TRAJECTORY TRACKING OF DELTA ROBOTS USING DELTA KINEMATICS FOR INDUSTRY 4.0 APPLICATIONS

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Abstract: *Industry 4.0 demands smart manufacturing systems that can process and handle tasks in a quick pace. Parallel robots with 3D kinematics will make a big impact in modern industrial applications. Since these robots target the industrial revolution with Machine to Machine communication and with the support of Industrial Internet of Things towards Industry 4.0, this category of robots are of great demand. Controlling of such robots with complex kinematic system in modern industries is quite challenging, because they handle physical rigid bodies in manufacturing assembly lines. This proposed work deals with the theoretical and practical aspects of forward and inverse kinematics associated with such kind of parallel robots and the challenges associated with them. Test trails on robot interaction environment were performed with the simulated model of Fanuc M-3ia6S delta robot using MATLAB simulation tool. After the analysis of performance of tracking strategies on the provided desired trajectory of the robot, it was observed that the Fanuc M-3ia6S delta robot provides the tracking accuracy of 96% with the applied forward and inverse kinematics on the simulated model of Fanuc M-3ia6S delta robot.*

Keywords: Trajectory tracking, Forward Kinematics, Inverse Kinematics, Delta Kinematics, Fanuc M-3ia6S delta robot, Industry 4.0.

1. Introduction

Automation tasks, which were once thought as infeasible are made quite flexible with the bloom of Robotics research. Robots have started dominating the industrial sector, thereby largely reducing the work load of human beings. This enables the human race to focus on other productive activities for enhancing their lifestyle [1]. Robots were designed to follow proper code of ethics as directed by human for assisting him and making his job quite easier. Being a fascinating field of science, lot of discoveries and innovations have imparted huge positive impact in the growth of robots and their applications. Industrial robots which were once static and performing material handling tasks, later on mobile robots started assisting in the industrial tasks to a larger extent. Current technological advances demand remote operating of the robotic systems for medical applications, industrial manufacturing, assembly tasks and many more. Also few modern industries demand distributed processing of robotic systems. To cater all their needs, bloom of Industry 4.0 with the supporting technologies such as artificial intelligence, machine learning and deep learning have made a huge impact in the robotic domain [2]. Robotic systems have also started learning from previous experience and able to think and process tasks as equivalent to human beings.

Robotic systems for modern industries gather concrete impetus for the automation today and in far future with various essential aspects towards automation in industries. All decisive simplifications in engineering on the way towards Industry 4.0 can be demonstrated with the associated engineering expenses with proper commissioning. Above all, programming can be eliminated by the help of dynamic CAD models and by simulating all process sequences. Considering the standard and demand for Industry 4.0, the way automation markup language actuates the robotic systems in modern industries are gaining dominance. Controlling a 3D kinematic system such as industrial robots with delta kinematics is highly challenging. Usage of the tripod with integrated motors including absolute encoders, controllers, power electronics with proper protection and decentralized soft motion controllers were in demand for robotic systems of these kinds. Robotic applications demanding 3D object handling and other robust applications can thus be effortlessly integrated into such kind of 3D kinematics robotic systems. Also versatile, modular and flexible distributed and control concepts can be implemented in the automation platform. Robotic Systems for Industry 4.0 also demand high speed communication interfaces with maximum flexibility for automation tasks. Better and simpler condition monitoring tasks can be invoked based on the long run operating conditions of the robotic systems. It yields critical visioning and better diagnostics, there by setting up a platform for more productivity and explores wide variety of automation in industries [3].

2. Problem Formulation and Modelling of Delta Robots for Industry 4.0

The trust of Industry 4.0 standards on certain category of robots makes the manufacturing sector to be smarter. It improves the accuracy level in material handling, improves economic aspects of the design, quick time to market and many more features are added up. Also it incorporates modern technological trends such as Internet of Things, Artificial Intelligence and machine learning approaches for making the Industry 4.0 technology towards smarter sector. Interaction of robots with the physical environment in the industries can be monitored, controlled and processing can be done from remote places with the support of Industry 4.0 standards. Few of the industrial applications are also capable of performing machine to machine communication, enabling the robots to communicate with each other autonomously. This communication feature enables the robots to raise their own demands when required and they can intimate the authorized persons about their status and progress in the industrial production.

