Control of Stationary Robots using Visual Basic Software

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ABSTRACT
The paper presents the inverse kinematic analysis, modeling design and fabrication of each part of a four axes SCARA indigenously developed robot with indigenous components and to control it with a personal computer using the visual basic language. The work was carried out as a sponsored consultation project taken up by the authors. The main objective of this work is to design a inverse kinematic mathematical model of an educational stationary robotic model that can do pick and place of objects by avoiding the obstacles in its path of motion from the source to the destination.

Keywords
SCARA Robot, Computer Control, Visual Basic, Interfacing , Drivers, Inverse Kinematics.

1. INTRODUCTION
Robotics is an interdisciplinary field that mixes various engineering disciplines such as electrical, electronics, instrumentation, mechanical, computer science, control engineering, mathematics, communications and many other fields into one. In this, work a unique 4 axes system is designed and fabricated with indigenous components with a brief kinematic analysis of the designed robot. The kinematically modeled designed robot is used for performing some PNP operations and was named as a **S**elective **C**ompliance **A**ssembly **R**obot **A**rm (SCARA). The primary motive behind the work was to develop a modular educational robotic system, the **CRUST 2002** (**C**omputerized **R**obotic **U**nit with **S**elective **T**ractability system) with the help of locally available components and sub-systems as shown in Fig. 1 and also to develop a user friendly GUI to control it [1].

The paper is organized as follows. First, a introduction to robotics, robots and the design of the mechanical assembly is presented in section 2. In section 3, the block diagram of the inverse kinematic model is presented. Fourthly, the inverse kinematic algorithm is presented in section 4. Section 5 gives the link coordinate diagram design and the kinematic parameter table of the robot. In Section 6, computation of the joint variables of the robot, i.e., q_1 , q_2 , q_3 and q_4 is presented. Section 7 gives the advantages of the inverse kinematically modeled robot and the

conclusions are finally presented in section 8 followed by the references.

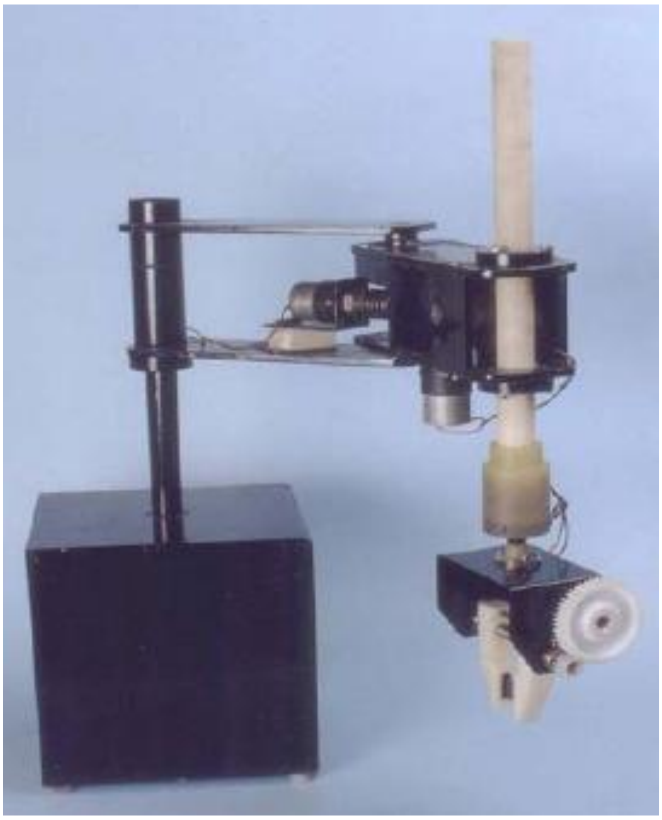

Fig. 1. The designed SCARA robot

2. PHYSICAL STRUCTURE DESIGN
A four axis / four DOF designed SCARA robot arm as shown in Fig. 1. A SCARA robot is a 4 DOF stationary robot arm having base, elbow, vertical extension and tool roll and consisting of both rotary and prismatic joints [2]. There is no tool yaw and tool pitch (only tool roll) [1]. There are 4 joints, 4 axis (three major axes - base, elbow, vertical extension and one minor axis - tool roll). The 4 DOF's are given by Base, Elbow, Vertical Extension and Tool Roll, i.e., there are three rotary joints and one prismatic joint. Since n = 4; 16 KP's are to be obtained and 5 RHOCF's are to be attached to the various joints [3].

