Designing, Fabrication and Controlling Of Multipurpose 3-DOF Robotic Arm

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Abstract. In the present work, we have successfully designed and developed a 3-DOF articulated Robotic Arm capable of performing typical industrial tasks such as painting or spraying, assembling and handling automobiles parts and etc., in resemblance to a human arm. The mechanical assembly is designed on SOLIDWORKS and aluminum grade 6061-T6 is used for its fabrication in order to reduce the structure weight. We have applied inverse kinematics to determine the joint angles, equations are fed into an efficient microcontroller ATMEGA16 which performs all the calculations to determine the joint angles on the basis of given coordinates to actuate the joints through motorized control. Good accuracy was obtained with quadrature optical encoders installed in each joint to achieve the desired position and a LabVIEW based GUI is designed to provide human machine interface.

Index Terms— Robotic Arm, Inverse kinematics, Microcontroller ATMEGA16 and Human machine interface (HMI).

1. INTRODUCTION

Nowadays industries are growing rapidly and they require solutions through which they can increase their productivity with precision and lower labor cost. Robotics is playing an important role in this aspect; it provides efficient, faster, safer and cost effective means to fulfill the industrial needs according to industrial standards. Robotic Arms are widely used all over the world; they came into existence in 1945 when da Vinci designed its first 4-DOF Robotic Arm with analog board for controlling [1]. First industrial Robotic Arm was made by Unimate in 1961; it has successively advanced into the PUMA Arm. Robotic Arms are extensively used in manufacturing and automobiles industries for welding, drilling, cutting, pick & place, quality assurance, assembling, safety and security, surgery, painting etc. to achieve high performance and precision. Depending upon the applications, Robotic Arms can be use in different configurations which include articulated (having at least three rotary joint), SCARA (having two parallel rotary joints), Cartesian (having three prismatic joints coincident with the Cartesian coordinates), anthropomorphic robot (similar to the human hand having fingers and thumb) [2]. We have designed an articulated Robotic Arm because it closely resembles human arm. As the articulated configuration contains all revolute joints, its movement is similar to human arm and can reach all the points within its work envelope. Autonomous electro-mechanical systems are more beneficial for the industries as compared to manual systems. A light weight, autonomous, computer-controlled Robotic Arm was developed by Lygorous [3], a different approach was adopted by C. Flanagan for controlling the mobile Robot [4], and PIC16F877 micro-
controller based system was designed by Hisham to control a 6-DOF articulated Robotic Arm [5]. Computer vision [6] technique is used to make a system autonomous where high precision and accuracy is required. However, those systems which do not require high precision and accuracy can be alternatively implemented using ultrasonic range finders [7].

In this work, we have designed and fabricated multipurpose Robotic Arm using ultrasonic range finders for object detection and obstacle avoidance instead of computer vision to provide a low cost industrial Robotic Arm. We have provided the flexibility to our designed Robotic Arm for having rotation of base and arms at 180 degree and 90 degree respectively. Designing of structure is done on “SOLIDWORKS” and Aluminum is used to make a light-weight manipulator. Inverse kinematic [9, 10] equations are used to determine the joint angle on the basis of given coordinates to actuate the joints. Three DC motors with quadrature optical encoders [8] are installed in each joint to achieve the desired position.

A microcontroller ATMEGA16 [12] is used to performs all the calculations based on the codes written in C-language using compiler AVR STUDIO. Inverse kinematic equations are fed into the controller to actuate the DC motors in order to reach the Robotic Arm at the required coordinates/positions in the work envelope. The driving circuitry based on IRFZ44N MOSFETS operates on the PWM techniques to drive the motors. We have also incorporated a Human Machine Interface (HMI) using “LABVIEW” to provide user friendly environment. The designed Robotic Arm can be used in industries for multiple applications such as material handling, automobile painting and etc.

