Design and Analysis of six DOF Robotic Manipulator

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Abstract. The robotic manipulators are nowadays used for many applications in the industries. This project involves the design and analysis of a six DOF manipulator for welding, pick and place application. We developed a robot in SolidWorks and analysed it motion, load withstanding capacity and path traceability. However, design and analysis of a robot involves modelling of it forward and inverse kinematics. We modelled the forward and inverse kinematics by D-H parameters. The proposed model makes it possible to control the manipulator to achieve any reachable position and orientation in an unstructured environment. The inverse kinematics provided many possible combinations of angles for a single end effector position. A GUI was created in MATLAB for studying the forward and inverse kinematics of the robot. It gave results with precision of 0.2 cm. the load analysis also gave the maximum load it can withstand 200 KN without permanent deformation. The approach presented in this work can also be applicable to solve the kinematics problem of other similar kinds of robot manipulators.

Keywords. Robot, Manipulator, MATLAB, kinematics, position.

1. Introduction

Nowadays robots are used in many areas like Industries, Hospitals, Warehouse, Harbours, etc.,. When it comes to industries mainly robotic manipulators are used extensively. Because it can carry heavy payloads and do work more faster and smarter than humans. These manipulators are introduced into the industries for increasing the productivity and quality of products in a greater extend. The modern commercial robotic systems are very complex. They are integrated with many sensors and actuators which, have many interacting DOF and most of them require user interfaces and programming tools. When it comes to designing a robotic arm first we have to design the mechanical structure and model its kinematics. While modelling the forward and inverse kinematics of a 5 DOF manipulator the singular problem was discussed after the forward kinematics is provided. For any given reachable position and orientation of the end-effector, the derived inverse kinematics will provide an accurate solution [11]. But inverse kinematics gave many possible positions and it was complex to solve as DOF increases.

The inverse kinematics solution of general SN(cylindrical robot with dome), CS (cylindrical robot), NR (articulated robot) and CC (selectively compliant assembly robot arm-SCARA, Type 2) robot manipulator belonging to each group mentioned above were provided as examples [8]. The inverse kinematics of the P2Arm, which makes it possible to control the arm to any reachable position in an unstructured environment. The strategies developed here could also be useful for solving the inverse
kinematics problem of other types of robotic arms [7]. The D-H parameters are used for solving robot kinematics. Here the forward and inverse kinematics of a KUKA KR-16KS robotic arm are studied for the forward kinematic modelling. A summary of calculation was obtained. Then a general D-H representation of forward and inverse matrix was obtained. Which was used for the welding operation movement based on KUKA KR-16KS robotic arm [1]. A 4-axis articulated robotic arm was developed and the describes the development of inverse kinematic models of the 4-axis robotic manipulator based on its arm equation. Finally, the results obtained from the analytical solutions are compared with the experimental results for a 4-axis articulated manipulator. Which were moreover similar [2]. A comparison of two robot postures with the same trajectory (path) and for the same length of time and establishing a computing code to obtain the kinematic and dynamic parameters. SolidWorks and MATLAB/Simulink software’s were used to check the theory and the robot motion simulation. The results of the simulations were discussed and an agreement between the two software’s was certainly obtained [14].

The problems of forward and inverse kinematics for the Aldebaran NAO humanoid robot was studied and the proposed solution using the Denavit-Hartenberg method, and the analytical solution of a non-linear system of equations. The main advantage of the proposed inverse kinematics solution compared to existing approaches is its accuracy, its efficiency, and the elimination of singularities. In addition, it suggest a generic guideline for solving the inverse kinematics problem for other humanoid robots [3]. An analytical solution for the forward and inverse kinematics of 5 DOF robotic arm was presented, to analyse the movement of arm from one point in space to another point. The 5 DOF robotic arm was a vertical articulated robot, with five revolute joints. This was solved using the D-H parameters method [4]. The kinematic models a 6 DOF robotic arms predicated on Denavit Hartenberg (DH) parametric scheme of robot arm position placement. The forward kinematic model has been validated using Robotics Toolbox for MATLAB while the inverse kinematic model has been implemented on a real robotic arm [12].