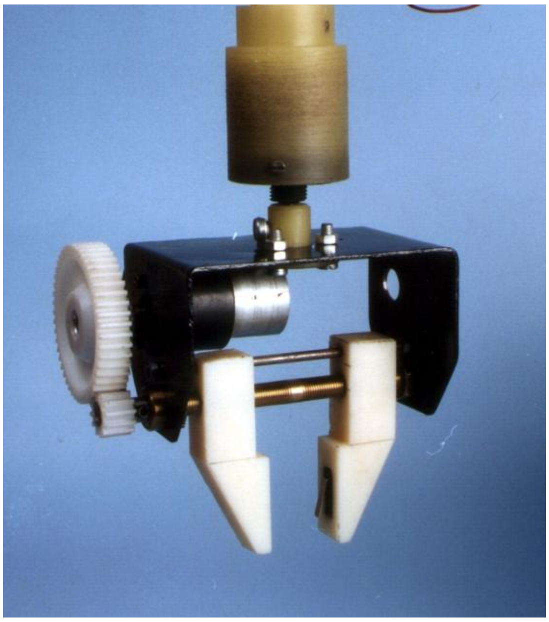

Fig. 2. Tool Roll DOF

3. BLOCK DIAGRAM OF INVERSE KINEMATIC MODELLING

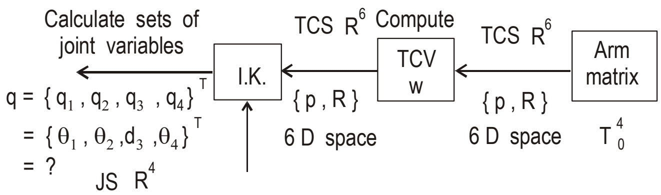

Fig. 3. Inverse Kinematic Model of the robot

The inverse kinematic model states as "given the geometric link parameters and the position and orientation or the tool configuration vector w, finding the sets of joint variables which will satisfy the same position and orientation". Referring Fig. 3 [9] for the IK block diagram, IK can also be defined as mapping from the Tool Configuration Space to the Joint Space. The link parameters are constant and are the physical dimensions or the geometric link parameters, which are constant for a given robot arm [8].

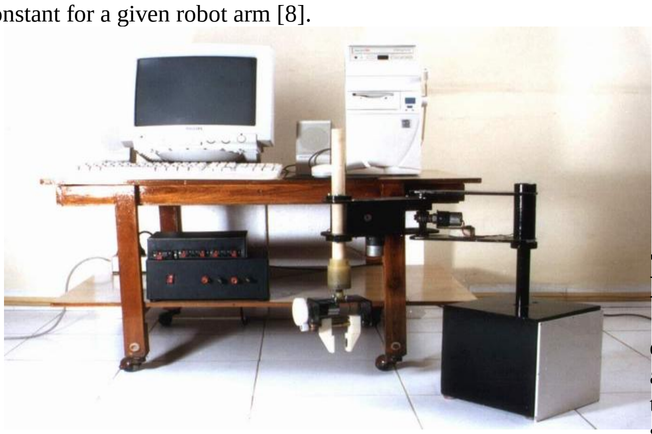

Fig. 4. The computer controlled SCARA robot

4. INVERSE KINEMATIC ANALYSIS ALGORITHM

The inverse kinematic algorithm is as follows [2].

