WORKSPACE SIMULATION AND ANALYSIS OF 5-DOF ARTICULATED ROBOT USING FORWARD KINEMATICS APPROACH

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ABSTRACT:
The kinematics of manipulators is a central problem in the automatic control of robot manipulators. The kinematics problem is defined as the transformation from the joint space to the Cartesian space. The kinematic equations of motion are derived using Denavit - Hartenberg (DH) representation. In this paper, an analytical solution for the forward kinematics of Lab Volt R5150 robot arm is presented, to analyze the movement of the robot arm from one point in space to another point, and analyzes its work space

The proposed model makes it possible to control the manipulator to achieve any reachable position and orientation in its environment. The forward kinematic model is predicated on Denavit Hartenberg (DH) parametric scheme of robot arm position placement.

The MATLAB 8.0 is used to solve the mathematical model for a set of joint parameter and to simulate the workspace of the 5DOF articulated robot arm. The kinematics solution of the MATLAB program was found to be identical with the robot arm's actual reading.

Keywords: **D-H Parameters, DOF, Transformation Matrices, Forward Kinematics, Work Space.**

تحليل ومحاكات حيز العمل لروبوت ممفصل ذا خمسة درجات حرية باستخدام التحليل الحركي

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الخلاصة:
يعرف التحليل الحركي في الروبوتات بانه التحويل من الاحداثيات المفصلية الى الاحداثيات الديكارتية ويعتبر التحليل الحركي عامل مهم في السيطرة على حركة الروبوت من موقع الى اخر. يقدم هذا البحث موديلا رياضيا مقترحا للتحليل الحركي المباشر من خلال اشتقاق المصفوفات الرياضية لجميع وصلات الروبوت باعتماد مفهوم (ديفنيت – هارتنبيرغ) وتم التطبيق لروبوت ممفصل ذا خمسة درجات حرية في مختبرات الجامعة التكنولوجية. تم استثمار مخرجات الموديل الرياضي المقترح لاستنتاج الموقع المؤثر النهائي للروبوت لجميع الاحتمالات وبناء حجم العمل الذي يمكن للروبوت العمل ضمنه.

استخدم برنامج الـ Matlab لمحاكات النتائج واظهار المخرجات على شكل رسوم ثلاثية الابعاد لحجم العمل للروبوت ومقارنة النتائج الرياضية للموديل المقترح مع الواقع العملي للروبوت حيث اظهرت النتائج تطابقا كبيرا لجميع الحالات الاختبارية حيث لم تتجاوز نسبة الخطأ عن 2 %.

1-INTRODUCTION :-

The workspace of robot manipulator is defined as the set of points that can be reached by its end-effector. Workspace is also called work volume or work envelope [Baki, et al-2007] .In the computation of robot workspace, the most concerned is its corresponding shape and volume. The both aspects of robot workspace have a significant importance because of their impact on the mechanism design and manipulator dexterity. The boundary surfaces of robot manipulators workspace have been studied using analytical or numerical methods [Hanming, et al-2012].

Analytical methods determine closed form descriptions of workspace boundary surfaces but these methods are usually complicated by nonlinear equations and matrix inversion involved in robot kinematics Numerical methods, on the other hand, are relatively simple and more flexible [Gupta, et al-1986].

2-PREVIOUS RESEARCH :-

Hanming Cai,and Tingting Xin used Monte Carlo method to analyze the workspace of an industrial robot and, modeled the robot with PRO/E [Mohammed, et al-2011]. The relationship between the robot position and joint variables were analyzed.

Yu Jie Cui deduced a formulation of modular robot based on Denevit and Hartenberg(D-H) and presented the kinematics simulation based on Matlab [Mostafa, et al-2012].

Mostafa Ghayour and Amir Zareei analysed the direct kinematics of position of non contact legs of a Hexapod Spider-like Mobile Robot [kumar, et al-2012]. Jun Xie, and etal established the kinematics model of practical series mechanical arm to act the manipulations with parallel executive mechanism, and solved the problem using Denavit-Hartenberg (D-H) transformation.