2.1. Interaction of Robots for Industry 4.0 Environments

Robotic systems can interact physically in its work space by first establishing a contact with the environment with appropriate configuration. Subsequently the robots are fed with required force for motion of its physical parts to perform certain desired tasks. Interaction by means of grasping of objects in work space and the desired motion control constrained to tasks are dealt. Beginning from the early inception of robotic research, manipulation of robots with their environment has been dealt by different researchers [4].

Robots supporting Industry 4.0 technology are in great demand for modern industries. Conventional robots can also be configured to cater the requirements of Industry 4.0 standard. Robots with delta kinematics, also called as delta robots can be a great support for the bloom of the smart industries by incorporating the features of Industry 4.0 standards.

2.2 Role of Delta Robots for Industry 4.0

Delta robot is a popular type of robot often used in pick-and-place applications consisting of three arms working in parallel. The mechanism converts the rotary motion of the three motors mounted 120 degrees apart on a circle into three degrees of purely translational motion at the end [5]. Few commercial controllers are available for controlling such robots. Through properly programmed controllers, it automatically maps the positions of the robots tooltip at the end-effector to the positions of the motors. It also permits the user to program in tooltip positions rather than motor positions [6].

Robotic controllers for delta robots transform hardware position, capture and compare the custom servo routine capabilities for positioning the tool tip at desired positions. Intelligent amplifiers are required for driving these kinds of delta robots to combine the intelligence and capability of the controller with motor drive technology. Certain motor drive for delta robots consist upto eight axis servo drive package along with a power stage supporting a maximum of eight amps. When running on a one or three phase AC input, it can drive brush, brushless or AC induction motors for actuating the end effector [7].

Grasping objects in the environment using delta robotic systems can be implemented based on either contact level method or knowledge based method. Contact level method applies force torque to the objects handled by the robot. Few of the variants of the contact based methods include frictionless contacts, soft contact and with frictional contact forces applied. Reliability of grasping potential can be estimated using force closure property by compensating external disturbances. Other possible forces of contact can also be random potential grasps, which may not be optimal but manages vector space that includes all feasible contact forces [8].

Industry assembling tasks in modern smart industries incorporated with Industry 4.0 demands very high speed processing. Robots with parallel kinematics added flexibility to meet the demands of modern Industries. This kind of robots possesses advantages of high speed, precise accuracy, strong stiffness, lesser inertia and many more. For performing repetitive jobs, particularly picking and placing in industries, usage of parallel robots with delta kinematics is more robust compared to conventional industrial robotic manipulators. Higher number of degrees of freedom in delta robots plays additional flexibility for performing complex manipulation tasks in industries. Control of robots with multiple degrees of freedom is highly challenging. Moreover, a lot of fine tuning on their control tasks is being carried out by various researchers now and then. Most of the tasks in industries do not require delta robots with multiple degrees of freedom. Even two degree of freedom delta robots can be used for handling tasks for multiple applications with high speed operation [9].