Input the arm matrix T_0^4

↓

Input the GLP ; a d α

↓

Compute the TCV

$$w(q) = \begin{bmatrix} w^1 \\ w^2 \end{bmatrix}$$

↓

Compute ($w_1^2 + w_2^2$)

↓

Compute shoulder angle

$$q_2 = \pm \text{arc cos} \left[\frac{w_1^2 + w_2^2 - a_1^2 - a_2^2}{2a_1a_2} \right]$$

↓

Compute base angle

$$q_1 = \text{a tan 2} \left[\frac{(a_1 + a_2C_2)\, w_2 + a_2S_2w_1}{(a_1 + a_2C_2)\, w_1 - a_2S_2w_2} \right]$$

↓

Compute GTRA

$$q_3 = d_1 - d_4 - w_3$$

↓

Compute GTRA

$$q_{1-2-4} = \text{a tan 2} \left(\frac{R_{21}}{R_{11}} \right)$$

↓

Compute tool roll angle

$$q_4 = \pi \, ln \, | \, w_6 \, |$$

OR

$$q_4 = q_1 - q_2 - q_{1-2-4}$$

Fig. 5. IK algo of the designed four axis SCARA robot

5. DEVELOPMENT OF THE LCD AND KPT

The analysis of the robot is developed in 2 passes, viz., development of the link coordinate diagram as shown in Fig. 4 and development of the kinematic parameter table as shown in the Table 1 [10]. The link coordinate diagram is developed as shown in the Fig. 6 with the kinematic parameter table as shown in Table 1 [2].

6. COMPUTATION OF THE JOINT VARIABLES

Rows of KP Table	Type of Joint	θ_k	d_k	a_k	α_k
1st row of KPT θ_1 , d_1 , a_1 , α_1	Base	$q_1 = \theta_1$	d_1	a_1	$\pm \pi$
2nd row of KPT θ_2 , d_2 , a_2 , α_2	Elbow	$q_2 = \theta_2$	0	a_2	0
3rd row of KPT θ_2 , d_3 , a_3 , α_3	Vertical Extn.	$\theta_3 = 0°$	$q_3 = d_3$ (variable)	0	0
4th row of KPT θ_4 , d_4 , a_4 , α_4	Roll	$q_4 = \theta_4$	d_4	0	0

Table 1 Kinematic parameter table of the robot

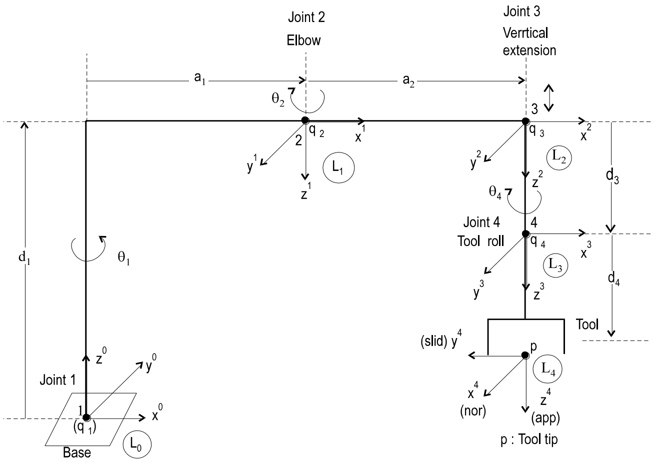

Fig. 6 L.C.D. of a four axis SCARA robot

L_0 to L_4 : Five RHOCF's ; 1 , 2 , 3 , 4 : Joints
d_4 : Tool length / length of gripper
q_1 to q_4 : Joint variables ($q = \theta , d$)
p : Tool – tip ; d_3 : Vertical extension

The output of the direct kinematics of the SCARA is [2]

$$T_{Base}^{Tool} = T_0^4 = \begin{bmatrix} C_{1-2-4} & S_{1-2-4} & 0 & a_1 C_1 + a_2 C_{1-2} \\ S_{1-2-4} & -C_{1-2-4} & 0 & a_1 S_1 + a_2 S_{1-2} \\ 0 & 0 & -1 & d_1 - q_3 - d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_0^4 = \begin{bmatrix} R_{11} & R_{12} & R_{13} & p_1 \\ R_{21} & R_{22} & R_{23} & p_2 \\ R_{31} & R_{32} & R_{33} & p_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} ; n = 4$$

$$= \begin{bmatrix} r^1 & r^2 & r^3 & p \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \quad n \quad s \quad a \quad \text{tip position}$$

$$p_1 = w_1 = a_1 C_1 + a_2 C_{1-2}$$
$$p_2 = w_2 = a_1 S_1 + a_2 S_{1-2}$$
$$p_3 = w_3 = d_1 - q_3 - d_4$$
$$R_{13} = R_{23} = R_{31} = R_{32} = w_4 , w_5 = \text{Constant} = 0$$
$$R_{33} = -1$$
$$n = 4$$
$$R_{11} = C_{1-2-4}$$
$$R_{21} = R_{12} = S_{1-2-4}$$
$$R_{22} = -C_{1-2-4}$$

