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Implementation of Straight-Line Motion For 6 DOF Industrial Robot

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Abstract: This paper focuses on the trajectory planning for the Fanuc S-430iW industrial robot, a 6-axis robotic arm used in heavy-duty industries. This robot is highly efficient and accurate. For tasks that require greater precision, it is critical to form straight-line motion. The tasks include additive manufacturing, material handling, assembly, etc. These tasks have to be performed in the shortest time. Trajectory planning ensures the robot's smooth motion and avoids any unexpected accidents. The work produces trajectory planning for a straight line in 3D space, i.e., the shortest path between two points. The trajectory planning is carried out by deriving a quintic path equation for X, Y, and Z using the initial and final points of the trajectory and constraints. The quintic path is used to determine the position, velocity, and acceleration. Then, the variation in the joint variables for the path is determined by inverse kinematics for the time-space, position, and dimensions specified. The forward and inverse kinematics are employed in calculating joint variables along the path. The output shows the robot's smooth motion along the path. The velocity along all three axes increases and decreases smoothly. The advantages of the robot lie in the fact that it can be used for various applications. Execution and cycle time are important to increase production efficiency.

***Index Terms* -** Forward and inverse kinematics, Fanuc S-430iW, trajectory planning, additive manufacturing, precision, straight line path

I. INTRODUCTION

Industries use robots to perform repetitive tasks in applications such as factory assembly lines. Robots have a great advantage when it comes to automating various processes. The use of robots in the manufacturing industry enables faster cycle times and efficient production. The efficiency of the production due to the robot depends on factors like precision, workspace, path planning, etc… Even if the robots are versatile, it is not deployed in all cases due to constraints like cost, space, and the nature of the task. It has to perform tasks in a specified order in a well-defined environment [2]. Robots can also work in a smaller environment where humans cannot work. It can be used to transport goods from one place to another. Intelligent robots are being developed day by day. Hall and Hall [1985] have defined intelligent robots are ones that respond to environmental changes through their sensors connected to the controller [3]. It can be used to work in a wide range of fields such as taking care of assembly lines, conducting surgery, military operations, household cleaning, education, and therapy. It doesn't require any physical environment and can work in any environmental condition. Fanuc robots have lots of applications such as spot welding, arc welding, assembling, handling, sealing, deburring, etc. For controlling the kinematic models there are two methods forward and inverse kinematics [8]. Forward kinematics is used to control each joint precisely. It is simple to use and has better efficiency. The main advantage of forward kinematics is that it is good at predefining motions such as walking, running, or waving. As it does not depend on iterative methods or factors that are used externally it is more stable. Inverse kinematics allows us to specify the endpoint, which makes the animation part easy. It uses equations to make a robot reach a desired point. The advantages of inverse kinematics are that it can be used to create a more natural and dynamic movement, and the animation process can be simplified by reducing the number of parameters needed to be controlled. It is very useful for efficient motion solving. Path planning helps a robot to follow an obstacle-free and shortest path. It requires start and endpoints. There are a lot of path-planning algorithms such as trajectory optimization algorithms, sampling-based algorithms, grid-based algorithms, etc. It also adds autonomy in vehicles like self-driving cars, unmanned ground vehicles, and unmanned aerial vehicles. The path planning creates end effector motion. Trajectory planning is important to avoid collisions, create smooth motion, and control closed-loop motion. It makes the computations simple. Based on the performance measure they considered the control algorithm changes. Though this paper focuses on developing path planning, optimal control is another important factor when designing a robot. The straight-line path is the shortest path between any two points. So, a straight line in 3D space is considered. Beginning with the specs of the Fanuc S-430iW robot—a 135 kg payload, 2643 mm reach, and 0.3 mm repeatability—this work creates a linear trajectory path for one. In Section 3, we discuss inverse kinematics, which involves figuring out the required joint angles for a desired position. In Section 2, we calculate the end-effector's position based on joint angles. Making a linear path between two places in three-dimensional space is the main topic of the last section, which is called trajectory planning. For accurate, collision-free operation, this guarantees fluid, effective motion and makes control easier.