2. DESIGNING AND FABRICATION
2.1 Mechanical Design
The mechanical structure was designed in such a way that it will have to support all the algorithms that will be applied on it. This mechanical design was successfully carried out using SOLIDWORKS. The specifications are given in the following table.

| Parts         | Maximum Angle (Degrees) | Speed (rpm) | Weight (Kg) |
|---------------|-------------------------|-------------|-------------|
| Rotating Base | 180                     | 12 ± 10 %   | 4.08        |
| Primary Arm   | 90                      | (19 ± 3%) /36 | 1.2872     |
| Secondary Arm | 90                      | 15.5 ± 10%  | 1.292       |

**TABLE I. MECHANICAL STRUCTURE SPECIFICATIONS**

The payload of Robotic Arm is 0.5 Kg, its reach is 762mm (2.5 feet) and weight is nearly 10 Kg.

2.1.1 CAD Designing
2.1.1.1 Base of the Arm The base consists of two parts; fixed and rotary. The function of fixed base is to hold first motor which causes the the rotation of base. The rotating base contains mounting of second motor and worm gear which increases the torque of second motor and reduces the speed of primary arm.

Figure1: CAD model of (i) fixed base (ii rotating base)
2.1.1.2 Primary Arm The upper part of the arm has smaller radius as compared to that of lower part. It was done so that point of gravity comes closer to the base. Mounting of third motor which holds the secondary arm is shown in Fig 2, square box showing space for the mounting of third motor, the coupling between the second motor and primary arm is also shown.

2.1.1.3 Secondary Arm The geometry of the secondary arm is similar to that of primary arm.

2.1.2 End-effector A manual spray gun was automated by using a small DC motor. Since motor was not able to actuate the trigger of spray gun that’s why a spring was used to aid the motor so that motor can easily actuate the trigger of spray gun.

2.1.3 Final Assembly

2.2 Motors selection

2.2.1 Selection of motors After studying about stepper, servo & DC motors, we have chosen DC motors with optical encoders as they are easy to use, easy to control and maintain as compare to others

2.2.2 Torque calculations for the motors selection Torque calculation has been done according to the geometry of the structure and SOLIDWORKS has been used to determine the required parameters for calculation which are not easier to find manually. Total torque is given by,

\[ \tau_m = \tau_g + I \alpha \]

Where, \( \tau_m \) = Total torque, \( \tau_g \) = Holding Torque

\( I \) = Moment of Inertia, \( \alpha \) = Angular acceleration

\[ \tau_{m_1} = 2.96 \, Nm \, , \, \tau_{m_2} = 13.245 \, Nm \, , \, \tau_{m_3} = 3 \, Nm \]
2.2.3 Specification of Selected Motors
Operating Voltage of motors= 12 volts
No load current = 0.25A, 2.5A and 0.55A
Stall Torque= 30, 100, 30 Kg.cm
Since the minimum torque required for the second motor is 11.245Nm as per calculations but the purchased motor has the torque of 10 Nm therefore, a worm gear is used to achieve the desired torque.

2.3 Implementation of Forward and Inverse Kinematics

2.3.1 Transformation Matrix
The general transformation matrix [9] is,

\[
\begin{bmatrix}
c\theta_i & -s\theta_i & 0 & a_{(i-1)} \\
s\theta_i c\alpha_{(i-1)} & c\theta_i c\alpha_{(i-1)} & -s\alpha_{(i-1)} & -s\alpha_{(i-1)}d_i \\
s\theta_i s\alpha_{(i-1)} & c\theta_i s\alpha_{(i-1)} & c\alpha_{(i-1)} & c\alpha_{(i-1)}d_i \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Where,
1. \( s\theta_i = \sin(\theta_i) \)
2. \( c\theta_i = \cos(\theta_i) \)
3. \( a \) is the length along x-axis
4. \( d \) is the length along z-axis
5. \( \alpha \) is the angle about x-axis

Transformation matrix from U frame to 4 frame,

Total transformation from U frame to 4 can be obtained by multiplying all the matrices,

\[
u_{U4}^T = u_{U0}^T \cdot u_{T1}^T \cdot u_{T2}^T \cdot u_{T3}^T \cdot u_{T4}^T
\]

\[
u_{U1} = \begin{bmatrix}
c2s3 - c1s2s - c3s2 & s1 \cdot 1.7s1 - 3s1 - 16.922c1c2 + 25.5c1(c2s3 + c3s2) \\
c2s3 - s2s3 & -c2s3 - c3s2 - c1 \cdot -1.7s1 - 3s1 - 16.922c1s1 + 25.5s1(c2s3 + c3s2) \\
c2s3 + c3s2 & c2s3 - s2s3 & 0 \cdot 1.3779 - 16.922c3 + 25.5(c2s3 - c3s2) \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