The first 3 columns of the above matrix gives the orientation of the gripper w.r.t. the base, i.e., the yaw (normal vector), pitch (sliding vector) and the roll (approach vector), while the last column [11] gives the position of the gripper tip w.r.t. base, thus solving the direct kinematic modeling of the robot [2].

The assumptions made in our IK analysis are

- $\cos q_1 = C_1$
  $\sin q_1 = S_1$
  $\cos (q_1 - q_2) = C_{1-2} = C_1C_2 + S_1S_2$
  $\sin (q_1 - q_2) = S_{1-2} = S_1C_2 - C_1S_2$
  $\sin (q_1 - q_2 - q_4) = S_{1-2-4}$
  $\cos (q_1 - q_2 - q_4) = C_{1-2-4}$

Check the norms of the rotation matrix of T_0^4. They are all unity. For ex., the norm of the 1st column of the matrix T_0^4 is $\| r^1 \| = \sqrt{(C_{1-2-4})^2 + (S_{1-2-4})^2 + (0)^2} = 1$.

These assumptions [2] are made to simplify the calculations [12]. The inverse kinematic equations are obtained by equating the output of direct kinematics to the soft home position matrix $T_0^4 = T_0^4$ (SHP) .

$$\begin{bmatrix} C_{1-2-4} & S_{1-2-4} & 0 & a_1C_1 + a_2C_{1-2} \\ S_{1-2-4} & -C_{1-2-4} & 0 & a_1S_1 + a_2S_{1-2} \\ 0 & 0 & -1 & d_1 - q_3 - d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 & a_1 + a_2 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & -1 & d_1 - d_3 - d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(1) $C_{1-2-4} = 0$
(2) $-C_{1-2-4} = 0$
(3) $S_{1-2-4} = -1$
(4) $S_{1-2-4} = -1$
(5) $a_1 C_1 + a_2 C_{1-2} = a_1 + a_2$
(6) $a_1 S_1 + a_2 S_{1-2} = 0$
(7) $d_1 - q_3 - d_4 = d_1 - d_3 - d_4$

We get seven inverse kinematic non - linear equations in 4 unknowns (Base , Elbow , VE , Roll).

The Tool Configuration Vector (TCV) is given by [2] [9]

$$w(q) = \begin{bmatrix} w^1 \\ \ldots \\ w^2 \end{bmatrix} = \begin{bmatrix} p \\ \ldots\ldots\ldots\ldots \\ \left\{ \exp\left(\frac{q_4}{\pi}\right) \right\} r^3 \end{bmatrix} = \begin{bmatrix} w_1 \\ w \\ w_3 \\ \ldots\ldots \\ w_4 \\ w_5 \\ w_6 \end{bmatrix}$$

$$= \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ \ldots\ldots\ldots\ldots \\ \exp\left(\frac{q_4}{\pi}\right) R_{13} \\ \exp\left(\frac{q_4}{\pi}\right) R_{23} \\ \exp\left(\frac{q_4}{\pi}\right) R_{33} \end{bmatrix} = \begin{bmatrix} a_1 C_1 + a_2 C_{1-2} \\ a_1 S_1 + a_2 S_{1-2} \\ d_1 - q_3 - d_4 \\ \ldots\ldots\ldots\ldots \\ 0 \\ 0 \\ -\exp\left(\frac{q_4}{\pi}\right) \end{bmatrix}$$

Note : To find out q_1, q_2, q_3, q_4; apply row operations used in mathematics to the components of w using various trigonometric identities [2], [11].