Fig.1 Fanuc S-430iW

II. 6 DOF INDUSTRIAL ROBOT SPECIFICATIONS

The Fanuc S-430iW is noted for having six degrees of freedom; thus, it makes highly complex movements in six axes that require precision. Its application has been proven best in various industrial practices that heavily require agility and accuracy. Since it has been designed to duplicate human arm movement, the S-430iW is apt to ace all dexterous tasks that come its way and is, therefore, a key contributor in major sectors such as automotive production, assembly, and material handling. It has a payload of 135 kg, which would enable it to lift even bigger parts or handle multiple small parts simultaneously. This often is of paramount importance in industries for productivity with efficiency and reliability. The large reach of the robot-2643 mm boosts working efficiency by giving easy access to every part of a manufacturing floor without requiring much repositioning. In addition, this also optimizes the workflow while offering minimal downtime, thus adding to productivity. The S-430iW offers the advantage of excellent repeatability at 0.3 mm, making it suitable for cutting and injection molding, machine tending, and even parts transmission applications requiring precision. It weighs in at a strong 1300 kg, which is one to withstand the demands of demanding harsh industrial environments to ensure consistent performance and durability. This model further led to highly advanced robotics, the Fanuc R-2000iA, which is destined to achieve even greater levels of efficiency in many industries. Subsequently, a company that has been at the forefront of offering robots is Fanuc, which has designed the S-430iW with features such as ease of programmability, low maintenance requirements, and high reliability. These benefits make it an essential machine for companies that want to mechanize their operations and expand. The S-430iW streamlines processes but also generates innovation for businesses to stay ahead of the game in such a highly mechanized environment. The below table shows the maximum speed and the minimum and maximum angle range for each joint of the robot.

Table 1 Joint speed and angle range

Joint	Motion	Maximum Speed (Degrees/sec)	Angle Range (Degrees)
1	Shoulder Rotation	150-200	-175 to 175
2	Shoulder Lift	120-160	-120 to 120
3	Elbow Bend	150-200	-150 to 150
4	Wrist Twist	360	0 to 360
5	Wrist Bend	150-200	-150 to 150
6	Wrist Roll	360	0 to 360

III. FORWARD KINEMATICS

The forward kinematics of Fanuc S-430iW are calculated using the Denavit-Hartenberg (DH) method to form the coordinate frame. There are 6 joints J1,J2,J3,J4,J5 and J6. In 1995, Denavit and Hartenberg proposed a matrix method to describe the translational and rotational relationships between the adjacent links to construct the coordinate system connected to each link in the robot's joint chains [1]. In forward kinematics, the joint parameters are known, and the positions are found. By substituting the parameter table in the corresponding place in the "A_{n+1}" matrix the transformation between two consecutive joints can be found. The below table 2 shows the calculated D-H parameters by considering the kinematic diagram of the corresponding 6-axis robot. To find the robot's kinematics this D-H table will be useful.

Table 2 D-H parameter table

Joint	θ (angle)	d (offset)	α (twist)	a (link length)
1	θ_1	d_1	-90°	a_1
2	θ_2-90°	0	180°	a_2
3	θ_3+180°	0	90°	a_3
4	θ_4	d_4	0°	0
5	θ_5	0	90°	0
6	θ_6	d_6	0°	0

