UNIT 5 TRAJECTORY PLANNING

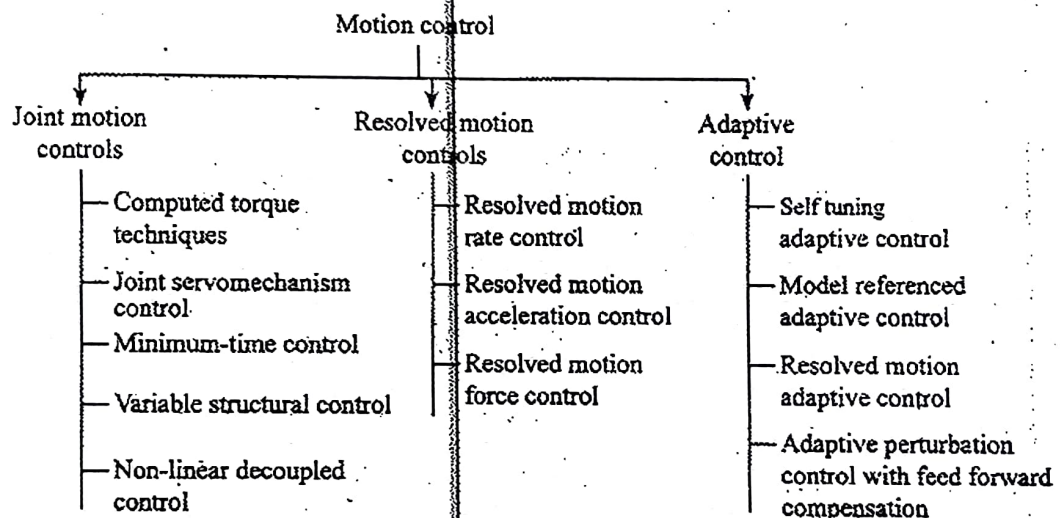
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PART-A
SHORT QUESTIONS WITH SOLUTIONS

Q1. Classify motion control with respect to a path trajectory problem.

Answer :

Based on path trajectory problem, motion control is classified as given below.



Q2. What are the advantages and disadvantages of trajectory planning in joint variable space?

Answer : [Nov.-11, Set-1, Q6(a) | Model Paper-I, Q1(e)]

Advantages of Trajectory Planning in Joint Variable Space

1. Easy to plan the trajectory.
2. Real time planning.
3. During movement of manipulator, planned trajectory can be expressed in controlled variable form.
4. Fast computational technique.
5. Dynamic constraints of manipulator is dealt with ease.

Disadvantages of Trajectory Planning in Joint Variable Space

1. Locating various links and joints is difficult.
2. Avoiding obstacles in the path or trajectory is very difficult.
3. Along the Cartesian path, it loses its accuracy.

Q3. Write about angular velocity of an n-DOF manipulator.

Answer :

n-DOF Manipulator

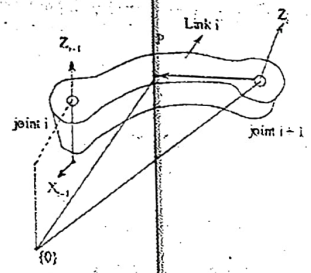


Figure: n-DOF Manipulator

Consider, frame $\{i\}$ and frame $\{i-1\}$ is attached to link i at two ends. Thus, the angular velocity of link i will be the sum of angular velocity of link $(i-1)$ and link $\{i\}$.

If joint i is prismatic, then it allows only translational motion between link i and $(i-1)$. Thus, the prismatic joint does not contribute to the angular velocity of link i.

At joint i,

$$\omega_i = \omega_{i-1}$$

If the joint (i) is rotary, then it contributes the angular velocity between link i and link $(i-1)$,

$$\therefore \quad \omega_i = \omega_{i-1} + {}^{i-1}\omega_i$$

Therefore, it can be concluded that, rotary joint (i) contributes to the angular velocities of link i to n.

Q4. Define Robot program. What is the purpose of it and what are the various methods used for programming robots?

Answer : Model Paper-III, Q1(f)

Definition

A "robot program" is defined as a path in space, through which the manipulator is directed to move.

Purpose

The purpose of robot programming is to teach actions like controlling the end-effector, receiving signals from sensors etc.

Various Methods

There are various methods used for programming robots. The two basic types are,

(i) Lead through methods

(ii) Textual robot languages.

Lead through Methods

In this method of programming, the robot is moved through the desired motion path and this path is recorded into the controller memory. There are two ways to accomplish the above task,

(a) Powered leadthrough

(b) Manual leadthrough.

Q5. What is a 'Robot program' language?

Answer :

A robot program may be defined as a path in space to be followed by the manipulator, combined with peripheral action that supports the work cycle.

Peripheral actions include,

(i) Opening and closing the gripper

(ii) Performing logical decision making

(iii) Communicating with other elements of equipment in the robot cell.

Robot languages have been developed for the ease of control of motions of robots having different structures and geometrical capabilities. Some of the programming languages are,

WAVE, AL, VAL, AML, MCL, RAIL, HELP, RPL, PAL and ADA.

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Q6. Compare lead through methods with textual language programming.

Answer : Model Paper-IV, Q1(c)

	Lead Through Programming		Textual Language Programming
1.	Work cycle is instructed to the robot by physically moving the manipulator through the required motion cycle and simultaneously recording the program into the controller.	1.	In this type of programming language, the robot is instructed by entering the commands in the robot controller.
2.	It is not preferred for frequent changing of the process cycle.	2.	It can be used for frequent changing of the process cycle.
3.	It is a simple, but less efficient method.	3.	It is a complex, but more efficient method.
4.	It requires less skilled operator.	4.	It requires highly skilled operator.
5.	The cost of programming is low.	5.	The cost of programming is high.

Q7. Write about robot software packages?

Answer : Model Paper-II, Q1(g)

Software Packages

A robot software is an interface between the user and robot, consisting of data and set of instructions (program), which on execution results in desired robot applications. The different types of softwares used are,

1. **Command and Control Software**

It is used for controlling graphical user interface of a robot suitable for tele operated robotic applications.

2. **Point and Click Command Software**

It is mainly used for controlling autonomous robots.

3. **Scheduling Software**

It is used in industries for scheduling of raw material, finished products, machining operations, etc., through mobile robots. Example: Automated guided vehicles uses scheduling softwares.

4. **Tasking Software**

It is used to control simple functions of a robot like pick and drop of objects, setting up delivery lines, etc. Example: Robot used in industries to transfer products from one conveyor belt to other.

Q8. Explain the end effector commands of robot languages.

Answer :

The end effector commands are used to control the action of robot's end effector such as gripper, tool, etc as per the required operation. The most basic type of commands are OPEN and CLOSE for opening and closing of gripper respectively. But, the commands SIGNAL5 and SIGNAL6 are also used for closing and opening gripper. The commands used in VALII are OPEN-I and CLOSE-I, which on execution causes the gripper action immediately without any delay, compared to the general commands.

To have a better control over the end effector, certain commands are used, which gives more refined instructions. For example, CLOSE 10 MM would be used to close the gripper to an opening of 10 mm CLOSE 2N for applying certain force on an object while gripping and CENTER for grasping an object at the center of arm. These type of commands also provides an additional information for determining position, force, displacement, etc. For controlling the tools (end effectors), different commands may be used such as OPERATE TOOL(TIME = 2 SECONDS), OPERATE TOOL (SPEED = 1000 RPS), etc. Thus, end effectors can be controlled by using various commands provided by robot programming languages.

Q9. Using the 8 × 8 grid of a robot with one rotational axis and one linear axis show the path taken by the robot if it is directed to move between point (2, 2) and point (7, 5) in the grid using joint-interpolation.

Answer :

Joint-Interpolation Method

Robot moves between point (2, 2) to point (7, 5)

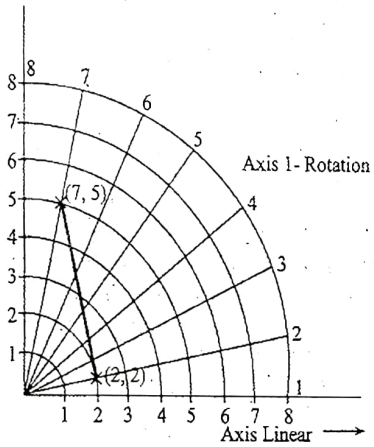


Figure: Square (8 × 8) Grid

The robot consists of combination of rotational moves (along axis 1) and linear moves (along axis 2).

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PART-B
ESSAY QUESTIONS WITH SOLUTIONS

5.1 GENERAL CONSIDERATIONS IN PATH DESCRIPTION AND GENERATION, TRAJECTORY PLANNING AND AVOIDANCE OF OBSTACLES

Q10. Define the following terms of trajectory planning.

(i) Trajectory

(ii) Spline

(iii) Joint space scheme

(iv) Cartesian space scheme.

Answer :

(i) Trajectory

A trajectory is a path in which kinematic equations of each point are defined as a function of time. Thus, trajectory represents the order of position, velocity and acceleration of every joint and link of the manipulator, by specifying in joint space or cartesian space. It represents spatial motion as well as temporal motion.

(ii) Spline

A smooth curve passing through number of points (knot points) in a trajectory of manipulator is called spline.

(iii) Joint Space Scheme

In joint space scheme or trajectory planning, every point has definite path and is defined by position and orientation of end-effector of the manipulator from reference system. After applying inverse kinematics, each point changes its position to set of joint positions. Thus, a smooth curve joining all these points is formed, for each joint.

(iv) Cartesian Space Scheme

In cartesian space scheme or trajectory planning, the trajectory is represented by cartesian coordinates and joint coordinates. The cartesian coordinates consists of path constraints such as, velocity, acceleration etc. whereas, joint coordinates specifies the joint actuators.

Q11. Explain the steps involved in trajectory planning.

Answer : Model Paper-II, Q3(a)

Trajectory planning involves three steps, they are,

(a) Task description

(b) Selecting and applying planning technique

(c) Determining the trajectory.

(a) Task Description

In case of motion planning problem, the first step is to determine type of motion required. The tasks to be performed is divided into three types, as follows,

(i) Point-to-Point Motion

In tasks like pick and place the starting and ending positions of end effector represents the task. This motion is called point-to-point motion and it should follow smooth curve. In this type of problem, for a known starting value, the final location in cartesian system is specified.

(ii) Continuous Path Motion

In continuous path motion, the end effector traces the starting and ending positions as well as a certain path between these positions, in cartesian space. The parameters of path to be traced is specified by the user. Examples are welding and plotting.

(iii) Path Points

In this, to specify a trajectory, the task needs more than two points, in order to enable efficient execution and enhanced control. In pick and place operation, number of points are identified in the path. The first point of the path is called 'initial point' and the last is called 'goal point', while the midpoints are called path points or via points.

(b) Selecting and Applying Planning Technique

Depending upon the type of task, the techniques are classified into two types,

(i) Joint Space Techniques

An example of point-to-point motion uses this technique, in which planning is accomplished with respect to joint level. This gives time dependent functions; whose derivatives represent the required motion of the manipulator.

(ii) Cartesian Space Techniques

Continuous path motion uses this technique, in which each point of end effector has position, velocity and acceleration as functions of time and using inverse kinematics, their derivatives are to be calculated.

(c) Determining the Trajectory

Using the above techniques and their solutions, the trajectory is to be determined, at an update rate, ranging from 20 Hz to 200 Hz.

Q12. Describe different methods of splitting a joint trajectory. Explain any one of them.

Answer :

Methods of Splitting a Joint Trajectory

(a) 4-3-4 Trajectory

It represents the positions of trajectory segments as,

(i) 4 - 4th degree polynomial specifying the segment from initial position to lift-off position.

(ii) 3 - 3rd degree polynomial specifying the segment from lift-off position to set down position.

(iii) 4 - 4th degree polynomial specifying the segment from set-down position to final position.

(b) 3-5-3 Trajectory

Similarly, it also represents the trajectory segment positions as,

(i) 3 - 3rd degree polynomial specifying the segment from initial to lift-off position.

(ii) 5 - 5th degree polynomial specifying the segment from lift-off to set-down position.