To Extract Elbow Joint Variable $q_2 = \theta_2$

$$p_1 = w_1 = a_1 C_1 + a_2 C_{1-2}$$
$$p_2 = w_2 = a_1 S_1 + a_2 S_{1-2}$$
$$p_3 = w_3 = d_1 - q_3 - d_4$$
$$w_6 = -\exp\left(\frac{q_4}{\pi}\right)$$
$$w_4 = w_5 = 0$$

Squaring and adding w_1 and w_2, we get q_2, since it is easier to extract the elbow angle as it is independent of base angle [2].

$$w_1^2 + w_2^2 = (a_1 C_1 + a_2 C_{1-2})^2 + (a_1 S_1 + a_2 S_{1-2})^2$$
$$= a_1^2 + a_2^2 + 2 a_1 a_2 C_2$$
$$2 a_1 a_2 C_2 = w_1^2 + w_2^2 - a_1^2 - a_2^2$$
$$\cos q_2 = \frac{w_1^2 + w_2^2 - a_1^2 - a_2^2}{2 a_1 a_2}$$

$$\boxed{q_2 = \pm \cos^{-1}\left[\frac{w_1^2 + w_2^2 - a_1^2 - a_2^2}{2 a_1 a_2}\right]}$$

$$q_2 = \pm \arccos\,(w_1^2 + w_2^2 - a_1^2 - a_2^2, 2 a_1 a_2)$$

From the above equations , we see that the IK solution is not unique and hence we get two solutions when looked from the top in the x-y plane given by

$q_2 = +$; left handed solution , i.e., > 0 ; link a_2 moves to right (from top) [13].

$q_2 = -$; right handed solution , i.e., < 0 ; link a_2 moves to left (seen from top) [14].

Hence , solution to IKP to the shoulder is not unique [10].

To Extract Base Joint Variable $q_1 = \theta_1$

$$w_1 = a_1 C_1 + a_2 C_{1-2}$$
$$w_2 = a_1 S_1 + a_2 S_{1-2}$$

Expand C_{12} and S_{12} using sum of sines and cosines ; isolate C_1, S_1 write in matrix form , collect all C_1 terms and S_1 terms , find A^{-1} and $|A|$, solve for q_1 [2], [15].

$$w_1 = a_1 C_1 + a_2 (C_1 C_2 + S_1 S_2) = (a_1 + a_2 C_2) C_1 + (a_2 S_2) S_1$$
$$w_2 = a_1 S_1 + a_2 (S_1 C_2 - C_1 S_2) = (-a_2 S_2) C_1 + (a_1 + a_2 C_2) S_1$$

Writing equations for w_1 and w_2 in matrix form ;

$$\begin{bmatrix} w_1 \\ w_2 \end{bmatrix} = \begin{bmatrix} a_1 + a_2 C_2 & a_2 S_2 \\ -a_2 S_2 & a_1 + a_2 C_2 \end{bmatrix} \begin{bmatrix} C_1 \\ S_1 \end{bmatrix}$$

$$\begin{bmatrix} C_1 \\ S_1 \end{bmatrix} = \begin{bmatrix} a_1 + a_2 C_2 & a_2 S_2 \\ -a_2 S_2 & a_1 + a_2 C_2 \end{bmatrix}^{-1} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix}$$

$$\text{Let } A = \begin{bmatrix} a_1 + a_2 C_2 & a_2 S_2 \\ -a_2 S_2 & a_1 + a_2 C_2 \end{bmatrix}$$

$$\text{Determinant } = |A| = (a_1 + a_2 C_2)^2 + (a_2 S_2)^2$$
$$= a_1^2 + a_2^2 + 2 a_1 a_2 C_2$$
$$= w_1^2 + w_2^2$$

$$A^{-1} = \frac{\begin{bmatrix} a_1 + a_2 C_2 & -a_2 S_2 \\ a_2 S_2 & a_1 + a_2 C_2 \end{bmatrix}}{w_1^2 + w_2^2}$$

$$= \begin{bmatrix} \frac{a_1 + a_2 C_2}{w_1^2 + w_2^2} & \frac{-a_2 S_2}{w_1^2 + w_2^2} \\ \frac{a_2 S_2}{w_1^2 + w_2^2} & \frac{a_1 + a_2 C_2}{w_1^2 + w_2^2} \end{bmatrix}$$