The general "A_{n+1}" matrix is given by;

$$A_{n+1} = \begin{bmatrix} C\theta_{n+1} & -S\theta_{n+1}C\alpha_{n+1} & S\theta_{n+1}S\alpha_{n+1} & a_{n+1}C\theta_{n+1} \\ S\theta_{n+1} & C\theta_{n+1}C\alpha_{n+1} & -C\theta_{n+1}S\alpha_{n+1} & a_{n+1}S\theta_{n+1} \\ 0 & S\alpha_{n+1} & C\alpha_{n+1} & d_{n+1} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The transformation matrix for each joint is given as follows,

$$T_1^0 = \begin{bmatrix} C\theta_1 & 0 & -S\theta_1 & a_1 C\theta_1 \\ S\theta_1 & 0 & C\theta_1 & a_1 S\theta_1 \\ 0 & -1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_2^1 = \begin{bmatrix} C(\theta_2 - 90°) & S(\theta_2 - 90°) & 0 & a_2 C(\theta_2 - 90°) \\ S(\theta_2 - 90°) & -C(\theta_2 - 90°) & 0 & a_2 S(\theta_2 - 90°) \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^2 = \begin{bmatrix} C(\theta_3 + 180°) & -S(\theta_3 + 180°) & 0 & a_3 C(\theta_3 + 180°) \\ S(\theta_3 + 180°) & C(\theta_3 + 180°) & 0 & a_3 S(\theta_3 + 180°) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_4^3 = \begin{bmatrix} C\theta_4 & -S\theta_4 & 0 & 0 \\ S\theta_4 & C\theta_4 & 0 & 0 \\ 0 & 0 & 1 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_5^4 = \begin{bmatrix} C\theta_5 & 0 & -S\theta_5 & 0 \\ S\theta_5 & 0 & C\theta_5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_6^5 = \begin{bmatrix} C\theta_6 & -S\theta_6 & 0 & 0 \\ S\theta_6 & C\theta_6 & 0 & 0 \\ 0 & 0 & 1 & d_6 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The final transformation matrix is the product of the transformation matrix of each joint and is given by,

$$T_6^0 = T_1^0 . T_2^1 . T_3^2 . T_4^3 . T_5^4 . T_6^5$$

$$T_6^0 = \begin{bmatrix} A_{11} & A_{12} & A_{13} & p_x \\ A_{21} & A_{22} & A_{23} & p_y \\ A_{31} & A_{32} & A_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$A_{11} = (S(\theta_1)\, S(\theta_4+\theta_5) - S(\theta_2 - \theta_3)C(\theta_1)C(\theta_4+\theta_5))\, C(\theta_6) - S(\theta_6)C(\theta 1)C(\theta_2 - \theta_3) \quad (3.1)$$

$$A_{12} = (-S(\theta_1)\, S(\theta_4 + \theta_5) + S(\theta_2 - \theta_3)C(\theta_1)\, C(\theta_4+\theta_5))S(\theta_6) - C(\theta_1)C(\theta_6)C(\theta_2 - \theta 3) \quad (3.2)$$

$$A_{13} = -S(\theta_1)\, C(\theta_4 + \theta_5) - S(\theta_2 - \theta_3)S(\theta_4 + \theta_5)C(\theta_1) \quad (3.3)$$

$$A_{21} = -(S(\theta_1)\, S(\theta_2 - \theta_3)C(\theta_4 + \theta_5) + S(\theta_4 + \theta_5)\, C(\theta_1))C(\theta_6) - S(\theta_1)S(\theta_6)C(\theta_2 - \theta_3) \quad (3.4)$$

$$A_{22} = (S(\theta_1)\, S(\theta_2 - \theta_3)C(\theta_4 + \theta_5) + S(\theta_4 + \theta_5)\, C(\theta_1))S(\theta_6) - S(\theta_1)C(\theta_6)C(\theta_2 - \theta_3) \quad (3.5)$$

Transformation matrices are essential for comprehending the kinematics of robotic arms because they provide a distinct connection between the joint configurations and the end effector's location and orientation. These matrices make it possible to compute the effects of different joint angles and link lengths on the robot's overall spatial arrangement, which offers important insights into its workspace. These transformations enable the precise control of the robot's movements by modeling its kinematic chain. Tasks like trajectory planning, whose objective is to specify a smooth path for the end effector while taking limitations like collision avoidance into account, require a fundamental understanding of this subject. Moreover, the comprehension of these interactions is essential for the deployment of adaptive control systems, which modify the robot's activities in response to dynamic alterations in its surroundings. These discoveries not only increase the precision of robotic tasks but also open the door to the development of sophisticated systems that can carry out difficult jobs in real-time situations including manufacturing lines, operating rooms, and unpredictably changing environments. Through the use of these principles, engineers can maximize path planning and guarantee the robot's precision in performing complex and synchronized movements.