3-ROBOT DESCRIPTION: -

LabVolt Robot 5150 is a small table top robotic arm manufactured by LabVolt Inc as shown in Figure (1). It is a five articulated coordinate robotic manipulator that uses stepper motors for joint actuators, and its motion are controlled by Robot CIM software.

Lab-Volt R5150 robot arm has base, shoulder, elbow, tool pitch and tool roll which are all consisting rotary joints and provide 5 directions of motion (DOF) plus a grip movement These joints provide shoulder rotation, shoulder motion, elbow rotation, wrist up and down motion, wrist rotation and gripper motion. Lab-Volt R5150 has five rotational joints, five axis (three major axes : base –shoulder-elbow to position the wrist, and two minor axes : pitch and roll to orient the gripper) and a moving grip.

4-ROBOT ARM KINEMATICS:-

Robot arm kinematics explain the analytical description of the motion geometry of the manipulator with the reference to a robot coordinate system fixed to a frame without the consideration of the forces or the moments causing the movements.[Tahseen-2013]

For the direct kinematics the inputs are the joint angle vectors and the link length parameters, while the output of the problem is the orientation and the position of the tool or gripper. The block diagram representation of the direct kinematics shown by Figure (2).

Many methods can be used in the direct kinematics calculation. The Denavit-Hartenberg (D-H) analyses is one of the most used, in this method the direct kinematics is determinate from some parameters that have to be defined, depending on each mechanism. However, it was chosen to use the homogeneous transformation matrix.This transformation specifies the location (position and orientation) of the hand in space with respect to the base of the robot, but it does not tell us which configuration of the arm is required to achieve this location. Applying the D-H algorithm, the link coordinate diagram can be represented as shown in figure (3) , the dotted diagonal line between the origin of link3 and the origin of link4 indicates that the origin of these two coordinate frames coincide

Since LabVolt R5150 robot is a five-axis articulated coordinate robot as shown in figures (1) and (3) then:

The vector of joint variables is given by: $\theta = [\theta_1 \quad \theta_2 \quad \theta_3 \quad \theta_4 \quad \theta_5]^T$

The vector of joint distances is given by: $d = [d_1 \quad d_2 \quad d_3 \quad d_4 \quad d_5]^T$

The vector of link lengths is given by: $a = [a_1 \quad a_2 \quad a_3 \quad a_4 \quad a_5]^T$

The vector of the link twist angle is given by: $\alpha = [\alpha_1 \quad \alpha_2 \quad \alpha_3 \quad \alpha_4 \quad \alpha_5]^T$

These four parameters are called Denavit-Hartenberg (D-H) parameters. The D-H representation provides a systematic method for describing the relationship between adjacent links and gives a mathematical description for all serial manipulators depending on the robot geometry [Yi Cao, et al-2011]. It defines the position and orientation of the current link with respect to previous one. Using figure(3), the set of kinematics D-H parameters for LabVolt R5150 robot are shown in Table (1).

5-POSITION OF THE END-EFFECTOR:-

In physical applications, it is important to describe the position of the end effector of the robot manipulator in one global coordinates. In transforming, the coordinates of the end effector from the local position to the global position, the robot movements are represented by a series of movements of rigid links. Each link defines a proper transformation matrix relating the position of the current link to the previous one [Yu Jie, et al-2012].

Once a set of link coordinates is assigned using D-H algorithm, then the transform from coordinate frame (i) to coordinate frame (i-1) can be achieved using homogeneous coordinate transformation matrix. To determine the transformation matrix rotation and translation of the frame i-1 have to be done successively to render it coincident with coordinate frame i, this involves four fundamental operations as illustrated in Table (2)

This can be expressed as a product of four homogeneous transformation relating coordinate frame of (i-1) link to that of link(i) this relation is known as Arm Matrix. [Tahseen-2013]