(iii) 3 - 3rd degree polynomial specifying the segment from set-down to final position.

(c) Cubic Trajectory

It consists of five trajectory segments from initial to final position. Each segment is a smooth curve of cubic spline with 3rd degree polynomial.

Cubic Polynomials

Consider the motion of tool from its initial position to final position in a certain amount of time.

Using the inverse kinematics, the set of joint angles that correspond to the final position and orientation can be calculated. The initial position of the manipulator is also known in the form of a set of joint angles.

Considering a single smooth motion, the constraints are given as,

$$\theta(0) = \theta_0, \quad \theta(t_f) = \theta_f \qquad \ldots (1)$$

$$\dot{\theta}(0) = 0, \quad \dot{\theta}(0)\,(t_f) = 0 \qquad \ldots (2)$$

A cubic polynomial has the form,

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \qquad \ldots (3)$$

$$\dot{\theta}(t) = a_1 + 2a_2 t + 3a_3 t^2$$

$$\ddot{\theta} = 2a_2 + 6a_3 t \qquad \ldots (4)$$

Combining equations (3) and (4) with the four desired constraints, yields four equations,

i.e.,
$$\theta_0 = a_0$$

$$\theta_f = a_0 + a_1 t_f + a_2 t_f^2 + a_3 t_f^3$$

$$0 = a_1$$

$$0 = a_1 + 2a_2 t_f + 3a_3 t_f^2 \qquad \ldots (5)$$

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Solving these equations for the a_i,

$$a_0 = \theta_0, \quad a_1 = 0,$$

$$a_2 = t_f^{\frac{3}{2}} (\theta_f - \theta_0)$$

$$a_3 = t_f^{-\frac{2}{3}} (\theta_f - \theta_0)$$

Using equation (6), the cubic polynomial that connects any initial joint angle position with desired final position can be determined.

Cubic Polynomials for a Path via Points

In a single final position, each path point is usually specified in terms of a required position and orientation of the tool frame with respect to the station frame.

The velocity constraints at each end are not zero, but have, some known velocity. The constraints of equation (3) become,

$$\dot{\theta}(0) = \dot{\theta}_0 \qquad \dot{\theta}(t_f) = \dot{\theta}_f$$

The four equations describing this general cubic are,

$$\theta_0 = a_0$$

$$\theta_f = a_0 + a_1 t_f + a_2 t_f^2 + a_3 t_f^3$$

$$\dot{\theta}_0 = a_1$$

$$\dot{\theta}_f = a_1 + 2a_2 t_f + 3a_3 t_f^2$$

Solving these equations for the a_i,

$$a_0 = \theta_0$$

$$a_1 = \dot{\theta}_0$$

$$a_2 = \frac{3}{t_f^2}(\theta_f - \theta_0) - \frac{2}{t_f}\dot{\theta}_0 - \frac{1}{t_f}\dot{\theta}_f$$

$$a_3 = \frac{-2}{t_f^3}(\theta_f - \theta_0) + \frac{1}{t_f^2}(\dot{\theta}_f + \dot{\theta}_0)$$

Using equation (9) the cubic polynomial that connects any initial and final positions with any initial and final velocities can be computed.

Q13. The motion of a joint from start to goal position is specified in terms of position, velocity and acceleration at the beginning and end of a path segment. Determine the coefficients of the optimistic (fifth-degree) polynomial for interpolating the smooth trajectory in the segment.

Answer :

Let, θ, $\dot{\theta}$ and $\ddot{\theta}$ represent the position, velocity and acceleration respectively. The optimistic polynomial required for smooth trajectory segment is given by,

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5$$

Where,

$a_0, a_1, a_2, \ldots a_5$ are necessary coefficients to obtain smooth trajectory. There constraints are,

$$\theta_0 = a_0$$

$$\theta_f = a_0 + a_1 t_f + a_2 t_f^2 + a_3 t_f^3 + a_4 t_f^4 + a_5 t_f^5$$

$$\dot{\theta}_0 = a_1$$

$$\dot{\theta}_f = a_1 + 2a_2 t_f + 3a_3 t_f^2 + 4a_4 t_f^3 + 5a_5 t_f^4$$

$$\ddot{\theta}_0 = 2a_2$$

$$\ddot{\theta}_f = 2a_2 + 6a_3 t_f + 12a_4 t_f^2 + 20a_5 t_f^3$$

These constraints specify a linear set of six equations consisting of six unknowns,

$$\therefore \quad a_0 = \theta_0$$

$$a_1 = \dot{\theta}_0$$

$$a_2 = \frac{\ddot{\theta}_0}{2}$$

$$a_3 = \frac{\ddot{\theta}_f - (2a_2 + 12a_4 t_f^2 + 20a_5 t_f^3)}{6t_f}$$

$$a_4 = \frac{\ddot{\theta}_f - (2a_2 + 6a_3 t_f + 20a_5 t_f^3)}{12t_f^2}$$

$$a_5 = \frac{\ddot{\theta}_f - (2a_2 + 6a_3 t_f + 12a_4 t_f^2)}{20t_f^3}$$

Q14. Solve for the coefficients of two cubics that are connected in a two-segmented spline with continuous acceleration at the intermediate via point. The initial angle is θ_0, the via point is θ_v and the goal point is θ_g.

Answer : Nov.-11, Set-3, Q6(a)

Given that,

Initial angle = θ_0

Via point = θ_v

Goal point = θ_g

Equation for first cubic polynomial is,

$$\theta(t) = a_{10} + a_{11} t + a_{12} t^2 + a_{13} t^3 \quad \ldots (1)$$

Equation for second cubic polynomial is,

$$\theta(t) = a_{20} + a_{21} t + a_{22} t^2 + a_{23} t^3 \quad \ldots (2)$$

Consider, start interval $t = 0$ and end interval $t = t_{1f}$ to evaluate the above cubic equations.

Now, constraints enforced are,

$$\theta_0 = a_{10}$$

$$\theta_v = a_{10} + a_{11} t_{1f} + a_{12} t^2_{1f} + a_{13} t^3_{1f}$$

$$\theta_v = a_{20}$$

$$\theta_g = a_{20} + a_{21} t_{2f} + a_{22} t^2_{2f} + a_{23} t^3_{2f}$$

$$\theta'(t) = a_{11} + 2a_{12} t + 3a_{13} t^2$$

$$\theta'(0) = a_{11}$$

$$a_{11} = 0$$

For second polynomial,

$$\theta'(t) = a_{21} + 2a_{22} t_{2f} + 3a_{23} t^2_{2f} = 0$$

$$a_{11} + 2a_{12} t_{1f} + 3a_{13} t^2_{1f} = a_{21}$$

$$2a_{12} + 6a_{13} t_{1f} = 2a_{22}$$

The above eight equations has eight unknown constraints which specifies a linear equation.

Take $t_f = t_{1f} = t_{2f}$ therefore,

$$\therefore a_{10} = \theta_0$$

$$a_{11} = 0$$

$$a_{12} = \frac{12\theta_v - 3\theta_g - 9\theta_0}{4t_f^2}$$

$$a_{13} = -\frac{-8\theta_v + 3\theta_g + 5\theta_0}{4t_f^3}$$

$$a_{20} = \theta_v$$

$$a_{21} = \frac{3\theta_g - 3\theta_0}{4t_f}$$

$$a_{22} = \frac{-12\theta_v + 6\theta_g + 6\theta_0}{4t_f^2}$$

$$a_{23} = \frac{8\theta_v - 5\theta_g - 3\theta_0}{4t_f^3}$$

Q15. A manipulator with a single link is to rotate from $\theta(0) = 30°$ to $\theta(2) = 100°$ in 2 seconds. The joint velocity and acceleration are both zero at the initial and final positions,

(a) Determine the coefficient of a cubic polynomial that accomplishes the motion.

(b) Determine the coefficients of a quadratic polynomial that accomplishes the motion,

(c) Determine the coefficients of a quintic polynomial that accomplishes the motion.

Answer :

Given that,

$$\theta(0) = 30°$$

$$\theta(2) = 100°$$

$$t = 2 \text{ seconds}$$

(a) A cubic polynomial form of motion equation,

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \quad \ldots (1)$$

Differentiate "θ" with respect to "t"

$$\frac{d\theta(t)}{dt} = \dot{\theta}(t) = 0 + a_1 + 2a_2 t + 3a_3 t^2$$

$$= a_1 + 2a_2 t + 3a_3 t^2 \quad \ldots (2)$$

Again differentiate "θ" with respect to "t"

$$\frac{d^2\theta(t)}{dt^2} = \ddot{\theta}(t) = 0 + 2a_2 + 6a_3 t$$

$$= 2a_2 + 6a_3 t \quad \ldots (3)$$

Applying given conditions,

$$t = 0, \quad \theta(0) = 30°$$

$$t = 2, \quad \theta(2) = 100°$$

From equation (1), $\theta_0 = a_0$

From equation (2), $\dot{\theta}(0) = a_1$

$$0 = a_1 + 2a_2 t + 3a_3 t^2$$

Solving above equations for "a_1".

$$a_0 = \theta_0 = 30°$$

$$a_1 = 0$$

$$a_2 = \frac{3(\theta_2 - \theta_0)}{t_2^2} = \frac{3(100-30)}{(2)^2}$$

$$= 52.5°$$

$$a_3 = \frac{-2(\theta_2 - \theta_0)}{(t_2)^3} = \frac{-2(100-30)}{(2)^3}$$

$$= -17.5°$$

$$\therefore \quad \theta(t) = 30 + 52.5t^2 - 17.5t^3$$

(b) A quadratic form has,

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 \quad \ldots (1)$$

$$\theta(t) = a_1 + 2a_2 t + 3a_3 t^2 + 4a_4 t^3 \quad \ldots (2)$$

$$\theta(t) = 2a_2 + 6a_3 t + 12a_4 t^2 \quad \ldots (3)$$

Combine equations (1), (2) and (3) with the following four constraints,

$$\theta_0 = a_0$$

$$\theta_f = a_0 + a_1 t_f + a_2 t_f^2 + a_3 t_f^3 + a_4 t_f^4$$

$$\dot{\theta} = a_1$$

$$\dot{\theta} = a_1 + 2a_2 t_f + 3a_3 t_f^2 + 4a_4 t_f^3$$

Solving these equation,

$$a_0 = \theta_0 = 30°, \; a_1 = 0$$

When, $t = 0, \; \theta = 30°$

$t = 2, \; \theta = 100°$

Substitute in equations (4), (5) and (6)

$$30 = a_0 \quad \ldots (4)$$

$$100 = a_0 + 2a_1 + 4a_2 + 8a_3 + 16a_4$$

$$\therefore \quad 2a_1 + 4a_2 + 8a_3 + 16a_4 = 70 \quad \ldots (5)$$

$$\dot{\theta}(t) = 0$$

$$a_1 + 2a_2(0) + 3a_3(0) + 4a_4(0) = 0$$

$$a_1 = 0 \quad \ldots (6)$$

$$\dot{\theta}(2) = 0$$

$$a_1 + 2a_2(2) + 3a_3(4) + 4a_4(2^3) = 0$$

$$4a_2 + 12a_3 + 32a_4 = 0 \quad \ldots (7)$$

$$\dot{\theta}(0) = 0$$

$$2a_2 + 6a_3(0) + 12a_4(0) = 0$$

$$a_2 = 0 \quad \ldots (8)$$

$$\dot{\theta}(2) = 0$$

$$2a_2 + 6a_3(2) + 12a_4(2^2) = 0$$

$$12a_3 + 24a_4 = 0 \quad \ldots (9)$$

Substitute, $a_2 = 0$ in equation (7)

$$12a_3 + 32a_4 = 0 \quad \ldots (10)$$

From equations (4), (6) and (8)

$$a_0 = 30, \; a_1 = 0, \; a_2 = 0$$

From equation (5)

