International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:1, No:4, 2007

Kinematic Modelling and Maneuvering of A 5-Axes Articulated Robot Arm

T.C. Manjunath

***Abstract*—**This paper features the kinematic modelling of a 5-axis stationary articulated robot arm which is used for doing successful robotic manipulation task in its workspace. To start with, a 5-axes articulated robot was designed entirely from scratch and from indigenous components and a brief kinematic modelling was performed and using this kinematic model, the pick and place task was performed successfully in the work space of the robot. A user friendly GUI was developed in C++ language which was used to perform the successful robotic manipulation task using the developed mathematical kinematic model. This developed kinematic model also incorporates the obstacle avoiding algorithms also during the pick and place operation.

***Keywords*—**Robot, Sensors, Kinematics, Computer, Control, PNP, LCD, Software.

I. INTRODUCTION

IMAGINE a day in your life when you wake up in the morning and find a machine walking up to you and saying "GOOD MORNING SIR ! Have a cup of tea". How would you respond to such a situation ? With so much progress made in the field of science, engineering and technology, this dream is absolutely realizable in the automation age with the advent of robotization. Robotics, thus became an interdisciplinary field which mixed various engineering disciplines into one. Keeping in pace with the current technology, we have designed and fabricated a stationary 5-axes articulated robot as shown in the Fig. 1. This fabricated unit is used to perform a brief kinematic analysis and further used to perform a PNP task without human intervention using sensors[12].

In this paper, a unique 5 axes articulated system was also simulated in MATLAB using the available toolboxes and a user friendly GUI in C++ is developed for doing the pick and place task on the computer screen. Once, it is successful in the simulation stage, then the same PNP task is transformed into the reality stage using the designed robot to verify the simulated results [13].

The paper is organized as follows. In section 2, a brief introduction about the designed and fabricated robotic manipulator is given. Sections 3 and 4 discusses about the direct kinematic modelling along with the mathematical treatment along with the development of the link coordinate diagram and the kinematic parameters. Finally, the conclusions are presented in the last section followed by the references.

II. DESIGNED & FABRICATED SYSTEM

The simulated robot is a 5 DOF stationary articulated robot arm having base, shoulder, elbow, tool pitch and tool roll and consisting of only rotary joints [1]. The robot design consisted of three parts, viz., mathematical modelling, mechanical design, electronic design and the software design [14]. There are 5 joints, 5 axis (3 major axes - base, shoulder elbow : to position the wrist and 2 minor axis - pitch and roll : to orient the gripper in the direction of the object). Since n = 5 ; 20 kinematic parameters are to be obtained and 6 unit frames are to be attached to the various joints [2] as shown in the link coordinate diagram in Fig. 2.

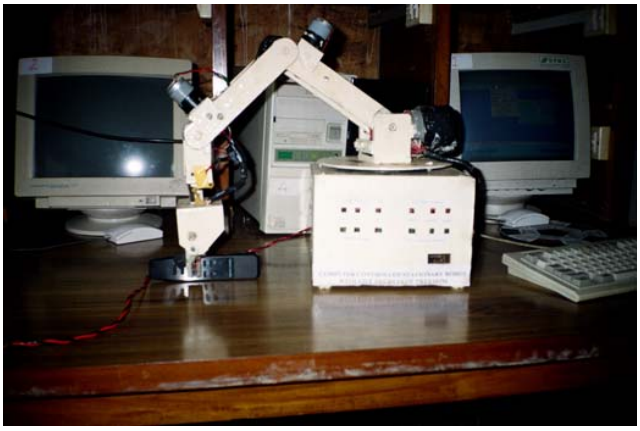


Fig. 1 Indigenously developed 5-axes articulated robot.

The vector of joint variables is given by [1]

$$q = \{\theta_1, \theta_2, \theta_3, \theta_4, \theta_5\}^T.$$

The vector of joint distances are given by [1]

$$d = \{d_1, d_2, d_3, d_4, d_5\}^T = \{25, 0, 0, 0, 15\}^T \text{ cm}.$$

The vector of link lengths are given by [1]

$$a = \{a_1, a_2, a_3, a_4, a_5\}^T = \{0, 23, 22, 8, 0\}^T \text{ mm}.$$

The vector of link twist angles are given by [1]

$$\alpha = \{\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5\}^T = \{-90°, 0, 0, 90°, 0\}^T.$$

L_0 to L_5	: Six unit frames.
d_5	: Tool length
q_1 to q_5	: Joint variables ($q = \theta$)
p	: Tool-tip
d_1	: Height of shoulder from base
1 , 2 , 3 , 4 , 5	: Rotary joints
a_2 a_3 , a_4	: Link lengths

