Design and Implementation of Low-Cost Articulate Manipulator for Academic Applications

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Abstract

The objective of this work is to design a low cost yet fully functional 4-DOF articulate manipulator for educational applications. The design is based on general purpose, programmable smart servo motors namely the Dynamixel Ax-12. The mechanism for motion was developed by formulating the equations of kinematics and subsequent solutions for joint space variables. The trajectory of end-effector in joint variable space was determined by interpolation of a 3rd order polynomial. The solutions were verified through computer simulations and ultimately implemented on the hardware. Owing to the feedback from the built-in sensors, it is possible to correct the positioning error due to loading effects. The proposed solution offers an efficient and cost-effective platform to study the trajectory planning as well as dynamics of the manipulator.

Keywords:

4 DoF Manipulator, Educational Robot, Programmable Robotic Arm.

1. Introduction

Robotics and automation has had a huge impact on the everyday life. With advancement in artificial intelligence, sensing and semiconductor technologies, the scope and application of robotics is ever growing. In this regard it is imperative that education of robotics at secondary and tertiary levels should not be limited to theory and simulation. A comprehensive robotics platform can help students comprehend complex concepts of robotics such as kinematics, dynamics and trajectory generation.

There are numerous programmable manipulators available in the market which offer user friendly interface, accuracy, configurability, and reliability. However, these features come at an exorbitant cost. The motive of this work is to design and implement a low cost, yet programmable platform which can help users develop practical understanding of kinematics, dynamics and even apply various control and trajectory generation techniques using open-source framework developed in python and using wealth of libraries; this platform can be easily interfaced with external sensors to completely automate the process.

A hardware and software framework has been developed to control the manipulator directly from the computer with real-time information about position, orientation, velocity and acceleration of the end-effector. Different trajectory planning techniques have been implemented on hardware in order to get smooth and continuous motion of the end-effector.

Although there exists an array of manipulator configurations which are suitable for different applications such a SCARA, cylindrical, gantry and parallel manipulators, articulate manipulators are the most versatile tool widely considered for industrial applications such as 3D printing, welding, painting, sorting, packaging, and other assembly line operations. Three and Four Degrees of Freedom (DoF) articulate manipulator systems have been widely studied in the literature; Authors in [1] have considered the design and simulation of one prismatic and 3 revolute joint manipulator, likewise [2-7] have considered design of an articulate manipulator with 4 revolute joints; [2-6] have verified their mathematical models through Matlab simulations, while [7] have considered simulation through ROS framework. Authors in [5] have developed an algorithm to obtain valid inverse kinematic solutions avoiding anomalous conditions. Authors in [6] have determined the dexterous workspace of an articulated manipulator, applying inverse kinematics in Matlab simulation.

Several authors have considered hardware implementation of robotic manipulators e.g. 6-DoF collaborative articulate manipulator is considered in [3], Implementation of an open-source 4-DoF articulate manipulator is considered in [8]. Authors in [9] discuss the implementation of 4-DoF manipulator with link offset and the distance between the joint axis. [10] is another interesting work which considers a 4 DoF articulate manipulator for educational applications, the authors have delved into kinematic

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Manuscript received January 5, 2024
Manuscript revised January 20, 2024
https://doi.org/10.22937/IJCSNS.2024.24.1.3

and dynamic modeling and implementation of motion control mechanism.

The contribution of this work is mathematical modeling and physical implementation of a 4 DoF articulated manipulator using DH parameters; forward and inverse kinematic solutions have been determined. These solutions have been used to move the manipulator arm in the cartesian workspace as a function of joint angles. Hardware implementation of the manipulator is based on Dynamixel (Ax-12/18) smart servo motors.

Dynamixel is a monolithic smart servo motor which provides real-time data about the joint angle, velocity, load / torque, and temperature [11]. These motors come in a large variety, offering industrial grade functionality but at a price. The working range of the servo motor (in joint mode) is 300° degrees; Instructions and feedback information is transferred seamlessly via serial interface with data rate of up to 1Mbps. As many as 254 motors can be simultaneously connected with a PC in daisy chain configuration. These servo motors have a 10-bit rotary encoder for accurate resolution per rotation. The built-in load sensors can be used to calculate torque requirement in different loading conditions, which can ensure smooth travel of manipulator through cartesian space.