$A_{23} = -S(\theta_1)\, S(\theta_2 - \theta_3)\, S(\theta_4 + \theta_5) + C(\theta_1)\, C(\theta_4 + \theta_5)$ (3.6)

$p_x = a_1C(\theta_1)+a_2 S(\theta_2)C(\theta_1)-a_3S(\theta_2-\theta_3)C(\theta_1)-d_4C(\theta_1)C(\theta_2-\theta_3)-d_6S(\theta_1)C(\theta_4+\theta_5)-d_6S(\theta_2-\theta_3)S(\theta_4+\theta_5)C(\theta_1)$ (3.7)

$p_y = a_1S(\theta_1)+a_2 S(\theta_1)S(\theta_2)- a_3S(\theta_1)S(\theta_2- \theta_3)- d_4 S(\theta_1)C(\theta_2-\theta_3)-d_6S(\theta_1)S(\theta_2 -\theta_3)S(\theta_4+\theta_5)+d_6C(\theta_1)C(\theta_4+ \theta_5)$ (3.8)

In the above 4x4 matrix, the first 3x3 matrix is known as orientation the last column is position and the lowest row is considered as the ineffective row.

IV. INVERSE KINEMATICS

The joint variables are calculated in the inverse kinematics. To find the Fanuc S-430iW joint angles the following formulas are used. The positions are known and the corresponding joint angles are calculated. The picture below shows that the forward and inverse kinematics are reversible if any other can be found. Inverse kinematics can be done in two ways one is the analytical method and the other is the iterative method. In the analytical method, the complexity increases when the number of joints to be solved is higher. The analytical method is the most precise. Analytical solvers produce all possible solutions. If there are enough degrees of freedom for the model for orientation then it has finite solutions. If there are less number of degrees of freedom then it has no solutions and if there are high number of degrees of freedom then there will be many solutions. The drawback of the analytical method is that it is difficult to find the best solution when there are too many solutions. The Jacobian matrix is used to calculate the inverse kinematics. Jacobian matrix is a linear approximation of a differentiable function near a given point [8].

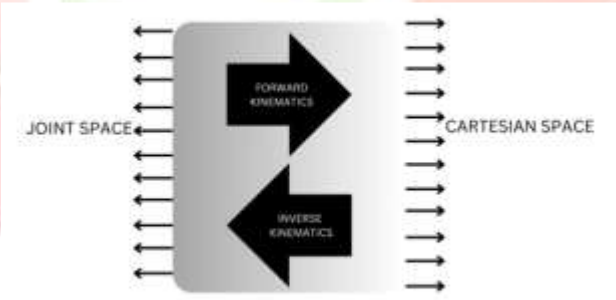

Fig.2 Forward and inverse kinematics

The θ_1 can be calculated using the position terms p_x and p_y. Thus it is in the x-y plane.

$$\theta_1 = \tan^{-1}\frac{p_y}{p_x} \quad (4.1)$$

By calculating the r and s which are radial distance and height and substituting the values the θ_3 can be found.

$$r = \sqrt{p_x^2 + p_y^2 - a_1} \quad (4.2)$$

$$s = p_z - d_1 \quad (4.3)$$

$$\theta_3 = \cos^{-1}\frac{r^2+s^2-a_2^2-a_3^2}{2a_2a_3} \quad (4.4)$$

Likewise, the other angles are also calculated by substituting the values from the forward kinematics.

$$\theta_2 = \tan^{-1}\frac{s}{r} - \sin^{-1}\frac{a_3\sin(\theta_3)}{\sqrt{r^2+s^2}} \quad (4.5)$$

$$\theta_5 = cos^{-1}A_{33} \quad (4.6)$$

$$\theta_4 = \tan^{-1}\frac{A_{23}}{A_{13}} \quad (4.7)$$

$$\theta_6 = \tan^{-1}\frac{A_{32}}{-A_{31}} \quad (4.8)$$

V. TRAJECTORY PLANNING

Trajectory planning is an important step when programming a robot for a particular path. Since the path can vary from straight lines to curved paths, the robots have to be programmed with the equations for the path.