After obtaining the table of DH convention, a series of homogeneous matrices can be derived depending on the number of the DOF. The transformation matrix for each joint from joint 1 to the joint *i* can be calculated as :[Z. Lai, et al-1988]

$$A_{i-1}^{i} = R_{(Z,\theta)} . T_{(0,0,d)} . T_{(a,0,0)} . R_{(x,\alpha)} \qquad (1)$$

$$A_{i-1}^{i}=\begin{bmatrix}\cos\theta & -\sin\theta & 0 & 0\\ \sin\theta & \cos\theta & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0 & 0 & a\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & d\\ 0 & 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos\alpha & -\sin\alpha & 0\\ 0 & \sin\alpha & \cos\alpha & 0\\ 0 & 0 & 0 & 1\end{bmatrix}$$

$$A_{i-1}^{i}=\begin{bmatrix}\cos\theta & -\sin\theta.\cos\alpha & \sin\theta.\sin\alpha & a.\cos\theta\\ \sin\theta & \cos\theta.\cos\alpha & -\cos\theta.\sin\alpha & a.\sin\theta\\ 0 & \sin\alpha & \cos\alpha & d\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (2)$$

While tool-tip position has been deduced by multiplying the five matrices $A_0^1.A_1^2.A_2^3.A_3^4.A_4^5$ as illustrated in equation (3) (fourth column in the final matrix):

$$A_{Base}^{Tool}=\begin{bmatrix}C_1C_{234}C_5+S_1S_5 & -C_1C_{234}S_5+S_1C_5 & C_1S_{234} & C_1(a_2C_2+a_3C_{23}+d_5S_{234})\\ S_1S_{234}C_5-C_1S_5 & -S_1C_{234}S_5-C_1C_5 & S_1S_{234} & S_1(a_2C_2+a_3C_{23}+d_5S_{234})\\ S_{234}C_5 & -S_{234}S_5 & -C_{234} & d_1+a_2S_2+a_3S_{234}-d_5C_{234}\\ 0 & 0 & 0 & 1\end{bmatrix} \quad (3)$$

$$\begin{aligned}P_X &= C_1(a_2C_2+a_3C_{23}+d_5S_{234})\\ P_Y &= S_1(a_2C_2+a_3C_{23}+d_5S_{234}) \qquad (4)\\ P_Z &= d_1+a_2S_2+a_3S_{23}-d_5C_{234}\end{aligned}$$

Where $S_{234}=\sin\ (\theta_1+\theta_2+\theta_3)$, $C_{234}=\cos\ (\theta_1+\theta_2+\theta_3)$

The above models have been invested to create of data base for various joint parameter and respective position and to simulate the positional coordinates of the end effector while it moves to a desired target.

6-CREATION OF DATA BASE FOR FORWARD KINEMATICS :-

For data generation, we considering all the combinations of five angles for the representation of robotic arm and store the output values. But to calculate the forward kinematics, only four angles has been considered as θ5 is independent of other angles, for every combination of θ1, θ2, θ3 and θ4 values, the Px , Py and Pz coordinates are deduced using the formulae for forward kinematics (eq. 4). The End effector starts in the configuration θ1= 0, θ2= -130, θ3= 130 , θ4= 90 and θ5 = 90 Its movement is limited within the range Maximum θ1= 153, θ2= 149 , θ3= 51 θ4= 180 and θ5 =360 , and also minimum θ1= -185, θ2= -32, θ3= -147, θ4= -5 , and θ5 = -360

The sample value of the tool tip position of the fifteen selected tests (data set values of the output) are listed in the table (3) using the proposed model of the forward kinematic solution as in equation (4).

7-WORK SPACE DETERMINATION AND SIMULATION :-

The reachable workspace of the end-effector depends on the maximum extension and shortening of the lengths and allowed ranges of joint rotation. The proposed sampling approach is applied to the joint space of the manipulator to approximate the workspace. For the 5 DOF robot arm , the computer yields values for the four joint variables $\theta_1, \theta_2, \theta_3, \theta_4$ (θ_5 not includ) in multi loops and generates a number of samples of the workspace, such as hundred or even more, depending on the desired accuracy and computing time. The values of joint variables are used to calculate the position of the end-effector (P_x, P_y, P_z) with forward kinematics and a dot is plotted at that position for each sample.

an algorithm has been proposed to determine the reachable workspace of a 5DOF Lab Volt robot end-effector with rotary joints. The algorithm employs forward kinematics solutions and is given below:

Input:

1- Identify each link parameters (D-H) of the robot as in table (1)

2- Identify the range of each joint angle ($\theta_1, \theta_2, \theta_3, \theta_4, \theta_5$)

Processing:

Mathematical processing according to the equation (4)

Output :

1- Three dimension graphical representation of the robot workspace using Matlap program.