It is apparent from review that only few instances of usage of such smart servo motors are available in literature. [8,9] have considered the use of Dynamixel servo motor. However, these articles are primarily limited to kinematics analysis of manipulator arms readily available at the website. Neither do they consider incorporating the feedback available through the on- board sensors.

One of the objectives of this work was to improve positioning and travel performance of the manipulator using the salient features of the smart servo motors.

Unlike the studies cited above which consider software simulation of trajectory planning schemes, this article presents results based on hardware implementation.

The objective of this work is to develop a versatile, low-cost, open-source hardware with rich features and real-time positioning, torque and travel velocity data for execution and analysis of various tasks.

The mathematical framework of 4-DoF articulate manipulator is implemented physically using Dynamixel smart servo motors. Open-source framework for trajectory and path-planning is developed. The onboard joint angle and payload sensing information is used to calibrate the positioning error of the end effector.

This paper is organized as follows. The next section describes the mathematical model of the articulate manipulator design considered in this paper. Based on this model, the theoretical framework for motion of the manipulator is also developed. Section 3 describes the physical implementation of the structure. The calibration of end-effector positioning in the presence of gravitational pull, friction and other mechanical imperfections is also described; In section 4, we discuss the results of the proposed intervention on the joint variable space and position of the manipulator. Section 5 summarizes the key outcomes of this work and outlines avenues for future research.

2. System Model

The mathematical model of the manipulator stems from homogenous transformation matrices developed under the framework of Dinavit-Hartenburg notation. The end-effector is expected to move in a predefined workspace, the dimensions of this workspace depend on the dimensions of link-lengths and the range of revolute joints. The DH parameters are defined in Table 1.

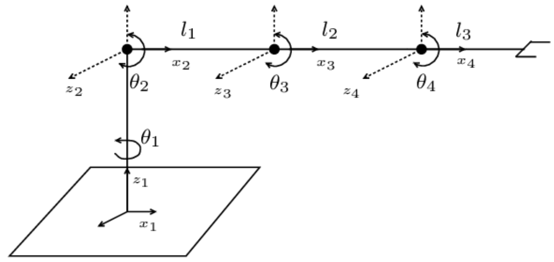

Figure 1: Description of 4 DoF articulate manipulator in DH convention.

The purposed hardware has a total dexterous work span of 700 mm and a maximum payload weight of 50 grams. The mechanical structure of the manipulator is illustrated in the figure 2.

Table 1: The DH parameter specification of the Manipulator

I	a_i	α_i	d_i	Θ_i
1	0	90°	d_1	Θ_1
2	l_1	0°	-	Θ_2
3	l_2	0°	-	Θ_3
4	l_3	90°	-	Θ_4-90°

where $l_1 = l_2 = 171$ mm, $l_3 = 51$ mm and d_1 =81mm respectively.

According to the DH table specified above, the homogenous transformation matrix associated with each link length of the manipulator arm are as follows

$$T_1^0 = \begin{bmatrix} \cos\theta_1 & \sin\theta_1 & 0 & 0 \\ \sin\theta_1 & -\cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_2^1 = \begin{bmatrix} \cos\theta_2 & \sin\theta_2 & 0 & l_1\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & l_1\sin\theta_2 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^2 = \begin{bmatrix} \cos\theta_3 & \sin\theta_3 & 0 & l_2\cos\theta_3 \\ \sin\theta_3 & \cos\theta_3 & 0 & l_2\sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

and the expression of end-effector link is defined as

$$T_4^3 = \begin{bmatrix} \sin\theta_4 & 0 & \cos\theta_4 & l_3\cos\theta_4 \\ -\cos\theta_4 & 0 & -\sin\theta_4 & -l_3\sin\theta_4 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

