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# An Analytical Approach of Determining the Position of Adjustable Dual Drill Tool End Effector inSCARA Robot

**Saravana M. MOHAN[a]**
**Dr. KahtanAZIZ[b] MIET, CEng, SMIEEE**

**[a]Department of Mechatronics Engineering,**
**Kumaraguru College of Technology, Coimbatore,**
**Tamil Nadu, India.**

**[b]Faculty of Science and Engineering**
**Anglia Ruskin University, Bishop Hall Lane,**
**Chelmsford, CM1 1SQ,**
**United Kingdom**
**kahtan.aziz@anglia.ac.uk**

**[$]Corresponding author: E-mail: saravana.moha@gmail.com and Telephone: +91-9894579694**

## ABSTRACT:

SCARA robot is very often usedfor light duty applications in manufacturing industries. In this paper an analytical forward kinematic approach is adopted and the positionof adjustable dual drillingtool (DDT)end effector of SCARA robot is determined. TheSCARA robots are usedto drill holes in-printed circuit board (PCB) in large electronic and electrical manufacturing industries, with less flexibility, in changing the spacing between the holes .The DDT attached to the adjustable tool head is having the capability of varying the center distance which is very useful in drilling symmetrical pattern of holes with specified spacing. Along with the commonly used CNC PCB drilling machine if this SCARA is employed in production line it will increase the productivity .The Denavit–Hartenberg(D-H) conventions and homogeneous transformation matrices are used tofind out the tool coordinates utilizing the joint angles, link offset, twist angles of proposed SCARA with five degrees of freedom(DOF). The coordinate equations results in achieving the specified position of the DDT. Hence thiswork enables the users tobe flexibleto provide spacing between the holes using the same end effector.

**KEYWORDS**: *SCARA, dual drill tool end effector, forward kinematic approach, PCBdrilling, D-H convention*

## INTRODUCTION:

The SCARA(Selective Compliance Articulated Robot Arm) is a popular configuration with RRP structure.The prototype of SCARA robot is introduced in the year 1978 in Japan [1]. SCARA is compact and the working envelopes are relatively limited. Today SCARA robots are very widely used in manufacturing industries for its high speed, short cycle time, advanced control for path precision and controlled compliance to perform the necessary light duty tasks to achieve high flexibility, dexterity and productivity. Few light duty applications of SCARA are: product inspection, touch-panel type evaluation, conveying masks for wafers, Screw tightening, stacking electronicscomponents, inserting components in printed circuit boards, tapping, and chamfering, deburring, drilling, welding, soldering and gluing, packing, loading and unloading parts of an automation lines.

AdelhardBeniRehiara [2] worked and authored an article explaining the forward kinematics and inverse kinematic approach to find the position of the SCARA robot end effector position using D-H convention and corresponding transformation matrices. Mark W. Spong, Seth Hutchinson, and M. Vidyasagar [3] explained the forward and inverse kinematics of various robot configurations including SCARA Comprehensively in his publication.Guo Qing Ma et al [4] developed the kinematics equations for a high speed robot for material handling to analyze forward and inverse kinematics problems based on modified D-H coordinate system theory for their proposed SCARA robot. MATLAB Simulation was used to validate that robot parameter design is reasonable and the trajectory planning by interpolation calculation in joint space is feasible.VictorHernandez et al [5] studied forward and inverse kinematics for SCARA, Cylindrical robot with four degrees of freedom to find the end-effector position and orientation which is applicable for TIG or MIG welding.

Yang Jin, Wang Xiaorong [6] used the dual number methods using the D-H parameters and studied forward and inverse kinematics principle of

SCARA robot. The solving process proved that the dual number allows compact formulations considerably facilitating the analysis of robot kinematics.Jian Fang and Wei Li [7] observed and verified the correctness of model problem in terms of motion of each joint. The proposed model of four degrees of freedom SCARA robot to achieve the desired goal. The researchers used the kinematic modeling and simulationtechniques. Mahdi et al [8] developed a complete mathematical model of SCARA robot which includes servo actuator dynamics and presented together with dynamic simulation in his research. He derived forward and inverse kinematics equations by using D-H convention. SitiNurHanisahUmara [9]performed the identical simulation, the result between derived direct dynamic mechanical system of robot manipulator and SimMechanic model .It was found out that both methods satisfied the principle of two-link manipulator model.