2- Tool-tip position (samples) as in table (3)

By creating the database, the workspace of robot is determined and the range of motion of the robot wrist in three dimensional spaces is obtained, which is the workspace of the Robot. These positions are plotted in Matlab to develop all the surfaces enveloping the workspace of the Robot. Then 3D shape and volume of robot workspace are generated. The space coordinates are plotted , the Cartesian parameters are found for different set of Joint parameters.
(Fig.4) shows the workspace of the 5 DOF Lab Volt robot arm which consisting of 3D points, these points manipulated as point cloud. More quantity of points is required for getting better result in subsequent steps of the proposed method.

8-RESULTS AND DISCUSSION :-

The adopted modeling has been tested in real environment at university of technology /Dep. of production engineering and metallurgy for fifteen different cases using a Lab-Volt R5150 robot arm, also the method has been tested by linking the output of the mathematical formulation with Matlab Software for simulation using robot toolbox. In each test the adopted model gives good results for all the tested cases as shown in the table (4).
The results of comparison in fifteen different cases as illustrated in table (4) shows that the derived solution is very accurate, it was found that the maximum error in the tool pose position do not exceed (0.4) mm. The derived analytical forward kinematics solution provides the correct joint position of the end-effector to any given reachable position.

9-CONCLUSIONS :-

A complete analytical solution to the forward kinematics of the 5 DOF LabVolt robot is derived in this paper by partitioning the kinematics problem into two sub-problems at the wrist joint which greatly simplified the solution of the robot arm. As it can be clearly seen from the formulation and the results that the roll angle (θ_5) has no effect on the final position of the tool pose, but it effects the orientation of the end effector.

The results of comparison in different cases as illustrated in table (4) shows that the adopted model is very effective, efficient and accurate, it was found that the maximum error in the tool pose position do not exceed (2%). We believe that the solution developed in this paper will make the 5 DOF LabVolt robot more useful in applications .

This study has also provided an approach of using popular matlab program to reconstruct 3D shape and volume of robot workspace that provides good visualization and easier calculations of 3D volume and other geometric properties. In a 3D design environment, a 3D model of robot workspace will help to determine whether the workspace of a selected robot is large enough to cover the work place or to implement desired tasks, and also it will help to determine the optimal placement location of the robot within an operation.

Finally the adopted solution can also be extended to other robot control such as path planning.