After straight forward calculation, the overall transformation matrix of the structure which expresses the coordinates of end-effector in terms of the base coordinates is defined as

$$T_4^0 = T_1^0 T_2^1 T_3^2 T_4^3$$

$$T_4^0 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_{14} \\ r_{21} & r_{22} & r_{23} & p_{24} \\ r_{31} & r_{32} & r_{33} & p_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where r_{ij} and p_{ij} represent the rotational and translational components of the homogenous transformation matrix T_4^0 , after straight forward calculation the expressions for rotational and translational components of the model are expressed as,

$r_{11} = \cos\theta_1 \cos(\theta_2 + \theta_3 + \theta_4)$,

$r_{12} = \sin\theta_1$,

$r_{13} = -\cos\theta_1 \sin(\theta_2 + \theta_3 + \theta_4)$,

$r_{21} = \cos\theta_1 \sin(\theta_2 + \theta_3 + \theta_4)$,

$r_{22} = -\cos\theta_1$,

$r_{23} = -\sin\theta_1 \sin(\theta_2 + \theta_3 + \theta_4)$,

$r_{31} = -\cos(\theta_2 + \theta_3 + \theta_4)$,

$r_{32} = 0$,

$r_{33} = -\sin(\theta_2 + \theta_3 + \theta_4)$,

Similarly, the translational components of the manipulator are defined as

$$p_{14} = \cos\theta_1\, l_1(\cos\theta_2 + \cos(\theta_2 + \theta_3)) + 5.1\sin(\theta_2 + \theta_3 + \theta_4) \tag{1}$$

$$p_{24} = \cos\theta_1\, l_1(\cos\theta_2 + \cos(\theta_2 + \theta_3)) + 5.1\sin(\theta_2 + \theta_3 + \theta_4) \tag{2}$$

$$p_{34} = \cos\theta_1\, l_1(\cos\theta_2 + \cos(\theta_2 + \theta_3)) + 5.1\sin(\theta_2 + \theta_3 + \theta_4) \tag{3}$$

The expressions p_{14}, p_{24} and p_{34} represent position of the manipulator end-effector in the cartesian coordinate space with reference to stationary frame, whereas $r_{11}, \ldots, r_{33}$ specify the orientation of the end-effector.

Once the mechanical structure of the manipulator is completely specified through DH parameters and the homogenous transformation matrix is forward kinematics relates the position and posture of the end-effector to joint angle vector and conversely the inverse kinematics relates the position and posture of the end-effector to the joint angle vector. These relations are obtained through trigonometric properties

$$\theta_1 = atan2(y, x) \tag{4}$$

$$\theta_2 = atan2\left(\frac{\frac{a^2 + b^2}{2l_1}}{\pm\sqrt{a^2 + b^2 - \left(\frac{a^2 + b^2}{2l_1}\right)^2}}\right) - atan2\left(\frac{b}{a}\right) \tag{5}$$

here, $a = d_1 - z$, $b = x\cos\theta_1 + y\cos\theta_1 + l_1$, furthermore, defining $u = a + b$ and $v = a - b$, we have,

$$\theta_3 = \tan^{-1}\left(\frac{\cos\theta_2(u) + \sin\theta_2(v) - l_1}{\pm\sqrt{2l_1^2 - (\cos\theta_2(u) + \sin\theta_2(v) - l_1)^2}}\right) \tag{6}$$

$$\theta_4 = \alpha - \theta_2 - \theta_3, \quad (7)$$

where α is defined as the end-effector pose and θ_4 is the angle used to adjust the attitude pose of the end-effector. The forward kinematic equations described in (1)-(3) provide unique solution, however evaluation of inverse kinematics can be a tricky proposition; the solutions (4)-(7) may yield multiple solutions; however, only a few of them can be implemented on the manipulator based on range of rotation of the actuator and the geometry.

The configuration space is defined as the set of all valid joint variables which translate into a valid position / orientation of the manipulator. In a serially link chain, the range of motion of an actuator at a given point depends on the position of other actuators. This factor must be taken into consideration. Trajectory for the end-effector is generated by incorporating the kinematics into the widely considered polynomial functions as described in [12].

3. Hardware Implementation

The mechanical dimensions of the manipulator have been specified in section 2. The smart servo motors are serially connected in a daisy chain configuration, connected to the computer using USB to Dynamixel interface. Commands are applied to the motors using *Pyax12* library.

