAILABLE INDUSTRIAL ROBOTS CAN BE CLASSIFIED INTO FOUR CATEGORIES ACCORDING TO THE PATH CONTROL SYSTEM.

- **LIMITED-SEQUENCE:** DO NOT USE SERVO-CONTROL TO INDICATE RELATIVE POSITIONS OF THE JOINTS.
  - 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 EXTREME LIMITS OF TRAVEL.

- **POINT-TO-POINT:** THESE ROBOTS ARE MOST COMMON AND CAN MOVE FROM ONE SPECIFIED POINT TO ANOTHER BUT CANNOT STOP AT ARBITRARY POINTS NOT PREVIOUSLY DESIGNATED. Robots programmed and controlled in this manner are programmed to move from one discrete point to another within the robot's working envelope. In the automatic mode of operation, the exact path taken by the robot will vary slightly due to variations in velocity, joint geometries, and point spatial locations. This difference in paths is difficult to predict and therefore can create a potential safety hazard to personnel and equipment.
CONTROLLED PATH: IS A SPECIALIZED CONTROL METHOD THAT IS A PART OF 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 THE PERFECT PATH MOTION.

This mode of movement ensures that the end of the robot's arm will follow a predictable (controlled) path and orientation as the robot travels from point to point. The coordinate transformations required for this hardware management are calculated by the robot's control system computer. Observations that result from this type of programming are less likely to present a hazard to personnel and equipment.
CONTINUOUS PATH: IS AN EXTENSION OF THE POINT-TO-POINT METHOD. THIS INVOLVES THE UTILIZATION OF MORE POINTS AND ITS PATH CAN BE ARC, A CIRCLE, OR A STRAIGHT LINE.

BECAUSE OF THE LARGE NUMBER OF POINTS, THE ROBOT IS CAPABLE OF PRODUCING SMOOTH MOVEMENTS THAT GIVE THE APPEARANCE OF CONTINUOUS OR CONTOUR MOVEMENT. This method ensures that the end of the robot's arm will follow a predictable (controlled) path and orientation as the robot travels from point to point. The coordinate transformations required for this hardware management are calculated by the robot's control system computer. Observations that result from this type of programming are less likely to present a hazard to personnel and equipment.