Figure (1) LabVolt R5150 robot arm

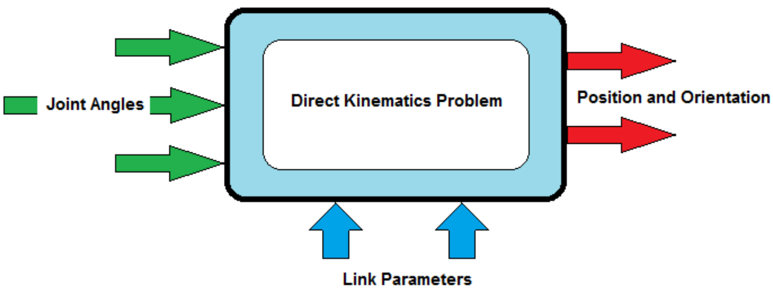

Figure (2) Direct Kinematic Block Diagram

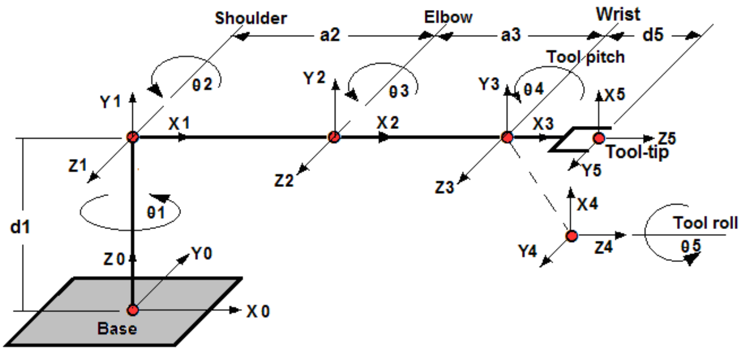

Figure (3) Link coordinate diagram of LabVolt 5150 robot arm

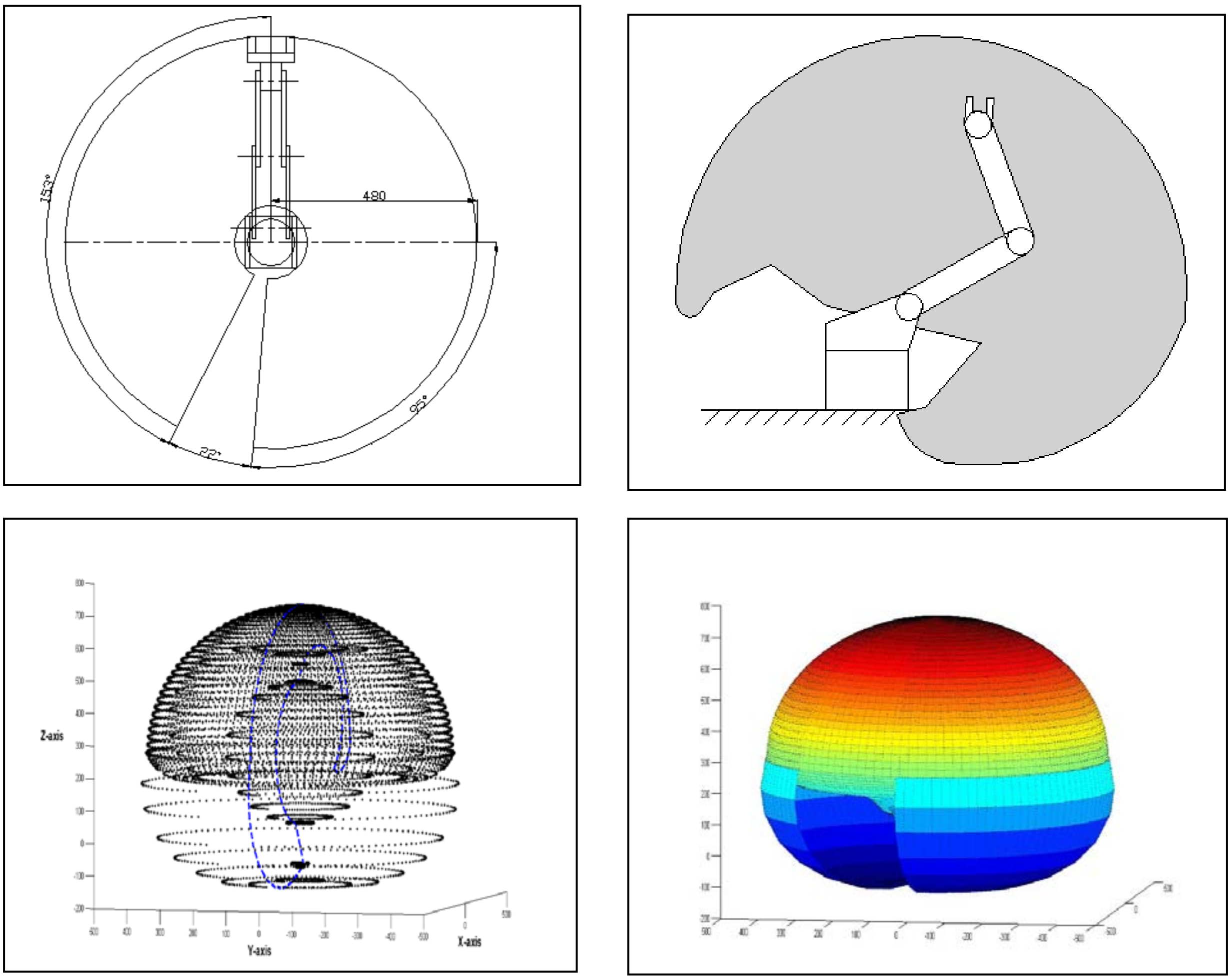

Figure (4). The generated Workspace of the LabVolt R 5150 robot a-Top view, b- Side view, c data set point d- Three dimension work space.

Table (1) Link parameters for LabVolt R5150 robot arm

Axis	θ		d	a	α
	θ_i	Range			
1	$\theta 1$	-185 : 153	255.5mm	0	90
2	$\theta 2$	-32 : 149	0	190mm	0
3	$\theta 3$	-147 : 51	0	190mm	0
4	$\theta 4$	-5 : 180	0	0	90
5	$\theta 5$	-360 : 360	115mm	0	0

Table (2) Transferring from frame i to frame i-1

Operation	Description
1	Rotation *about* z_{i-1} *by* θ_i
2	Translate *along* z_{i-1} *by a disance* d_i
3	Translate *along* x_{i-1} *through a length ai*
4	Rotation *about* x_{i-1} *by twist* α_i

Table 3: Home position and other selected set of joint parameters .

Test No.	Joint Coordinates					Tool tip position		
	θ_1	θ_2	θ_3	θ_4	θ_5	P_x mm	P_y mm	Pz mm
1	0	130	-130	90	90	182.55	0	401.48
2	-185	-32	-147	-5	-360	21.31	-1.87	266
3	153	149	51	180	360	270.39	-137.77	381.46
4	-108	131	30	153	129	120	369.32	381.46
5	13.6	-24	32.7	111.8	36.5	448	108.38	265.25
6	0.5	3	50.3	90.8	88	371.06	3.26	511.25