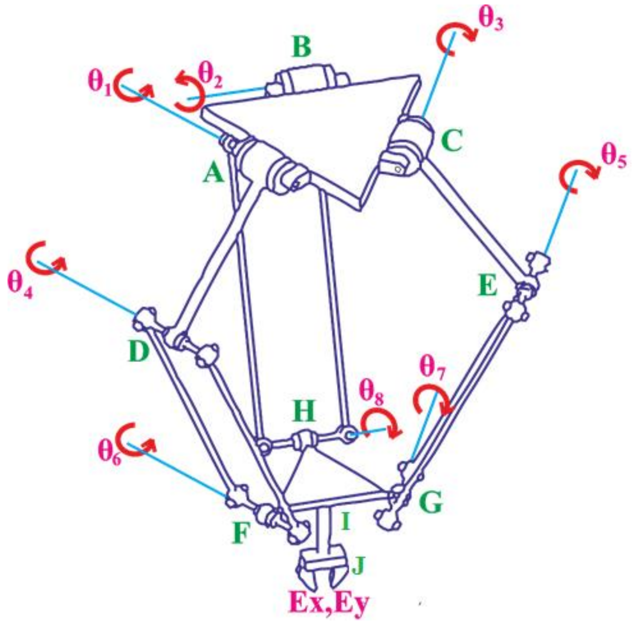

Fig. 1 Schematic structure of a Delta Robot

3. Forward Kinematics of Delta Robots

Kinematic transformations are necessary when the relationship between the motors and the tooltip is mathematically nonlinear, where standard linear axis definitions cannot be used. Kinematics can be easily set up by programming the mathematical relationship between the motor positions and the axis positions into the forward and inverse kinematics subroutines [10]. These can be run automated at the rate for specific physical interaction of the tooltip with the environment. Kinematic transformations come standardized with commercial controllers along with many other advanced features including dynamic look-ahead coordinate system [11].

The coordinate relationship of the delta robots are derived from the base X-Y axis. Its configuration represents the simple category of parallel robots. The robot assembly as a whole will be rotated and translated along the X-Y plane [12]. The midpoint of object handling by the end-effector is considered as (Ex,Ey) coordinate point. Forward kinematic expression can be derived from the motion model, recognized by relation of motion to the link lengths and joint angles of the delta robot. The fixed plane with base points A, B and C in figure represents the absolute coordinate system. The moving plane with end-effector coordinate (Ex,Ey)

The end effector coordinates Ex and Ey are estimated using the joint angles of two active arms θ_1 and θ_3 as input. Using the Equation 1, relation between all the joint angles is derived.

$$\begin{cases} -l_1\cos\theta_1 + l_4\cos\theta_4 + l_7 + l_5\cos\theta_5 - l_3\cos\theta_3 - l_6 = 0 \\ -l_1\sin\theta_1 - l_4\sin\theta_4 + l_5\sin\theta_5 + l_3\sin\theta_3 = 0 \end{cases} \quad (1)$$

The end effector coordinates (Ex,Ey) can be estimated from the Equation 1 and given as shown as Equation 2 and 3 for one side of the link.

$$E_x = -\frac{1}{2}l_6 - l_1\cos\theta_1 + l_4\cos\theta_4 + \frac{1}{2}l_7 \quad (2)$$

$$E_y = -l_1\sin\theta_1 - l_4\sin\theta_4 \quad (3)$$

For the other side of the link the end effector coordinates (Ex,Ey) can be represented as shown in Equation 4 and 5.

$$E_x = \frac{1}{2}l_6 + l_3\cos\theta_3 - l_5\cos\theta_5 - \frac{1}{2}l_7 \quad (4)$$

$$E_y = -l_3\sin\theta_3 - l_5\sin\theta_5 \quad (5)$$

Equation 6 gives the final expression for one side of the links from the base to tool tip of the end effector with reference to the schematic of the delta robot shown in Fig. 1.

$$A + C\sin\theta_5 + E\cos\theta_5 + G = 0 \quad (6)$$

From Equation 6, the parameters are expressed as shown in Equation 7 to 10.

$$A = l_1^2 - l_4^2 + l_5^2 + l_3^2 + l_6^2 + l_7^2 \quad (7)$$

$$C = -2l_1 l_5\sin\theta_1 + 2l_5 l_3\sin\theta_3 \quad (8)$$

$$E = -2l_1 l_5\cos\theta_1 - 2l_5 l_3\cos\theta_3 + 2l_5 l_7 - 2l_5 l_6 \quad (9)$$

$$G = -2l_1 l_3\sin\theta_1\sin\theta_3 + 2l_1 l_3\cos\theta_1\cos\theta_3 - 2l_1 l_7\cos\theta_1 + 2l_1 l_6\cos\theta_1 - 2l_3 l_7\cos\theta_3 + 2l_3 l_6\cos\theta_3 - 2l_6 l_7 \quad (10)$$

By using the trigonometric rules in Equation 6, we get

$$A + C\frac{2\varphi}{1+\varphi^2} + E\frac{1-\varphi^2}{1+\varphi^2} + G = 0 \quad (11)$$