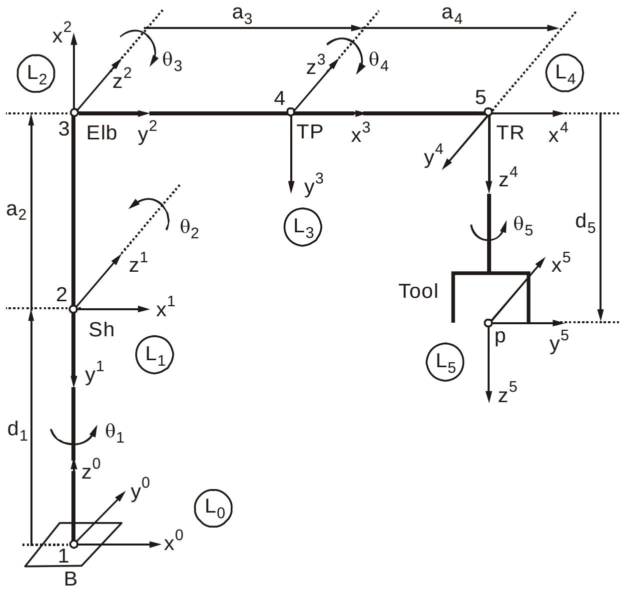


Fig. 2 Link coordinate diagram of the robot arm [1]

The designed robot is a educational five axis articulated table-top robot entirely designed and fabricated and is having a non-spherical wrist, i.e., the pitch and the roll axes meets at different points. The five axes are : five DOF - Base, Shoulder, Elbow, Pitch, Roll and no Tool Yaw. Base motor is mounted vertically on a horizontal plane. Shoulder, elbow, tool pitch motors are mounted horizontally on the base [16]. The tool roll and grip motors are mounted at the wrist joint and are very small. Base axis is fixed and is vertical, while the shoulder, elbow and tool pitch axes are horizontal and rotates about the base axes, i.e., the base and shoulder are perpendicular, shoulder and elbow are parallel, elbow and pitch are parallel, while the pitch and roll are perpendicular [17]. All the joints are rotary / revolute / articulated in nature, $q = \theta$ is the joint variable.

Our designed robot is computer controlled and electrically driven and is shown in the one line diagram in Fig. 2. It uses D.C. servos and incremental encoders and open loop control / closed loop control, electrically driven, uses PTP control and the load shaft precision is very good. Power is transmitted to the shoulder, elbow and tool pitch using gears and chains. The power transmission devices are the chains and gears [7].

The designed and fabricated robot is used for illustrating the theoretical concepts and practical concepts relating to a robot and to perform some laboratory experiments. Each axis is driven by a DC servomotor (with built in gears) that has a incremental encoder attached to the high speed shaft. The encoders resolve the high speed position to 60°. Since , each motor has a built in gear head with a turns ratio of 66.1 : 1 or 96 : 1, this results in a precision for each load shaft of 0.624° / count [18].

There are 20 kinematic parameters and 6 RHOCF's in the Link Coordinate Diagram (LCD) shown in Fig. 2. Each joint has its own set of sprocket and chains which then determine the joint angle precision [15]. There are three links a_2 and a_3 and a_4. The height of the shoulder from the base is d_1 and the tool / gripper length is d_5. d_1 is the height of the shoulder from the base which can be seen in Fig. 4.

III. Direct Kinematic Analysis Algorithm & the Kinematic Moel

Given the joint variable vector q (θ for rotary joint) and the Geometrical Link Parameters (GLP - physical dimensions of the robot arm : constant for a given robot), finding the position p of the tip of the gripper and the orientation R of the gripper of the robot arm w.r.t. base of the robot from the reference position is called as *direct kinematics* as shown in Fig. 3. To solve the DKP means to find the p and R of the tool w.r.t. base [1].

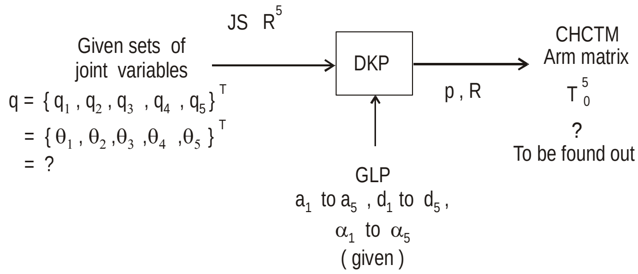


Fig. 3 Direct kinematic input-output model of the designed robot arm

To find the position and orientation of the robot arm means, we have to find a matrix called as the *arm matrix*, i.e., the composite homogeneous coordinate transformation matrix, which is a (4 × 4) matrix [19]. How does this matrix give the position and orientation of the robot w.r.t. base from the reference position ? The 1st three columns gives the three possible orientations (Yaw, Pitch, Roll) of the gripper and the last column gives the position of the tip of the gripper 'p' , thus solving the DK problem. If we give this matrix as input to the robot, the robot will go and stop in that particular position and in that particular orientation [1].