When considering a path, it is essential to know the equation of the path. If a starting and ending point is taken, then the shortest path is a straight line unless the application requires the robot to move along a curve. Depending on the application the robot orientation may remain constant or vary. It is used to maintain the robot in a specified orientation. Linear interpolation is used to compute the points between the initial and final.

The initial and final points are the main parameters. For the smooth motion of the manipulator, it is necessary to have constraints on the other parameters such as velocity, acceleration, and jerk. Based on the number of constraints, the order of the polynomial path equation can be found.

Order of the polynomial = number of constraints - 1.

In this paper, there are six constraints considered. So, the order of the polynomial equation is 5. This is also called a quintic path. The two points are in 3D space and involve X, Y, and Z. The constraints for X are,

$X(t_0) = 1$, $X(t_f) = 3$, $X'(t_0) = 0$, $X'(t_f) = 0$, $X''(t_0) = 0$, $X''(t_f) = 0$

The constraints of Y are,

$Y(t_0) = 1$, $Y(t_f) = 2.5$, $Y'(t_0) = 0$, $Y'(t_f) = 0$, $Y''(t_0) = 0$, $Y''(t_f) = 0$

The constraints of Z are,

$Z(t_0) = 1$, $Z(t_f) = 2$, $Z'(t_0) = 0$, $Z'(t_f) = 0$, $Z''(t_0) = 0$, $Z''(t_f) = 0$.

Some assumptions are made to simplify the calculations,

1. Axis 4, 5, and 6 are considered to be stationary. That is, $\theta_6 = \theta_5 = \theta_4 = 0$

2. The link lengths are assumed as follows: a1= 3; a2 = 3; a3 = 2; d1 = 2; d6 = 4.

The general form of the quintic path equation is given as,

$$X(t) = a_0 + a_1t + a_2t^2 + a_3t^3 + a_4t^4 + a_5t^5 \quad (5.1)$$

The quintic equation for X is given as,

$$X(t) = 1 + 0.02t^3 - 0.003t^4 + 0.00012t^5 \quad (5.2)$$

The quintic equation for Y is given as,

$$Y(t) = 1 + 0.015t^3 - 0.00225t^4 + 0.00009t^5 \quad (5.3)$$

The quintic equation for Z is given as,

$$Z(t) = 1 + 0.01t^3 - 0.0015t^4 + 0.00006t^5 \quad (5.4)$$

The results are plotted on a graph and shown below.

The provided equations are evaluated for ten seconds, and the velocity and acceleration profiles are obtained by performing their differentiation. The necessary joint angles needed for movement are then calculated using these velocity and acceleration values as inputs for inverse kinematic equations. MATLAB R2023b software is used for all computations, including differentiation and inverse kinematics, using a laptop with a 12.0 GHz 12th Gen Intel® CoreTM i5-12500H processor. This configuration guarantees effective handling for the necessary calculations.