ElaikhEH.Talib[10] studied andinvestigates the kinematics of SCARA robots using kinematic and vibration methods in dynamic conditions of the manipulator. He analyzed the position, velocity and acceleration using the simulation study.The researchers like PrabathWijesekaraArachchigeand Mohamed Salem Abderrahmane[11] worked on reconfigurable end effectors. The SCARA robot was reconfigured from 4-DOF to 6-DOF. The state of the joint has been selected by the motion of the end effector, and the constraints. This methodology is applied to the SCARA robot manipulator to improve its last joint capability. The researchers replaced the last joint with new reconfigurable joint and robot kinematic theory is applied for model evaluation.Sarosh Patel and Tarek Sobh [12] made a comprehensive study on manipulator performance measures which are very essential to design, study and the applications of robotic manipulators. The kinematic indices, manipulabilityindices and important performance parameters are referred in his paper to develop a robot with improvised configuration.

The researchers [1] to[10] studied the positioning of tool in SCARAof fourdegrees of freedom having conventional single tool without having the tool head with the flexibility in changing the tool spacing especially in drilling. In the work [11] four degrees of freedom SCARA was transformed to six degrees of freedom by applying the idea of reconfigurable end effectors. In this paper, the forward kinematic analytical approach was adopted to determine the position of dual drill tool in adjustable end effector in SCARA robot with five degrees of freedom.It has the capability of changing the center distance between the tool tipsexplores the possibility to have varying drill tool spacing.

The present paper is organized as follows. Section II explains the kinematics and the structure of proposed dual drilling SCARA Robot and forward kinematic analysis to determine the position of the DDT. Detailedanalytical calculations for positioning the dual tool arepresented in Section III, and the results of case studies of the present work are given in Section IV.

## 2. Kinematics of Robot Manipulator

Robot Kinematics is a geometrical study of motion of a robotic manipulator with respect to the datum coordinate system. The forward kinematics deals with computing the position and orientation of the end effector for given joint variables. Where as in the inverse kinematics the joint variables are determined for the desired position and orientation of the end effector of the robot. The proposed dual drilling tool SCARA model is explained in the following subsection .The Denavit-Hartenberg (D-H) method of forward kinematic analysisand inverse kinematics to determine the joint angle is described in the subsequent subsection.

### *2.1. Description of the proposed model*

The SCARA robot with RRP configuration with a DDT as end effector is shown in the Fig. 1.Our proposed SCARA robot has a main arm, a fore arm and a prismatic arm .The main arm and fore arm with two rotary joints whose axes are parallel to each other which facilitates the selective compliance with in the plane due to its mechanical configuration .The prismatic arm holds the end effector, capable of moving up and down quickly. It is compact and the working envelopes are relatively limited. In our system the tool head attached to the prismatic arm is capable of holding DDT. The Centre distance between the tools can also be adjusted by means of the groove provided in the tool head .The tool head is attached firmly to the lower end of the prismatic joint. This proposed work is carried out for Drilling holes in PCB which needs specific spacing between the holes. The holes are important for inserting components as well as to fix the PCBs to the testing devices and housings.