$$2a_1 + 4a_2 + 8a_3 + 16a_4 = 70$$

$$a_1 = 0, \; a_2 = 0$$

$$8a_3 + 16a_4 = 70 \quad \ldots (11)$$

From equation (10), $12a_3 + 32a_4 = 0 \quad \ldots (12)$

Solve equations (11) and (12), $a_3 = 45$

$$a_4 = -16.875$$

$$\theta(t) = 30 + 45t^3 - 16.875t^4$$

(c) A quintic polynomial is given by,

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5$$

Where constraints,

$$\theta_0 = a_0$$

$$\theta_f = a_0 + a_1 t_f + a_2 t_f^2 + a_3 t_f^3 + a_4 t_f^4 + a_5 t_f^5$$

$$\dot{\theta}_0 = a_1$$

$$\dot{\theta}_f = a_1 + 2a_2 t_f + 3a_3 t_f^2 + 4a_4 t_f^3 + 5a_5 t_f^4$$

$$\ddot{\theta}_0 = a_2$$

$$\ddot{\theta}_f = 2a_2 + 6a_3 t_f + 12a_4 t_f^2 + 20a_5 t_f^3$$

These constraints specify a linear set of six equation with six unknowns whose solution is,

$$a_0 = \theta_0 = 30°, \; a_1 = \dot{\theta}_0 = 0$$

$$a_2 = \frac{\ddot{\theta}_0}{2} = 0$$

$$a_3 = \frac{20\theta_f - 20\theta_0 - (8\theta_f + 2\theta_0)t_f - (3\theta_g - \theta_f)t_f^2}{2t_f^3}$$

$$= \frac{20(100) - (20)(30) - 0 - 0}{2(2)^3}$$

$$= 87.5$$

$$a_4 = \frac{30(100) - (30)(30) + 0 + 0}{2(2)^4}$$

$$= 65.625$$

$$a_5 = \frac{12(100) - 12(30) - 0 - 0}{2(2)^5} = 13.125$$

$$\therefore \quad \theta = 30 + 87.5t^3 + 65.625t^4 + 13.125t^5$$

Q16. A one-degree of freedom manipulator with rotary joint is to move from 113° to 210° in 7 seconds. Find the coefficients of a linear trajectory with parabolic blends to interpolate a smooth trajectory.

Answer :

Consider, a 1-D freedom manipulator with rotary joint.

The trajectory of a particular joint of manipulator is specified with two via (113° to 210°) points (Four path points) as q^i = [15°, 40°, 30°, 12°]

[Sum of angles = 210° – 113° = 97°] and the travel time (7 seconds).

The segment seconds are [2.5, 2, 2.5].

The segment time duration, velocity and blend time duration are calculated as follows.

Blend duration at starting is,

$$t_1 = T_{12} - \sqrt{T_{12}^2 - \frac{2(q_2 - q_1)}{\ddot{q}_1}}$$

$$\cong 2.5 - \sqrt{(2.5)^2 - \frac{2(40-15)}{55}}$$

Where,

$\ddot{q}_1$ = Constant acceleration assumed as 55 degree/sec^2.

$t_1 = 0.18895$ sec $\cong 0.189$ sec

The constant velocity for the linear segments are,

$$\dot{q}^{12} = \frac{40-15}{2-(2.5-2)\times 0.189}$$

$$= 13.12 \text{ degree/sec.}$$

$$\dot{q}^{23} = \frac{30-40}{2.0} = -5.0 \text{ degree/sec}$$

The second blend duration is computed from,

$$t_2 = \frac{30-40}{2.0} = \frac{-5.0-13.12}{-55(\text{Deceleration})}$$

$$\cong 0.33 \text{ seconds}$$

$$t_{12} = T_{12} - t_1 - \frac{t_2}{2} = 2.5 - 0.189 - \frac{0.33}{2}$$

$$\cong 2.146 \text{ sec}$$

Also, $t_4 = 2.5 - \sqrt{2.5^2 + \frac{2(12-30)}{55}}$

$$= 0.135 \text{ sec.}$$

$$\dot{q}^{34} = \frac{q^4 - q^3}{T_{34} - \frac{t_4}{2}} = \frac{12-30}{2.5 - \frac{0.135}{2}}$$

$$= -7.4 \text{ degree/sec}$$

Similarly, for the third segment,

$$t_3 = \frac{\dot{q}^{34} - \dot{q}^{23}}{\ddot{q}^3}$$

$$= \frac{-7.4 + 5.0}{-55}$$

$$= 0.0436 \text{ sec}$$

$$t_{23} = T_{23} - \frac{t_2}{2} - \frac{t_3}{2}$$

$$t_{23} = 2 - \frac{1}{2}(0.33) - \frac{1}{2}(0.0436)$$

$$= 1.813 \text{ sec}$$

$$t_{34} = 2.5 - \frac{1}{2} \times 0.0436$$

$$= 2.478 \text{ sec}$$

The parameters for the trajectory are tabulated in tables below with blend duration of each parabolic segment at each path point and linear velocity and duration of linear velocity for each segment respectively.

Path Point	t_b(sec)	Segment	$\dot{q}$ (deg/sec)	t(sec)
1	0.189	1-2	13.12	2.146
2	0.33	2-3	–5.0	1.813
3	0.0436	3-4	–7.4	2.478
4	0.135			

Q17. A single cubic trajectory is given by, θ(t) = 8 + 10t + 45t² + 35t³ and is used over the time interval from t = 1 to t = 2. What are the initial and final velocities and accelerations.

Answer : May/June-14, Set-2, Q6(b)

Given that,

A single cubic trajectory,

$$\theta(t) = 8 + 10t + 45t^2 + 35t^3$$

Time interval, $t = 1$ to $t = 2$

Equations for given cubic trajectory are,

For displacement,

$$\theta(t) = 8 + 10t + 45t^2 + 35t^3$$

For velocity,

$$\dot{\theta}(t) = 10 + 90t + 105t^2$$

For acceleration,

$$\ddot{\theta}(t) = 90 + 210t$$

At initial stage, i.e., $t = 1$

Displacement $\theta(1) = 8 + 10 \times 1 + 45 + 1^2 \times 35 \times 1^3$

$= 98$

Velocity, $\dot{\theta}(1) = 10 + 90 \times 1 + 105 \times 1^2$

$= 205$

Acceleration, $\ddot{\theta}(1) = 90 + 210 \times 1$

$= 300$

At final stage, i.e., $t = 2$

Displacement, $\theta(2) = 8 + 10 \times 2 + 45 + 2^2 + 35 \times 2^3$

$= 488$

Velocity, $\dot{\theta}(2) = 10 + 90 \times 2 + 105 \times 2^2$

$= 610$

Acceleration, $\ddot{\theta}(2) = 90 + 210 \times 2$

$= 510$

Q18. A single link robot with a rotary joint is motionless at q = –2 degrees. It is required to move the joint in a smooth manner to q = 50 degrees in 2.5 seconds and stop smoothly. Compute the parameters of a linear trajectory with parabolic blends.

Answer : Nov.-10, Set-3, Q6(a)

Consider a linear trajectory of cubical form i.e.,

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \quad \ldots (1)$$

Joint velocity along this path,

$$\dot{\theta}(t) = a_1 + 2a_2 t + 3a_3 t^2 \quad \ldots (2)$$

By combining equations (1) and (2) with the four constraints yields four equations with four unknowns in terms of initial time (t_0) and final time (t_f).

$$\theta_0 = a_0 + a_1 t_0 + a_2 t_0^2 + a_3 t_0^3 \quad \ldots (3)$$

$$\dot{\theta}_0 = a_1 + 2a_2 t_0 + 3a_3 t_0^2 \quad \ldots (4)$$

$$\theta_f = a_0 + a_1 t_f + a_2 t_f^2 + a_3 t_f^3 \quad \ldots (5)$$

$$\dot{\theta}_f = a_1 + 2a_2 t_f + 3a_3 t_f^2 \quad \ldots (6)$$

These four equations are combined to form a single matrix equation,

$$\begin{bmatrix} 1 & t_0 & t_0^2 & t_0^3 \\ 0 & 1 & 2t_0 & 3t_0^2 \\ 1 & t_f & t_f^2 & t_f^3 \\ 0 & 1 & 2t_f & 3t_f^2 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} \theta_0 \\ \dot{\theta}_0 \\ \theta_f \\ \dot{\theta}_f \end{bmatrix} \quad \ldots (7)$$

Apply the constraints in equations (3) and (4),

(i) At $t_0 = 0$, $a_0 = \theta_0$

(ii) At $\dot{\theta}_0 = 0$, $a_1 = 0$

(iii) At $t_f = 1$ sec

On substituting the constraints value in the above equation (7),

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 \\ 0 & 1 & 2 & 3 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} \theta_0 \\ 0 \\ \theta_f \\ 0 \end{bmatrix}$$

On solving the above matrix,

$$a_0 = \theta_0$$

$$a_1 = 0$$

Substituting the values of a_0 and a_1 in equations (4) and (5),

$$a_1 + 2a_2 + 3a_3 = 0$$

$$2a_2 + 3a_3 = 0 \quad (\because a_1 = 0) \quad \ldots (8)$$

$$a_0 + a_1 + a_2 + a_3 = \theta_f$$

$$\theta_0 + a_2 + a_3 = \theta_f$$

$$a_2 + a_3 = \theta_f - \theta_0 \quad \ldots (9)$$

Multiply equation (9) by '2',

$$2a_2 + 2a_3 = 2(\theta_f - \theta_0) \quad \ldots (10)$$

Solve equation (8) and (10)

$$2a_2 + 3a_3 = 0$$

$$2a_2 + 2a_3 = 2(\theta_f - \theta_0)$$

$$a_3 = -2(\theta_f - \theta_0)$$

Substitute the value of a_3 in equation (9),

$$a_2 - 2(\theta_f - \theta_0) = \theta_f - \theta_0$$

$$a_2 = 3(\theta_f - \theta_0) \quad (\because a_3 = -2(\theta_f - \theta_0))$$

Given,

$$\theta_0 = -2°$$

$$\theta_f = 50°$$

$$t = 2.5 \text{ sec}$$

On substituting the values of θ_0, θ_f and t in a_0, a_1, a_2 and a_3,

$$a_0 = -2$$

$$a_1 = 0$$

$$a_2 = 3(\theta_f - \theta_0)$$

$$= 3(50 - (-2)) = 3(52)$$

$$\therefore a_2 = 156$$

$$a_3 = -2(\theta_f - \theta_0)$$

$$= -2(50 - (-2)) = -2(52)$$

$$\therefore a_3 = -104$$

Therefore, the equation for cubic polynomial for displacement as,

$$\theta(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3$$

$$\theta(t) = -2 + 156t^2 - 104t^3$$

For velocity,

$$\dot{\theta}(t) = a_1 + 2a_2 t + 3a_3 t^2$$

$$= 312t - 312t^2$$

For acceleration,

$$\ddot{\theta}(t) = 2a_2 + 6a_3 t$$

$$\ddot{\theta}(t) = 312 - 624t$$

Q19. A single link rotary robot is required to move from θ (0) = 30° to θ (2) = 100° in 2 seconds. The joint velocity and acceleration are both zero at the initial and final positions. Determine the coefficients of a quadratic polynomial that accomplishes the motion.

Answer : Nov.-11, Set-1, Q6(b)

Given that,

$\theta(0) = 30°$, $\theta(2) = 100°$ and time, $t = 2$ sec

Quadratic equation is given by,

$$\theta(t) = a_0 + a_1 t + a_2 t^2$$

$$\dot{\theta}(t) = a_1 + 2a_2 t$$

$$\ddot{\theta}(t) = 2a_2$$

Combining the above equations with three desired constraints,

At, $t = 0$; $\theta(0) = a_0$

$t = f$; $\theta(f) = a_0 + a_1 t_f + a_2 t_f^2$

$t = 0$; $\dot{\theta}(0) = a_1$

$t = f$; $\dot{\theta}(f) = a_1 + 2a_2 t_f$

Solving the above equations,

$$a_0 = \theta(0) \quad a_1 = \dot{\theta}(0)$$

$$\theta(f) = \theta(0) + \dot{\theta}(0) t_f + a_2 t_f^2$$

$$\theta(f) - \theta(0) = a_2 t_f^2$$

$$a_2 = \frac{\theta(f) - \theta(0)}{t_f^2}$$

Substituting $\theta(0) = 30°$, $\theta(2) = 100°$, $t_f^2 = 2$ sec in above equations,

$$a_0 = 30°, \; a_1 = 0$$

$$a_2 = \frac{\theta(2) - \theta(0)}{4} = \frac{100 - 30}{4}$$

$$a_2 = \frac{70}{4} = 17.5$$

$a_0 = 30°$, $a_1 = 0$ and $a_2 = 17.5$

Quadratic equations,

$$\theta(t) = 30 + 17.5 t^2$$

$$\dot{\theta}(t) = 2(17.5) t = 35 t$$

$$\ddot{\theta}(t) = 2(17.5) = 35$$

Q20. The trajectory of a particular joint is specified as follows,

Path points in degrees: 15, 40, 30, 15. The duration of these three segments should be 3, 1, 4 respectively. Assume a linear path with parabolic blends and an acceleration of 60 degrees/sec². Calculate all segment velocities, blend times and linear times for the trajectory.