The kinematics model of an RA02 (4 DOF) robotic arm. The direct kinematic problem is addressed using both the Denavit-Hartenberg (DH) convention and the product of exponential formula, which is based on the screw theory. By comparing the results of both approaches, it turns out that they provide identical solutions. Finally, simulation results for the kinematics model using the MATLAB program based on the D-H convention are presented. Since the two approaches are identical [6]. The forward and inverse kinematic of 5 DOF and 6 DOF robotic manipulator. A movement flow planning is designed and further evaluate all the DH parameter to calculate the desire position and orientation of the end effector. Forward kinematics is simple to design but for inverse kinematic solution traditional method (iterative, DH notation, transformation) are used. And compare the result with analytical solution and see there were acceptable error [5]. Robotics toolbox provides a great simplicity to us dealing with kinematics of robots with the ready functions on it [8]. An articulated type industrial robotic arm was designed in SoildWorks software and load analysis was done in ANSYS software. In order to compensate the work, the kinematic analysis also performed in a 2-D scale through computer simulation. This shows the 2D plot for the different combinations of joint angle within its work envelope. The MATLAB simulation result has been compared with the theoretical analysis for various link positions and it has been found that both the results are in phase and have good agreement with each other [15].

Here only the robot is designed approximately in MATLAB software and kinematic analysis were done. In some cases the kinematic solutions of already present robots were given. They are not modelling the actual robots with its real dimensions. So, only the kinematic solutions for same kind of vary from each other. Now we are going the design a six axis robotic arm in SoildWorks software with actual dimensions of a robot in reality. Then we will export this model to MATLAB Simulink platform and model the forward and inverse kinematics analytically and compare it with algorithms available in the MATLAB robotic toolbox to validate the results.
2. Design of Six DOF Robotic Arm

A simple design was created with referred models from literature and online. The manipulator was designed using solid works software shown in figure 1. The factors such as Density, Tensile Strength, Yield Strength, Modulus of elasticity, Machinability and Weldability are considered for the process of material selection. The Aluminum 7075 t6 is chosen since its easy availability in market, good weldability and more yield Strength. It is also commonly used as building material in robots. So, the links are made of Aluminum 7075 t6 and Gray cast Iron is used for base and gripper tool because it absorbs high vibration and has low wear and tear. The FOS is 2.

![Figure1. Six DOF Manipulator](image1.png)

2.1. Forward Kinematics

In forward kinematics the joint angles of the robot is given then the end effector position of the robotic arm which is calculated using the kinematics equations. This six DOF robotic manipulator has 6 links and 6 angles. The length of links is

- Link 1 = 325 mm
- Link 2 = 600 mm
- Link 3 = 475 mm
- Link 4 = 360 mm
- Link 5 = 140 mm
- Link 6 = 70 mm

![Figure2. Manipulator Links](image2.png)
The representation of links and frame assignment of the manipulator is shown in the figure 2. The D-H parameter convention is used to assign coordinate frames to each joint of the robotic arm in a simple and consistent way. From these parameters, a homogeneous transformation matrix can be defined, which is useful for both forward kinematics and inverse kinematics of the robotic arm. The DH parameters for the 6 DOF robotic manipulator are calculated and shown in Table 1.

| Link | $a_i$ | $\theta_i$ | $d_i$ | $\alpha_i$ |
|------|-------|------------|-------|------------|
| 1    | 0     | $\theta_1$| 627   | 90         |
| 2    | 800   | $\theta_2$| 0     | 0          |
| 3    | 575   | $\theta_3$| 0     | 90         |
| 4    | 0     | $\theta_4$| 370   | -90        |
| 5    | 140   | $\theta_5$| 0     | 90         |
| 6    | 0     | $\theta_6$| 70    | 0          |