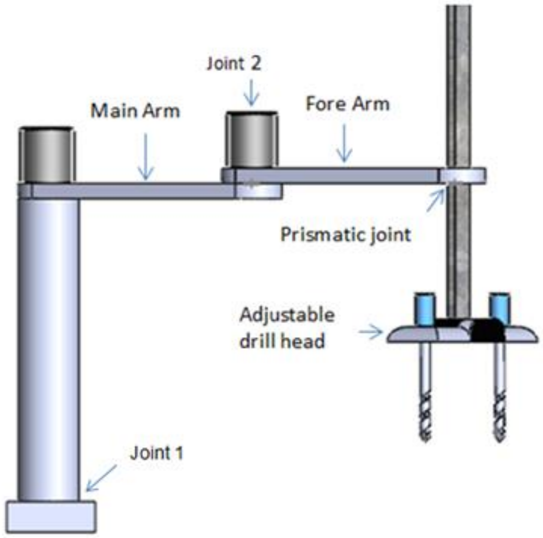


Fig-1 Solid Works model of SCARA with proposed adjustable drill tool head

### *2.2 Forward kinematics of dual drilling SCARA*

The forward kinematic approach is adopted in this work todetermine the position of the dual drilling end effector attached to the SCARA manipulator as end effector shown in the Figure 1 and 2 for the desired joint angles.The Denavit-Hartenberg (D-H) convention is used for forward kinematic analysis.In the D-H convention the coordinate frames are assigned to each joint as shown in Figure 2 and eachjoint will have its own axis. The D-H parameters are twist angle ($\alpha_i$), link length ($a_i$), Link offset ($d_i$), and joint angle($\Theta_i$) are given in the table. The four important D-H parameters $\theta_i$, $a_i$, $d_i$, $\alpha_i$are associated with link i and joint I are required to construct the homogeneous transformationmatrix $A_i$to find the tool position.

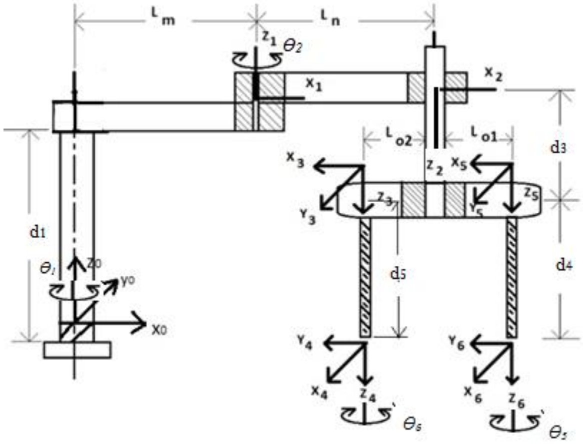
The homogenous transformation $A_i$is represented as a product of four basic transformations.

$$A_i = \text{Rot } z, \Theta_i \text{Trans } z, d_i \text{Trans } x, a_i \text{Rot } x, \alpha_i \qquad (1)$$

$$Ai = \begin{bmatrix} C\theta_i & -S\theta_i & 0 & 0 \\ S\theta_i & C\theta_i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C\alpha_i & -S\theta_i & 0 \\ 0 & S\theta_i & C\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

$$A_i = \begin{bmatrix} R_i^{i-1} & O_i^{i-1} \\ 0 & 1 \end{bmatrix} \quad (3)$$

$A_i$ is the homogeneous transformation matrix that expresses the position and orientation of $o_i x_i y_i z_i$ with respect to $o_{i-1} x_{i-1} y_{i-1} z_{i-1}$. In the equation (3) $R_i^{i-1}$ , $O_i^{i-1}$ denotes the rotation matrix position matrix of the end effector.



In the table 1,$a_i$indicates the link length along X- axis, $D_i$indicates the distance along Z-axis as from the reference frame. $\alpha_i$ is the angle between the adjacent axis passing the joints .θi is the angular displacement about the respective Z-axis about each joints.