Nov.-11, Set-2, Q6(b)

Answer :

Given that,

Acceleration, $q_1 = 60$ degrees/sec²

$q_1 = 15$, $q_2 = 40$, $q_3 = 30$, $q_4 = 15$

Duration, $T_{12} = 3$, $T_{23} = 1$, $T_{34} = 4$

Blend duration at starting is,

$$t_1 = T_{12} - \sqrt{(T_{12})^2 - \frac{2(q_2 - q_1)}{q_1}}$$

$$= 3 - \sqrt{(9) - \frac{2(40-15)}{60}}$$

$$\therefore t_1 = 0.142$$

Constant velocity for the linear segments are,

$$q^{12} = \frac{q_2 - q_1}{T_{12} - \left(\frac{t_1}{2}\right)}$$

$$= \frac{40 - 15}{3 - \left(\frac{0.142}{2}\right)}$$

$$q^{12} = 8.535$$

$$q^{23} = \frac{q_3 - q_2}{T_{23}}$$

$$= \frac{30 - 40}{1}$$

$q^{23} = -10$ and $q_2 = -60$ (deceleration).

The second blend duration is computed from,

$$t_2 = \frac{q^{23} - q^{12}}{q_2} = \frac{-10 - 8.535}{-60}$$

$$t_2 = 0.308$$

$$t_{12} = T_{12} - t_1 - \left(\frac{t_2}{2}\right)$$

$$= 3 - 0.142 - \left(\frac{0.308}{2}\right)$$

$$t_{12} = 2.704$$

And, $q_4 = 60$

Also, $t_4 = T_{34} - \sqrt{(T_{34})^2 + \frac{2(q_4 - q_3)}{q_4}}$

$$= 4 - \sqrt{16 + \frac{2(15-30)}{60}}$$

$$t_4 = 0.062$$

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$$q_{34} = \frac{q_4 - q_3}{T_{34} - \left(\frac{t_4}{2}\right)}$$

$$= \frac{15 - 30}{4 - \left(\frac{0.062}{2}\right)}$$

$\therefore \; q^{34} = -3.779$ and $q_3 = 60$

Similarly for third segment,

$$t_3 = \frac{q^{34} - q^{23}}{q_3} = \frac{-3.779 + 10}{60}$$

$$t_3 = 0.103$$

$$t_{23} = T_{23} - \frac{t}{2} - \frac{t_3}{2}$$

$$= 1 - \left(\frac{0.308}{2}\right) - \left(\frac{0.103}{2}\right)$$

$$t_{23} = 0.794$$

$$t_{34} = T_{34} - \frac{t_3}{2} - \frac{t_4}{2}$$

$$= 4 - \left(\frac{0.103}{2}\right) - \left(\frac{0.062}{2}\right)$$

$$\therefore t_{34} = 3.917$$

The parameters for the trajectory are tabulated in tables below with blend duration of each parabolic segment at each path point and linear velocity and duration of linear velocity for each segment respectively.

Path Point	t_b (sec)
1	0.142
2	0.308
3	0.103
4	0.062

Segment	q(deg/sec)	t (sec)
1–2	8.535	2.704
2–3	−10	0.794
3–4	−3.779	3.917

Q21. For a two segment spline with continuous acceleration at the via point, solve for the coefficients of the two cubics, given the initial angle $\theta_0 = 10°$, the via point $\theta_v = 15°$ and the goal point $\theta_g = 35°$. Take the time of each segment as 2 seconds.

Answer : Nov.-11, Set-4, Q6(a)

Given that,

Initial angle, $\theta_0 = 10°$

Via point, $\theta_v = 15°$

Goal point, $\theta_g = 35°$

Time of each segment, $t_f = 2$ sec

Coefficients are,

$$\therefore a_{10} = \theta_0 = 10°$$

$$\therefore a_{11} = 0$$

$$a_{12} = \frac{12\theta_v - 3\theta_g - 9\theta_0}{4t_f^2}$$

$$= \frac{12(15) - 3(35) - 9(10)}{4 \times 4}$$

$$\therefore a_{12} = -0.9375$$

$$a_{13} = \frac{-8\theta_v + 3\theta_g + 5\theta_0}{4t_f^3}$$

$$= \frac{-8(15) + 3(35) + 5(10)}{4 \times 8}$$

$$\therefore a_{13} = 1.0937$$

$$\therefore a_{20} = \theta_v = 15°$$

$$a_{21} = \frac{3\theta_g - 3\theta_0}{4t_f}$$

$$= \frac{3(35) - 3(10)}{4 \times 2}$$

$$\therefore a_{21} = 9.375$$

$$a_{22} = \frac{-12\theta_v + 6\theta_g + 6\theta_0}{4t_f^2}$$

$$= \frac{-12(15) + 6(35) + 6(10)}{4 \times 4}$$

$$\therefore a_{22} = 5.625$$

$$a_{23} = \frac{8\theta_v - 5\theta_g - 3\theta_0}{4t_f^3}$$

$$= \frac{8(15) - 5(35) - 3(10)}{4 \times 8}$$

$$\therefore a_{23} = -2.656$$

5.2 PATH PLANNING, SKEW MOTION, JOINT INTEGRATED MOTION, STRAIGHT LINE MOTION

Q22. What is path planning? Explain the need for path planning.

Answer : Model Paper-III, Q5(b)

Path Planning

Path planning technique in robots is used to control the motion of manipulator. It is classified into two types i.e., model based and non-model based. In model based technique, the geometry and working requirements of robots can be known, whereas in non-model based, all the geometry and workspace requirements can be obtained using sensing devices.

Path planning is further divided into two types, based on the obstacle formation. They are,

(i) Path planning for stationary obstacles.

(ii) Path planning for moving obstacles – It is sub-classified into two problems,

(a) To avoid collision with stationary obstacles, path has to be planned.

(b) To avoid collision with moving obstacles, velocity of path should be planned.

The solution should be collision free, shortest among all and should have greatest minimum clearance along collision free path.

The main types of robots, which requires path planning are,

(a) Robot manipulators

(b) Mobile robots

(c) Mobile manipulators.

Path planning for these kind of robots is of two types i.e., global and local. The robot is fixed and workspace is chosen arbitrarily in global path planning, while the robot shape is chosen arbitrarily in local path planning. This type of path planning problem is complicated, as the number of degrees of freedom is high, but, it has more flexibility in providing collision free path.

In case of joint space obstacles, the points of the manipulator configuration collide with obstacles and each point is defined with a the path by solving path planning problem, after knowing the joint space obstacles.

Q23. Discuss the Cartesian space techniques.

Answer :

Cartesian space techniques are used to find the trajectory planning by considering cartesian coordinates and cartesian space. The location and orientation of an object can be specified properly in cartesian space. In order to find the path followed by the manipulator, these techniques are preferred. For this purpose, end effector path, time required for motion and tool positioning should be known. The different cartesian space techniques are,

(i) Parametric description of path

(ii) Straight line path

(iii) Circular path

(iv) Position planning

(v) Orientation planning.

(i) Parametric Description of Path

In this technique, a path coordinate is defined and the path is given by an equation, which is a function of time.

For a manipulator of 'n' degrees of freedom, the path traced by its end-effector is 'P' with reference frame, as shown below.

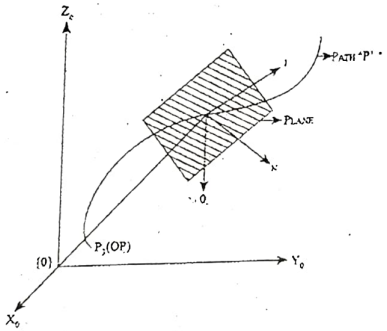


Figure: Path Traced by End-effector

From the figure, the final equations can be framed as,

$$\hat{i} = \frac{d({}^{o}p)}{dr}$$

$$\hat{n} = \frac{1}{\left\| \frac{d^2({}^{o}p)}{dr^2} \right\|} \frac{d^2({}^{o}p)}{dr^2}$$

$$\hat{o} = \hat{i} \times \hat{n}$$

Where,

$\hat{i}$ – Unit vector

$\hat{n}$ – Normal unit vector at 'P'

r – Path coordinate.

Using these relations, the trajectory can be determined.

(ii) Straight Line Path

For a straight line path, the equation for path is,

$$F(r) = {}^{o}p = {}^{o}p_s + \frac{r}{\left\| {}^{o}p_g - {}^{o}p_s \right\|} ({}^{o}p_g - {}^{o}p_s)$$

Where,

${}^{o}p_g$ – Path goal (final) position

${}^{o}p_s$ – Path start position.

Unit vectors are given as,

$$\hat{i} = \frac{d({}^{o}p)}{dr} = \frac{1}{\left\| {}^{o}p_g - {}^{o}p_s \right\|} ({}^{o}p_g - {}^{o}p_s)$$

Also, $\frac{d^2({}^{o}p)}{dr^2} = 0$

Thus, $\hat{n}$ and $\hat{o}$ are defined arbitrarily.

(iii) Circular Path

The specifications of circular path are,

(a) Radius of path is α in $x'y'$ plane.

(b) Direction of unit vector $\hat{a}$ is based on right hand rule.

(c) A point on circle axis passes through centre and its position vector is ${}^{o}D$ with respect to reference frame {0}.

(d) Position vector of point on circle ${}^{o}p_f$ in frame {0}.

In this case, circular path is given by,

$$P'(r) = \begin{bmatrix} \alpha \cos\left(\frac{r}{\alpha}\right) \\ \alpha \sin\left(\frac{r}{\alpha}\right) \\ 0 \end{bmatrix}$$

Unit vectors are defined as,

$$\hat{i} = \frac{d({}^{o}p)}{dr} = R \begin{bmatrix} -\sin\left(\frac{r}{\alpha}\right) \\ \cos\left(\frac{r}{\alpha}\right) \\ 0 \end{bmatrix}$$

$$\hat{n} = \frac{\frac{R}{\alpha}}{\left\| \frac{d^2({}^{o}p)}{dr^2} \right\|} \begin{bmatrix} -\cos\left(\frac{r}{\alpha}\right) \\ -\sin\left(\frac{r}{\alpha}\right) \\ 0 \end{bmatrix}$$

Where, R – Rotation matrix for $P'(x)$

(iv) Position Planning

After calculating the path traced by end effector, determine the time required for motion, velocity and acceleration. The equations are given by,

Linear velocity of end-effector,

$${}^{o}\dot{p} = \dot{r} \frac{d({}^{o}p)}{dr} = \dot{r}\hat{i}$$

Unit vector, $\hat{i} = \frac{d({}^{o}p)}{dr}$

Linear acceleration,

$${}^{o}\ddot{p} = \dot{r}^2 \frac{d^2({}^{o}p)}{dr^2} + \ddot{r} \frac{d({}^{o}p)}{dr}$$

Similarly,

Parameter	Straight-line Motion	Circular Motion
Velocity	$^{o}\dot{p} = \frac{\dot{s}}{\|^{o}p_g - {}^{o}p_s\|}(^{o}p_g - {}^{o}p_s) = \hat{i}\dot{r}$	$^{o}\dot{p} = R\dot{r}\begin{bmatrix} -\sin\left(\frac{r}{\alpha}\right) \\ \cos\left(\frac{r}{\alpha}\right) \\ 0 \end{bmatrix}$
Acceleration	$^{o}\ddot{p} = \frac{\ddot{s}}{\|^{o}p_g - {}^{o}p_s\|}(^{o}\ddot{p}_g - {}^{o}\ddot{p}_s) = \hat{i}\ddot{r}$	$^{o}\ddot{p} = \begin{bmatrix} \frac{\dot{r}^2}{\alpha}\cos\left(\frac{r}{\alpha}\right) - \ddot{r}\sin\left(\frac{r}{\alpha}\right) \\ \frac{-\dot{r}^2}{a}\sin\left(\frac{r}{\alpha}\right) + \ddot{r}\cos\left(\frac{r}{\alpha}\right) \\ 0 \end{bmatrix}$

(v) **Orientation Planning**

After determining position, velocity and acceleration of end effector, evaluate the time sequence of the orientations of end-effector.