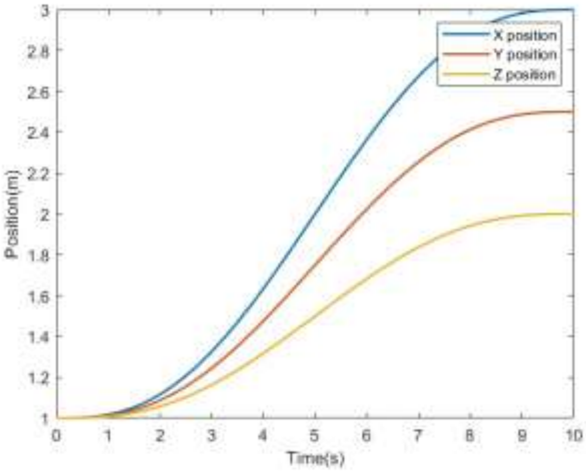

Fig.3 Position vs time

The x-direction position's nonlinear variation over time points to a complicated interplay between a number of variables, including changes in velocity, outside forces, and dynamic control inputs. Nonlinear movement, as opposed to uniform motion, suggests that acceleration or deceleration is happening. This is most often the result of changing external forces (such as drag or friction) or deliberate control input adjustments in response to dynamic environmental conditions or real-time sensor output. In robotic systems, for example, nonlinearity in the x-direction position can arise from the control system's modulation of speed to maximize performance, avoid obstructions, or conserve energy. On the other hand, the restricted y-direction movement, which is evident in the smaller positional changes, suggests potential limitations on lateral movement.

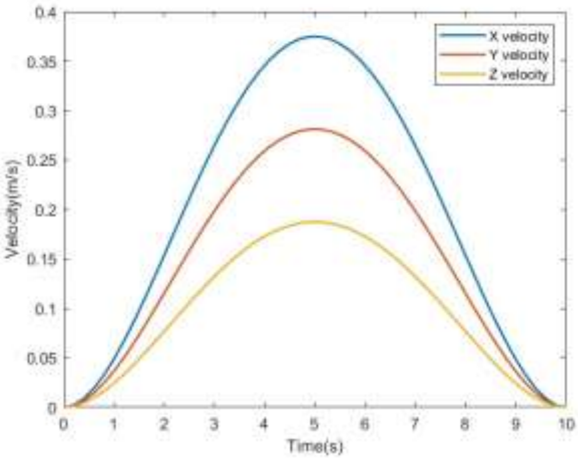

Fig.4 Velocity vs time

The x, y, and z velocity curves in Figure 4 all start at 0, go to a peak, and then go back to zero. The x-direction has the highest peak, suggesting that this is the direction in which the object travels at its fastest speed, which is probably due to its main operational focus. As opposed to the x-direction, the y-direction reaches a lower peak velocity, indicating that the lateral movement is not as important. The lowest peak velocity is seen in the z-direction, suggesting that vertical motion is either restricted or handled more carefully. To preserve stability and control during operation, this velocity pattern proposes a strategic design where the system maximizes speed in the x direction while maintaining more moderate speeds in the y and z directions.

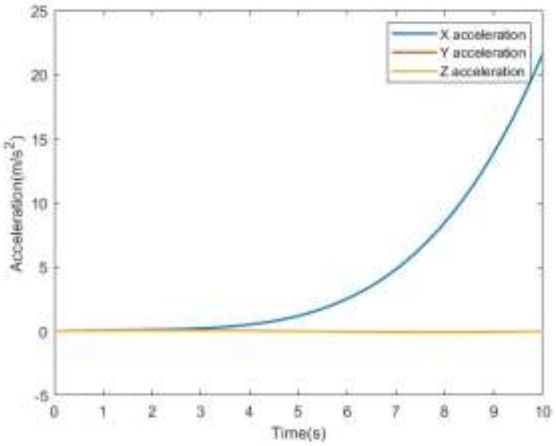

Fig.5 Acceleration vs time

A growing force is shown by the acceleration along the x-axis in Figure 5, which may be the result of improved motor input, or an adaptive control technique meant to maximize performance. The y and z axes, on the other hand, exhibit continuous acceleration, indicating that the purpose of these movements is to maintain a steady condition to prioritize horizontal acceleration. This design decision can indicate an emphasis on accomplishing operational objectives while maintaining stability in the y and z axes to avoid any unintended deviations during mobility. All things considered; the dynamics point to a deliberate focus on quick movement in the x direction while retaining control in other dimensions.