**Table 1.D-H parameters of theproposed SCARA robot with DDT**

| Axis number | Joint angle ($\Theta_i$) | Link offset ($d_i$) | Link length($a_i$) | Twist angle($\alpha_i$) |
|---|---|---|---|---|
| 1 | $\Theta_1$ | $d_1$ | $L_m$ | 0 |
| 2 | $\Theta_2$ | 0 | $L_n$ | $180^0$ |
| 3 | 0 | d3 | $L_{o1}$ | 0 |
| *4* | *0* | *d3* | $-L_{o2}$ | *0* |
| *5* | $\Theta_5$ | $d_4$ | *0* | *0* |
| *6* | $\Theta_6$ | $d_5$ | *0* | *0* |

The first row of the table explains that ,about coordinate $x_0$, $y_0$, $z_0$ ,the main arm experienced an angular displacement is $\Theta_1$ ,link offset length along Z-axis passing through the joint 1 is $D_1$ , $L_m$ is the length of the main arm link and twist angle $\alpha_1$ is zero.

Similarly the successive rows describes that,about the coordinate $x_1$, $y_1$, $z_1$ the angular displacement is $\Theta_2$ ,link offset length is $d_2$ , length of the fore arm link is $L_n$and twist angle $\alpha_2$ between the Z-axes passing through the joint 2 and joint 3 is $180^0$,because the as per the assigned coordinate system the Z axes passing through the joint 2 and joint 3 is opposite to each other with respect to the reference frame .

The values of$\Theta_3$ ,$\Theta_4$ are zero because about its coordinates$x_3$, $y_3$, $z_3$ and $x_4$, $y_4$, $z_4$ it is not making rotation it is fixed ,because the attachment carrying the spindle of the drilling tool is fixed with the tool head.$d_3$ is the offset length for both the toolattachments. The$L_{o1}$and $L_{o2}$ is the length of the tool head flange along X-axis on which the tool A and B are mounted .The minus sign assigned to $L_{o2}$, because it is assumed that it is projecting opposite to the given coordinate configuration for the joint 3.

The homogeneous transformation matrix $A_i$ is computed as given in the Eqs. (4)-(9) for the D-H parameters in the each row of the Table. 1.

$$A_1 = \begin{bmatrix} C_1 & -S_1 & 0 & L_mC_1 \\ S_1 & C_1 & 0 & L_mS_1 \\ 0 & 0 & 1 & D_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$A_2 = \begin{bmatrix} C_2 & S_2 & 0 & L_nC_2 \\ S_2 & -C_2 & 0 & L_nS_2 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$A_3 = \begin{bmatrix} 1 & 0 & 0 & L_{o1} \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

$$A_4 = \begin{bmatrix} 1 & 0 & 0 & -L_{o2} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

$$A_5 = \begin{bmatrix} C_5 & -S_5 & 0 & 0 \\ S_5 & C_5 & 0 & 0 \\ 0 & 0 & 1 & d_4 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

$$A_6 = \begin{bmatrix} C_6 & -S_6 & 0 & 0 \\ S_6 & C_6 & 0 & 0 \\ 0 & 0 & 1 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

$$T_A = A_1.A_2.A_3.A_5 \quad (10)$$

The transformation matrix $T_A$ is formed after multiplying the appropriate matrices as given in Eq. (11).The position and orientation of the tool A can be found using the matrix equation $T_A$.

Similarly matrix $T_B$ isformed by multiplyingthe matrices as given in Eq. (14) and the position and orientation of the tool B can be found using the matrix equation $T_{B.}$

The first three variables of the last column of the matrix $T_A$ and$T_B$ are the X,Y and Z components of tool A and tool B respectively. In this paper, it is only focused on position of the tool A and B.

$$T_A = \begin{bmatrix} C_5(C_{1+2}) + S_5(S_{1+2}) & -S_5(C_{1+2}) + C_5(S_{1+2}) & 0 & (L_{o1} + L_n)C_{1+2} + L_m C_1 \\ C_5(S_{1+2}) - S_5(C_{1+2}) & -S_5(S_{1+2}) - C_5(C_{1+2}) & 0 & (L_n + L_{o1})S_{1+2} + L_m S_1 \\ 0 & 0 & -1 & -d_4 - d_3 + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (11)$$