The above Equation 11 can be simplified as,

$$\varphi^2(A - E + G) + \varphi(2C) + (A + E + G) = 0 \quad (12)$$

where,

$$\varphi = \frac{-C \pm \sqrt{-C^2(A-E+G)(A+E+G)}}{A-E+G} \quad (13)$$

$$\theta_3 = 2\tan^{-1}\varphi \quad (14)$$

$$\theta_4 = \sin^{-1}\frac{-l_1\sin\theta_1 + l_5\sin\theta_5 + l_3\sin\theta_3}{l_4} \quad (15)$$

By substituting Equation 15 in Equation 2 and 3, we get

$$\begin{cases} E_x = -\frac{1}{2}l_6 - l_1\cos\theta_1 + l_4\cos\theta_4 + \frac{1}{2}l_7 \\ E_y = -l_1\sin\theta_1 - l_4\sin\theta_4 \\ \theta_4 = \sin^{-1}\frac{-l_1\sin\theta_1 + l_5\sin\theta_5 + l_3\sin\theta_3}{l_4} \end{cases} \quad (16)$$

By substituting Equation 15 in Equation 4 and 5, we get

$$\begin{cases} E_x = \frac{1}{2}l_6 + l_3\cos\theta_3 - l_5\cos\theta_5 - \frac{1}{2}l_7 \\ E_y = -l_3\sin\theta_3 - l_5\sin\theta_5 \\ \theta_3 = 2\tan^{-1}\varphi \end{cases} \quad (17)$$

The Equation 16 and 17 give the estimated end effector position of the delta robot by the implementation of forward kinematics.

4. Inverse Kinematics of Delta Robots

Based on the available coordinates (Ex,Ey) of the end effector, inverse kinematics of the delta robot can be analyzed. From the known coordinates, the rotation angles of the robotic joints can be estimated. Inverse kinematics of any robotic systems gives multiple solutions. One such solution for one side of the links from base to tool tip can be estimated from the Equation 2 and 3 as, shown in Equation 18.

$$A_1 + C_1\cos\theta_1 + E_1\sin\theta_1 + G_1 = 0 \quad (18)$$

From Equation 18, the parameters are expressed as shown in Equation 19 to 22.

$$A_1 = E_x^2 + E_y^2 + l_1^2 - l_4^2 + 0.25\,l_6^2 + 0.25\,l_7^2 \quad (19)$$

$$C_1 = 2E_x l_1 + l_1 l_6 - l_1 l_7 \quad (20)$$

$$E_1 = 2E_y l_1 \quad (21)$$

$$G_1 = E_x l_6 - E_x l_7 - 0.5E_y l_7 \quad (22)$$

By using the trigonometric rules in Equation 18, we get

$$A_1 + C_1\frac{2\omega}{1+\omega^2} + E_1\frac{1-\omega^2}{1+\omega^2} + G_1 = 0 \quad (23)$$

$$\omega^2(A_1 - C_1 + G_1) + \omega(2C_1) + (A_1 + C_1 + G_1) = 0 \quad (24)$$

where,

$$\omega = \frac{-C_1 \pm \sqrt{-C_1^2(A_1-E_1+G_1)(A_1+E_1+G_1)}}{A_1-E_1+G_1} \quad (25)$$

$$\theta_1 = 2\tan^{-1}\omega \quad (26)$$

For the other side of the links from base to tool tip, the inverse kinematics can be estimated from the Equation 4 and 5 as, shown in Equation 27.

$$A_2 + C_2 \cos\theta_3 + E_2 \sin\theta_3 + G_2 = 0 \qquad (27)$$

From Equation 27, the parameters are expressed as shown in Equation 28 to 31

$$A_2 = E_x{}^2 + E_y{}^2 + l_3{}^2 - l_5{}^2 + 0.25\, l_6{}^2 + 0.25\, l_7{}^2 \qquad (28)$$

$$C_2 = -2E_x\, l_3 + l_3\, l_6 - l_3\, l_7 \qquad (29)$$

$$E_2 = 2E_y\, l_3 \qquad (30)$$

$$G_2 = -E_x\, l_6 + E_x\, l_7 - 0.5E_y\, l_7 \qquad (31)$$

By using the trigonometric rules in Equation 27, we get

$$A_2 + C_2 \frac{2\delta}{1+\delta^2} + E_2 \frac{1-\delta^2}{1+\delta^2} + G_2 = 0 \qquad (32)$$