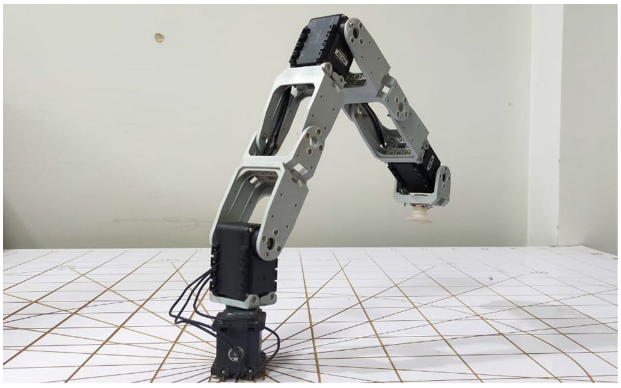

Figure 2: Physical implementation of 4 DoF Manipulator.

It is apparent from the operation of the robot that the manipulator suffers from positioning offset error due to effect of gravity on the mechanical structure of the manipulator. Since this effect is not considered during kinematic design, additional measures are required to mitigate these imperfections. A careful estimate of this offset error was obtained through the joint position feedback of the Dynamixel smart servos.

The offset error can be easily calculated as the difference of the joint angle value transmitted to and received from the servo motor. A set of 5 initial and 5 final points are arbitrarily selected. Details are provided in Table 2.

Table 2: Set of start and end points for calibration of end-effector positioning error (all units in cm)

it.	Start points	End point
10	(0,15,15),(15,0,-15), (-15,0,15),(18,18,15), (-18,18,15)	(0,25,5),(5,20,8), (10,15,11),(15,10,14), (20,5,7)

As the manipulator travels from every start point to an end point, the actual position of joint variable is obtained through telemetry. The error of each joint variable is calculated and this process is repeated iteratively over a set of selected points. The coordinate positioning error of the end-effector is calculated using the equations of forward kinematics. This allows us to calculate the accuracy of manipulator in cartesian space. It can be observed that after incorporating the correction factor the accuracy of manipulator in the cartesian space improved considerably. The magnitude of positioning error in cartesian space and joint variable error before and after correction is illustrated in the next section.

It is pertinent to note that the magnitude of offset error in z- axis is more substantial as compared to x and y axis due to gravitational pull. Likewise, the magnitude of rotation error of different servo motors is also different. The positioning error and joint angle errors before and after correction are illustrated in the next section.

4. Results

Hardware implementation results are in accordance with the theoretical model. Due to the structural limitations, the manipulator arm experiences an offset error. The manipulator also suffers from multiplicative error which is subject to the payload and position of the end-effector. Figure 3 illustrates the performance of the manipulator in the joint configuration space in the presence of offset error is quantified as Mean Squared Error (MSE), which is defined as $|\theta_i - \hat{\theta}_i|^2$, (with $\theta_i = \theta_1, \dots, \theta_4$) where θ_i and $\hat{\theta}_i$ are the desired and measured joint angle values respectively. Figure 4 presents the error performance of manipulator in joint variable space after correction of offset error. It is apparent that the compensation helps significantly reduce the MSE of θ_2 (the shoulder joint) which bears the thrust of the payload and arm itself.

The effect of these joint angle errors on the end-effector position is illustrated in figure 5. An offset in the position of end-effector is observed when solutions of inverse kinematics are applied forward kinematic equations (1)-(3) without any compensation. Figure 6 illustrates the positioning error after correction of the offset error.

After incorporating the correction factor, the positioning error in cartesian space in each dimension reduces to $x \pm 1.5mm$, $y \pm 1.8mm$ and $z \pm 3mm$ respectively.