The X, Y and Z Components of Tool A is given in the Eqs. (12) – (14)

$$X_A = (L_{o1} + L_n)C_{1+2} + L_m C_1 \quad (12)$$

$$Y_A = (L_n + L_{o1})S_{1+2} + L_m S_1 \quad (13)$$

$$Z_A = -d_4 - d_3 + d_1 \quad (14)$$

**Table. 2 Values of the D-H parameters**

| Parameters | Values | Parameters | Values |
|---|---|---|---|
| $L_m$ | *250 mm* | $d_2$ | *0* |
| $l_n$ | *200 mm* | $d_3$ | *5mm to 320mm* |
| $d_1$ | *400* | $d_4 = d_5$ | *80mm* |

The homogeneoustransformation matrix for tool B is $T_B$given in the Eq. (16)

$$T_B = A_1.A_2.A_4.A_6 \quad (15)$$

$$T_B = \begin{bmatrix} C_6(C_{1+2}) + S_6(S_{1+2}) & -S_6(C_{1+2}) + C_6(S_{1+2}) & 0 & (L_n - L_{o2})C_{1+2} + L_m C_1 \\ C_6(S_{1+2}) - S_6(C_{1+2}) & -S_6(S_{1+2}) - C_6(C_{1+2}) & 0 & (L_n - L_{o2})(S_{1+2}) + L_m S_1 \\ 0 & 0 & -1 & -d_5 - d_3 + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (16)$$

$$X_B = (L_n - L_{o2})C_{1+2} + L_m C_1 \quad (17)$$

$$Y_B = (L_n - L_{o2})(S_{1+2}) + L_m S_1 \quad (18)$$

$$Z_B = -d_5 - d_3 + d_1 \quad (19)$$

In the Eqs 11-13 and 16 -18, $C_{1+2} = \text{Cos}(\Theta_1 + \Theta_2)$,

$S_{1+2} = \text{Sin}(\Theta_1 + \Theta_2)$

Substituting the values of fore arm angular displacement $\Theta_2$ , main arm angular displacement $\Theta_1$ in the Eqs. 12 -13 to get the X,Y coordinate and the Z coordinate value by substituting the offset values given in the table 2 in Eq. (12)-(14) .thus X ,Y,Z coordinates of the tool A is found out.

Likewise Substituting the values of $\Theta_2$, $\Theta_1$, and the offset length values in the Eqs. (17)- (19) to get the X, Y, and Z coordinate values for tool B.

### *2.3.Inverse kinematics for the end effector*

The algebraic methods [2] of inverse kinematics are used to verify the joint angles using the coordinate Squaring the coordinate Equations (12) and (13), we get

$$X_A{}^2 + Y_A{}^2 = [(L_{o1} + L_n)\ C_{1+2} + L_m C_1]^2 + [(L_n + L_{o1})(S_{1+2}) + L_m S_1]^2 \tag{20}$$

By simplifying the equation (20) it will take the form

$$X_A{}^2 + Y_A{}^2 = L_m{}^2 + (L_{o1} + L_n)^2 + 2L_m(L_{o1} + L_n)\ C_2 \tag{21}$$

Thus $\Theta_2$ can be obtained as the inverse of cosine function

$$\theta_2 = \arccos\left(\frac{X_A{}^2 + Y_A{}^2 - L_m{}^2 + L_{o1}{}^2 + L_n{}^2 + 2L_{o1}L_n}{2L_m(L_{o1} + L_n)}\right) \tag{22}$$

The coordinate equations (12) and (13) of drill tool A can be rewritten using rule of sinus and cosines as

$$X_A = L_m C_1 + (L_{o1} + L_n)\ C_1 C_2 - (L_{o1} + L_n)\ S_1 S_2 \tag{23}$$

$$Y_A = L_m S_1 + (L_{o1} + L_n)\ S_1 C_2 + (L_{o1} + L_n)\ C_1 S_2 \tag{24}$$

Solving these equations $\Theta_1$ can be obtained as the inverse of sinus function

$$\theta_1 = \arcsin\left(\frac{L_m Y_A + Y_A L_{o1} C_2 + Y_A L_n C_2 - X_A L_{o1} - X_A L_n}{X_A{}^2 + Y_A{}^2}\right) \tag{25}$$