The transformation matrixes $T_1$, $T_2$, $T_3$, $T_4$, $T_5$, $T_6$ and Final transformation matrix $T$ are calculated based on the above D-H Table and it is shown as follows,

$$T_1 = \begin{bmatrix}
    c_1 & 0 & s_1 & 0 \\
    s_1 & 0 & -c_1 & 0 \\
    0   & 1 & 0 & 627 \\
    0   & 0 & 0 & 1
\end{bmatrix}$$ (1)

$$T_2 = \begin{bmatrix}
    c_2 & -s_2 & 0 & 800c_2 \\
    s_2 & c_2 & 0 & 800s_2 \\
    0   & 0 & 1 & 0 \\
    0   & 0 & 0 & 1
\end{bmatrix}$$ (2)

$$T_3 = \begin{bmatrix}
    c_3 & 0 & s_3 & 575c_3 \\
    s_3 & 0 & -c_3 & 575s_3 \\
    0   & 1 & 0 & 0 \\
    0   & 0 & 0 & 1
\end{bmatrix}$$ (3)

$$T_4 = \begin{bmatrix}
    c_4 & 0 & -s_4 & 0 \\
    s_4 & 0 & c_4 & 0 \\
    0   & 1 & 0 & 370 \\
    0   & 0 & 0 & 1
\end{bmatrix}$$ (4)

$$T_5 = \begin{bmatrix}
    c_5 & 0 & s_5 & 140c_5 \\
    s_5 & 0 & -c_5 & 140s_5 \\
    0   & 1 & 0 & 0 \\
    0   & 0 & 0 & 1
\end{bmatrix}$$ (5)

$$T_6 = \begin{bmatrix}
    c_6 & -s_6 & 0 & 0 \\
    s_6 & c_6 & 0 & 0 \\
    0   & 0 & 1 & 70 \\
    0   & 0 & 0 & 1
\end{bmatrix}$$ (6)
From solving the equations 1 to 7 we get the final transformation matrix $T$, which has $P_x$, $P_y$, $P_z$. This gives the position of the end effector. If the link parameters and joint angles are given the position of the end effector of the robotic manipulator can be found.

2.2. Inverse Kinematics

In Inverse kinematics if the end position is known that is the $P_x$, $P_y$, $P_z$ and the link parameters we can find all the joint angles using inverse kinematics. The inverse kinematics will give different combination of joint angles for a single position of end effector. By solving the equations 8 the results obtained are shown as follows,

$$ T = T1 * T2 * T3 * T4 * T5 * T6 $$

$$ T = \begin{bmatrix} n_x & o_x & a_x & P_x \\ n_y & o_y & a_y & P_y \\ n_z & o_z & a_z & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ T1 - 1 * T = T2 * T3 * T4 * T5 * T6 $$

$$ \theta_1 = \text{atan2d} (P_y, P_x) $$

$$ d = \sqrt{r_x^2 + r_y^2} $$

$$ r_4 = d - a_4 * \cos(\theta_{234}) $$

$$ z_4 = P_z - a_4 * \sin(\theta_{234}) $$

$$ s = \sqrt{(z_4 - a_1)^2 + r_4^2} $$

$$ \theta_3 = \text{acosd}((s^2 - a_2^2 - a_3^2)/(2 * a_2 * a_3)) $$

$$ \beta = \text{atan2d}(a_3 * \sin(\theta_3), a_2 + a_3 * \cos(\theta_3)) $$

$$ \alpha = \text{atan2d}(z_4 - a_1, r_4) $$

$$ \theta_2 = \alpha + \beta $$

$$ \theta_4 = \theta_{234} - \theta_3 - \theta_3 $$

$$ \theta_5 = \text{acosd}((( \sin(\theta_1) * P_x) - (\cos(\theta_1) * P_y))/(\sin(\theta_4) * a_5)) $$

$$ \theta_6 = \text{atan}(\cos(\theta_5) * \cos(\theta_4) * \sin(\theta_2 + \theta_3) + \sin(\theta_5) * \cos(\theta_2 + \theta_3) - \sin(\theta_4) * \cos(\theta_5) / (\cos(\theta_4) + \sin(\theta_4) * \sin(\theta_2 + \theta_3))) $$