Q24. Explain about the considerations involved in joint-interpolated trajectories.

Answer :

Considerations Involved in Joint-interpolated Trajectories

The manipulator of the robot arm is servoed, only when the starting and ending positions of the arm are specified. The following considerations are involved in joint-interpolated trajectories,

(a) An object is selected and picked up in such a way that, the hand crash with the object surface is avoided.

(b) When a lift-off position is defined along the surface normal vector and object is moved along this position, valid lift-off motion is attained. The speed of lifting the object is also controlled by defining the time required for its motion.

(c) Similar to lift-off specifications, set-down positions for the object are also defined to obtain exact direction of motion.

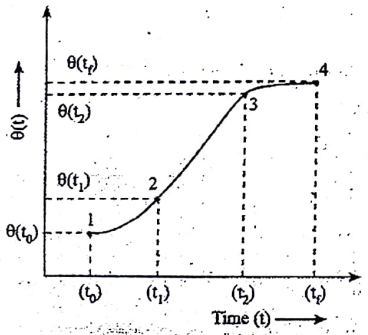
(d) Thus, the arm motion comprises of four positions. They are,

(i) Initial position-1

(ii) Lift-off position-2

(iii) Set-down position-3

(iv) Final position-4.



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These positions are shown in the graph, plotted between time and position of the object.

(e) Each position of the arm motion has certain constraints, such as,

Initial position : Velocity = 0 and acceleration = 0

Lift-off position : Path points possess continuous path motion

Set-down position : Similar to lift-off position i.e., path points have continuous path motion.

Final position : Velocity = 0 and acceleration = 0

(f) The maximum positions of each joint trajectory should be within the specified limits (physical and geometric limits).

(g) For initial and final positions, time depends on motion of the hand towards or away from the object surface and it is taken as fixed constant, as per the standards of joints.

For path points, time depends on extreme values of velocity and acceleration of the joints. Since, time is baseed on velocity and acceleration, the maximum time value is considered.

Q25. Differentiate between path planning and trajectory planning.

Answer : Model Paper-IV, Q6(a)

Differences between path planning and trajectory planning.

	Path Planning		Trajectory Planning
1.	Path planning technique involves the geometrical motion of the robot manipulator in joint space.	1.	Trajectory planning technique involves the kinematic motion of each point in the path, as function of time.
2.	The input for path planning is description of the task.	2.	The inputs for trajectory planning is path description, path constraints and constraints due to manipulator dynamics.
3.	Path planning is mostly used in automation.	3.	It is mostly applicable for industrial robots.
4.	It defines the initial and final points, as well as the intermediate points of a path.	4.	It defines different motion trajectories, necessary for trajectory planning.
5.	It is based on environmental information like position, co-ordiante value, etc, for determining motion start and end points.	5.	In this, the segments of trajectory are determined using an algorithm, to represent motion start and end points.
6.	It involves less computations.	6.	It involves more computations.
7.	It is the initial stage of motion planning.	7.	It is the subsequent stage of motion planning.
8.	Velocities and accelerations are not taken into consideration.	8.	Velocities and accelerations are taken into consideration.

Q26. What are the different types of motion that a robot manipulator can make in travelling from point to point? Explain.

Answer : [Nov.-10, Set-2, Q8(a)] [Model Paper-I, Q2(b)]

The different types of motion that a robot manipulator can make in travelling from point to point are,

1. Slew motion
2. Joint interpolated motion
3. Straight line motion.

1. Slew Motion

It is the most simple type of motion. In this, the robot manipulator when instructed to travel from one point to other point, it moves very fastly, thus, all the joint axes undergoes motion at same time, but, each axis stops after some elapsed time. This motion can cause high wear of joints. It is also called simultaneous full speed motion.

The main disadvantages of this motion are, the power utilization is more compared to other motions and smooth trajectories cannot be obtained.

2. Joint-Interpolated Motion

In this type, all the joints of the manipulator start and stop moving at the same time. In order to travel from point to point, the angular motion of each joint should be proportional to the angular distance moved by the joint. Smooth trajectory motion is possible in joint-interpolated motion.

The disadvantages of this type of motion are, it requires specified speeds to achieve motion in minimum time interval and greater computational overheads than slew motion.

3. Straight-line Motion

In this type, the robot travels from one point to other i.e., between the initial and final positions, along a straight line or path. This motion of tool becomes difficult at the boundary locations of the workspace and results in irregular type of motion. In this type, the tool moves only in straight line path, in a space.

Q27. Discuss about motion interpolation.

Answer :

A variety of motion interpolation schemes are available to enable a manipulator to follow a trajectory (time course along a path). For example, an improvement is possible, by using splines of lower order polynomials instead of higher order polynomials.

Robot motion is specified as a Cartesian trajectory of its end-effector. For executing the end effector trajectory, certain points on the trajectory is used to generate joint trajectories.

Based on inverse kinematic solution, interpolation algorithms are used for robot trajectory control. The fundamental interpolation algorithms are based on straight line motion and circular motion.

Straight Line Interpolation

Figure below shows the interpolation algorithm,

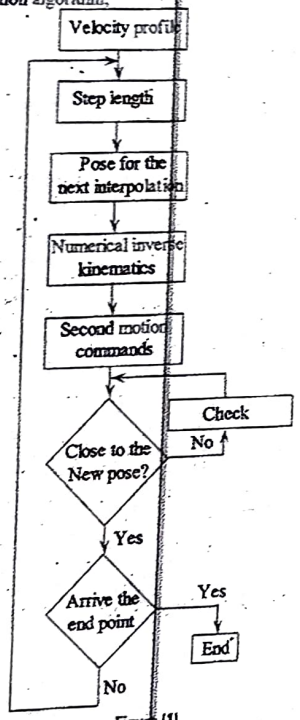


Figure (1)

The representation of interpolation and command points is,

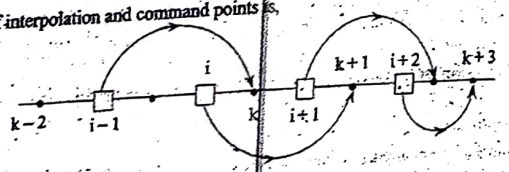


Figure (2)

Where,

k – The k^{th} interpolation

i – Sending the i^{th} motion command.

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Q28. Explain a 3-5-3 trajectory plan to represent a pick and place movement for an assembly operation.

Answer :

In planning of manipulator trajectories, each joint of robot has the following three trajectory segments, the first segment is a three-degree polynomial specifying the trajectory from the initial position to the lift-off position. The second trajectory segment (or mid-trajectory segment) is a five-degree polynomial specifying the trajectory from the lift-off position to the set-down position. The last trajectory segment is a three-degree polynomial specifying the trajectory from the set down position to the final position.

First Trajectory Segment

$$h_1(t) = \left[\delta_1 - V_0 t_1 - \frac{a_0 t_1}{2}\right] t^3 + \left[\frac{a_0 t_1^2}{2}\right] t^2 + (V_0 t_1) t + \theta_0$$

$$V_1 = \frac{h_1(1)}{t_1} = \frac{3\delta_1}{t_1} - 2V_0 - \frac{a_0 t_1}{2}$$

$$a_1 = \frac{h_1(1)}{t_1^2} = \frac{6\delta_1}{t_1^2} - \frac{6V_0}{t_1} - 2a_0$$

Second Trajectory Segment

$$h_2(t) = \left[6\delta_2 - 3V_1 t_2 - 3V_2 t_2 - \frac{a_1 t_2^2}{2} + \frac{a_2 t_2^2}{2}\right] t^5 + \left[-15\delta_2 + 8V_1 t_2 + 7V_2 t_2 + \frac{3a_1 t_2^2}{2} - a_2 t_2^2\right] t^4 +$$

$$\left[10\delta_2 - 6V_1 t_2 - 4V_2 t_2 - \frac{3a_1 t_2^2}{2} + \frac{a_2 t_2^2}{2}\right] t^3 + \left[\frac{a_1 t_2^2}{2}\right] t^2 + (V_1 t_2) t + \theta_1$$

$$V_2 = \frac{h_2(1)}{t_2} = \frac{3\delta_n}{t_n} - 2V_f + \frac{a_f t_n}{2}$$

$$a_2 = \frac{h_2(1)}{t_2^2} = -\frac{6\delta_n}{t_n^2} + \frac{6V_f}{t_n} - 2a_f$$

Last Trajectory Segment

$$h_n(t) = \left[\delta_n - V_f t_n + \frac{a_f t_n^2}{2}\right] t^3 + (-3\delta_n + 3V_f t_n - a_f t_n^2) t^2 + \left[3\delta_n - 2V_f t_n + \frac{a_f t_n^2}{2}\right] t + \theta_2$$

Q29. An articulated robot (RRR) is to move all three axes so that the first joint is rotated through 45°, the second joint is rotated through 60° and the third joint is rotated through 45°. Maximum speed of any rotational joints is 15°/s. Ignore effects of acceleration and deceleration.

(i) Determine the time required to move each joint if skew motion is used.

(ii) Determine the time required to move the ram to the desired position and the rotational velocities of each joint, if joint interpolation motion is used.

Answer : [May/June-14, Set-4, Q5(a) | Model Paper-I, Q5]

Given that,

Joint-1 is rotated through 45°

Joint-2 is rotated through 60°

Joint-3 is rotated through 45°

Maximum speed = 15°/s.

(i) Time Required to Move each Joint if Skew Motion is Used

Joint-1 will complete its move in 45° max. speed,

$$= \frac{45^\circ}{(15^\circ/s)} = 3 \text{ sec}$$

Joint-2 will complete its move in $\frac{60°}{(15°/s)} = 4$ sec.

Joint-3 will complete its move in $\frac{45}{(15°/s)} = 3$ sec

(ii) **Time Required if Joint-Interpolation Motion is Used**

Joint-2 has the longest distance to travel and hence it requires maximum time to complete its move.

The time for joint-2 to travel the 60° is $\frac{60°}{(15°/s)} = 4$ sec.