Substituting the coordinate values and the required parameter values given in Table 2 in the Eqs. 22,25 the joint angles are computed .Thus the position achieved by the forward kinematics is verified

## RESULTS AND DISCUSSION

The position of the drilling tool A and B can be obtained by substituting the joint angles and constant parameters mentioned in the Table.1 in the Eqs. (12)-(14) and Eqs.(17)-(19)-.The case studies mentioned in this section justifies the position of the dual tool, for variable angular displacements of main arm and fore arm.

***3.1First case.*** The rotation about the joint 1 by the Main arm is keptas constant $\Theta 1=30^{0}$ and assuming varying joint 2 displacement $\Theta_2$from $30^{0}$ to $270^{0}$ in the interval of $30^{0.}$

The Figure 3 and 4shows the X, Y coordinate position of tool A with respect to the rotation of fore arm about joint 2.

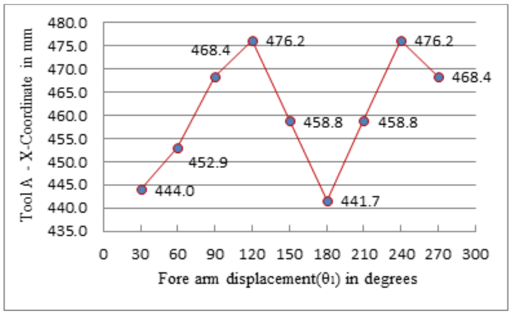


**Fig. 3. Tool A Position in X- Axis for varying $\Theta_2$**

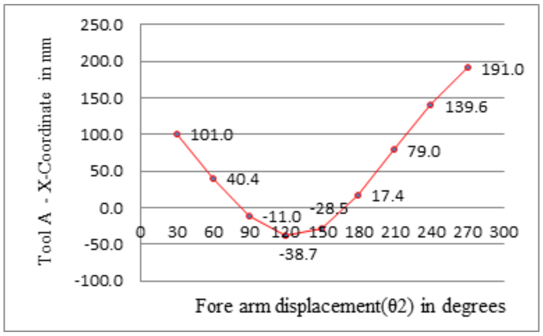


**Fig. 4. Tool A Position in Y- Axis for varying Θ2**

The XY coordinate values of tool B for varying fore arm displacement about joint 2 angular displacement in the is varying in equal intervals as mentioned earlier in this section is indicated in the Figure 3 and 4 .The Z coordinate value for tool A and B is obtained by substituting the offset values in the Eqs. 14 and 19

Similarly the Figure 5 and 6 depicted the values of X Y coordinates of tool A for angular displacement of main arm about joint 1 .Figure 7 and 8 interpolates the XY coordinate values of tool B for varying$\Theta_1$ and constant $\Theta_1$

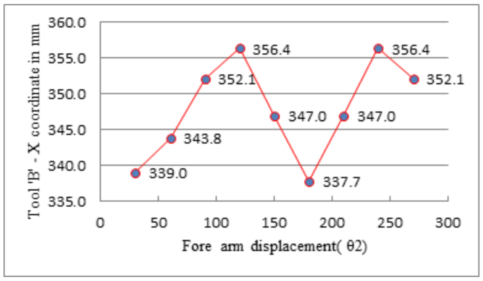


**Fig. 5. Tool B Position in X- axis for varying ϴ2**

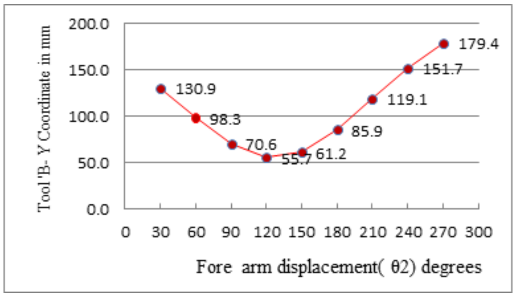


**Fig. 6. Tool B Position in Y- axis for varying ϴ2**

***3.2 Second case***: The rotation of fore arm about the joint 2 is kept as constant $\Theta_1 = 30^0$ and assuming varying main arm displacement$\Theta_2$about joint 2 in the range of $30^0$ to $270^0$ in equal intervals of $30^0$ .