3. Simulation and Creation of GUI

3.1. Conversion of SolidWorks Model Into MATLAB

The SolidWorks model of six DOF robotic manipulator is converted into simmechanics model in order to simulate the designed model in the Simulink environment. The final workable file in MATLAB which is created after this conversion is used for simulation in MATLAB is shown in the figure 3. By running this simulation, we can control the joint motion of the manipulator in MATLAB.
3.2. Creation of GUI

Here GUI is used for study of forward and inverse kinematics of the six DOF robotic manipulator simulation. The GUI is shown in the figure 4. Using this GUI, we can get and send data from various model. The GUI will start the simulation if we click the run button in the GUI. The data can be sent to the simulation file and can be obtained. We can use the GUI to control the six DOF robotic manipulator and calculate the forward kinematics and inverse kinematics.

![GUI](image)

**Figure 3.** Simmechanics model of the manipulator

**Figure 4.** GUI

In GUI if we enter the joint angles it will give the position of the end effector. The angles can be entered in the text boxes are can be changed used the sliders. If we enter the position of the end effector in the inverse kinematics panel in will calculate and give the joint angles for it. The GUI not only gives the values it also animates or moves the robotic manipulator in the simulation based upon the data to understand the performance of it. It is able to start, stop and animate the manipulator using the GUI.
4. Analysis of Manipulator

4.1. Kinematic Analysis

For kinematic analysis, the joint angles were given as inputs. These positions were given as inputs for forward kinematics and the joint angles were calculated. This was calculated for more than 100 different combinations of joint angles and these were compared. The comparison results show that the joint angles provided by inverse kinematics equation is not same as the joint angles given for forward kinematics calculation. Only 10% of the results are similar. Mostly the values of one or two joint angles varies in a single combination. A randomly selected 5 such combinations are shown in figure 5. Some joint values obtained by inverse kinematics contains the joint angles that exceeds the offsets of the joint angles.

4.2. Inverse Kinematics Algorithm

Since the results of the inverse kinematics equations we derived were not satisfactory we created a RigidBodyTree model of the manipulator using the robotics system toolbox. This model is used to calculate the forward kinematics of the manipulator. Here we have also used the Broyden-Fletcher-Goldfarb-Shanno (BFGS) gradient projection algorithm. Using this model, we validated the results of forward and inverse kinematics of the manipulator. The forward kinematics results from these models are compared in the figure 6. In the table only 5 results are compared from more than 100 results. The same for inverse kinematics is shown in figure 7 and 8.

| Equation Results | BFGS Algorithm | Peter Croke Model |
|------------------|----------------|-------------------|
| X (mm) | Y (mm) | Z (mm) | X (mm) | Y (mm) | Z(mm) |
| 1277.929 | -841.186 | 1029.450 | 1277.979 | 1029.150 | 1277.929 |
| 1017.415 | 1122.537 | 187 | 1017.315 | 1122.527 | 187 |
| 67.822 | -887.131 | -180.796 | 67.712 | -887.131 | -180.796 |
| -64.590 | 88.773 | -343.920 | -64.590 | 88.773 | -343.920 |
| -713.909 | 764.695 | -236.599 | -713.709 | 764.625 | -236.579 |

Figure 5. Forward Kinematics

Figure 6. Forward Kinematics Comparison
Thus, from comparing the results of forward kinematics got by the equation, by BFGS algorithm and Peter Croke Toolbox we can come to a conclusion that the End effector position we got are comparatively ± 0.2 mm imprecision. The results of inverse kinematics of BFGS Algorithm and Peter Croke model is same.