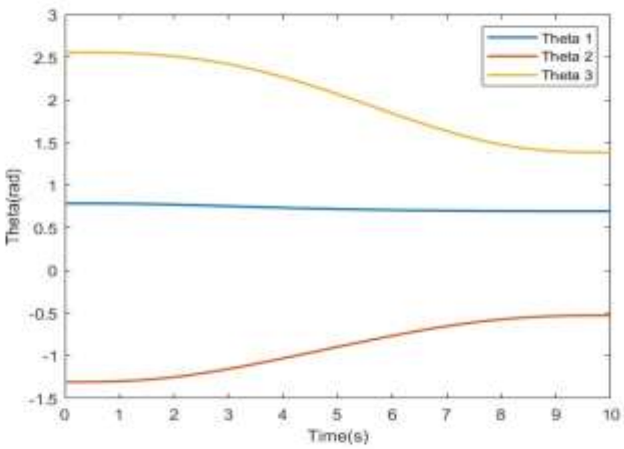

Fig.6 Joint angle vs time

Fig 6 graph shows how the joint angle varies in 10 seconds. theta 1 is in a negative axis, theta 2 is a flat line, and theta 3 is in a positive direction. A trajectory in 3D space in Fig 7 shows the path of motion of an object from initial to final position in a 3-Dimensional space. It is defined by the position, velocity, and acceleration, at each point of the object along the path. It is the path that an object takes while moving across a certain area. If the object's velocity is parallel to its constant acceleration, it will have a straight trajectory. At the same time, it is a path that an object moves along as a function of time via space, carrying mass.

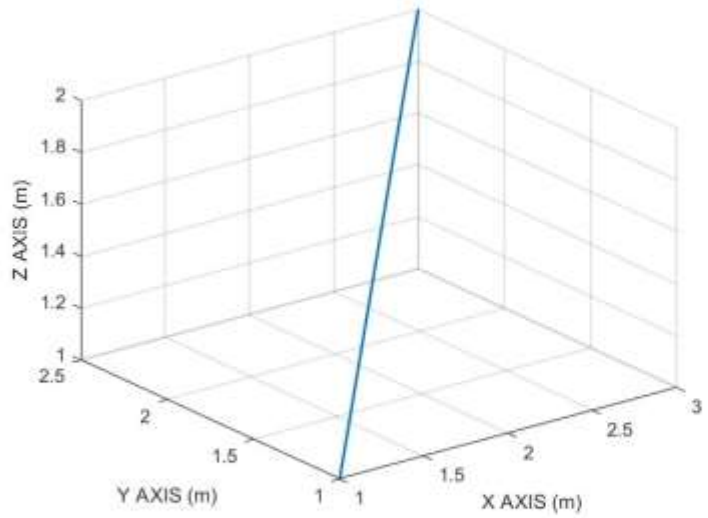

Fig.7 Trajectory in 3D space

VI. CONCLUSION

The Fanuc S-430iW robot seems to be versatile in every industrial application, and thus, it needs a path catered to specific environmental needs. This work focuses on the implementation of a simple straight-line trajectory in 3D space described by an initial and final position. Results: Graphical results illustrating the position, velocity, and acceleration of the robot over 10 seconds have been given. The analysis shows how nicely the process has been changed from the initial into the final position, but with higher velocities over the X-axis than on the Y-axis and, again, more over the Y-axis than on the Z-axis. The joint value for the variable theta1, representing the robot base, does not change in the course of the run at all. The two others vary similarly but in opposite directions. The implementations have shown the usefulness of inverse kinematics and forward kinematics in simplifying the path planning of the robot. The scheme of trajectory planning with the use of straight-line paths for movement is simple and effective in achieving motion with high accuracy. This method will provide a smooth and controlled movement which could be crucial in industrial applications. It enhances understanding of the kinematic performance of the robot through the joint values computed, hence leading to better control over the six degrees of freedom of the robot. Data obtained from this analysis are critical for optimizing the movement of the robot, particularly in dynamic or constrained environments. In summary, the contribution of this work lies in the broader field of robotic motion planning and control, indicating insights that may improve industrial operational efficiency.

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