Velocity for joint-1 is $\frac{45°}{4} = 11.25°/sec.$

For joint-3, the velocity is $\frac{45°}{4} = 11.25°/sec.$

And, for joint-2, the velocity is, $\frac{60°}{4} = 15°/sec.$

Q30. For a three degree of freedom, cylindrical manipulator, design a linear trajectory with parabolic blends. The initial position of the end-effector is expressed by homogeneous matrix T_s and the goal position by T_g as,

$$T_s = \begin{bmatrix} 0 & 1 & 0 & 200 \\ 1 & 0 & 0 & 100 \\ 0 & 0 & -1 & -100 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad T_g = \begin{bmatrix} 1 & 0 & 0 & -50 \\ 0 & -1 & 0 & 200 \\ 0 & 0 & 0 & 400 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Answer :

Given that,

$$T_s = \begin{bmatrix} 0 & 1 & 0 & 200 \\ 1 & 0 & 0 & 100 \\ 0 & 0 & -1 & -100 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{... (1)}$$

$$T_g = \begin{bmatrix} 1 & 0 & 0 & -50 \\ 0 & -1 & 0 & 200 \\ 0 & 0 & 0 & 400 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{... (2)}$$

Consider the known position and orientation of the end point of arm given by,

$$T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ r_{41} & r_{42} & r_{43} & r_{44} \end{bmatrix} \quad \text{... (3)}$$

For the matrix T_s to obtain three unknown joint variables (i.e., θ_1^s, θ_2^s and d_3^s). Equate matrices (1) and (3), we get,

$$\begin{bmatrix} 0 & 1 & 0 & 200 \\ 1 & 0 & 0 & 100 \\ 0 & 0 & -1 & -100 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ r_{41} & r_{42} & r_{43} & r_{44} \end{bmatrix}$$

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Then, $\theta_1^s = A\tan 2(-r_{24}, -r_{14})$

$$\therefore \quad q_1^s = \theta_1^s = \tan^{-1}\left(\frac{-r_{24}}{-r_{14}}\right)$$

$$= \tan^{-1}\left(\frac{-100}{-200}\right)$$

$$= 26.565 \simeq 27°$$

$$\theta_2^s = A\tan 2\left(+\sqrt{r_{14}^2 + r_{24}^2}, r_{34}\right)$$

$$\therefore \quad q_2^s = \theta_2^s = \tan^{-1}\left(\frac{\sqrt{r_{14}^2 + r_{24}^2}}{r_{34}}\right)$$

$$= \tan^{-1}\left(\frac{\sqrt{200^2 + 100^2}}{-100}\right)$$

$$= -66°$$

$$q_3^s = d_3^s = \sqrt{r_{14}^2 + r_{24}^2 + r_{34}^2}$$

$$= \sqrt{200^2 + 100^2 + (-100)^2}$$

$$= 244.9 \simeq 245 \text{ m}$$

For the matrix T_g to obtain three unknown joint variables i.e., θ_1^g, θ_2^g and d_3^g, equate matrices (2) and (3),

$$\begin{bmatrix} 1 & 0 & 0 & -50 \\ 0 & -1 & 0 & 200 \\ 0 & 0 & 0 & 400 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} \\ r_{21} & r_{22} & r_{23} & r_{24} \\ r_{31} & r_{32} & r_{33} & r_{34} \\ r_{41} & r_{42} & r_{43} & r_{44} \end{bmatrix}$$

Then, $\theta_1^g = A\tan 2(-r_{24}, -r_{14})$

$$\therefore \quad q_1^g = \theta_1^g = \tan^{-1}\left(\frac{-r_{24}}{-r_{14}}\right)$$

$$= \tan^{-1}\left(\frac{-200}{-(-50)}\right) = -76°$$

$$q_2^g = \theta_2^g = \tan^{-1}\left(\frac{-\sqrt{r_{14}^2 + r_{24}^2}}{r_{34}}\right)$$

$$= \tan^{-1}\left(\frac{-\sqrt{(-50)^2 + (200)^2}}{400}\right) = -27°$$

$$\therefore \quad q_3^g = d_3^g = \sqrt{r_{14}^2 + r_{24}^2 + r_{34}^2}$$

$$= \sqrt{(-50)^2 + 200^2 + 400^2}$$

$$= 450 \text{ m}$$

For linear trajectory with parabolic blends, evaluate default acceleration for each link to satisfy the constraints i.e.,

$$\ddot{q}^c \geq \frac{4(q^g - q^s)}{t_g^2} \quad [\text{Where, } \ddot{q}^c \neq 0] \quad \text{... (4)}$$

Assume, $t_g = 5$ sec.

For link 1, substitute values of q_1^g and q_1^s in equation (4),

$$\ddot{q}_1^c \geq \frac{4(q_1^g - q_1^s)}{t_g^2}$$

$$\ddot{q}_1^c \geq \frac{4(-76 - 27)}{(5)^2} \geq -16.48 \text{ deg/s}^2$$

$$\therefore \quad \ddot{q}_1^c \equiv -17 \text{ deg/s}^2$$

For link 2, substitute values of q_2^g and q_2^s,

$$\ddot{q}_2^c \geq \frac{4(-27 - (-66))}{(5)^2}$$

$$= 6.24 \text{ deg/s}^2$$

$$\ddot{q}_2^c \equiv 7 \text{ deg/s}^2$$

For link 3, substitute values of d_3^g and d_3^s,

$$\ddot{q}_3^c \geq \frac{4(450 - 245)}{(5)^2}$$

$$\ddot{q}_3^c \geq 32.8 \text{ deg/s}^2$$

Take, $\ddot{q}_3^c \equiv 33 \text{ deg/s}^2$

The trajectory for each link is computed using blend duration formula as,

Blend duration,

$$t_{b_1} = \frac{1}{2}t_g - \frac{1}{2}\sqrt{\frac{t_g^2\dot{q}_1^c - 4(q_1^g - q_1^s)}{\ddot{q}_1^c}} \quad \text{... (5)}$$

$$t_{b_1} = \frac{1}{2}(5) - \frac{1}{2}\sqrt{\frac{(5)^2(-17) - 4(-76 - 27)}{-17}}$$

$$t_{b_1} = 2.06 \text{ sec.}$$

To design a linear trajectory with parabolic blends a sequence of polynomial for the time history of joint position, velocity and acceleration is to be determined, by considering t_b and t_g values, as illustrated below,

Joint position,

$$q(t) = \begin{cases} q^s + \frac{1}{2}\ddot{q}^c t^2 & ;if\ 0 \le t \le t_b \\ q^s - \frac{1}{2}\ddot{q}^c t_b^2 + \ddot{q}^c t_b t & ;if\ t_b < t \le t_g - t_b \\ q^g - \frac{1}{2}\ddot{q}^c (t_g - t)^2 & ;if\ t_g - t_b < t \le t_g \end{cases} \quad \ldots (6)$$

For link 1,

$q_1^s = 27°$, $\ddot{q}_1^c = -17$ deg s^2, $t_b = 2.06$ sec, $q_1^g = -76°$, $t_g = 5$ sec

Joint position, $q_1(t) = \begin{cases} 27 + \frac{1}{2}(-17)t^2 & ;if\ 0 \le t \le 2.06 \\ 27 - \frac{1}{2}(-17)(2.06)^2 + (-17)(2.06)t & ;if\ 2.06 < t \le 5 - 2.06 \\ -76 - \frac{1}{2}(-17)(5-t)^2 & ;if\ 5 - 2.06 < t \le 5 \end{cases}$

$$q_1(t) = \begin{cases} 27 - 8.5t^2 & ;if\ 0 \le t \le 2.06 \\ 63 - 35.02t & ;if\ 2.06 < t \le 2.94 \\ -76 + 8.5(5-t)^2 & ;if\ 2.94 < t \le 5 \end{cases}$$

For link 2,

$q_2^s = -66°$

$\ddot{q}_2^c = 7$ deg/s^2

$q_2^g = -27°$

$t_g = 5$ sec

t_{b_2} is calculated using equation (5), as,

$$t_{b_2} = \frac{1}{2}(5) - \frac{1}{2}\sqrt{\frac{(5)^2(7) - 4(-27-(-66))}{7}}$$

$t_{b_2} = 1.676 \cong 1.68$ sec.

Substituting in equation (6),

Joint position,

$$q_2(t) = \begin{cases} -66 + \frac{1}{2}(7)t^2 & ;if\ 0 \le t \le 1.68 \\ -66 - \frac{1}{2}(7)(1.68) + (7)(1.68)t & ;if\ 1.68 < t \le 5 - 1.68 \\ -27 - \frac{1}{2}(7)(5-t)^2 & ;if\ 5 - 1.68 < t \le 5 \end{cases}$$

$$\therefore\ q_2(t) = \begin{cases} -66 + 3.5t^2 & ;if\ 0 \le t \le 1.68 \\ -71.88 + 11.76t & ;if\ 1.68 < t \le 3.32 \\ -27 - 3.5(5-t)^2 & ;if\ 3.32 < t \le 5 \end{cases}$$

For link 3,

$q_3^s = 245$ m

$\ddot{q}_3^s = 33$ deg/s^2

$q_3^g = 450$ m

$t_g = 5$ sec

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t_{b_3} is calculated using equation (5), as,

$$t_{b_3} = \frac{1}{2}(5) - \frac{1}{2}\sqrt{\frac{(5)^2 \times 33 - 4(450-245)}{33}}$$

$t_{b_3} = 2.305$

$\simeq 2.31$ sec

Substitute in equation (6),

Joint position, $q_3(t)$

$$= \begin{cases} 245 + \frac{1}{2}(33)t^2 & ;if\ 0 \le t \le 2.31 \\ 245 - \frac{1}{2}(33)(2.31)^2 + (33)(2.31)t & ;if\ 2.31 < t \le 5 - 2.31 \\ 450 - \frac{1}{2}(33)(5-t)^2 & ;if\ 5 - 2.31 < t \le 5 \end{cases}$$

$$\therefore\ q_3(t) = \begin{cases} 245 + 16.5t^2 & ;if\ 0 \le t \le 2.31 \\ 156.95 + 76.23t & ;if\ 2.31 < t \le 2.69 \\ 450 - 16.5(5-t)^2 & ;if\ 2.69 < t \le 5 \end{cases}$$

Velocity for all the three links is calculated by,

$$\dot{q}(t) = \begin{cases} \ddot{q}^c t & ;if\ 0 \le t \le t_b \\ \ddot{q}^c t_b & ;if\ t_b < t \le t_g - t_b \\ \ddot{q}^c (t_g - t) & ;if\ t_g - t_b < t \le t_g \end{cases}$$

For link1, by equation (7),

$$\dot{q}_1(t) = \begin{cases} -17t & ;if\ 0 \le t \le 2.06 \\ -17 \times 2.06 & ;if\ 2.06 < t \le 5 - 2.06 \\ -17(5-t) & ;if\ 5 - 2.06 < t \le 5 \end{cases}$$

$$\dot{q}_1(t) = \begin{cases} -17t & ;if\ 0 \le t \le 2.06 \\ -35 & ;if\ 2.06 < t \le 2.94 \\ -17(5-t) & ;if\ 2.94 < t \le 5 \end{cases}$$

For link 2, by equation (7),

$$\dot{q}_2(t) = \begin{cases} 7t & ;if\ 0 \le t \le 1.68 \\ 7 \times 1.68 & ;if\ 1.68 < t \le 5 - 1.68 \\ 7(5-t) & ;if\ 5 - 1.68 < t \le 5 \end{cases}$$

$$\dot{q}_2(t) = \begin{cases} 7t & ;if\ 0 \le t \le 1.68 \\ 11.76 & ;if\ 1.68 < t \le 3.32 \\ 7(5-t) & ;if\ 3.32 < t \le 5 \end{cases}$$

For link 3, by equation (7),

$$\dot{q}_3(t) = \begin{cases} 33t & ;if\ 0 \le t \le 2.31 \\ 33 \times 2.31 & ;if\ 2.31 < t \le 5 - 2.31 \\ 33(5-t)^2 & ;if\ 5 - 2.31 < t \le 5 \end{cases}$$

$$\dot{q}_3(t) = \begin{cases} 33t & ;if\ 0 \le t \le 2.31 \\ 76.23 & ;if\ 2.31 < t \le 2.69 \\ 33(5-t)^2 & ;if\ 2.69 < t \le 5 \end{cases}$$

Acceleration for all the three links is calculated by,

$$\text{Acceleration } \ddot{q}(t) = \begin{cases} \ddot{q}_3^c & ; if\ 0 \le t \le t_b \\ 0 & ; if\ t_b < t \le t_g - t_b \\ -\ddot{q}_3^c & ; if\ t_g - t_b < t \le t_g \end{cases} \quad \ldots (8)$$

For link 1, by equation (8),

$$\ddot{q}_1(t) = \begin{cases} -17 & ; if\ 0 \le t \le 2.06 \\ 0 & ; if\ 2.06 < t \le 2.94 \\ 17 & ; if\ 2.94 < t \le 5 \end{cases}$$

For link 2, by equation (8),

$$\ddot{q}_2(t) = \begin{cases} 7 & ; if\ 0 \le t \le 1.68 \\ 0 & ; if\ 1.68 < t \le 3.32 \\ -7 & ; if\ 3.32 < t \le 5 \end{cases}$$

For link 3, by equation (8),

$$\ddot{q}_3(t) = \begin{cases} 33 & ; if\ 0 \le t \le 2.31 \\ 0 & ; if\ 2.31 < t \le 2.69 \\ -33 & ; if\ 2.69 < t \le 5 \end{cases}$$

5.3 ROBOT PROGRAMMING, LANGUAGES AND SOFTWARE PACKAGES, DESCRIPTION OF PATHS WITH A ROBOT PROGRAMMING LANGUAGE

Q31. What are the basic elements of the robot language? Explain.