The Figure 3 and 4 shows the X, Y coordinate position of tool A with respect to the rotation of fore arm about the joint 2.The Z value is a constant, obtained by substituting offset values in Eq.(14)

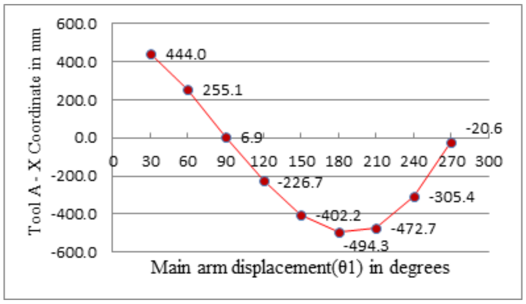


**Fig. 7. Varying ϴ1 and Tool A Position about X- Axis**

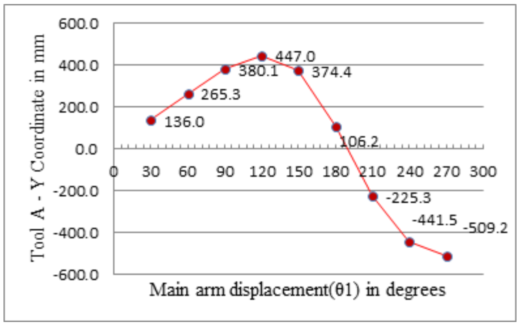


**Fig. 8. Varying Θ1 and Tool A position about Y- Axis**

The XY coordinate values of tool B for varying forearm displacement about joint 2 angular displacement in the varying equal intervals as mentioned earlier in this section is indicated in the Figure 5 and 6

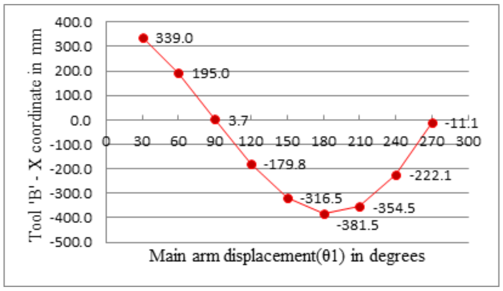


**Fig. 9. Varying Θ1 and Tool B position about X- Axis**

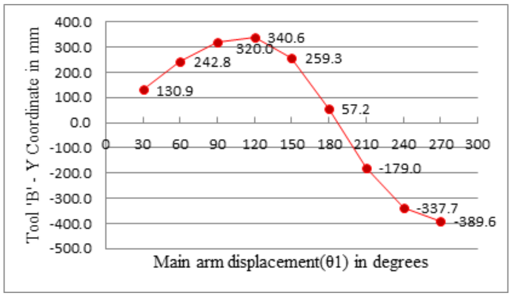


**Fig. 10. Varying $\Theta_1$ and Tool B position about Y- Axis**

## 4. CONCLUSION

In conclusion the present study in this paper put forth an analytical approach of forward kinematics to find the position of the dual drilling tool attached to the adjustable tool head of SCARA robot with 5 DOF. The position of tools are verified by the algebraic method of inverse kinematics .The calculations and the values indicated in graphs reveals that, the mathematical model and the equations developed using D-H convention to find the position of tools are appropriate. The adjustable tool spacing between the tools is an added advantage because it will be useful in PCB manufacturing industries to drill holes in different spacing as required per specification. The coordinate values plotted graphically indicates the position of the tool A and Tool B as per the required joint angles .So it is concluded that the desired position can be achieved for the given design of the SCARA robot with dual drilling tool . This work can be extended for multiple tools and thus the productivity can be improvised.

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