$$\delta^2 (A_2 - C_2 + G_2) + \delta(2C_2) + (A_2 + C_2 + G_2) = 0 \qquad (33)$$

where,

$$\delta = \frac{-C_2 \pm \sqrt{-C_2{}^2 (A_2 - E_2 + G_2)(A_2 + E_2 + G_2)}}{A_2 - E_2 + G_2} \qquad (34)$$

$$\theta_3 = 2\, tan^{-1}\delta \qquad (35)$$

The Equation 26 and 35 give the estimated joint angles of the delta robot by the implementation of inverse kinematics.

5. Case Study of Fanuc M-3ia6S Robot with Delta Kinematics for Industry 4.0 Applications

The Fanuc M-3ia6S Robot is a delta robot manipulator with parallel dynamics that was designed targeting the scientific research community. It is also an ideal choice for high speed material handling tasks in industries.

Fig. 2. The FANUC M3 iA 6S Delta Robotic Manipulator
[Image Courtesy: https://www.fanuc.eu]

Fig.2 shows the picture of Fanuc M-3ia6S delta robot manipulator. It is fitted with very powerful servomotors for high frequency and high acceleration in its interaction with physical environment. It enables enhanced productivity, maximizes energy saving and also compact and portable. Since, it is a best choice for high speed materials handling tasks, Fanuc M-3ia6S Robot is considered in our case study for physical interaction with the environment. It is also used for development and validation of delta kinematics for Industry 4.0 applications.

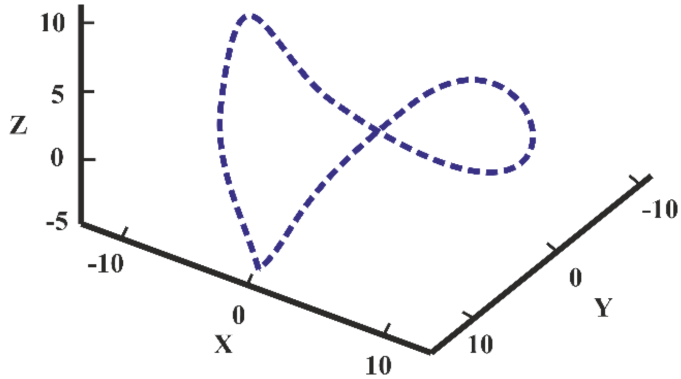

Fig. 3. End Effector (Ex, Ey) Trajectory for desired material handling application

Investigations on the Fanuc delta robot are performed by choosing a trajectory as shown in Fig. 3. Simulation on the model of Fanuc delta robot is performed using MATLAB 2018a tool. The end effector position Ex, Ey is fixed based on the trajectory tracked by the support of the motors at position I and J of the robot. Actuation of the motors at those positions, oscillates such that for tracking the complex trajectory as shown in Fig. 4. In the proposed study, derived kinematics are transformed to actuate the chosen Fanuc M-3ia6S Robot for investigation. The performance of the robot is evaluated by testing with up 60 different trials, by actuating each joints of the robot to track the desired trajectory as per the test routine.

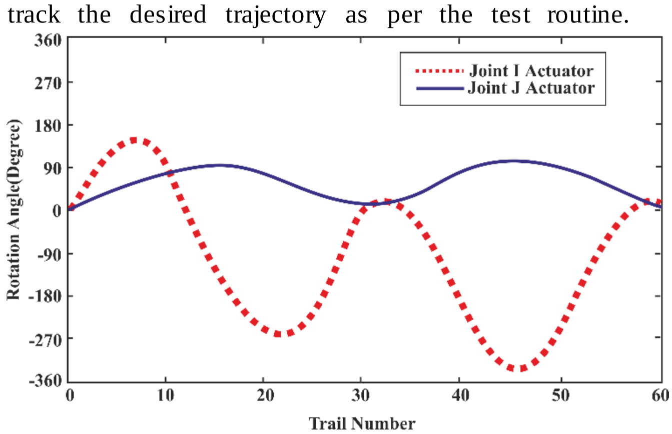

Fig. 4. The Rotation Angle of the Joint I and J Actuators

The base motors actuating the joints A, B and C of the robot is responsible for the movement of the links of the arms. Rotation angle tracked for the trials carried on the robot for those joints are plotted in Fig. 4 and 5. It is evident that the joint B actuator moves clockwise and the joint C actuator moves anticlockwise to counter act and position the tool tip at a desired position based on the given trajectory points.