Answer : [Nov.-10, Set-2, Q6(b) | Model Paper-III, Q2(b)]

The basic elements of the robot language are,

1. Constants and variables
2. Motion commands
3. End effector and sensor commands
4. Computations and operations
5. Program control and subroutines
6. Monitor mode commands
7. Data processing and communication

1. Constants and Variables

Constant is defined as a value used in the program. During the execution of program, constants does not vary or changes its value. Variable is defined as a parameter that alters its value while executing the program.

Constants and variables can be real numbers, integers, decimals or strings, etc.

The computer systems on which the language is being implemented can give a wide range of the values for numerical constants and variables.

2. Motion Commands

Controlling the movement of the manipulator arm is the significant function in a robot language. The motion commands includes,

(i) Move and related statements

(ii) Speed control

(iii) Definition of points in the workspace

(iv) Path and frames.

The motion commands describes the position, speed and path of the robot's arm.

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3. End Effector and Sensor Commands

End effector and sensor commands are used to initiate the robots arm and control the motions as per the required operations. End effector and sensor commands includes,

(i) End effector operation

(ii) Sensor operations and

(iii) React statement.

4. Computations and Operations

In the robot programming, arithmetic computations and other operations have to be manipulated on constants, variables and other data objects.

In the second generation language the mathematical operators includes,

Addition (+)

Subtraction (–)

Multiplication (×)

Division (/)

Exponential (**)

Equal to (=)

5. Program Control and Subroutines

When the statements of the robot program are executed by using the subroutines and branches, controlling the program is necessary on the program's sequence to obtain the desired task. Program control and subroutines includes program sequence control commands and instructions.

6. Monitor Mode Commands

These commands in the programm are meant to carry out the following functions or activities,

- Define locations
- Load a particular register
- Store information in the memory
- Save or transfer programs from storage into computer control memory.

7. Data Processing and Communication

The robot system communicate with the operator or other computer based system with the help of a device called cathode ray tube (CRT).

This communication allows robot system to request information from the operator and to inform the operator about its work. The interaction of the operator with the system allows the preparation and editing of programs.

Q32. Discuss the characteristics of robot level languages.

Answer : [Nov.-10, Set-1, Q5(b)]

The characteristics of robot level languages are as follows,

1. Position specification
2. Motion specification
3. Sensing and flow of control.

1. Position Specification

Coordinate frame is the common method used for describing the orientation and position of the objects in the workspace. This frame consists of 3×3 sub-matrix, which specifies the orientation and a vector specifies the position of the objects. It is represented as 4×4 homogeneous transformation matrix.

The robot languages AL and AML are used for programming. The predefined structures for frames (FRAME), rotational matrices (ROT) and vectors (VECTOR) are provided by the language AL. The configuration of the base is defined as shown in the example below.

Example

base ← FRAME(nilrot, VECTOR(20, 0, 15) * inches)

General structure known as aggregate is provided by the language AML. The configuration of the base in AML language is defined as shown below,

Example

base = << 20, 0, 15>, EULERROT (<0, 0, 6>)>

2. Motion Specification

Robots while performing an operation need to move from an initial configuration to a final configuration. However, just specifying initial and final configuration of the robot is not acceptable. The path along which robot moves between its initial and final configuration should be planned considering the objects and obstacles present in its workspace. Thus, to ensure a collision free path, enough intermediate points (also called as via points) must be provided by the programmer. The intermediate points or positional goals provide a safe path and are specified in joint-variable space or in Cartesian space, depending on the language. However, specification of this type needs the programmer to preplan the entire motion and select suitable intermediate points. A complex path to be described as a sequence of intermediate points leads to a long program.

3. Sensing and Flow Control

In robot-oriented language type of programming, an assembly task is explicitly described as a sequence of robot motions. The robot is guided and controlled by the program through the entire task with each statement of program corresponding to one action of the robot.

A robot-oriented language is difficult to use, because it requires the user to program each detailed robot motion for completing a task.

Its characteristics are,

(i) Supports data aggregation

(ii) Provides absolute and relative motions

(iii) Provides sensor monitoring, that can interrupt motion

(iv) Supports features of LISP-like and APL-like constructs

(v) Provides environment, where different user-interface can be built.

Q33. What are characteristics of task-level programming languages?

Nov.-11, Set-2, Q8(a)

Answer :

The characteristics of robot task-level languages are,

1. Robot task-level languages relate to the third level of robot programming methodology.
2. The task-level language helps the user in direct commanding the preferred subgoals of the task. Thus, reducing the work load of the user.
3. Task specification in a high-level language is provided by the task-level programming system.
4. The task level robot programming system must be able to perform large number of planning operations.
5. It describes the assembly task as sequence of positional goals of the objects, rather than the motions of the robot needed to achieve the goals.
6. In this type of programming, no explicit motion is specified.
7. In this system, when the user provides the input-output requirements of a desired program, the generation of the program is accomplished by the generator simultaneously. Thus, producing the expected input or output behaviour.

Q34. What are the features and capabilities of structured programming languages? Explain.

Answer :

Structured programming languages in robotics manipulates through the use of sensors and communication paths. Some of the programming languages are WAVE, RAIL, MCL, RPL, PAL, HELP, AL, VAL and ADA etc.

Measures and Capabilities

1. Structured programming languages are developed for the easier control of motion of robots having different structures and geometrical capabilities.
2. These provides flexibility to the user in defining the task to be performed.
3. These provide a more general approach in solving the human-robot communication problems.
4. This type of programming languages allow robots to operate in spatially complex environment.
5. It possess a small memory space to record angular positions.
6. These languages enables data aggregation.
7. It also allows world modeling.
8. They provide absolute and relative motions to end effector
9. They possess sensor monitoring feature, that can interrupt motion at any instant, etc.

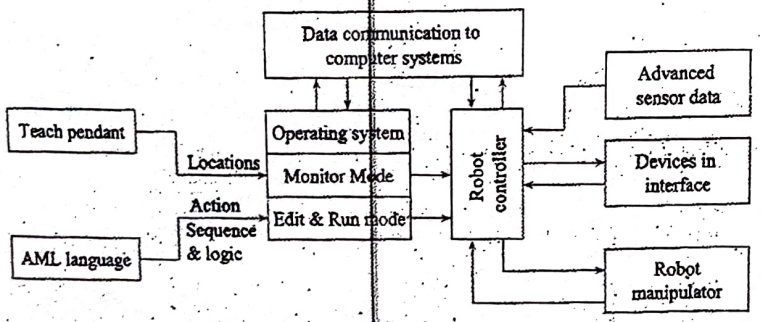
Q35. Discuss about AML language and its structure.

Answer :

A Manufacturing Language (AML)

An AML is a structured programming language and possess structured control features used in programming. The different features of this language are motion control, data processing and communication, sensor capabilities, etc. The locations in the work envelope are usually defined by a teach pendant. The structure of AML language is shown below.

Structure



Figure

The operating system provides a means of writing, storing, editing and executing a program and also for performing various other functions. The three different modes in an operating system are monitor mode, edit mode and run mode. The monitor mode is used for controlling and supervising the robot. The edit mode and run mode enables the editing and execution of program resulting in desired robot action.

Q36. Explain the REACT statement of robot languages, which is used to monitor an incoming signal and to respond to a change in the signal.

Answer :

REACT Statement

This statement is used in continuous monitoring of an incoming signal and to respond to a change in the signal in an appropriate manner. It illustrates various types of commands, that are used in order to interrupt regular execution of the robot program in case of a high priority event i.e., when some form of error or safety hazard occurs in the work cell, which is detected by the sensor. When the incoming signal which is normally expected to stay within limits for safer operation of the cell crosses limits, the regular execution of the program must be interrupted. REACT is the statement, that facilitates in interrupting the system, by transferring the control from one level to another level i.e., to a subroutine.

A typical REACT statement is shown below,

REACT 15, SAFETY.

The above statement instructs the controller that the input line 15 should be continuously monitored and in case of a change in signal value, the control should be branched to a subroutine called SAFETY.

Q37. What are the different types of robotic programming techniques? Explain.

Answer : [May/June-14, Set-4, Q8(a) | Model Paper-IV, Q7(b)]

Methods of Robot Programming

Robot programming methods are classified into three types. They are,

1. Physical setup or manual programming method
2. Teach mode programming method
3. Teach by showing program method.

1. Physical Setup or Manual Programming Method

In this method, the robot is controlled manually i.e., an operator is responsible to set up the program. Components such as switches, cams stops, control relays etc., of a robot to be controlled are fixed or set by the operator. The robots operated by this method are used for pick and place, loading and unloading of objects.

2. Teach Mode Programming Method

In this method, the robot is guided as per the requirement of the operator. The controller is interfaced with a teach box and a teach pendant, which are essential to lead the robot to various locations. The angular positions of the manipulator are recorded in digitalized format, to obtain smooth trajectory and the instructed motions are recorded in the form of coordinates during the operation. The controller memory stores the position of each joint of the robot as it reaches the desired location. The recorded position of each joint can be edited as per the requirements.

Teaching of a robot involves the movement of each its single joint separately in such a manner that, the combinatio of all the arm positions gives the required end effector positio

3. Teach by Showing Program Method

In this method, the operator uses a detachable grip handle to lead the robot and while operating a robot, the sequence of operations related to the trajectories and programmes involving various auxiliary commands like motion speed, input handling gripper in and out, etc., are entered into a teach pendant which is connected to a controller. It uses a high level language similar to operators language, which allows the operator to edit and write the programs in it. Programs fed in a computer are transmitted to a robotic controller by means of a cable connection.

Offline programming mainly depends upon an explicit programming language, wherein the program is handled using motion oriented commands. It also depends on a world modeling language, which enable the programmer to handle the given task easily, as it describes the task with a problem oriented description.

Q38. Discuss the following methods of robot programming.

(i) Lead through teaching

(ii) Walk through teaching

(iii) Off-line programming.

Answer :

(i) Lead through Teaching

(a) Powered Lead Through

Powered lead through is the common programming method for playback robots with point to point control. In this method, various joint motors having toggle switches or contact buttons, controlling the movement of the manipulator joints are controlled by a hand held control box.

The toggle switches are used by the programmer for moving the robot arm to the desired positions in sequential order. These positions are recorded into the memory. During the next playback, the robot moves through the sequence of positions by itself.

(b) Manual Lead Through

Manual lead through method is suitable for a continuous path programming, where the continuous path is an a regular motion pattern, such as in spray painting.

In this method, the programmer physically grasps the tools attached to the arm and manually moves it through the motion sequence. This arm movement is recorded into the memory. The robot arm possesses large mass and it is physically difficult to move, therefore the actual robot is replaced by a special programming device for the teach procedure. But, the programming device has the same geometry as the robot. The programming device has a provision for a trigger handle or other control switch which are activated, when the motions are to be recorded into memory, by the operator. The motions are recorded in a sequence of closely spaced points. Through the same sequence of points, the path during the playback is recreated by controlling the actual robot arm.

(ii) **Walk Through Teaching**

In walk through teaching, the operator has a physical contact with the robot arm. The operator controls and walks with the robot's arm in desired positions within the robot's working area. The robot's controller scans and stores the co-ordinate values on a fixed-time interval basis. The coordinate values and other functional data are replayed in the automatic mode. Replaying may be done in various speeds, than that used in walk-through.

This method uses triggers on manual handles to move the robot. When the trigger is lowered or held down, the controller memorizes the position. As the program is played, the controller generates the movement between the points. The walk through teaching requires the operator to be within the working area along with the robot's controller. In this method, the operator is in an unsafe position, as the safeguarding devices are deactivated.

(iii) **Off-line Programming**

In off-line programming, the computers are positioned away from the robot area and a simulation software is used to generate data. The data is then sent to the robot's controller, where it is converted into instructions. This software also contains a modelling data, which helps in the selection of the best robot configuration for certain applications.