TABLE I Kinematic parameter table of the developed robot

Axis	**Type**	θ_k	d_k	a_k	α_k	**SHP**
1	Base	θ_1	d_1	0	$-\pi/2$	0
2	Shoulder	θ_2	0	a_2	0	$-\pi/2$
3	Elbow	θ_3	0	a_3	0	$\pi/2$
4	Tool pitch	θ_4	0	a_4	$-\pi/2$	0
5	Tool roll	θ_5	d_5	0	0	$-\pi/2$

A. Direct kinematic algorithm :

- Draw the SLD of the designed robot with links represented by straight lines ; joints by small circles called as nodes [8].

- Using 1st pass of DH algorithm, assign (5 + 1) = 6 right handed orthonormal coordinates L_0 to base, L_1 to shoulder, L_2 to the elbow, L_3 to the tool pitch, L_4 to tool roll, L_5 to the tip of the gripper, 'p' as shown in the Fig. 2 [20].

- Using 2nd pass of the DH algorithm, find the (4 × 5) = 20 KP's and obtain the kinematic parameter table KPT as shown in the table 1 [21].

- Put k = 1 to 5 and the different rows of the KPT in the general link coordinate transformation matrix T_{k-1}^{k} and obtain the various fundamental homogeneous coordinate transformation matrices T_0^1, T_1^2, T_2^3, T_3^4, T_4^5.

- Since n > 4, partition the arm matrix T_0^5 at the wrist so that we get two wrist partitioned matrices [22]. One which gives the position and orientation of the wrist w.r.t. the base, i.e., T_0^3 and the other which gives the position and orientation of the gripper w.r.t. the wrist , i.e., T_3^5.

- Multiply the first three fundamental HCTM's T_0^1, T_1^2, T_2^3. Obtain the arm matrix $T_0^3 = T_0^1 \ T_1^2 \ T_2^3$

  Multiply the next two fundamental HCTM's T_3^4, T_4^5. Obtain the arm matrix $T_3^5 = T_3^4 \ T_4^5$

  Multiply the two wrist partitioned matrices, T_0^3 and T_3^5 to obtain the output of direct kinematic problem, i.e., T_0^5.

- Substitute the soft home position - SHP angles (last column of KPT) in the computed arm matrix T_0^5 and compute T_0^5 in the home position. Verify the LCD & get the arm equations which are very useful in the kinematic modelling [1], [23].

B. Arm Matrix

- The arm matrix is divided into three parts, viz., first partitioned matrix T_0^3, second partitioned matrix T_3^5 and the final arm matrix T_0^5 [9], [24].

- To find the position p and orientation R of gripper w.r.t. base , use successive HCTM' s starting from the tip of the gripper and ending at the base [1], [25]

$$T_{Base}^{Tool}(q) = T_{Base}^{Shoul} \ T_{Should}^{Elbow} \ T_{Elbow}^{Pitch} \ T_{Pitch}^{Roll} \ T_{Roll}^{Tip} \quad (1)$$

$$T_0^5 = T_0^1 \ T_1^2 \ T_2^3 \ T_3^4 \ T_4^5. \quad (2)$$

$$T_0^5 = \left[T_0^1 \ T_1^2 \ T_2^3\right]\left[T_3^4 \ T_4^5\right] \quad (3)$$

$$T_0^5 = T_0^3 \ T_3^5 \quad (4)$$

$$T_{Base}^{Tool\text{-}tip} = T_{Base}^{Wrist\ (Pitch)} \ T_{Wrist\ (Pitch)}^{Gripper\text{-}tip} \quad (5)$$

$$f\begin{pmatrix} \theta_1 & \theta_2 \\ \theta_3 & \theta_4 \\ \theta_5 & \end{pmatrix} \quad f\begin{pmatrix} \text{major axes} \\ \theta_1 \quad \theta_2 \quad \theta_3 \end{pmatrix} \quad f\begin{pmatrix} \text{minor axes} \\ \theta_4 \quad \theta_5 \end{pmatrix}$$

C. Computation of the First Wrist Partitioned Arm Matrix

$$T_0^3 = T_0^1 \ T_1^2 \ T_2^3 \quad (6)$$

$$= \begin{bmatrix} C_1 & 0 & -S_1 & 0 \\ S_1 & 0 & C_1 & 0 \\ 0 & -1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_2 & -S_2 & 0 & a_2 C_2 \\ S_2 & C_2 & 0 & a_2 S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_3 & -S_3 & 0 & a_3 C_3 \\ S_3 & C_3 & 0 & a_3 S_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_1C_2 & -C_1S_2 & -S_1 & a_1 C_1 C_2 \\ S_1C_2 & -S_1S_2 & C_1 & a_1 S_1 S_2 \\ -S_2 & -C_2 & 0 & d_1 - a_2 S_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_3 & -S_3 & 0 & a_3 C_3 \\ S_3 & C_3 & 0 & a_3 S_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_1(C_2C_3-S_2S_3) & -C_1(S_2C_3+C_2S_3) & -S_1 & C_1\{a_3(C_2C_3-S_2S_3)+a_2C_2\} \\ S_1(C_2C_3-S_2S_3) & -S_1(S_2C_3+C_2S_3) & C_1 & S_1\{a_3(C_2C_3-S_2S_3)+a_2C_2\} \\ -(S_2C_3+C_2S_3) & -(C_2C_3+S_2S_3) & 1 & d_1-a_2S_2-a_3(S_2C_3+C_2S_3) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_0^3 = \begin{bmatrix} C_1 C_{23} & -C_1 S_{23} & -S_1 & C_1(a_2 C_2 + a_3 C_{23}) \\ S_1 C_{23} & -S_1 S_{23} & C_1 & S_1(a_2 C_2 + a_3 C_{23}) \\ -S_{23} & -C_{23} & 0 & d_1 - a_2 S_2 - a_3 S_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