4.3. Load Analysis

This manipulator has been analysed for various displacement, stress, and strain of materials by applying different loads using SolidWorks software and shown in Table 2. Using mate controller and motion study in SolidWorks we animated the pick and place operation. In the animation the robot will be in home position initially then it will move to the objects position and picks it. Later it moves to the final position and places the object there and moves to the home position again. This manipulator is designed for both welding and pick and place application. When it comes to welding operation the manipulator must move in complex path to make a proper weld. We have designed a gripper tool for welding operation. The manipulator is shown in figure 9. This is attached with the manipulator to study how it traces a path. Here a circular path is constructed, and the manipulator is animated using the motion study to trace it. This robot is designed for pick and place application so, it important to know how much load the manipulator can handle and the results of it.

| Load Applied (kN) | Stress (N/mm²) | Strain | Displacement (mm) |
|-------------------|----------------|--------|-------------------|
| 100               | 2.412 e+02     | 2.257 e+03 | 2.518 e+01 |
| 150               | 3.629 e+02     | 3.383 e+03 | 3.777 e+01 |
| 200               | 4.597 e+02     | 4.377 e+03 | 4.852 e+01 |
| 250               | 7.737 e+02     | 7.562 e+03 | 8.257 e+01 |
The final model is analysed with the Equivalent stress. Four different loads have been applied to the manipulator are 100 KN, 150 KN, 200 KN, 250 KN. The load applied with the base of the robot as a fixed support. These highest stresses are found in the sharp corner near the joints of the manipulator. The deformation behavior is also noted for the model that the maximum displacements are found in link 5 and link 4. The deformed structure after the application of stress will be noted for precautions in design with some tolerances to be given in the design. Analysis of Strain will give complete details on material properties and their load withstanding capabilities. Strains are maximum at the sharp edges of link 2. The strain has no unit. It is a dimensionless. If the edges are smooth then the strain will be less in edges.

Since the Factor of Safety is 2 the maximum load that can be applied is limited to 100 KN. This load analysis shows that as the load applied to the manipulator increases the maximum stress and strain are found near the links joints. Especially the stress and strain near the joint between link 3 and link 4 is significantly high. When the load is increased further the location of maximum stress and strain is found near the edges of link 2 near the joint between link 1 and link 2. This Stress is higher than the stress found between link 3 and link 4. This shows a change in the location of maximum stress and strain in the manipulator as the load increases. We have to change the design of the link as there will be less stress and strain near the joints. The strain for 250 KN is 7.562-03. This will not affect the manipulator. If we have to reduce the strain then we have to redesign the links edges. It is better to design all the links as hollow structure as link 3.

5. Conclusion

The six DOF robotic manipulator was successfully designed in SolidWorks for welding, pick and place application. A teach pendant for study the forward and inverse kinematics of the six DOF robotic manipulator is done. The forward and inverse kinematics was modelled and was implemented in GUI for studying the performance of the robotic manipulator. The inverse kinematics is comparatively complex has the DOF increases. An experimental analysis was done by calculating the end effector position for various joint angles and the joint angles for various position of end effector using the forward and inverse kinematics with the help of GUI. The joint angles obtained in the inverse kinematics had many combinations for a single manipulator position. The Results obtained have a precision of about ±.2mm.

We also studied the motion analysis, path tracing, load analysis for the manipulator in SolidWorks. The animation of motion analysis for pick and place operation is created in SolidWorks. The Path tracing animation which is used to verify the welding application is also created. The highest strain for a load of 250 KN is 7.562e-03 was developed in sharp edges near the joints in the manipulator. The stress which caused this strain exceeds the yield strength of the material used. So, we can conclude
that we can apply load less than 100 KN to the manipulator. In order to reduce the strain, we have to smooth the sharp edges of the links near the joints. We can also change the material selected or design all the links as hollow structures.

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