The main advantages of off-line programming is that, the production is not interrupted, while creating a primary or modified program.

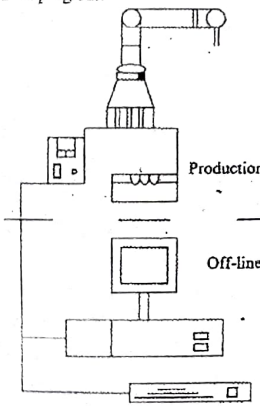


Figure: Off-line Programming

Q39. Explain the limitations of lead through programming.

Answer : Nov.-10, Set-4, Q5(b)

The limitations of lead through programming are,

1. At the time of programming of robots, they cannot be used in production.
2. It is difficult to integrate sensory feedback information into the control system, through this method of programming.
3. Due to increase in the difficulty of programming, the level of difficulty in accomplishment of lead through programming also increases.
4. With the modern computer based technologies like CAD/CAM, data communication and networking, lead through programming cannot be readily used.
5. The interfacing of robots to other computer based systems in the organizations leads to problems.
6. When robots are used for functioning in difficult areas, programming these functions becomes highly complex.
7. With the use this programming, the components of CIM systems will not be able to communicate with each other, as the lead through method restricts itself from communications.
8. The time to run the program is inversely proportional to the lot size, i.e., if the lot size decreases the time for running the program increases and vice-versa.

Q40. Explain the advantages and disadvantages of off-line programming method.

Answer :

Advantages of Off-line Programming

1. In off-line programming of robots, there is no effect on production, as the robots does not occupy the production equipment, during programming.
2. The programming is effective, resulting in well documented simulation of model.
3. Programming can be carried out, by utilization of previous CAD data.
4. Effective programming removes error from the robots.
5. By utilizing simulation and visualisation techniques, programs can be verified.
6. It is cost effective programming, in terms of production.
7. Welding tools can be selected instantly, by changing the parameters of programs.

Disadvantages of Off-line Programming

1. It requires highly skilled operators for high-level programming.
2. Off-line programming is an approximate technique and requires more calibrations.
3. Programming should be carried out in short time and efficiently.
4. This programming requires high initial cost.

Q41. A robot is to be programmed to unload parts from one pallet and load them onto another pallet. The parts are located on the unload pallet in a 3 by 4 pattern in known fixed positions, 40 mm apart in both directions. The two directions of the pallet are assumed to be parallel to the x and y world coordinate axes of the robot. The parts are to be placed on the load pallet to the x and y world coordinate axes of the robot. Make a sketch of the workstation setup before you begin programming.

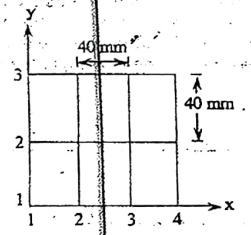
[April/May-13, Set-3, Q4 | Model Paper-I, Q7(a)]

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Answer :

Given that,

Distance between two rows and column = 40 mm



Figure

Consider the following variables and constants in the program,

Location Constants

CORNER : The starting point on pallet

PICK UP : The pickup point on chute.

Location Variables

DROP : Drop off point

Standard Variable

X - x-coordinate value

Y - y-coordinate value.

ROW - row number

COLUMN - column number.

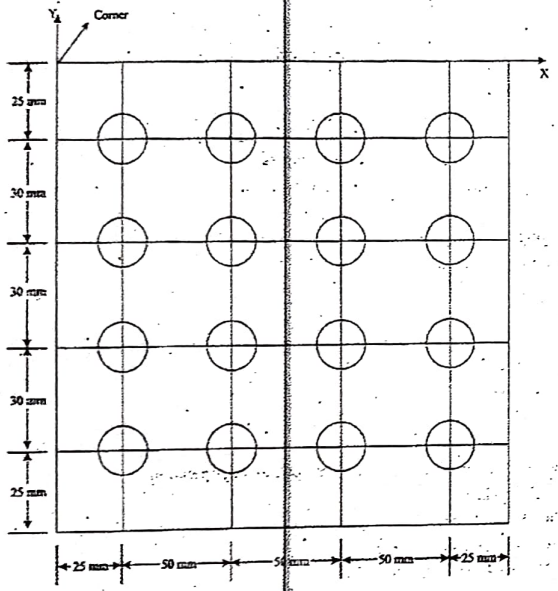
The following is the program, in order to perform the palletizing operation.

PROGRAM PALLETIZE
DEFINE PICKUP = JOINTS (1, 2, 3, 4)
DEFINE CORNER = JOINTS (1, 2, 3, 4)
DEFINE DROP = COORDINATES (x, y)
OPEN

VAL STATEMENT	DESCRIPTION
ROW = 0	Initialize ROW
10 Y = ROW*40.0	Compute 'y' for drop off point
COLUMN = 0	Initialize COLUMN
X = COLUMN * 40.0	Compute 'x' for drop off point
DROP = CORNER + <x, y>	Define DROP for each iteration
APPRO PICKUP,	40 PICK UP sequence
MOVES PICKUP	PICK UP sequence
CLOSE	PICK UP sequence
DEPART 40	PICK UP sequence
APPRO DROP, 40	Drop off sequence
MOVES DROP	Drop off sequence
OPEN	Drop off sequence
DEPART 40	Drop off sequence
COLUMN = COLUMN + 1	Increment column variable
IF COLUMN LT 4 GOTO 20	Check if column limit reached
ROW = ROW + 1	Increment ROW variable
IF ROW LT 3 GOTO 10	Check if ROW limit reached
END PROGRAM	End of program

Q42. In a pallet objects protruding 50 mm from the face of the pallet are located in a number of rows and columns. The pallet has 4 rows that are 30 mm apart and 4 columns that are 50 mm apart. The plane of the pallet is assumed to be parallel to the X-Y plane. The rows are parallel to X-axis and the columns are parallel to Y-axis. The objects are to be picked up one after another from the pallet and placed in a location chute. The robot end effector should stop at 70 mm above the pickup point as safe position. Gripper should hold the object at 30 mm from base. Write the program in VAL to pickup the object at left top corner moving towards y-axis and then moving to the next columns.

Answer :



Figure

Let, the pallet variables be denoted as follows,

ROW – Integer ROW count

COLUMN – Integer COLUMN count

X – Coordinate value along *x*-axis

Y – Coordinate value along *y*-axis.

Locational Variable

DROP– Point of dropping

Locational Constants

CORNER – Start of point in the pallet

Pick-up– Point of pick-up of objects

The pelletizing program in VAL is given as follows,

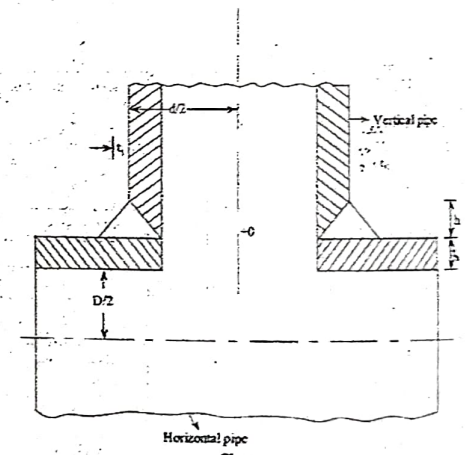
VAL Statement	Description of Statement
PROGRAM PALLETIZE	Start of program
DEFINE PICK-UP = JOINTS (1, 2, 3, 4, 5)	Definition of constants
DEFINE CORNER = JOINTS (1, 2, 3, 4, 5)	
DEFINE DROP = COORDINATES (X, Y)	Definition of variables
OPEN	Gripper action control to open fingers
ROW = 0	Initialize the row count.
10 Y = ROW*20	Computation of dropping point.

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COLUMN = 0	Initialise the column count
20 X = COLUMN × 20	Computation of drop off point.
DROP = CORNER + (X, Y)	Define drop for every iteration.
APPRO PICKUP, 20 –20, 70	Approach above pallet for pick-up.
MOVE PICK UP	Positioning pickup action.
CLOSE	
DEPART 0, 0, –30	Action sequence for arm to move away from pick-up position.
APPRO DROP, 30	Approach command to position above drop point.
MOVE DROP	Command to drop object.
OPEN	
DEPART 70	Move away from drop point.
COLUMN = COLUMN + 1	Column increment
IF COLUMN LT5 GO TO 20	
ROW = ROW + 1	ROW increment
IF ROW LT3 GO TO 10	ROW increment
MOVE PICK-UP –150, –30, 0	
END PROGRAM	End of program

Q43. A vertical hollow cylinder is to be welded to a horizontal hollow cylinder at right angles. The set up is CO_2 MIG welding interfaced with a robot controller. Describe the robot task and indicate the program for welding.

Answer :



Figure

Robot Task

A PUMA robot is used for execution of welding torch along the trajectory of weld. The robot cannot move its torch across the point, since the swivel of the robot is 320°. Thus, the program is prepared for 180°, so that the direction of rotation changes at each pass.

After completion of first layer weld, the torch is shifted along z-direction in order to reach the starting point of next layer. In the same way, each pass and layer are programmed and the robot follows the motion until all the layers are completed.

Weld Trajectory

The robot movement in x-direction is given by,

$$x_j = x_o - \left(\frac{d}{2} + \Delta, P_y\right) \cos\theta$$

Similarly, in y-direction,

$$y_j = y_o - \left(\frac{d}{2} + \Delta_r . P_v\right) \sin\theta$$

And, z-direction,

$$z_j = z_o + \left[\left(\frac{d}{2} + \Delta_r . l_v\right)^2 + \left(\frac{d}{2} + \Delta_r . P_v\right)^2 \sin^2\theta\right]^{\frac{1}{2}}$$

Where,

d – Diameter of vertical pipe

D – Diameter of horizontal pipe

l_v – Arbitrary layer number

P_v – Arbitrary pass number

Δ_r – Width of arbitrary pass

θ – Angle contained in vertical pipe

x_o, y_o, z_o – Coordinates at the intersection of vertical and horizontal pipe

x_j, y_j, z_j – Absolute coordinates.

Program

The VAL program for welding is a follows,

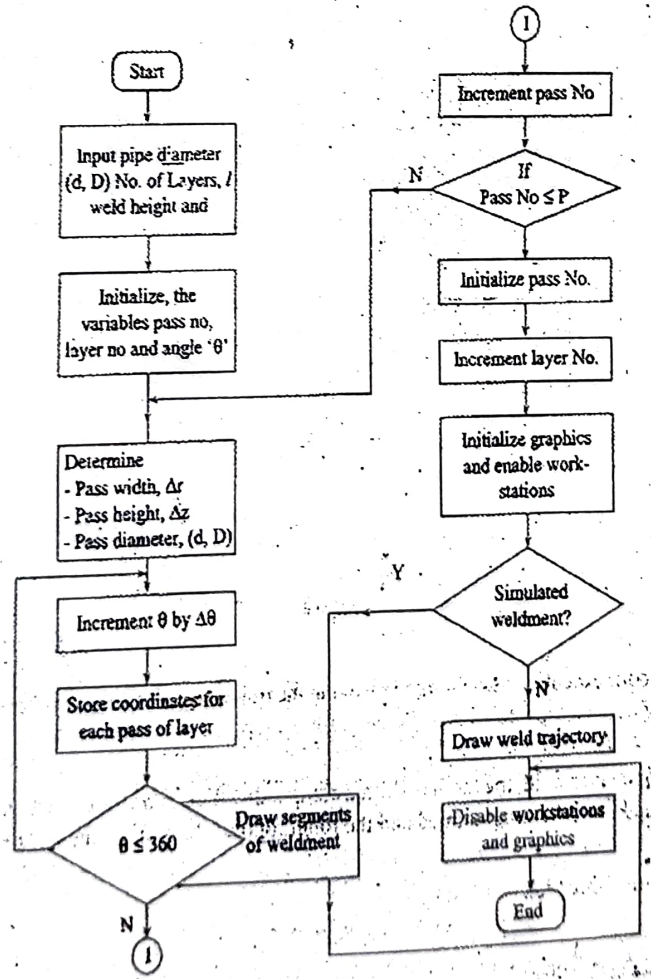


Figure: Flow Chart

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