This matrix T_0^3 gives position and orientation of the wrist (pitch) coordinate frame L_3 w.r.t. the base frame L_0.

To check this whether the matrix obtained is correct or not, evaluate it at the Soft Home Position [SHP] by putting the values of the angles given in the last column of KP table in T_0^3 ;

i.e., put $q = [\ 0\ , -90°\ , 90°\ ]^T = \{q_1\ , q_2\ , q_3\}^T$ in the computed T_0^3 matrix, we get ;

$$T_0^3\,(\text{home}) = \begin{bmatrix} 1 & 0 & 0 & a_3 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & d_1 + a_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_0^3 = \begin{bmatrix} R_{11} & R_{12} & R_{13} & p_1 \\ R_{21} & R_{22} & R_{23} & p_2 \\ R_{31} & R_{32} & R_{33} & p_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

Note that this is coincident from the LCD shown in Fig. 2, hence the LCD is also verified [1], [25].

D. *Computation of the Second Wrist Partitioned Arm Matrix*

$$T_3^5 = T_3^4 \quad T_4^5 \tag{9}$$

$$T_3^5 = \begin{bmatrix} C_4 & 0 & -S_4 & a_4 C_4 \\ S_4 & 0 & C_4 & a_4 C_4 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_5 & -S_5 & 0 & 0 \\ S_5 & C_5 & 0 & 0 \\ 0 & 0 & 1 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_4 C_5 & -C_4 S_5 & -S_4 & a_4 C_4 - d_5 S_4 \\ S_4 C_5 & -S_4 S_5 & C_4 & a_4 S_4 + d_5 C_4 \\ -S_5 & -C_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

This matrix T_3^5 gives the position and orientation of the tip coordinate frame L_5 w.r.t. the wrist coordinate frame L_3.

To check this whether the matrix obtained is correct or not, evaluate it at the Soft Home Position [SHP] by putting the values of the angles given in the last column of KP table in T_3^5, i.e., put $q = \{ 0 , -90°\}^T = \{q_4 , q_5 \}^T$ in the computed T_3^5, we get [11], [26];

$$T_3^5 \text{(home)} = \begin{bmatrix} 0 & 1 & 0 & a_3 \\ 0 & 0 & 1 & d_5 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^5 = \begin{bmatrix} R_{11} & R_{12} & R_{13} & p_1 \\ R_{21} & R_{22} & R_{23} & p_2 \\ R_{31} & R_{32} & R_{33} & p_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

Note that this is coincident from the LCD. Thus, the LCD is also verified.

E. *Computation of the Final Arm Matrix / CHCTM,* T_0^5

To compute the final arm matrix ; multiply the two wrist partitioned matrices T_0^3 and T_3^5 given by Eqs. (7) and (10). Simplify the arm matrix by using some assumptions as

$$T_0^5 = T_0^3 \quad T_3^5$$

$$= \begin{bmatrix} C_1 C_{23} & -C_1 S_{23} & -S_1 & C_1 (a_2 C_2 + a_3 C_{23}) \\ S_1 C_{23} & -S_1 S_{23} & C_1 & S_1 (a_2 C_2 + a_3 C_{23}) \\ -S_{23} & -C_{23} & 0 & d_1 - a_2 S_2 - a_3 S_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_4 C_5 & -C_4 S_5 & -S_4 & a_4 C_4 - d_5 S_4 \\ S_4 C_5 & -S_4 S_5 & C_4 & a_4 S_4 + d_5 C_4 \\ -S_5 & -C_5 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_1 C_{234} C_5 + S_1 S_5 & -C_1 C_{234} S_5 + S_1 C_5 & -C_1 S_{234} & C_1 (a_2 C_2 + a_3 C_{23} + a_4 C_{234} - d_5 S_{234}) \\ S_1 C_{234} C_5 - C_1 S_5 & -S_1 C_{234} S_5 - C_1 C_5 & -S_1 S_{234} & S_1 (a_2 C_2 + a_3 C_{23} + a_4 C_{234} - d_5 S_{234}) \\ -C_5 S_{234} & S_{234} S_5 & C_{234} & d_1 - a_2 S_2 - a_3 S_{23} - a_4 S_{234} - d_5 S_{234} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_0^5 = \begin{bmatrix} R_{11} & R_{12} & R_{13} & p_1 \\ R_{21} & R_{22} & R_{23} & p_2 \\ R_{31} & R_{32} & R_{33} & p_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{12}$$