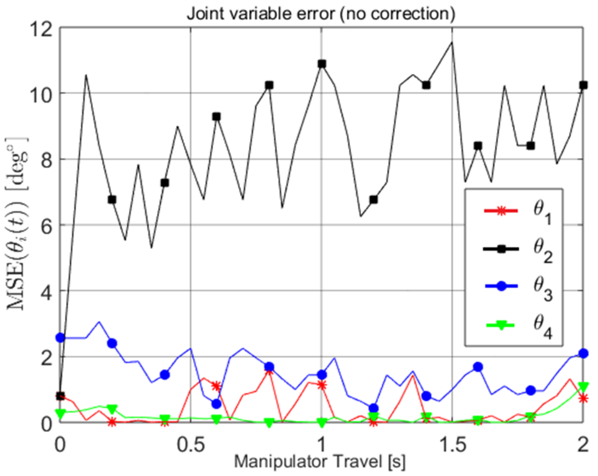

Figure 3. Joint variable MSE error during travel with no correction applied.

The real-time feedback of joint angle values is a very useful feature, this in conjunction with load sensing feature can allow for design of manipulator with precise control on velocity and orientation in the presence of variable loading conditions.

5. Conclusions

This work has proposed a low-cost, and highly configurable 4-DoF articulate manipulator using Dynamixel Ax-12/18 smart servo motors.

The proposed manipulator provides as an accurate, feature rich and cost-effective framework, which may serve as a test-bed for various control algorithms. Dynamic analysis plays an important role in control of the velocity and orientation of the end-effector as it traverses through a trajectory path; Computation of precise torque values for different joints while taking into the consideration the end-effector load and mass distribution of the manipulator frame should be explored further.

Acknowledgment

Authors would like to thank the Department of Electrical Engineering, Sukkur IBA University for providing necessary resources to carry out this research.

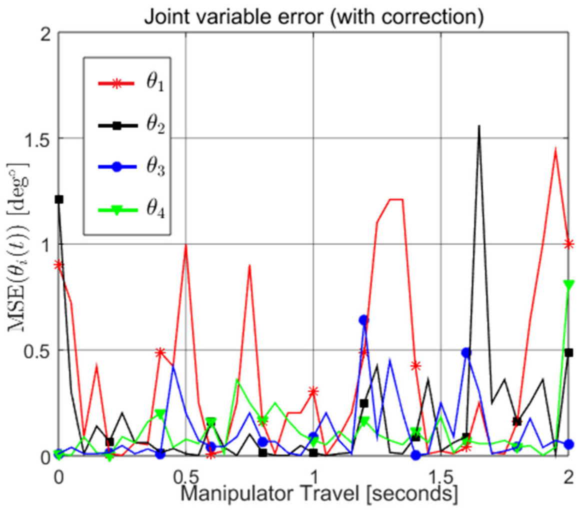

Figure 4: Joint variable MSE error during travel with correction applied.

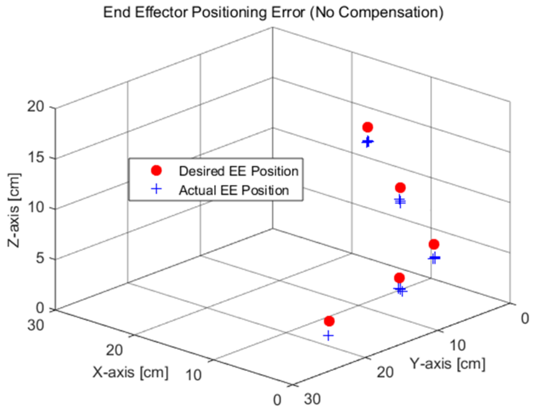

Figure 5. Joint variable error during travel with no correction applied.

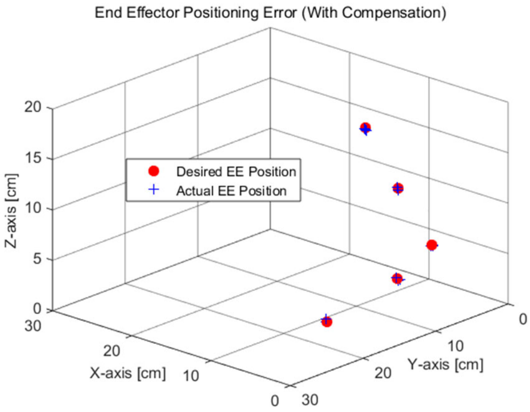

Figure 6. Joint variable error during travel with no correction applied.

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