7	36.1	20.1	-3	12.1	50.8	336.59	245.45	276.27
8	102.9	33.6	49.6	133	5	-25.10	109.6	643.01
9	-185	51.6	-51.6	-51	28.1	-362.12	31.68	306.27
10	10	18.6	-99	82.1	4.4	211.96	37.38	13.53
11	64	42.6	21	139.1	-31.6	78.93	161.83	661.22
12	1	87.3	50.5	90.8	88	-278.91	-4.01	649.81
13	-38.9	125	51	117	140.9	-315.74	254.77	379.97
14	9	-32	14.9	66	36	424.5	67.34	22.99
15	-135	147.1	6	55	2	271.94	271.94	546.55

Table (4) measured and calculated for a sample set of test of end effector

Test No.	**Measured values (mm) Robot Software**			**Calculated values (mm) PROPOSED MODEL**		
	X	Y	Z	XX	YY	ZZ
1	182.55	0	401.48	182.870	0	401.098
2	21.31	-1.87	266	20.7407	-1.8146	266.269
3	270.39	-137.8	381.46	269.147	-137.14	180.359
4	120	369.32	381.46	119.597	368.082	380.917
5	448	108.38	265.25	447.563	108.277	265.377
6	371.06	3.26	511.25	370.7071	3.235	510.986
7	336.59	245.45	276.27	336.231	245.184	276.327
8	-25.10	109.6	643.01	-25.19	109.984	642.158
9	-362.1	31.68	306.27	-361.851	31.658	305.57
10	211.96	37.38	13.53	211.905	37.364	13.864
11	78.93	161.83	661.22	78.889	161.747	660.434
12	-278.9	-4.01	649.81	-218.032	-3.806	649.017
13	-315.7	254.77	379.97	-314.702	253.932	379.509
14	424.5	67.34	22.99	424.103	67.171	23.4
15	271.94	271.94	546.55	271.918	271.918	546.160

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