To check this matrix whether it is correct or not, evaluate it at SHP, by putting the SHP angles which are given in the last column of the KPT in this computed final arm matrix, T_0^5, i.e., $q = \{ q_1 , q_2 , q_3 , q_4 , q_5\}^T = \{ \theta_1 , \theta_2 , \theta_3 , \theta_4 , \theta_5\}^T = \{ 0°, -90°, 90° , 0° , 90° \}^T$ in T_0^5. Check that the norms of the rotation matrix of T_0^5. They are all unity. This arm matrix T_0^5 given by Eq^n (12) is the output of direct kinematics of the designed five axes articulated robot arm, thus giving the position and orientation of the gripper w.r.t. base . The 1st three columns gives the orientation of the frame L_5 w.r.t. base, while the last column gives the position of the tip of the gripper p w.r.t. base, thus obtaining a unique direct kinematic model of the designed robot [1], [27].

$$T_0^5 \text{ (SHP)} = \begin{array}{c} \\ x^0 \\ y^0 \\ z^0 \\ \\ \end{array} \begin{array}{c} \begin{array}{cccc} x^5 & y^5 & z^5 & p \end{array} \\ \begin{bmatrix} 0 & 1 & 0 & a_3 + a_4 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & d_1 + a_2 - d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{array}$$

Obtain the arm equations by equating $T_0^5 = T_0^5$ (SHP).

$R_{11} = C_1 C_{234} C_5 + S_1 S_5 = 0$

$R_{21} = S_1 C_{234} C_5 - C_1 S_5 = 1$

$R_{31} = - C_5 S_{234} = 0$

R_{21} = $-C_1S_5C_{234} + S_1C_5 = 1$
R_{22} = $-S_1S_5C_{234} - C_1C_5 = 0$
R_{32} = $S_{234}S_5 = 0$
R_{31} = $-C_1S_{234} = 0$
R_{32} = $-S_1S_{234} = 0$
R_{33} = $-C_{234} = -1$
p_1 = $C_1(a_2C_2 + a_3C_{23} + a_4C_{234} - d_5S_{234}) = a_3 + a_4$
p_2 = $S_1(a_2C_2 + a_3C_{23} + a_4C_{234} - d_5S_{234}) = 0$
p_3 = $d_1 - a_2S_2 - a_3S_{23} - a_4S_{234} - d_5C_{234} = d_1 + a_2 - d_5$

We get 12 kinematic non-linear equations in five unknowns (Base, Shoulder, Elbow, Pitch, Roll). The final arm matrix T^{Tip}_{Base} can be used to find the position and orientation of the robot arm by giving the values of the joint variables and the geometric link parameters, viz., a's and d's [1], [10], [28].

IV. Development of the LC Diagram

(1) Skeletal Drawing : Draw the SLD of the robot with links represented by straight lines and joints represented by small circles called as nodes. Number the joints as J_1, J_2, J_3, J_4, J_5. Name the joints as B , S , E , P , R and the gripper-tip as p.

(2) Base Coordinate Frame : Assign a RHOCF L_0 to the base – F, $L_0 = \{x^0, y^0, z^0\}$.
z^0 along the axis of J_1 (Base) ; vertically up ↑
$x^0 \perp$ to z^0.
Complete the frame L_0 by adding y^0 such that the RHOCF property is satisfied.

(3) Shoulder Coordinate Frame : Set k = 1 ; Assign a RHOCF L_1 to the shoulder - M. $L_1 = \{x^1, y^1, z^1\}$.
z^1 along the axis of J_2 (Shoulder) ; into the plane of the paper '→' (select z^1 inwards).
$\because z^1 \perp z^0$, assign x^1 such that it is $\perp$ to both z^0 as well as z^1.
Complete the frame L_1 by adding y^1 such that the RHOCF property is satisfied.

(4) Elbow Coordinate Frame : Set k = 2 ; Assign a RHOCF L_2 to the Elbow - M. $L_2 = \{x^2, y^2, z^2\}$.
z^2 along the axis of J_3 (Elb) ; into the plane of the paper '→' (select z^2 inwards).
$\because z^2$ is $||^{ell}$ to z^1, assign x^2 such that it is pointing away from z^1 or along the common normal joining the two joint axes z^1 and z^2 [33]
Complete the frame L_2 by adding y^2 such that the RHOCF property is satisfied.

(5) Pitch Coordinate Frame : Set k = 3 ; Assign a RHOCF L_3 to the tool pitch - M. $L_3 = \{x^3, y^3, z^3\}$.
z^3 along the axis of J_4 (pitch) ; into the plane of the paper '→' (select z^3 inwards).
$\because z^3$ is $||^{ell}$ to z^2, assign x^3 such that it is pointing away from z^2 or along the common normal joining the two joint axes z^2 and z^3.
Complete the frame L_3 by adding y^3 such that the RHOCF property is satisfied [29].