2.3.2 Inverse Kinematics for base motor (\( \theta_1 \)):
The inverse of u to 0 transformation matrix is taken for the calculation of \( \theta_1 \),

\[
\theta_1 = \sin^{-1}(-1.7/\sqrt{Px^2 + Py^2}) + \tan^{-1}(Py/Px)
\]

2.3.3 Inverse Kinematics for secondary arm (\( \theta_3 \))

\[
\theta_3 = \sin^{-1}((936.6 - Px^2 - Py^2 - (Pz - 1.3779)^2 - 6Py s_1 - 6Pxc_1)/863.02)
\]
2.3.4 Inverse Kinematics for primary arm ($\theta_2$): For calculation of $\theta_2$, inverse kinematics as well as geometry has been used.

\[
\theta_2 = \sin^{-1}\left( \frac{P_z'}{r} \right) + \cos^{-1}\left( \frac{(16.922^2 + r^2 - 25.5^2)}{2 \cdot 16.922 \cdot r} \right)
\]

2.4 Electronic Controller Board

2.4.1 Motor Driver Circuit

An H-bridge circuit for controlling DC motor is designed. The circuit consists of four IRFZ44N, two IR2110 to drive the MOSFETs, Schmitt trigger circuitry for generating delayed and inverted PWM signal, diodes 1N5817 are used to provide the alternate path in case of back EMF and bootstrap capacitors are used to maintain $V_{GS}$ of 12 volt for each MOSFET.

Schmitt trigger 74hc14/7414

A single RC integrating circuit between the output and the input of an inverting Schmitt trigger produces a continuous square wave whose frequency depends on the values of $R$ and $C$, and the threshold points of the Schmitt trigger.

Circuit has frequency range of 1KHZ to 50KHZ. RCD values are perfectly all right for this frequency range. The mentioned diode direction is used to produce the positive dead time and both channels need dead time not just one. If the diode direction is reversed then you will have a negative dead time which is not required.

Layout for motor driving circuit is designed by using software “Circuit Wizard” and FR4 material is used for fabrication of PCB.

2.4.2 ATML AVR Microcontroller

Microprocessor and microcontroller act as the brain of the robot which tells it to perform tasks based on the inputs taken either from HMI or from the sensors. The overall operation of the robotic arm is controlled by programming the AVR microcontroller. Atmega16 [12] (8-bit microcontroller) is used because of its unique features including robustness, RISC architecture, high Endurance Non-volatile Memory segments, JTAG Standard Interface, Byte-oriented Two-wire Serial Interface, wide frequency range (0- 16 MHz), low power consumption and exclusive peripheral features.

The main features of Atmega16 which are used for the programming of robotic arm are:
- External Interrupts
- Three PWM channels
- USART
- EEPROM Data Memory

An LCD interface is also provided so that encoder count, joint angles or any other message can be displayed for the user.

2.4.3 LabVIEW Based GUI

LabVIEW oriented GUI is developed to make the system user friendly. User enters coordinates via GUI and three motors of robotic arm will actuate so that end-effector achieve the desired coordinates in space. GUI contains two buttons, one for sending $x$, $y$ and $z$-axis
values to microcontroller and other for terminating program, and three blocks for taking x, y and z-axis.

3. CONCLUSION

In this work, we have successfully designed and fabricated a multipurpose articulated Robotic Arm having 3-DOF capable to perform various industrial tasks. By utilizing the Inverse kinematic equations the designed Robotic Arm has performed the all designated tasks assigned in a selected work envelop. We have also provided a user friendly environment using LabVIEW to control the functions of this manipulator by an unskilled labor or a technician in an industry. In future, image processing can be used to provide vision, and PID controller can be applied to develop a fully automated Robotic Arm.

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