Substituting the value of A^{-1} [16]

$$\begin{bmatrix} C_1 \\ S_1 \end{bmatrix} = \begin{bmatrix} \frac{a_1 + a_2 C_2}{w_1^2 + w_2^2} & \frac{-a_2 S_2}{w_1^2 + w_2^2} \\ \frac{a_2 S_2}{w_1^2 + w_2^2} & \frac{a_1 + a_2 C_2}{w_1^2 + w_2^2} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \end{bmatrix}$$

Eq^n 3.12:4

$$C_1 = \frac{(a_1 + a_2 C_2)\, w_1 - (a_2 S_2)\, w_2}{w_1^2 + w_2^2} = \cos q_1$$

Eq^n 3.12:5

$$q_1 = \pm \cos^{-1}\left\{\frac{(a_1 + a_2 C_2)\, w_1 - (a_2 S_2)\, w_2}{w_1^2 + w_2^2}\right\}$$

$$S_1 = \frac{(a_1 + a_2 C_2)\, w_2 + (a_2 S_2)\, w_1}{w_1^2 + w_2^2} = \sin q_1$$

$$q_1 = \pm \sin^{-1}\left\{\frac{(a_1 + a_2 C_2)\, w_2 + (a_2 S_2)\, w_1}{w_1^2 + w_2^2}\right\}$$

Using C_1 or S_1, we can find the value of q_1. But , it gives the base angles only over the range $(-90°, +90°)$ or $\left\{-\frac{\pi}{2}, +\frac{\pi}{2}\right\}$, i.e., 180° range [17].

$\therefore$, dividing S_1 by C_1, we get

$$\tan q_1 = \frac{S_1}{C_1} = \frac{\sin q_1}{\cos q_1} = \left[\frac{(a_1 + a_2C_2)\, w_2 + (a_2S_2)\, w_1}{(a_1 + a_2C_2)\, w_1 - (a_2S_2)\, w_2}\right]$$

$q_1 = \text{arc tan } 2\ \{(a_1 + a_2C_2)\, w_2 + a_2S_2w_1\, ,\ (a_1 + a_2C_2)\, w_1 - a_2S_2w_2)\}$

$$\boxed{q_1 = \tan^{-1}\left\{\frac{(a_1 + a_2C_2)\, w_2 + (a_2S_2)\, w_1}{(a_1 + a_2C_2)\, w_1 - (a_2S_2)\, w_2}\right\}}$$

This solution given by this gives the values of the base angle q_1 over the complete range $(-\pi, +\pi)$; since , we had used the arc tan 2 function . Hence , if we use the arc tan 2 function , we can recover the base angles over the complete range , i.e., 360° [17], [18]

To Extract Vertical Extension Joint Parameter , $q_3 = d_3$

This is a prismatic motion and d_3 is variable in this case . This is associated with the movement of sliding the tool up / down along tool roll axis or along the approach vector r^3. The third variable is the easiest to extract since it involves only distances [12], [19].

From the 3rd component of TCV ; w , we have

$w_3 = d_1 - q_3 - d_4$

The 3rd variable q_3 is extracted as [13]

$$\boxed{q_3 = d_1 - d_4 - w_3}$$

where d_1 = Height of the SCARA robot from the base .

and d_4 = Length of the tool [20].

To Extract Tool Roll Angle , $q_4 = \theta_4$ [2]

The tool roll angle is computed from the last component of the TCV , i.e., w_6 [14].

From TCV, we have ;

$w_4 = w_5 = 0$, i.e., there is no yaw and pitch .

Using the equation [15]

$$q_n = \pi\, ln\, \sqrt{w_4^2 + w_5^2 + w_6^2} = \pi\, ln\, \sqrt{0^2 + 0^2 + w_6^2}$$

$$\boxed{q_4 = \pi\, ln\, |\, w_6\, |}$$

Calculating Joint Variables from the Components of the Rotation Matrix [2]**:**

From the arm matrix T_0^4 , we have

$$R = \begin{bmatrix} C_{1-2-4} & S_{1-2-4} & 0 \\ S_{1-2-4} & -C_{1-2-4} & 0 \\ 0 & 0 & -1 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix}$$