(6) Roll Coordinate Frame : Assign a RHOCF L_4 to the tool roll - M. $L_4 = \{x^4, y^4, z^4\}$.
z^4 along the axis of J_4 (roll) ; vertically ↓ or ↑ (select z^4 downwards).
$\because z^4 \perp z^3$, assign x^4 such that it is $\perp$ both to z^3 as well as z^4.
Complete the frame L_4 by adding y^4 such that the RHOCF property is satisfied [30].
k = n =5 ; Is 5 < 5 **?** No . Stop the iteration and come out of the loop and assign the last coordinate frame to p.

(7) Tool / Hand Coordinate Frame HCF : Assign the last coordinate frame L_5 to the tool-tip p - M.
z^5 along the approach vector r^3 ; ↓ (select z^5 downwards , since EE is facing downwards) [34].
y^5 along the sliding vector r^2, i.e., along the open / close axis of the gripper.
x^5 along the normal vector r^1 or $x^5 \perp^r y^5 \perp^r z^5$ or complete the frame L_5 by adding x^5 such that the RHOCF property is satisfied [1].

V. Development of the KP Table

(8) Joint variables : Put k = 1 , 2 , 3 , 4 , 5 ;
Compute θ_k as the angle of rotation about z^{k-1} needed to make x^{k-1} parallel with x^k.
Vector of joint variables :
$q = \{q_1, q_2, q_3, q_4, q_5\}^T$
$= \{\theta_1, \theta_2, , \theta_3, \theta_4, \theta_5\}^T$
$= \{0°, -90°, 90°, 0°, 90°\}^T$.

(9) Joint distances : Put k = 1 , 2 , 3 , 4 , 5 ;
Compute d_1, d_2, d_3, d_4, d_5 as the translation along z^{k-1} needed to make x^{k-1} intersect / aligned with x^k.
Vector of joint distances :
$d = \{d_1, d_2, d_3, d_4, d_5\}^T$
$= \{25, 0, 0, 0, 15\}^T$ cm.

(10) Link lengths Put k = 1 , 2 , 3 , 4 , 5 ;
Compute a_1, a_2, a_3, a_4, a_5 as the translation along x^k needed to make z^{k-1} intersect / aligned with z^k.
Vector of link lengths :
$a = \{a_1, a_2, a_3, a_4, a_5\}^T$
$= \{0, 23, 22, 8, 0\}^T$ cm.

(11) Link twist angles Put k = 1 , 2 , 3 , 4 , 5 ;

Compute α_k as the amount rotation about x^k needed to make z^{k-1} parallel with z^k.

Vector of link twist angles :

$$\alpha = \{ \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5 \}^T$$
$$= \{ -\pi/2, 0, 0, -\pi/2, 0 \}^T \text{ rads} .$$

Since n = 5, we get 20 KP's. Tabulate all the KP's neatly in the form of a table called as KPT. The KP Table is shown in Table 1. From this KPT, we see that 8 out of 20 KP's are zeros and hence, the robot what we have designed has become a kinematically simple robot [1].

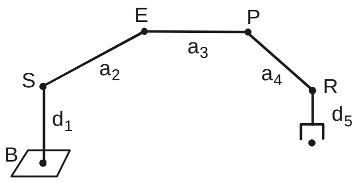


Fig. 4 One line diagram depicting the kinematic parameters of the designed robot.

VI. Simulation Results

A user friendly GUI was developed in C++ and the graphical model of the developed system was obtained on the screen. The homing of the system was also done using the in-built limit switches and sensors [31]. The software module application facilitates the user interaction with the system and has many in built features such as the security and authentication. The software is designed for maximum robot control & working efficiency. It is so designed that the user can have complete control over each movable part of the robot [6]. When the control software is executed, the default GUI screen appears as shown in the Figs. 5 and 6.

For activating a particular motion, the input variables can be entered and the program can be run and the robot comes from the home position as shown in the Fig. 5, picks up the object as shown in the Fig. 7(a) and keeps it at the appropriate place position as shown in the Fig. 7(b). The software is integrated with the system in real time such that when the input variables such as the angles are given to the computer, these variables along with the physical dimensions are processed by the kinematic model and the robot goes and stops at that specified position and orientation [32].

VII. Conclusions

A unique 5-axes articulated system was used to obtain the kinematic model of the same and was used to perform a successful pick and place task using a user-friendly developed graphical user interface and real time implementation. The simulated results were exactly verified with implementation results, thus demonstrating a effective PNP manipulation.