The results presented in Fig. 6 for the chosen Fanuc M-3ia6S Robot for pick and place operation in industries. It is plotted for three different Z-axis trajectories specifies as Z1, Z2 and Z3 in the 3D axis of navigation. From this figure it is evident that the tracked points from the robot almost coincides with the desired trajectory. The deviation in accuracy of tracking the position is observed to be of 4%. This ensures that the proposed kinematic solutions applied on the Fanuc M-3ia6S delta robot provides the tracking accuracy of 96%.

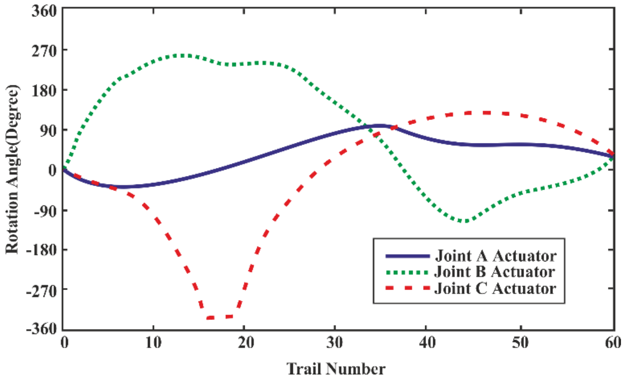

Fig. 5. The Rotation Angle of the Joint A, B and C Actuators

The demands of Industry 4.0 standards are high accuracy, high speed operations, large workspace coverage, appropriate monitoring and control, independent task coordination between machines. The solutions put forward, will add a feather to the cap of the bloom of industrial sector in smart manufacturing and material handling using robots with less or negligible human interventions.

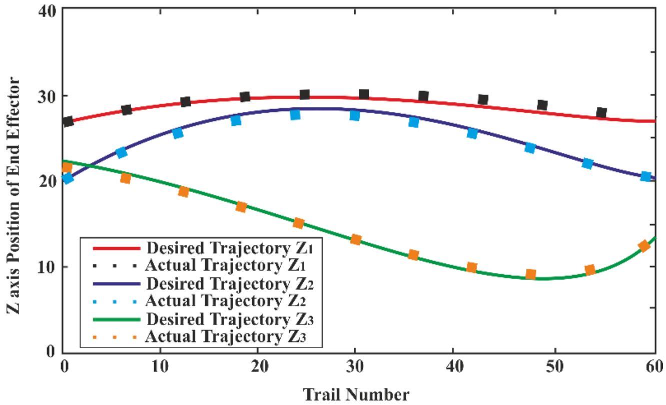

Fig. 6. Trajectory tracking verification in Z-axis for Fanuc M-3ia6S Robot for material handling application

Conclusions

The goal of this research work is to derive the forward and inverse kinematic solutions for the driving the actuators of delta robots with improved accuracy for targeting the Industry 4.0 application standards. The objective was to test the performance of the Fanuc M-3ia6S Robot manipulator for its physical interaction with an industrial environment and control its manipulation using the derived forward and inverse kinematic solutions. It is accomplished by implementation of controller for task handling applications in industries with high speed and targeting high accuracy. For appropriate task handling operations in industries, toward and inverse kinematics were derived. Followed by, 60 number of test trails were performed with the simulated model of Fanuc M-3ia6S delta robot using MATLAB. After the analysis of performance of tracking strategies on the provided desired trajectory of the robot, it was observed that the deviation in accuracy of tracking the position is of 4%. This in turn ensures that the proposed forward and inverse kinematic solutions applied on the Fanuc M-3ia6S delta robot provide the tracking accuracy of 96% in its third dimension Z-axis. This is much needed performance measure for the day to day Industry 4.0 applications. It can be further improved by implementing appropriated non-linear and adaptive control approaches.

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