$$\frac{R_{21}}{R_{11}} = \frac{S_{1-2-4}}{C_{1-2-4}} = \tan q_{1-2-4}$$

$$q_{1-2-4} = \tan^{-1}\left(\frac{R_{21}}{R_{11}}\right);$$

$$= \text{arc tan } 2\ (R_{21}\, , R_{11})$$

$$= (q_1 - q_2 - q_4)$$

Since q_1 and q_2 are already found out , we can find q_3 using the GTR angle [2], [16]

$$\boxed{q_4 = q_1 - q_2 - q_{1-2-4}}$$

q_{1-2-4} = Global tool roll angle , i.e. angle made by tool roll q_4 w.r.t. the x – axis.

Thus, we have found out joint variables using different methods as

There is 1 methods of finding q_1 , viz.,

$$q_1 = \tan^{-1}\left\{\frac{(a_1 + a_2C_2)\, w_2 + (a_2S_2)w_1}{(a_1 + a_2C_2)\, w_1 - (a_2S_2)w_2}\right\}$$

and 1 method of finding q_2 , viz.,

$$q_2 = \pm \cos^{-1}\left[\frac{w_1^2 + w_2^2 - a_1^2 - a_2^2}{2a_1a_2}\right]$$

and 1 method of finding q_3 , viz.,

$q_3 = d_1 - d_4 - w_3$

and there are 2 methods of finding q_4 , viz.,

$q_4 = \pi\, ln\, |\, w_6\, |$

$q_4 = q_1 - q_2 - q_{1-2-4}$

Methods of Obtaining Solutions to the IKP :

$$q = \{q_1\, , q_2\, , q_3\, , q_4\}^T \leftarrow \boxed{\text{I K P}}$$

$$\uparrow$$

$$w(q) = \{\, w_1\, , w_2\, , w_3\, , w_4\, , w_5\, , w_6\, \}^T$$

In the Tool Configuration Vector TCV [18], three major axes variables (p) and three minor axes variables (R) has to be given as the input to the IKP with the GLP to compute the set of joint variables . w_1 , w_2 are used to compute q_1 and q_2 . Using w_3 , q_3 can be found out [19]. Using w_6 , q_4 can be found out . w_4 and w_5 are not used in the computation of the joint variables as they are constants and equal to zero [2].

$$q_1 \text{ to } q_4 \boxed{\text{I K P}} \leftarrow \tilde{w}\,(q) = \{\, p_1\, , p_2\, , p_3\, , q_{1-2-4}\}^T$$

In the Reduced Tool Configuration Vector RTCV , three major axes variables (p) and one minor axes variable (orientation variable) is given as the input to the IKP with the GLP to compute the set of joint variables . p_1 , p_2 are used to compute q_1 or q_2 . From p_3 , q_3 can be found out . From the global tool roll angle ; q_{1-2-4} , q_4 can be found out . The advantage of using RTCV is there is need to [20] specify only four variables instead of six in the TCV , thus reducing the number of computations .

7. ADVANTAGES OF THE INVERSE KINEMATICALLY MODELED SCARA ROBOT

- Approach vector r^3 is fixed ; $r^3 = -i^3 = -z^0 = -1$ and $r^3 \perp^r x^0\, y^0$ plane ,
- Tool is always pointing vertically down .
- Hence , SCARAS are used to manipulate objects directly from above the object and in applications where exact perpendicularity is required such as in

- Example :
  - Insertion of components onto PCB ' s .
  - Inserting peg into holes .
  - Fastening a nut onto a bolt .
  - Performing straight line motions .
  - Performing screw transformations .
  - Doing light assembly tasks where high precision is required .
  - Threading and unthreading operations .

The thing is, if we just give the amount of rotation or translation as input to this algorithm, it just goes and stops at that prescribed position and orientation. This is what is called as direct kinematics as kinematics is defined as the study of motion of objects without taking the forces / torques / moments into consideration [7].

8. CONCLUSION

A four axes inverse kinematic analysis was performed for the designed robot and was successfully implemented in the laboratory. The robot was controlled using a GUI developed in visual basic language in various modes. A number of pick and place operations were successfully performed by the developed robot by using teaching mode, manual mode and programming modes and the inverse kinematic model.

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