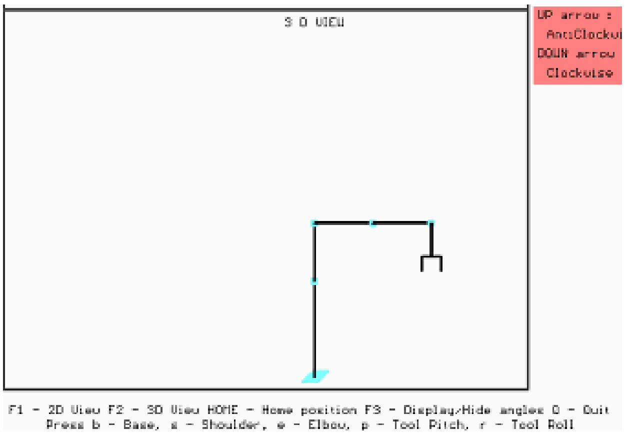


Fig. 5 One line diagram depicting the kinematic chain in the soft home position of the robot

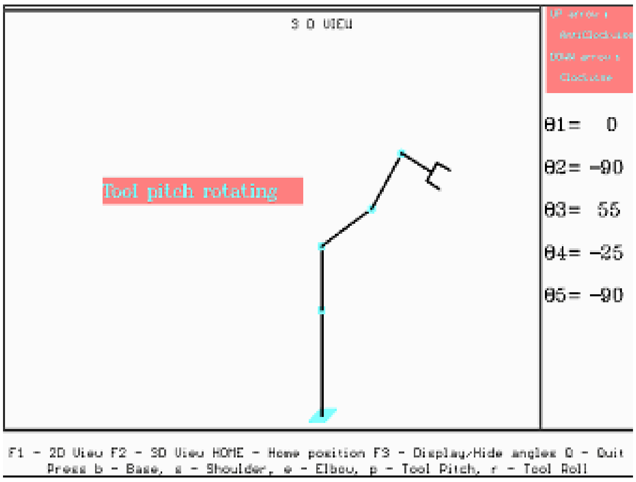
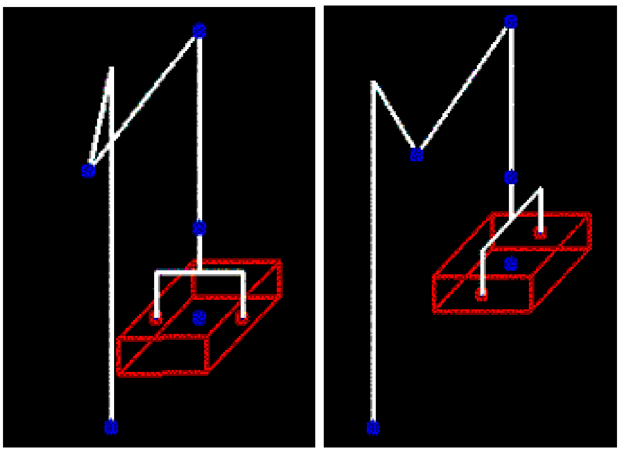


Fig. 6 One line diagram depicting the kinematic modelling in the GUI



Figs. 7 (a) and 7(b) Simulation and real time implementation of the pick and place operation

REFERENCES

[1]. Robert, J.S., "Fundamentals of Robotics : Analysis and Control", *PHI*, New Delhi., 1992.

[2]. Klafter, Thomas and Negin, "Robotic Engineering", *PHI*, New Delhi, 1990.

[3]. Fu, Gonzalez and Lee, "Robotics : Control, Sensing, Vision and Intelligence", *McGraw Hill*, Singapore, 1995.

[4]. Ranky, P. G., C. Y. Ho, "Robot Modeling, Control & Applications", *IFS Publishers*, *Springer*, UK., 1998.

[5]. T.C.Manjunath, "Fundamentals of Robotics", *Nandu Publishers, 5th Revised Edition*, Mumbai., 2005.

[6]. T.C.Manjunath, "Fast Track To Robotics", *Nandu Publishers*, *3rd Edition*, Mumbai, 2005.

[7]. Ranky, P. G., C. Y. Ho, "Robot Modeling, Control & Applications", *IFS Publishers*, *Springer*, UK, 2005.

[8]. Groover, Weiss, Nagel and Odrey, Industrial Robotics, *McGraw Hill*, Singapore, 2000.

[9]. William Burns and Janet Evans, "Practical Robotics – Systems, Interfacing, Applications", *Reston Publishing Co*., 2000.

[10]. Phillip Coiffette, "Robotics Series, Volume I to VIII, *Kogan Page*, London, UK, 1995.

[11]. Luh, C.S.G., M.W. Walker, and R.P.C. Paul, "On-line computational scheme for mechanical manipulators", *Journal of Dynamic Systems, Measurement & Control*, Vol. 102, pp. 69-76, 1998.

[12]. Mohsen Shahinpoor, "A Robotic Engineering Text Book", *Harper and Row Publishers*, UK.

[13]. Janakiraman, "Robotics and Image Processing", *Tata McGraw Hill.*

[14]. Richard A Paul, "Robotic Manipulators", *MIT press*, Cambridge.

[15]. Fairhunt, "Computer Vision for Robotic Systems", New Delhi.

[16]. Yoram Koren, "Robotics for Engineers", *McGraw Hill*.

[17]. Bernard Hodges, "Industrial Robotics", *Jaico Publishing House*, Mumbai, India.

[18]. Tsuneo Yoshikawa, "Foundations of Robotics : Analysis and Control", *PHI*.

[19]. Dr. Jain and Dr. Aggarwal, "Robotics : Principles & Practice", *Khanna Publishers*, Delhi.

[20]. Lorenzo and Siciliano, "Modeling and Control of Robotic Manipulators", *McGraw Hill*.

[21]. Dr. Amitabha Bhattacharya, "Mechanotronics of Robotics Systems".

[22]. S.R. Deb, "Industrial Robotics", *Tata MacGraw Hill*, New Delhi, India.

[23]. Edward Kafrissen and Mark Stephans, "Industrial Robots and Robotics", *Prentice Hall Inc*., Virginia.

[24]. Rex Miller, "Fundamentals of Industrial Robots and Robotics, *PWS Kent Pub Co*., Boston.

[25]. Doughlas R Malcom Jr., "Robotics … An introduction", *Breton Publishing Co*., Boston.

[26]. Wesseley E Synder, "Industrial Robots : Computer Interfacing and Control", *Prentice Hall.*

[27]. Carl D Crane and Joseph Duffy, "Kinematic Analysis of Robot Manipulators", *Cambridge Press*, UK.

[28]. C Y Ho and Jen Sriwattamathamma, "Robotic Kinematics … Symbolic Automatic and Numeric Synthesis", *Alex Publishing Corp*, New Jersey.

[29]. Francis N Nagy, "Engineering Foundations of Robotics", *Andreas Siegler*, Prentice Hall.

[30]. William Burns and Janet Evans, "Practical Robotics - Systems, Interfacing, Applications", *Reston Publishing Co.*

[31]. Robert H Hoekstra, "Robotics and Automated Systems".

[32]. Lee C S G, "Robotics , Kinematics and Dynamics".

[33]. Gonzalez and Woods, "Digital Image Processing", Addison Wesseley. Anil K Jain, "Digital Image Processing", PHI.

[34]. Joseph Engelberger, "Robotics for Practice and for Engineers", PHI, USA.

T.C.Manjunath, born in Bangalore, Karnataka, India on Feb. 6, 1967 received the B.E. Degree in Electrical Engineering from the University of Bangalore in 1989 in First Class and M.E. in Electrical Engineering with specialization in Automation, Control and Robotics from the University of Gujarat in 1995 in First Class with Distinction and Ph.D. from the Interdisciplinary Programme in Systems and Control Engineering Department of Indian Institute of Technology Bombay in the year 2007, respectively. He has got a teaching experience of 17 long years in various engineering colleges all over the country (Karnataka, Tamil Nadu, Gujarat, Maharashtra) and is currently working as Professor and Head of the Department of Electronics and Communication Engineering in East West Institute of Technology in Bangalore, Karnataka, India. He also worked as a Research Engineer in the Systems and Control Engineering (IIT Bombay, India) for nearly a year and worked on control of space launch vehicles using FOS feedback technique. He has published 90 papers in the various National, International journals and Conferences and published two textbooks on Robotics, one of which has gone upto the fourth edition, titled, 'Fast Track to Robotics' and the other, which has gone upto the fifth edition, titled, 'Fundamentals of Robotics' in 2 volumes, Vol.-1 and Vol.-2 along with a CD which contains about 150 C / C++ programs for performing various simulations on robotics. He also published a research monograph in the International level from the Springer-Verlag publishers based on his Ph.D. thesis topic titled, "Modeling, Control and Implementation of Smart Structures", Vol. 350, LNCIS, costing 79.95 Euros. He was a student member of IEEE for 6 years, SPIE student member and IOP student member for 4 years, life member of ISSS (India), life member of the ISTE (India), life member of ISOI (India), life member of SSI (India) and life member of the CSI (India) and a fellow of IETE (India). He has visited Singapore, Russia, United States of America and Australia for the presentation of his research papers in various international conferences. His biography was published in 23rd edition of Marquis's Who's Who in the World in 2006 issue. He has also guided more than 2 dozen robotic projects. Many of his guided projects, interviews have appeared in various national newspapers and magazines. He has also presented a number of guest lectures and various seminars and participated in more than a dozen CEP / DEP courses, seminars, workshops, symposiums in the various parts of the country in different institutions and also conducted a few courses. His Ph.D. research work was based on the mathematical modeling, control and implementation of smart structures and its applications. His current research interests are in the area of Robotics, Smart Structures, Control systems, Network theory, Mechatronics, Process Control and Instrumentation, Electromagnetic fields and waves, MATLAB, Signals and systems (CT and DT), Industrial automation, Artificial intelligence, Digital signal processing, Digital Image Processing, Periodic output feedback control, Fast output feedback control, Sliding mode control of SISO and multivariable systems and many of the control related subjects and its allied labs and their various applications.